

University of Southampton Research Repository

Copyright © and Moral Rights for this thesis and, where applicable, any accompanying data are retained by the author and/or other copyright owners. A copy can be downloaded for personal non-commercial research or study, without prior permission or charge. This thesis and the accompanying data cannot be reproduced or quoted extensively from without first obtaining permission in writing from the copyright holder/s. The content of the thesis and accompanying research data (where applicable) must not be changed in any way or sold commercially in any format or medium without the formal permission of the copyright holder/s.

When referring to this thesis and any accompanying data, full bibliographic details must be given, e.g.

Thesis: Author (Year of Submission) "Full thesis title", University of Southampton, name of the University Faculty or School or Department, PhD Thesis, pagination.

Data: Author (Year) Title. URI [dataset]

University of Southampton

Faculty of Engineering and Physical Sciences

School of Civil, Maritime and Environmental Engineering

Carbon Footprinting of Railway Embankments and Cuttings: Assessing Potential for Carbon Reduction and Carbon Offsetting to Reach Net Zero

by

Tracey Anne Najafpour Navaei BSc (Hons), MSc, WhSch

ORCID: 0000-0002-7348-5761

A thesis for the degree of Doctor of Philosophy

May 2025

University of Southampton

Abstract

Faculty of Engineering and Physical Sciences

School of Civil, Maritime and Environmental Engineering

Doctor of Philosophy

**Carbon Footprinting of Railway Embankments and Cuttings:
Assessing Potential for Carbon Reduction and Carbon Offsetting to Reach Net Zero**

by Tracey Anne Najafpour Navaei

There are two overarching aims of this thesis. First, to identify and categorise different geotechnical assets, specifically embankments and cuttings, across the UK mainline railway and quantify the Business As Usual (BAU) Carbon Footprint (embodied CO₂e Carbon dioxide equivalent) of the materials and processes used by these geotechnical assets. The second aim is to assess the potential for emissions reduction and offset over the lifecycle of these assets to contribute towards Network Rail (NR) meeting its Net Zero Carbon by 2050 obligations under the Environment Act. NR's goals for net zero over the coming decades are aligned with Science Based Targets to enable this journey to be within the 1.5°C pathway set out in the Paris Agreement.

The academic literature review has identified gaps in data collection and a lack of consistent alignment of data to the current key guidance on carbon management, Publicly Available Specification 2080 (PAS2080), life cycle stages. To fill this gap a novel carbon data capture form has been created which is subsequently utilised in the collation of data for 50 small scale case studies over the GB mainline railway. These case studies encompass maintenance, refurbishment and renewal interventions in embankments, soil cuttings, and rock cuttings.

Data collected using this novel form has been utilised to create carbon footprints of the BAU scenario for these interventions via the Rail Safety Standards Board (RSSB) Rail Carbon Tool (RCT) aligned with PAS2080 life cycle stages to enable identification of carbon hotspots by life cycle stage. An in-depth analysis of the A0 life cycle stage carbon emissions for mainline railway earthworks has also been carried out, assessing the relative weighting of emissions in this stage. The BAU scenarios have been expanded from the current limited A1-5 before use stages to include the B stages for in use, and C stages for EOL activities, initiating the journey towards whole Life Cycle Analysis (LCA) for these earthworks.

Using the identified carbon hotspots as a starting point for emissions reduction, a variety of emerging and established emissions reduction technologies have been reviewed and applied to the 50 case studies, demonstrating the potential for emissions reduction in the areas of transport, both of staff, and materials & plant, and construction, in terms of processes and materials. An overview of offsetting methods and their applicability on a project-by-project basis for the renewal case studies, followed by an extrapolation to the extensive NR estate, has been explored (including assessment of the co-benefits of offsetting such as biodiversity), determining that emissions reduction in conjunction with offsetting actions can aid NR in reaching Net Zero by 2050 with a theoretical 1/7 of their reduced whole company emissions able to be offset via Enhanced Weathering (EW).

Table of Contents

Table of Contents.....	i
Table of Tables.....	xvi
Table of Figures	xix
List of Accompanying Materials	xxiii
Research Thesis: Declaration of Authorship.....	xxv
Acknowledgements	xxvii
Abbreviations	xxviii
Chapter 1 Background.....	1
1.1 Introduction	1
1.2 Aims and Objectives	7
1.3 Overview of Methodology.....	8
1.4 Scope of Thesis	10
1.4.1 Equating Differing GHG Gases with CO ₂ and GWP100.....	14
1.4.2 System Boundary.....	15
1.4.3 Operating Carbon	16
1.5 Key Terminology	16
1.5.1 Carbon Neutral/Net Zero.....	16
1.5.2 Carbon Footprinting and Carbon Accounting.....	16
Chapter 2 Literature Review	17
2.1 Introduction	17
2.2 Policy and Legislative Initiatives.....	17
2.2.1 International Initiatives.....	17
2.2.2 UK National Initiatives	18
2.2.3 UK Rail Initiatives	24
2.3 Research in Rail Infrastructure.....	26
2.3.1 Carbon Footprints of Rail Infrastructure	27

Table of Contents

2.3.2	Offsetting Carbon and Payback Time	31
2.3.3	UK Mainline Railway Whole Industry Carbon Footprint.....	32
2.3.4	Where is the Carbon in NR?	43
2.4	NR Perspective.....	46
2.4.1	Environmental & Biodiversity Policies	46
2.4.2	Waste Management & Sustainability	49
2.4.3	Low & Whole Life Carbon Initiatives	50
2.4.4	Consolidating Issues & Outlining Problems	51
2.4.5	Carbon Literacy	54
2.5	Circular Economy (CE) and Waste Hierarchy.....	55
2.5.1	NR Implementation of CE	60
2.6	Lifecycle Analysis (LCA)	65
2.6.1	Link Between CE and LCA.....	65
2.6.2	Literature Relating to LCA of Railways	68
2.6.3	Boundaries and Phases of LCA in the Literature.....	71
2.7	Transport & Rail Carbon Accounting Process Worldwide	75
2.7.1	Methodologies for Calculating Railway Infrastructure Carbon Footprints... 75	
2.8	Summary	77
Chapter 3	Carbon Footprinting Method	79
3.1	Introduction	79
3.2	Carbon Footprinting.....	79
3.2.1	Choice of RSSB RCT as Carbon Tool for Thesis	79
3.2.2	Steps to Produce a Carbon Footprint	84
3.2.3	Errors in Footprinting.....	85
3.3	Databases Used by Carbon Footprint Tools: Constraints & Assumptions	86
3.3.1	Primary Data in RSSB RCT – Bath ICE and DEFRA.....	87
3.3.2	Choice of Database	88
3.3.3	Verification of Primary Data Sources	89

3.3.4	Validity & Justification of Databases Used	90
3.3.5	Data Quality.....	90
3.4	Method: Case Studies Identification, Data Collection & Footprint Method ..	91
3.4.1	Case Studies Identification.....	91
3.4.2	Data Collection via Carbon Calculation Data Form.....	93
3.4.3	Footprint Production	100
3.4.4	Baseline Carbon Accounts	100
3.4.5	Assumptions in Carbon Footprints.....	101
3.5	Summary	102
Chapter 4	Results	103
4.1	Results of all 50 Case Studies	103
4.1.1	Overview of Whole Data Set.....	103
4.1.2	Correlation Analysis of Whole Data Set	108
4.1.3	Functional Unit kgCO ₂ e Volume/Year (Vol/Yr).....	110
4.1.4	Maintenance Case Studies	114
4.1.5	Refurbishment Case Studies	123
4.1.6	Renewal Case Studies.....	130
4.1.7	Summary of all Case Studies	135
4.1.8	NR Assets Compared to Case Studies & Extrapolation Exercise	138
4.2	Expanding Raw BAU A1-5 to Whole Lifecycle A1-C4 and A0 Carbon	140
4.2.1	BAU A1-5 to A1-C4 Expansions for Renewal Interventions.....	140
4.2.2	Calculation of A0 Carbon Lifecycle Stage	142
4.2.3	Uncertainty in Expansion.....	148
4.3	Comparison with the Literature	168
4.3.1	Introduction.....	168
4.3.2	Parameters for Comparative Literature Selection	168
4.3.3	Comparison with HS2 Earthworks (A1-5).....	168
4.3.4	Comparison with Mott Macdonald NW&C Carbon Assessment (A1-3, A4).....	170

4.3.5 Comparison with NR Switches & Crossings: Rempelos (2023)	171
4.3.6 Comparison with Measuring Railway Infrastructure: Lokesh, Densley-Tingley and Marsden (2022a)	172
4.3.7 Correlation Comparison: Ozcan-Deniz and Zhu (2017)	173
4.4 Conclusion.....	174
Chapter 5 Assessing Potential for Emissions Reduction.....	177
5.1 Introduction to Assessing Emissions Reduction.....	177
5.2 Reducing Transport Carbon: Assessing the Options	178
5.2.1 Staff Transport – A Change to EVs?.....	178
5.2.2 HGVs – A Move Towards Greener Biofuel?	179
5.2.3 Concluding Table of Emissions Factors to Use in Transport	182
5.3 Construction Industry Emissions including Hand-Held Tools & NRMMS	182
5.3.1 Electric Powered Tools and Equipment	184
5.3.2 Battery Power for Hand Tools and NRMMS.....	185
5.3.3 Hydrogen & Biodiesel Powered Tools & Equipment Including NRMMS.....	187
5.3.4 Alternative Decarbonisation Strategies	188
5.3.5 Concluding Table of EFs for Plant and Equipment.....	191
5.4 Assessing Emissions Reduction from Materials	192
5.4.1 Introduction to Materials Used in the Case Studies.....	192
5.4.2 EF Review of Aggregates, Granite, Limestone, Sand, Slate, Stone & Gravel 192	
5.4.3 Emission Factor Review of Bricks.....	193
5.4.4 Emission Factors Review of Concrete & Cement	193
5.4.5 Emission Factor Review of Geotextiles.....	197
5.4.6 Emissions Factors Review of Paint.....	198
5.4.7 Emissions Factors Review of Steel.....	198
5.4.8 Emission Factor Review of Timber.....	199
5.4.9 Concluding Table of Material ER EFs	199

5.5	Applying Emission Reduction to Case Studies.....	201
5.6	Results of Applying Emissions Reduction to Case Studies	201
5.7	Applying ER to Expansion A0-C4	204
5.8	Discussion of Results of Applying Emissions Reduction	206
5.8.1	Transport.....	206
5.8.2	Construction	207
5.8.3	Materials	207
5.8.4	Databases	209
5.8.5	Summary.....	209
Chapter 6	Assessing Potential for Emission Offsets.....	212
6.1	Introduction to Offsetting	212
6.2	Overview of NETs, CDR and NbS	213
6.2.1	Afforestation and Reforestation (AR)	214
6.2.2	Permanence of Storage, Saturation & Leakage	217
6.2.3	Sequestration Rates.....	218
6.3	Rail Corridor Vegetation, Hedgerows and Other Linear Forest Formations.	219
6.3.1	Linear Forest Formations (LFFs) and Other Linear Vegetation.....	223
6.3.2	Sequestration via Hedgerows	225
6.3.3	Choice of Vegetation	225
6.4	Applying Emissions Offsets to Case Studies	226
6.4.1	Using WCC Method to Increase Vegetation	227
6.4.2	Using EW – Area required to Offset Residual Carbon.....	234
6.5	Assessing Net Zero Potential of Combined CO₂e Reduction & Offsetting ...	235
6.5.1	Applying Emission Offsets to NR Land Assets	235
6.5.2	Climate Change Adaption.....	239
6.5.3	Pay Back Time.....	240
6.5.4	Ethics of NETs.....	240
6.6	Assessing Potential Sustainability Co-Benefits of CO₂e Offsetting	242

6.6.1 Increased Reforestation Co-Benefits	242
6.7 Concluding Remarks on Offsetting	243
Chapter 7 Conclusions	245
7.1 Meeting the Aims and Objectives	245
7.2 Interpretation of LCA	248
7.3 Addressing the UNSDGs	250
7.4 Research Impact	250
7.4.1 Meeting Net Zero by 2050	250
7.4.2 Sustainability Co-Benefits	252
7.5 Future Direction of Research.....	252
7.6 Final Remarks	253
Appendix A Appendices Relating to Chapter 1	256
A.1 Intervention Options: Maintenance, Refurbishment & Renewal of Earthworks	256
A.1.1 Intervention Options to Maintain Earthworks for Two-Year Lifetime	256
A.1.2 Intervention Options to Refurbish Earthworks for 20-Year Lifetime	258
A.1.3 Intervention Options to Renew Earthworks for 120-Year Lifetime.....	259
A.2 GWP Selected Gases	260
A.2.1 IPCC GWP Weightings for Selected Major GHGs Over Differing Lifetimes	260
A.2.2 IPCC GWP Weightings for Selected Major GHGs Over Differing Lifetimes	260
A.2.3 Emission Metrics for Selected Species.....	261
A.3 GHG Emissions, Scopes, and Streams.....	262
A.3.1 GHG Protocol Scope 1, 2, & 3 Emissions	263
A.4 Boundaries.....	264
A.4.1 Cradle-to-X Lifecycle Stages.....	264
A.5 Carbon Neutral/Net Zero	264
A.5.1 Boundary, Ambition and Residual Emissions.....	265

A.5.2	Balanced Carbon Scales	266
A.5.3	to Align with Objectives 3, 4 & 5 of Thesis	266
A.6	Carbon Footprint	266
A.6.1	Carbon Footprint, Climate Footprint and GHG Inventory Boundaries.....	267
Appendix B	Appendices Relating to Chapter 2	268
B.1	Timeline of UK environmental Legislative Commitments 1976-2016.....	268
B.2	UN Sustainability Development Goals	269
B.3	Pie Charts Showing Relative Percentages of OpCarb and CapCarb	270
B.3.1	Increasing Significance of Capital Carbon	270
B.4	ICR Themes Mapped onto CE Thinking.....	270
B.4.1	ICR Themes Mapped onto CE Thinking	270
B.5	Radiative Forcing Graph.....	272
B.5.1	Positive Radiative Forcing of Climate (1750-2005) due to Anthropogenic Emissions.....	273
B.6	NR's Biodiversity Delivery Model	273
B.7	Carbon Budget/NDCs	273
B.7.1	Pathways to Net Zero	274
B.8	Potential Routemap to Net Zero Carbon Rail.....	276
B.9	Errors in Footprinting	278
B.9.1	Framework to Assist and Guide Policy Makers.....	278
B.9.2	Key Elements of GHG Impacts of Rail Infrastructure	279
B.10	Low and Whole Carbon Initiatives	281
B.11	Carbon Accounting Methods and LULUC	282
B.12	UIC Ten Methodologies: Further Details.....	284
B.13	Transparency Rating of the Methodologies	286
B.14	System Boundaries Summary for Each Methodology	286
B.15	Elements of the Railway Infrastructure Included in Assessment.....	287

Appendix C Appendices Relating to Chapter 3	288
C.1 RSSB Tool Data Input & Training	288
C.1.1 Other Databases.....	289
C.1.2 Variation in Embodied Energy for Materials in the ICE V2 Database (amended from Hammond and Jones 2011 cited in Shillaber)	290
C.2 Example of Case Study Descriptions	291
C.3 Example of Carbon Calculation Data Form	292
C.3.1 Blank Form	292
C.3.2 FAQ Document	293
C.3.3 Completed Exemplar Form.....	296
C.4 Example of Carbon Calculation Data Form Queries & Responses	299
C.5 Example of Assumptions Made to Case Study	300
C.6 Example of A-Z .csv data download from RSSB RCT.....	301
C.7 Example of A-Z .pdf report download from RSSB RCT	302
C.8 Definition of 5Ch Earthworks.....	308
C.8.1 Definition of 5Ch Earthworks	308
C.9 Evolution of Carbon Calculation Data Form	309
C.10 Details Tracking Sheet for Case Studies	310
C.10.1 Example Headings from Tracking Sheet LHS	311
C.10.2 Example Headings from Tracking Sheet RHS	312
C.11 Differentiation of Footprints by Rural-Urban Classification	313
C.11.1 Method for Assigning Rural/Urban Classification.....	313
C.11.2 Rural Urban Classification: Descending Order of A4 Transport to Raw BAU 314	
C.11.3 Map of all 50 Case Studies Rural/Urban Classification	317
C.11.4 Rural Urban Classification Discussion	318
C.11.5 Percentage Contribution of A4 Transport to Raw BAU A1-5 for Rural Sites	319

C.11.6	Percentage Contribution of A4 Transport to Raw BAU A1-5 for Urban Sites	320
C.11.7	Top 5 Intervention Types for Rural Classification Case Studies.....	321
C.11.8	Top 5 Intervention Types for Urban Classification Case Studies	321
C.12	Proportional Embodied Carbon in Plant & Machinery	322
C.12.1	Embodied Carbon in Plant and Machinery Calculation	322
C.12.2	Other Methods of Calculating Apportioned Carbon	323
C.12.3	Comparison Table of Embodied Carbon Factors	324
Appendix D	Appendices Relating to Chapter 4	325
D.1	Complete Data Set of 50 Case Studies.....	325
D.2	Rankings: Staff Hours, Staff Transport, Functional Unit	328
D.2.1	Rankings of 35 Maintenance Case Studies	328
D.2.2	Rankings of 10 Refurbishment Case Studies	333
D.2.3	Rankings of 5 Renewal Case Studies.....	335
D.2.4	Comparison Graph of Top Four Maintenance Rankings.....	337
D.3	Descriptive Statistics of Raw BAU A1-5	337
D.4	Histogram for all 50 Case Studies' Functional Unit	338
D.5	Cross Reference Exercise of Case Studies Against NR Interventions.....	339
D.5.1	Maintenance Soil Cutting	339
D.5.2	Maintenance Rock Cutting	340
D.5.3	Maintenance Embankment.....	341
D.5.4	Maintenance Summary	342
D.5.5	Refurbishment Soil Cutting.....	343
D.5.6	Refurbishment Rock Cutting.....	344
D.5.7	Refurbishment Embankment.....	345
D.5.8	Refurbishment Summary.....	346
D.5.9	Renewal Soil Cutting	347
D.5.10	Renewal Rock Cutting.....	348

Table of Contents

D.5.11 Renewal Embankment	349
D.5.12 Renewal Summary	350
D.6 Maintenance Bar Graphs.....	351
D.7 Correlation Length of Works Hrs vs BAU A1-A5 Metric kgCO₂e/£1k Spend .	353
D.7.1 R, R2 and Equations of Trend Line for Different Maintenance Earthworks: Variables are Total Length of Works vs BAU A1-A5 Metric of kgCO ₂ e per £1k Spend.....	354
D.8 Correlation Staff Transport km vs Total Raw BAU A1-A5.....	355
D.8.1 R, R2 and Equations of Trend Line for Different Maintenance Earthworks.	356
D.9 Correlation Length of Works vs Total BAU: Embankment, Rock & Soil Cutting	357
D.9.1 R, R2 and Equations of Trend Line for Different Maintenance Earthworks.	358
D.10 Eastern Assets Extrapolation to All of NR.....	359
D.10.1 Raw Data Provided for Eastern Region	359
D.10.2 Extrapolation Exercise.....	375
D.11 Renewals BAU A1-5 to EXP Scenario A1-C4 Actions Per Stage	376
D.12 Average Functional Unit for Maintenance Interventions BAU Scenarios	379
D.12.1 Embankment Vegetation Intervention	379
D.12.2 Soil Cutting Vegetation Intervention.....	379
D.12.3 Scour Refurbishment Intervention	380
D.13 Breakdown of Lifecycle Stage Carbon for BAU Scenarios	381
D.14 Renewal Type Interventions: A0 Stages' Estimated Carbon Allocation.....	382
D.15 Breakdown of Lifecycle Stage Carbon Using A0 & EXP Data	383
D.16 BAU Expansion Scenario kgCO₂e per Stage	384
D.17 BAU Expansion Scenario Percentage Contribution per Stage	384
D.18 End-of-Life Pathways for Concrete and Steel	384
D.19 Confidence in Results.....	385
D.19.1 Data Confidence amended from (RSSB, 2021b, p.42)	385

D.19.2 Magnitude of Data amended from (RSSB, 2021b, p.42)	386
D.20 A0-C4 Expansion of Renewal Examples Comparison	387
D.21 Comparative Literature Assessment Against Suitability Factors	388
D.22 HS2 Rail Infrastructure Carbon Emissions by PAS Lifecycle Stages	395
D.23 Comparison of NR and HS2 by Lifecycle Stage Percentage Contribution ...	396
D.24 Descriptive Statistics for HS2 Data Set vs NR Renewals Functional Unit ...	397
Appendix E Appendices Relating to Chapter 5	398
E.1 Comparison of BEV vs PHEV in RSSB Tool	398
E.1.1 Emission Factors for EVs per km (A+C or B+C)	398
E.2 Determination of EF to Use for BEVs	398
E.2.1 Calculation of EF for PHEV Car and BEV Car & Van	399
E.2.2 Calculation of EF for PHEV Car and BEV Car & Van	400
E.3 Analysis of EV EFs from the Literature and Comparison to Tool	400
E.3.1 Comparison of Emissions from Differing Powered Vehicles	402
E.4 Literature Review Analysis of Biofuels	403
E.4.1 Consumption of Feedstocks & Average Emissions Savings	404
E.5 Table showing Biofuel Carbon Emissions Factors /% Reductions	406
E.6 Calculation of EF Percentage Reduction to Use for Biofuels	409
E.6.1 Total Carbon for all 50 Case Studies using Fossil Fuels and Biofuels	409
E.7 Determination of EF to use for Biofuel	410
E.7.1 Emissions Factors for Fuels (per Litre)	411
E.7.2 Emissions Factors for Fossil Fuels 2023 Factors	412
E.7.3 Metrics for Diesel and Petrol to Calculate Mileage per Litre of Fuel	413
E.7.4 Net and Gross CV per kWh and GJ per litre of fuel	414
E.7.5 Total Carbon for all 50 Case Studies using Fossil Fuels and Biofuels	415
E.8 Calculations to Determine L of Biodiesel for Diesel Machinery	417
E.8.1 Diesel Engine - Calculation of kgCO ₂ e/hr Using Differing EFs	418
E.8.2 kgCO ₂ e/hr Using Differing EFs	419

E.9 Calculations to Determine L of Bioethanol for Petrol Machinery	419
E.9.1 Petrol Engine - Calculation of kgCO ₂ e/hr Using Differing EFs	421
E.9.2 kgCO ₂ e/hr Using Differing EFs for Petrol vs Biofuel.....	421
E.10 Emissions Reduction from Materials	422
E.10.1 Selected Materials' Percentage Contributions to A1-3 Stage for BAU Scenario	422
E.10.2 EF Review of Aggregates, Granite, Limestone, Sand, Slate, Stone and Gravel 422	
E.10.3 Aggregates, Granite, Limestone, Sand, Slate, Stone, Gravel BAU EF & ER EF 422	
E.10.4 Emission Factor Review of Bricks.....	424
E.10.5 Emission Factor Review of Concrete & Cement	425
E.10.6 Concrete and Cement Percentage Contributions	427
E.10.7 Percentage contribution of Aggregates to A1-3 & A4 Stages.....	428
E.10.8 Percentage Contribution of Aggregates to A1-5 BAU	428
E.10.9 Concrete BAU EF and ER EF	428
E.10.10 EF Percentage Difference from Differing Portland Cement Mixes	429
E.10.11 Cement BAU EF and ER EF	430
E.10.12 Emission Factor Review of Geotextiles Geogrid BAU EF and ER EF 430	
E.10.13 EF Review of Steel Percentage Contributions of Steel to BAU	430
E.10.14 Steel BAU EF and ER EF	433
E.10.15 Emission Factor Review of Timber: Wood BAU EF and ER EF.....	434
E.11 Summary Table of Materials' ER Emissions Factors.....	434
E.11.1 Table of Materials in Case Studies	434
E.12 ER Actions Applied to Each Case Study.....	436
E.13 ER New A1-5 Totals for all 50 Case Studies.....	440
E.14 ER Scenario Renewal Type Interventions: A0 Stages'	442
E.15 Descriptive Statistics for ER Scenarios	444

E.16 Descriptive Statistics for ER Scenarios	445
E.17 Descriptive Statistics for ER Scenarios Percentage Reduction on BAU	446
E.18 Summary Table & Graph of Descriptive Statistics for ER Scenarios	447
E.19 Descriptive Statistics for ER & BAU Scenarios	447
E.20 Descriptive Statistics for ER Scenarios	448
E.21 Average Functional Unit for Maintenance Interventions	448
E.21.1 Embankment Vegetation Intervention	448
E.21.2 Soil Cutting Vegetation Intervention	448
E.21.3 Scour Refurbishment Intervention	449
E.22 Aldercar & Station Plantation Recalculation C1-4 Based on ER Scenario ...	449
E.23 Expansion of 5 Renewals ER to Include A0 Stage	450
E.24 ER new EXP Scenario (A0-C4) Totals for 5 Renewals.....	451
E.25 ER EXP Scenario Totals for Renewals Percentage Contribution per Stage ..	451
E.26 Data Used for BAU to ER EXP Comparison.....	452
E.27 Extrapolation of Asset Data for Maintenance Interventions	453
Appendix F Appendices Relating to Chapter 6	454
F.1 Benefits of NETs	454
F.2 Positive and Negative Issues of Differing CO₂ Sequestration Routes	455
F.3 Peatlands and Grasslands	456
F.4 Country Assignment Using Postcode	456
F.5 Assumptions in WCC Small Project Carbon Calculator	458
F.6 Cove LX Differing Broadleaf Planting Scenarios to Offset Carbon Using WCC	458
F.6.1 Differing Parameters to Investigate Options for Broadleaf Planting Regime	459
F.7 Cove LX Differing Conifer Planting Scenarios to Offset Carbon Using WCC	469
F.7.1 Differing Parameters to Investigate Options for Conifer Planting Regime .	470
F.8 WCC Mid-Point Carbon Calculations for Remaining 4 Renewals	482

F.9 EW Carbon Storage Potential	489
F.10 NR Pixel Data	491
F.11 NR All Land Asset AR Scenarios from WCC Exercise.....	494
F.12 Calculation of 25 Year NR Carbon Footprint	498
F.13 Climate Change Adaptation	498
F.14 Proctor Lecture Payback Times	500
F.14.1 Assumptions for Proctor Lecture Payback Times	501
F.15 Overview of NETs, CDR and NbS	518
F.15.1 Afforestation and Reforestation (AR)	520
F.15.2 Permanence of Storage, Saturation and Leakage.....	526
F.15.3 Sequestration Rates.....	526
F.16 Rail Corridor Vegetation, Hedgerows and Other Linear Forest Formations.	528
F.16.1 Linear Forest Formations (LFFs) and Other Linear Vegetation.....	532
F.16.2 Sequestration via Hedgerows	534
F.16.3 Choice of Vegetation	535
F.17 Assessing Net Zero Potential of Combined CO₂e Reduction & Offsetting ..	536
F.17.1 Applying Emission Offsets to NR Land Assets	537
F.17.2 Climate Change Adaption.....	543
F.17.3 Pay Back Time.....	543
F.17.4 Ethics of NETs.....	543
F.18 Assessing Potential Sustainability Co-Benefits	545
F.18.1 Increased Vegetation Co-Benefits.....	545
F.18.2 Biodiversity Co-Benefits	546
F.18.3 Social Co-Benefits	550
F.18.4 UNSDG Co-Benefits	551
F.18.5 Disbenefits	552
F.18.6 Circular Economy Co-Benefits.....	552
Appendix G Appendices Relating to Chapter 7	553

Table of Contents

G.1	FU Comparison of Means from BAU to ER.....	553
G.2	Five Major Impacts	553
	Glossary of Terms	555
	List of References	568

Table of Tables

Table 1.1	UK, Transport and Railway GHG Emissions in CO ₂ e 2018-2021.....	3
Table 2.1	Details of Selected Emissions Subcategories	37
Table 2.2	2019 GHG Figures for UK, Transport, Rail and NR	45
Table 2.3	NR Carbon Reduction Aligned to CP and SBT/IPCC Targets.....	45
Table 2.4	CE Thinking Aligned with Carbon Reduction Curve and BVRT	63
Table 2.5	Standardised Units for Study	73
Table 2.6	Allocation of Emissions by Categories and PAS2080 Lifecycle Stages	76
Table 3.1	Alignment of PAS2080 Modules to Asset Renewal/Replacement Work	80
Table 3.2	Available LCA Software Tools.....	82
Table 3.3	Guiding Principles from GHG Protocol 2004.....	83
Table 3.4	Common Footprint Mistakes & Mitigation Used in this Thesis	86
Table 3.5	Breakdown of Case Studies by Earthwork Type & Expected Lifespan.....	97
Table 3.6	Current and Proposed Footprint Scope	101
Table 4.1	Descriptive Statistics for All 50 Case Studies' for BAU Functional Unit	110
Table 4.2	Summary Table: Four Highest Functional Unit Maintenance Case Studies..	118
Table 4.3	Maintenance: Descriptive Statistics for Functional Unit BAU A1-5	119
Table 4.4	No. of Maintenance Case Studies Within Each Earthwork Type Which Have a Lifecycle Stage Contributing Greater Than Half of the Total Footprint	121
Table 4.5	Detailed Description of Rock Cutting Maintenance Case Studies	122
Table 4.6	Refurbishment Interventions: Ranking of Selected Metrics	126
Table 4.7	Renewals Ranking of Selected Metrics against Functional Unit Rankings....	131
Table 4.8	Percentage of Case Studies that Contribute Greater Than Half of Each PAS2080 Lifecycle Stage to Total BAU	135

Table of Tables

Table 4.9	Contribution of “Average Case Studies” by Absolute Carbon per Volume... 136
Table 4.10	Primary and Secondary “Hot Spots” from “Average Case Studies” Data 137
Table 4.11	NR Figures for Earthworks 139
Table 4.12	Eastern Region Assets Extrapolated to All NR for Whole of CP 139
Table 4.13	Renewals BAU and Expansion (EXP) Scenario Footprints A1-C4 141
Table 4.14	Renewal Type Interventions: A0 Stages' Estimated Carbon Allocation 143
Table 4.15	Contribution of Carbon Emissions from Earthworks Subdivided by Stage ... 146
Table 4.16	Average Functional Unit for Maintenance of Embankment 149
Table 4.17	Average Functional Unit for Maintenance of Soil Cutting 149
Table 4.18	Functional Unit for Scour Maintenance of Soil Cutting 150
Table 4.19	Renewals BAU A1-5 to EXP Scenario A1-C4 Actions Per Stage 158
Table 4.20	Calculation Approach and Sources of Uncertainty in Expansion 160
Table 4.21	Details of Carbon Per Lifecycle Stage for Expansions – as used for in this thesis 164
Table 4.22	Details of Carbon Per Lifecycle Stage for Expansions Using Highest Boundary Figures for A0, B and C..... 165
Table 4.23	Details of Carbon Per Lifecycle Stage for Expansions Using Lowest Boundary Figures for A0, B and C..... 166
Table 4.24	Comparison of Renewals with Rempelos (2023) A4 Data 171
Table 4.25	Comparison Table of Rempelos and Renewal Case Studies 172
Table 4.26	Comparison Table of Selected Correlations..... 174
Table 5.1	Total Carbon All 50 Case Studies: Fossil Fuels and Biofuels for Scope 1&3.. 181
Table 5.2	Concluding Table of EFs to Use in Transport ER Scenario..... 182
Table 5.3	Concluding Table of NRMM Emissions Factors with Examples 191
Table 5.4	Concluding Table of Material Factors Used in Case Studies 200

Table of Tables

Table 5.5	Mean ER Scenario Carbon Reduction Percentage from BAU kgCO ₂ e	201
Table 5.6	Hierarchy of Interventions by Stage for Differing Expected Lifespans	204
Table 6.1	Positive and Negative Side Effects of EW	217
Table 6.2	Habitat Sequestration Rates	218
Table 6.3	Country Assignment for 5 Renewal Case Studies	228
Table 6.4	Differing Planting Scenarios for Cove LX to meet NZ by 2050	230
Table 6.5	Renewals: Area Required to Sequester Carbon to Meet Net Zero Targets ..	233
Table 6.6	Land Area Required to Sequester Carbon by 2050 for Differing EW Rates ..	234
Table 6.7	Application of EW Low, Mid and Upper Values to Track Side 1m Strip	237
Table 7.1	Positive and Negative Side Effects of EW	525
Table 7.2	Habitat Sequestration Rates	527
Table 7.3	Application of EW Low, Mid and Upper Values to Track Side 1m Strip	540

Table of Figures

Figure 1.1	Surface Temperatures Observed and Modelled “Hockey Stick Shape”	1
Figure 1.2	Differing Emissions Pathways	2
Figure 1.3	PAS2080: 2016 Infrastructure Lifecycle Stages.....	5
Figure 1.4	Visualisation of Simple Embankment and Cutting.....	11
Figure 1.5	Scope of Earthworks for this Thesis	13
Figure 2.1	Timeline of UK National and NR Initiatives	19
Figure 2.2	Summary of UK Climate Policy Net Zero Strategy Schematic.....	20
Figure 2.3	Carbon Reduction Curve	21
Figure 2.4	Movement Away from Siloed Thinking.....	23
Figure 2.5	High Level Map of Industry Context, Main Carbon Targets and Plans	25
Figure 2.6	Key Elements of T1197 Methodology	33
Figure 2.7	Emissions by Stakeholder, Split by Emissions Activity	34
Figure 2.8	Rail Sector Carbon Footprint Split by Emission Source in tCO ₂ e.....	35
Figure 2.9	Embodied Emissions Split by Category and Stakeholder in ktCO ₂ e	35
Figure 2.10	Whole Mainline Rail Industry Carbon Emissions Baseline (FY 2019-20).....	37
Figure 2.11	GHG Protocol (2004) Relationship to This Thesis	40
Figure 2.12	System Boundary of Study	43
Figure 2.13	NR Pathway to Net Zero.....	44
Figure 2.14	Selected NR Environmental & Biodiversity Policies	47
Figure 2.15	Key Elements of Capital and Operational Carbon.....	51
Figure 2.16	NR Document Hierarchy	52
Figure 2.17	NR Biodiversity Documents Hierarchy	53
Figure 2.18	Movement from Linearity to Circularity	56

Table of Figures

Figure 2.19	Circular Framework of LCA Stages for Transport Infrastructure	57
Figure 2.20	Circularity of PAS2080 Lifecycle CO ₂ e Footprints	59
Figure 2.21	Waste Hierarchy.....	60
Figure 2.22	Waste Hierarchy Shape Illustrated with NR Extrapolated RRR Figures	62
Figure 2.23	CE Principles Mapped onto Asset Hierarchy.....	64
Figure 2.24	LCA Phases Used in this Thesis.....	67
Figure 2.25	LCA/LCC Integrated Model Framework	70
Figure 2.26	LCA/LCC System Boundaries	70
Figure 3.1	Network Rail Regions 2022	93
Figure 3.2	Alignment of Carbon Calculation Data Form with PAS2080 Stages.....	96
Figure 3.3	Case Studies' Located on GB Map Coded by Earthworks' Type	98
Figure 3.4	Case Studies' Located on GB Map Coded by Intervention Lifespan	99
Figure 4.1	Raw BAU (A1-5) Footprint Value (kgCO ₂ e) for All 50 Case Studies.....	105
Figure 4.2	Box Plots: Total BAU A1-A5, Total Staff Hrs, Total Staff Transport Mileage .	107
Figure 4.3	Log-Log Scatter Graph: Total BAU A1-5 (kgCO ₂ e) vs Project Length.....	108
Figure 4.4	Log-Log Scatter Graph: Total BAU A1-5 (kgCO ₂ e) vs Transport Mileage	109
Figure 4.5	Log-Log Scatter Graph: Total BAU A1-5 (kgCO ₂ e) vs Total Cost.....	109
Figure 4.6	Functional Unit BAU A1-5 (kgCO ₂ e Vol/Yr) for All 50 Case Studies.....	113
Figure 4.7	Maintenance Interventions Percentage Contribution of Each Stage BAU ...	115
Figure 4.8	Maintenance Interventions Pareto Graph of Functional Unit BAU	117
Figure 4.9	Total Raw BAU (kgCO ₂ e) per Hr of Works for Maintenance Interventions ..	120
Figure 4.10	Refurbishment Interventions Functional Unit BAU A1-5	124
Figure 4.11	Total Raw BAU kgCO ₂ e per Hour of Works for Refurbishments	125
Figure 4.12	Stacked Percentage Chart for BAU kgCO ₂ e.....	128

Table of Figures

Figure 4.13	Refurbishments: Absolute Contribution A1-3, A4 & A5 BAU kgCO ₂ e to A1-5129
Figure 4.14	Renewals Functional Unit BAU kgCO ₂ e per Volume/Per Year 131
Figure 4.15	Renewals BAU kgCO ₂ e Showing Percentage Contribution of Each Stage..... 133
Figure 4.16	Renewals Absolute Contribution A1-3, A4 & A5 BAU kgCO ₂ e to BAU A1-5 . 134
Figure 4.17	Percentage of case studies that contribute greater than Half of each lifecycle stage to total BAU A1-5 136
Figure 4.18	Percentage Contribution of "Average Case Studies" to Each Stage 137
Figure 4.19	Pre-Construction Site Activities 143
Figure 4.20	Renewals 100% Stacked Chart for Carbon Footprint Expanded to A0-C4 147
Figure 4.21	Uncertainty in Expansion 157
Figure 4.22	Comparison of Scenario Used for Expansion Against Highest and Lowest Values 167
Figure 4.23	Contribution of Stages for Renewal Case Studies & HS2 Interventions 169
Figure 4.24	Comparison of Renewal Interventions and HS2 Assets 170
Figure 4.25	System Boundary 173
Figure 5.1	Lifecycle Emissions Attributed to Each Phase for Hand-Held Power Tools .. 185
Figure 5.2	Diagram of Replacement Materials Available for Green Concrete..... 196
Figure 5.3	Mean ER Percentage Reduction by Stage Against BAU for Each Lifespan.... 202
Figure 5.4	Percentage Contribution of Each Lifecycle Stage for BAU Expansion A0-C4 205
Figure 5.5	Percentage Contribution of Each Lifecycle Stage for ER Expansion A0-C4... 205
Figure 5.6	Minimum Cost Route to Net Zero Carbon 211
Figure 6.1	Six Major Offsets 214
Figure 6.2	Carbon Sequestration Rate vs Cumulative Storage 215
Figure 6.3	Carbon Capture Placement Guidance for Rail Track infrastructure 222
Figure 6.4	Gap in Research Schematic 222

Table of Figures

Figure 6.5	Ecosystem Services & Disservices of Verges Adjacent to Linear Infrastructure	224
Figure 6.6	Conceptualization of differing land use carbon stocks	229
Figure 6.7	Broadleaf and Conifer Planting for Cove LX Net Zero by 2050	231
Figure 6.8	Amount of Planting to Meet 4 tCO ₂ e for Net Zero by 2050 for Cove LX.....	232
Figure 6.9	Graph of Cumulative Carbon Sequestration for Cove LX.....	233
Figure 6.10	WCC Carbon Storage Potential of Converted Grassland & Arable Land.....	236
Figure 6.11	EW Carbon Storage Potential of 1m Strip Adjacent to Track.....	237
Figure 6.12	Taxonomy of ER and Carbon Removal	241
Figure 6.13	Example of Net Zero Aligned Portfolio of Offsetting Interventions.....	242
Figure 7.1	Comparison of CCC's Balanced Pathway Compared to NR's	251
Figure 7.2	Carbon Sequestration Rate vs Cumulative Storage	521
Figure 7.3	Carbon Capture Placement Guidance for Rail Track infrastructure	531
Figure 7.4	Gap in Research Schematic	532
Figure 7.5	Ecosystem Services & Disservices of Verges Adjacent to Linear Infrastructure	534
Figure 7.6	WCC Carbon Storage Potential of Converted Grassland & Arable Land.....	539
Figure 7.7	EW Carbon Storage Potential of 1m Strip Adjacent to Track.....	540
Figure 7.8	Taxonomy of ER and Carbon Removal	544
Figure 7.9	Example of Net Zero Aligned Portfolio of Offsetting Interventions.....	545
Figure 7.10	Biodiversity Stripes, from (Richardson, 2021)	547

List of Accompanying Materials

- A to Z NR Carbon Calculation Data FINAL 50 CASE STUDIES Rev 1
DOI :10.5258/SOTON/D3242
 - A to Z Case Study Descriptions FINAL 50 CASE STUIDES Rev 1
 - A to Z NR Carbon Calculation Data Completed Forms FINAL 50 CASE STUDIES Rev 1
 - A to Z NR Carbon Calculation Data Queries and Responses FINAL 50 CASE STUDIES Rev 1
 - A to Z NR Case Study Assumptions FINAL 50 CASE STUDIES Rev 1
 - A to Z NR Case Study CSV Download FINAL 50 CASE STUDIES BAU Rev 1
 - A to Z NR Case Study CSV Download FINAL 50 CASE STUDIES ER SCENARIO Rev 1

- User Manual for Footprint Creation in RSSB RCT Using PAS2080 Template and Carbon Calculation Data Form Rev 1
DOI :10.5258/SOTON/D3243

- NR Carbon Data Calculation Form Rev 3
DOI:10.5258/SOTON/D3127

Research Thesis: Declaration of Authorship

I declare that this thesis and the work presented in it is my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

Navaei, T. et al. (2022) 'Carbon Footprinting of Railway Embankments and Cuttings: A Circular Framework', *Energy Reports*, 8 (11), pp. 8-13. Available at:
<https://doi.org/10.1016/j.egy.2022.05.051.Elsevier>

Najafpour Navaei, Tracey Anne, Blainey, Simon, Powrie, William and Preston, John (2022) Carbon accounting in mainline railway geotechnical solutions: Reducing embodied carbon in conjunction with offsetting to reach net zero. In, *Conference Proceedings of the World Congress on Railway Research 2022. World Congress on Railway Research 2022 (06/06/22 - 10/06/22)* (In Press)

Tracey Najafpour Navaei, Simon Blainey, John Preston & William Powrie (2024) Carbon footprinting of railway infrastructure: a standardized, consistent data collection method, *Carbon Management*, 15:1, 2368839, DOI: 10.1080/17583004.2024.2368839

Accompanying data set:

Najafpour Navaei, Tracey Anne (2024) Dataset supporting the publication "NR: Carbon Calculation Data form Rev 3". University of Southampton doi:10.5258/SOTON/D3127 [Dataset]

Najafpour Navaei, T., Blainey, B., Powrie, P., Preston, J. (2024) Decarbonisation of Small-Scale Railway Earthwork Interventions Using PAS 2080 Life-Cycle Methodology in Proceedings of the 5th International Conference on Transportation Geotechnics (ICTG) 2024, Volume 7, DOI: 10.1007/978-981-97-8237-6_20

Disclaimer: While every effort has been made to check the accuracy of the data used and control for anomalies, it is impossible to be entirely certain that all raw data supplied by Network Rail and others is entirely accurate, and this should be borne in mind when considering the results obtained.

Acknowledgements

This project was financed by an Engineering and Physical Sciences Research Council (EPSRC) Studentship and Network Rail as part of EPSRC Centre for Doctoral Training in Sustainable Infrastructure Systems Research Grant (EP/L01582X/1).

I would like to express my gratitude to my research supervisors, Professor Simon Blainey, Professor John Preston and Professor William Powrie, for their continuous support, guidance, constructive critiques and feedback of the numerous drafts of this research. My thanks are also extended to Doctor John Armstrong and Professor Ian Williams for their advice and constructive critiques of the intermediate stages of this research effort.

I am also very grateful to all the members of Network Rail who contributed to the data collection and especially to Simon Abbott, Gavin Jessamy, and numerous other NR staff for facilitating the entire process.

Thanks, are also extended to the Climate Change Committee for kindly giving their permission to cite Figure 1 from the Sixth Carbon Budget and to the IPCC for granting non-exclusive permission to reproduce Box TS.2, Figure 2 Panel (b) in IPCC, 2021: Technical Summary.

I would also like to say thank you to my husband Dr Reza Najafpour Navaei and my son Ryan Najafpour Navaei, for their unwavering support throughout my studies.

And finally, did you really think mummy would forget about the interrobang Ryan

?

Abbreviations

AGB	Above Ground Biomass
AR	Afforestation and Reforestation
AW	Ancient Woodland
BAU	Business As Usual
BECCS.....	Bioenergy with Carbon Capture and Storage
BECD	Built Environment Carbon Database
BEIS	Department for Business Energy & Industrial Strategy
BEV	Battery Electric Vehicle
BG	Bioenergy Grass
BGB	Below Ground Biomass
BIM	Building Information Model
BOM.....	Bill Of Materials
BRE.....	Building Research Establishment
BSI	British Standards Institute
BVCM.....	Beyond Value Chain Mitigation – see glossary for definition
BVRT	Better Value Rail Toolkit
CCC	Climate Change Committee
CCS.....	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CDW	Construction and Demolition Waste
CE.....	Circular Economy
CED	Cumulative Energy Demand
CMWG	Carbon Management Working Group
CNP	Compressed Natural Gas
COP	Conference of the Parties
CP.....	Control Period

DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
Defra	Department for Environment, Food & Rural Affairs
DESNZ	Department for Energy Security and Net Zero
DfT	Department for Transport
DOI	Digital Object Identifier
EcAp	Ecosystem Approach
EF	Emissions Factor
EFFC	European Federation of Foundation Contractors
ESG	Environmental, Social, and Governance
EOL	End Of Life
EPD	Environmental Product Declaration
ER	Emissions Reduction
EU	European Union
EV	Electric Vehicle
EW	Enhanced Weathering
FAME	Fatty Acid Methyl Esters
FOI	Freedom of Information
GA	General Assembly
GB	Great Britain
GDP	Gross Domestic Product
GGR-D	Greenhouse Gas Removal Demonstrator
GHG	Greenhouse Gas
GRIP	Governance for Railway Investment Projects
GWP	Global Warming Potential
HGV	Heavy Goods Vehicle
HSR	High Speed Rail
HWP	Harvested Wood Product

Abbreviations

ICE.....	Inventory of Carbon and Energy
ICE.....	Institute of Civil Engineers
ICEV	Internal Combustion Engine Vehicle
ICR.....	Infrastructure Carbon Review
IPCC.....	Intergovernmental Panel on Climate Change
IStructE	Institute of Structural Engineers
ISO	International Standards Organisation
IWA.....	International Workshop Agreement
LCA.....	Lifecycle Analysis
LCC.....	Lifecycle Cost
LCI	Lifecycle Inventory
LFF	Linear Forest Formations
LGV	French: <i>Ligne à Grande Vitesse</i> ; English: Mediterranean high-speed line
LNG	Liquified Natural Gas
LULUCF	Land Use, Land-Use Change and Forestry
Mi-ROG	Major Infrastructure - Resource Optimisation Group
MPA.....	Mineral Products Association
NbS	Nature Based Solutions
NC.....	National Communication
NDCs	Nationally Determined Contributions
NETs.....	Negative Emissions Technologies
NIC	National Infrastructure Commission
NR	Network Rail
NRMM	Non-Road Mobile Machinery
NW&C.....	North West and Central (NR Region)
OLE.....	Overhead Line Equipment
OF	Ocean Fertilisation
ONS.....	Office for National Statistics

ORR.....	Office of Rail and Road
PACE	Project Acceleration in a Controlled Environment
PHEV	Plug-in Hybrid Electric Vehicle
PPN	Policy Procurement Note
R&D	Research & Development
RCT.....	Rail Carbon Tool
RIA	Rail Industry Association
RICS.....	Royal Institution of Chartered Surveyors
RRR	Reuse, Recycling, Recovery
RSSB.....	Rail Safety and Standards Board
SBT.....	Science Based Target
SBTi.....	Science Based Target initiative
SCM	Supplementary Cementitious Material
SCS	Soil Carbon Sequestration
SDGs	Sustainable Development Goals
SNCF	Société nationale des chemins de fer français
SOC	Soil Organic Carbon
SPEED.....	Swift, Pragmatic and Efficient Enhancement Delivery
SSSI	Sites of Special Scientific Interest
UIC	International union of railways
UK NEA	UK National Ecosystem Assessment
UN.....	United Nations
UNSDGs	UN Sustainable Development Goals
UNFCCC	United Nations Framework Convention on Climate Change
VFS/VS	Vegetated Filter Strip and Swale
WCC.....	Woodland Carbon Code
WRACCA	Weather Resilience And Climate Change Adaption
WTW.....	Well to Wheel

Chapter 1 Background

1.1 Introduction

There is increasing evidence that global temperatures are rising, with human-induced warming of over 0.2°C per decade Forster *et al.* (2024), and that the world is in the grips of a climate emergency. The terminology has recently been upgraded from climate warming to climate boiling to focus the public's attention on the serious and urgent nature of the crisis (UN Secretary-General António Guterres, 2023). This stark temperature rise in the past century has been explicitly conveyed by Mann, Bradley and Hughes (1999) [ENREF 265](#), in their original “hockey stick” graph, subsequently validated and extrapolated in the recent United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) report (Arias *et al.*, 2021), see Figure 1.1.

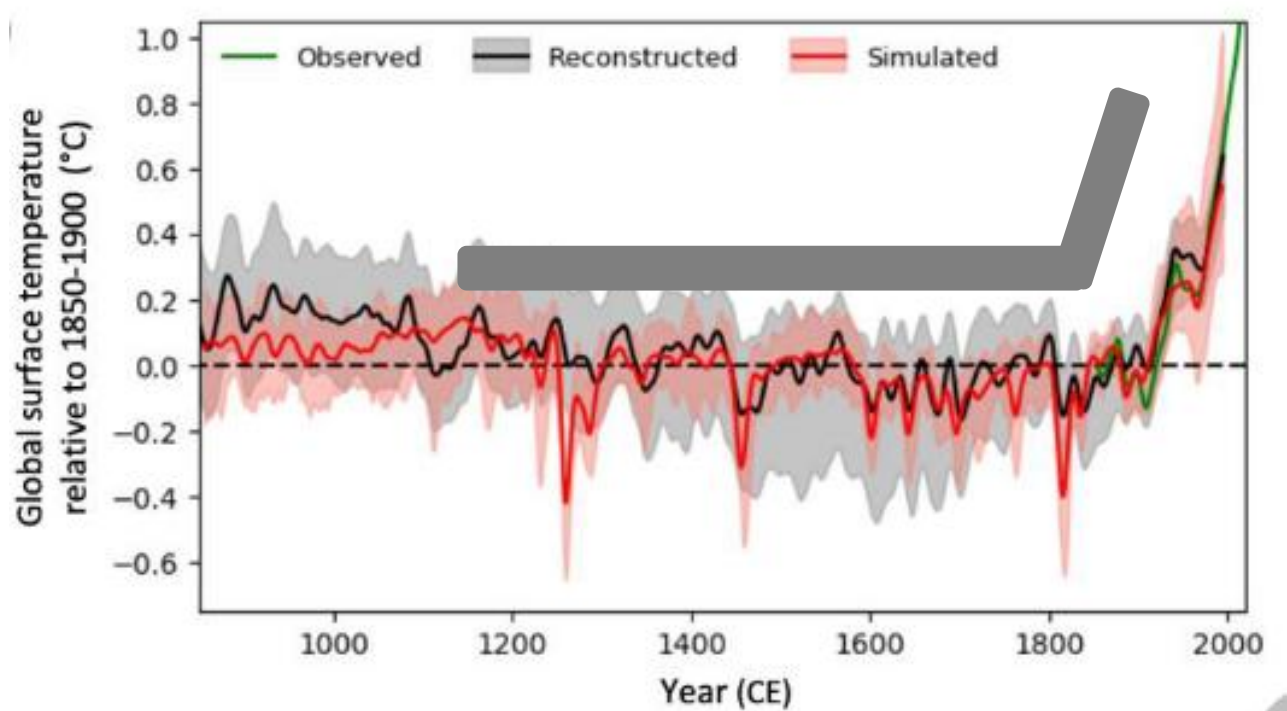


Figure 1.1 Surface Temperatures Observed and Modelled “Hockey Stick Shape”, amended from Arias *et al.* (2021, p.TS-103)

Figure 1.1 illustrates the sharp upwards trajectory of global surface temperatures during and post 20th century. The IPCC reported that the relationship between cumulative carbon dioxide (CO_2) emissions and the maximum global mean surface air temperature is near-linear, and it is now an

established fact that there is human influence on the climate system¹. The IPCC estimate that the 1.5°C line of global warming will be crossed in the early 2030s, ten years earlier than previously estimated (IPCC, 2021) and also detail the potential impacts of global warming reaching 1.5°C in their special report (IPCC, 2018).

The IPCC Working Group provide a description of the differing emission pathways the world is facing, and their predicted outcomes in terms of CO₂ emissions. These are affected by the amount of greenhouse gas (GHG) emissions, the amount of global warming this will cause, and the subsequent response of the climate system to this warming (Arias *et al.*, 2021). The five main emissions pathways are illustrated in Figure 1.2. Only the very low pathway can achieve net zero by 2050.

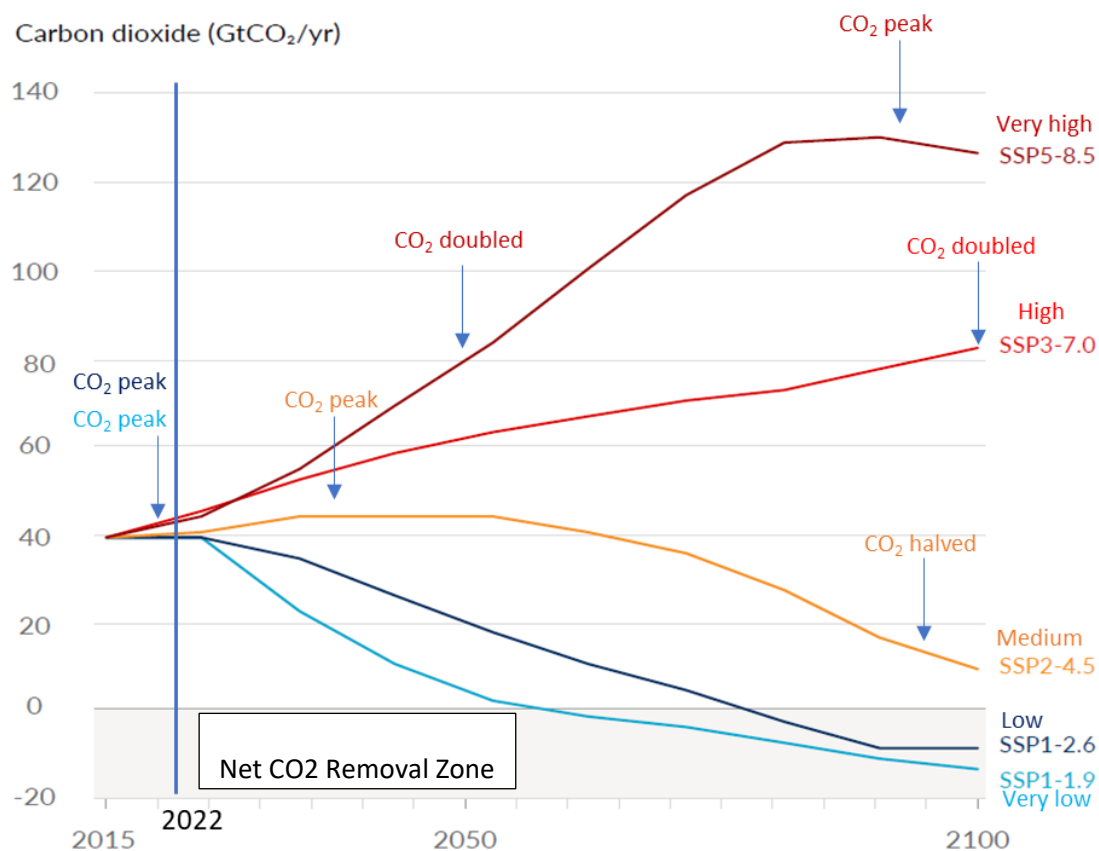


Figure 1.2 Differing Emissions Pathways, amended from Arias *et al.* (2021, p.TS-53) and IPCC (2021)

Reaching net zero GHG emissions will not result in declining temperatures, merely temperature stabilisation, and net negative CO₂ emissions may be required to return warming to lower levels in

¹ When discussing carbon throughout this report the terminology carbon or CO₂e shall be used when referring to the Carbon Dioxide equivalent Kyoto basket of gases (including the Doha Amendment gases) UNFCCC (2013) *United Nations Framework Convention on Climate Change Amendment to the Kyoto Protocol Decision1 CMP.8 FCCC/KP/CMP/2012/13/Add.1*. Available at: https://treaties.un.org/doc/source/docs/Doha_Decision1_CMP.8-E.pdf. These being the, originally six, and now seven, gases that are included in global accounting of GHG emissions.

the long term, see Figure 1.2. There is huge uncertainty around the remaining carbon budget, the amount of CO₂ that can be added to the atmosphere while still limiting warming. For the 1.5°C warming scenario the 50th percentile range, including recent emissions and historical temperatures, is 500 GtCO₂ with a variation of at least ± 220 GtCO₂. This excludes variations from other geophysical uncertainties (IPCC, 2021).

A survey of the UK's contribution to global carbon emissions for 2018, 2019, 2020 and 2021 shows that transport accounts for around ¼ of emissions and rail around 0.5% (HM Government, 2023b). See Table 1.1 for relative comparison to total UK emissions.

Table 1.1 UK, Transport and Railway GHG Emissions in CO₂e 2018-2021, amended from (HM Government, 2023b)

Carbon Contribution	2018	2019	2020	2021
Total UK estimated territorial GHG emissions	464.8Mt	450.4Mt	406.3Mt	426.5Mt
Transport (NC Sector classification)	125.0Mt	123.1Mt	99.3Mt	109.5Mt
Transport Percentage of UK Total	26.89%	27.33%	24.44%	25.67%
Railways (mobile combustion)	1.8Mt	1.9Mt	1.4Mt	1.6Mt
Rail Percentage of UK Total	0.39%	0.42%	0.34%	0.38%

UK territorial emissions are allocated into eight high level National Communication (NC) sectors. These sectors comprise: Energy supply, business, transport, public residential, agriculture, industrial processes, land use, land use change and forestry (LULUCF) and waste management. To contextualise, 1.7 MtCO₂e is broadly equivalent to 17,000 UK flights of around 500km with 200 passengers (Network Rail, 2021e). The figures in Table 1.1 show that while rail is a small proportion of transport and the UK total overall, it is not an inconsequential figure. Within the transport sector some consider these emissions by rail as “marginal” (representing less than 0.5% of direct transport emissions) (European Union Agency for Railways, 2020, p.12), as illustrated in the figures above. The NC sectors encompass more detailed source categories, defined by the IPCC for annual reporting to the UNFCCC. Analysis of the subcategories for transport and aviation indicates that these emissions are operational and exclude infrastructure. It may therefore be the case that additional emissions, attributable to transport, and specifically the rail sector, are not adequately captured, or, are accounted for elsewhere, for example as cement production within the industrial processes NC sector. Due to the current figures for transport only including operational emissions, to properly inform efforts to decarbonise transport, there is a need to quantify whole life carbon emissions associated with transport infrastructure.

Given work on emissions is often operationally focused (Trevisan and Bordignon, 2020), an understanding of how infrastructure lifecycles are related to GHG emissions is of paramount importance to this thesis as embodied and infrastructure related emissions can be significant (Baron,

Martinetti and P  pion, 2011; Cuenot and Hernandez, 2016; Landgraf and Horvath, 2021). The whole lifecycle analysis (LCA) in relation to rail was first identified in the seminal work of Chester and Horvath (2009) see Section 2.5.

The main research gaps addressed by this thesis are the lack of detailed data regarding carbon in railways and specifically earthworks. These, along with a lack of adherence to standardised terminology such as PAS2080 in describing carbon is explored further in Section 2.3. Furthermore, where carbon footprints are found in the literature, they are limited in scope in terms of lifecycle stages covered. This thesis aids this research gap by expanding the lifecycle stages from A1-A5 to incorporate A0 through to selected B and C stages. The lack of a consistent unit to allow for comparison between railway footprints has also been identified and addressed in this thesis via the inclusion of the functional unit to allow for comparison between differing physical size and expected lifespan case studies, see Section 2.6.1. This functional unit measurement will aid in filling both the literature and NR knowledge gaps. Specifically, the NR knowledge gaps that are addressed by this thesis include data on a range of differing earthwork interventions split by intervention type of maintenance, refurbishment and renewal.

The contributions to knowledge from this thesis include a standardised and consistent method for data collection using the Carbon Data Collection form created to collect data for this project. Creation and advocacy of use of this form contributes towards the need for accurate and complete records recommended in the literature by Krezo *et al.* (2018), with data for fuel consumption (calculated from hours running of machinery) and emissions from machinery used in the A5 construction processes of these case studies being collected from NR. This form will also contribute to knowledge for NR as this form has been advocated by the author to be utilised by NR as they move forward and expand their database of carbon footprints for their portfolio of assets. Use of this form to collect data, alongside the emissions reduction strategies outlined in Chapter 5 will aid NR in aligning their carbon reduction pathway to align with current net zero by 2050 UK legal targets.

A tool to visualise lifecycles is provided by the Institution of Structural Engineers (2020). The original version appearing in BS EN 15978 (BSI, 2011). The four main lifecycle stages in building construction are given in this tool as: Product, Construction, Use, and End of Life (EOL). Outside these lifecycle stages are the benefits and loads beyond the system boundary, such as reuse, recycling, and recovery potential (linking with circularity principles, see Section 2.5). The embodied emissions are those inherent in the materials themselves and the processing and transport of those materials to site, shown as the product and construction process stages of the lifecycle. However, operational emissions are those emissions released at the point of use, the use stage. On the one hand, tackling operational emissions is going to result in significant emissions reductions due to the quantity of

emissions associated with the use stage. On the other hand, reducing the embodied emissions, which can account for over half of all emissions related to building construction, (and averaging 70% of materials embodied in rail infrastructure compared to much smaller percentages in operation (Marsden, Lokesh and Densley-Tingley, 2022, p.6)) is also vital, to ensure that carbon budgets (see Appendix B.7) are not exceeded and global warming is limited (BSI, 2011). The split between operational and embodied emissions for transport infrastructure are less clear and are reviewed further in Chapter 2. These four lifecycle stages are then revised, expanded, and updated to form the backbone for the lifecycle information provided in the publicly available specification, PAS2080: 2016 Carbon Management in Infrastructure, see Figure 1.3.

Figure 1.3 builds on the main lifecycle stages outlined previously with the amalgamation of product and construction phases into the before use stage, along with the addition of the A0 stage to account for preliminary studies and consultations' carbon emissions. To date there has been little analysis of the A0 stage, which could potentially be a large carbon hotspot but is not currently accounted for in carbon footprints using the RSSB Rail Carbon Tool (RCT)². There are also additional B stages in this updated and revised figure which include operators' and users' utilisation of the infrastructure, along with a wider definition for stage D to include additional infrastructure functions. The D stage does not specifically mention such activities as carbon sequestration via tree planting or enhanced weathering, after application of carbon reduction measures have been exhausted, to reach net zero.

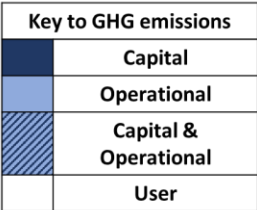
Infrastructure assessment life cycle information					
Before use stage		Use stage		End of life stage	
A0-5		B1-9		C1-4	
Pre-construction stage					
A0	Preliminary studies, consultations	B1	Use	C1	Deconstruction
Product stage		B2	Maintenance	C2	Transport
A1	Raw material supply	B3	Repair	C3	Waste processing for recovery
A2	Transport	B4	Replacement	C4	Disposal
A3	Manufacture	B5	Refurbishment	Key to GHG emissions 	
Construction stage		B6	Operational energy use		
A4	Transport to works site	B7	Operational water use		
A5	Construction/installation processes	B8	Other operational processes		
		B9	Users utilisation of infrastructure	Supplementary information beyond the infrastructure life cycle D Benefits and loads beyond the system boundary GHG emissions potential of: • Recovery including: ○ Reuse ○ Recycling • Benefits and loads of additional infrastructure functions	

Figure 1.3 PAS2080: 2016 Infrastructure Lifecycle Stages, amended from BSI (2016) and previously published in (Rujikiatkamjorn, 2024)

² The RSSB RCT is a free to use, for UK train industry, tool to produce Carbon Footprints of rail projects.

This thesis is undertaken in the geotechnical arena, taking into account that geotechnical practices have not previously based their decisions on the environmental impacts of a project, performance and cost being the key drivers in decision making (Shillaber, 2016, p.112). Due to the prevalence of policy and international concerns in the environmental arena, environmental decisions are starting to move to the fore (IPCC, 2021) and (HM Government, 2019a), see Section 2.2.

Network Rail's (NR) Environmental Sustainability Strategy (ESS) for 2020-2050, sets their ambition of achieving net zero carbon emissions by 2050, with four core priorities (Network Rail, 2020b): 1) Low-emission railway, 2) Reliable railway service, resilient to climate change, 3) Improved plant and wildlife biodiversity and 4) Minimal waste, sustainable use of materials.

With over 52,000 hectares of land assets containing some 6.3 million trees, outlined in The Network Rail Vegetation Review (Varley, 2018), NR is well positioned to implement long lasting change in terms of reducing its embodied carbon and improving its biodiversity. Clear goals are specified in this review, including:

- “Clear requirements for Network Rail to support delivery of the 25 Year Environment Plan,” (Varley, 2018, p.8) (which preceded the Varley Vegetation Review, detailing goals and actions via policies for the government relating to sustainable land use and nature recovery, aimed at improving the environment).
- “Lineside vegetation should be managed in line with other operational assets,” along with “a commitment to biodiversity net gain” (Varley, 2018, p.8).

NR, as the fourth largest public sector landowner in Britain, and one of the largest UK landowners, (Varley, 2018), has the land assets available to enable a substantial contribution to not only its own carbon reduction via carbon sequestration, but also to contribute to reducing UK carbon emissions as a whole. The spread of NR land assets is varied, over 11,600 hectares of deciduous and coniferous woodland and 6.6 thousand hectares of various types of grasslands (Dr Neil Strong, 2021), and these could potentially be profitable assets in terms of carbon sequestration and biodiversity potential.

Given NR has significant levels of embodied carbon this provides huge potential for carbon savings associated with their geotechnical infrastructure. Nonetheless quantities of carbon associated with the various standard details of NR's geotechnical solutions are currently unknown. That is, differentiating between the embodied carbon in the differing elements such as a given linear length of embankment, rock or soil cutting. The most efficient methods for either reducing or offsetting this embodied carbon are presently not well established. These present the gaps in the knowledge that this thesis aims to fill.

1.2 Aims and Objectives

This research has two aims, fulfilled via six objectives:

Aim 1: To identify and categorise different geotechnical assets, specifically embankments and cuttings, across the UK mainline railway and quantify the Business As Usual (BAU) Carbon Footprint (embodied CO₂e) of the materials and processes used by these geotechnical assets.

Objective 1: Identify and categorise geotechnical solutions across the UK mainline railway by asset and intervention type and determine which will be addressed as part of this research.

Objective 2: Quantify the BAU Carbon Footprint for embodied CO₂e within these differing solutions and identify carbon hotspots.

Aim 2: To assess the potential for emissions reduction and offset over the lifecycle of these assets.

Objective 3: Explore CO₂e reduction methods with potential applicability to railway embankments and cuttings, such as lower carbon concrete.

Objective 4: Consider the applicability of CO₂e offsetting methods such as sequestration via vegetation and the enhanced weathering of minerals, to railway embankments and cuttings.

Objective 5: Assess whether the combination of CO₂e reduction and offsetting methods may be able to balance the CO₂e account (to reach net zero) of railway embankments and cuttings.

Objective 6: Assess potential sustainability co-benefits of CO₂e offsetting.

The outcomes of this thesis will assist NR in meeting three of the four core priorities of the NR ESS, see Section 1.1, low-emission railway, improved biodiversity of plants and wildlife, and minimal waste and sustainable use of materials (Network Rail, 2020b).

The hierarchy of embodied carbon reduction methods and offsetting measures this thesis produces, provides a starting point for the railway geotechnical infrastructure becoming low emission. This also aids NR as it works towards minimal waste and sustainable use of materials, outlined in Chapters 5 and 6, with the additional sequestration via further vegetation planting also contributing to improved biodiversity.

It is envisaged that the thesis outcomes will also assist NR in addressing the goals of The Network Rail Vegetation Review, see Section 2.2.3. Based on this review, the government must set out a clear policy position for NR in terms of delivering for the environment. NR should publish an ambitious vision for the lineside estate (this should include a commitment to biodiversity gain), and NR must value and manage its lineside estate as an asset (Varley, 2018). It is hoped that a low carbon culture can be fostered by NR staff to strive to achieve the lowest possible carbon with the greatest possible vegetation. This will be achieved by making carbon reduction part of BAU for NR staff via the use of the hierarchy of interventions when designing and maintaining geotechnical assets. This will result in a win-win, for carbon reduction and biodiversity gain.

Other potential impacts of this thesis are the potential for this hierarchy to be implemented by other rail infrastructure owners in different countries or other linear infrastructure owners, both in the UK via National Highways (previously Highways England), or in different countries.

The most efficient methods for either reducing or offsetting this embodied carbon are not well established, and these present the gaps in the knowledge that this thesis aims to fill (via Objective 2), with the intent to address the challenge of reducing embodied carbon in transport infrastructure in general (via Objective 3).

1.3 Overview of Methodology

The first aim of this thesis will be addressed via objectives 1 and 2.

Objective 1 defines what a railway earthwork is (to include embankments and cuttings), followed by definition of what earthwork interventions (such as maintenance, refurbishment and renewal) includes. Application of these definitions to those found within NR via use of their Costs and Volumes Handbook and determination of the scope of the thesis (see Section 1.4). Identification of the size of earthwork (around 100m) and time range for data collection (Jan 2021-April 2023) from interrogation of earthworks to be undertaken (“workplans”) within this time period in conjunction with NR contacts in the regions with a view to amass a suitably sized data set (case studies) covering a range of railway earthworks and intervention types.

Objective 2 will be met via collection of data (via case studies) from NR interventions utilising a data collection form created for this purpose, aligned with PAS2080. This form will align with templates in the RSSB RCT (dictated by NR to be used for the carbon footprinting of NR assets) to enable production of PAS2080 A1-5 lifecycle footprints (the BAU scenario).

The RSSB RCT is a web-based carbon reduction tool to assist the UK rail industry in understanding its carbon footprint, free to use for persons working in the UK rail industry. The data collected for each

case study is added to the tool and, using embedded carbon factors from the Bath ICE carbon database, DEFRA database, and bespoke product EPDs, it calculates the carbon footprint. These case studies can then have products and construction processes altered to gauge their impact on the footprint with the aim being to make carbon savings. It is in this way a comparative tool rather than an absolute measure (Network Rail, 2021e).

This definition of the tool as comparative is important, as when comparisons are made in the method section, a comparative tool means that the figure of a particular project can be compared to the literature and with other low-carbon versions of itself, rather than just presenting a standalone figure, which on its own has little meaning. The boundary conditions and caveats to the carbon footprint figure will require careful analysis to ensure like-for-like comparisons are made.

The basic formula used in the tool is as given below in Equation 1 (Calculation for Embodied Carbon Value, amended from Institution of Structural Engineers (2020) where * also known as an Emissions Factor (EF)):

Equation 1

$$\text{Carbon Conversion Factor} * (\text{KgCO}_2(e)/\text{Kg}) \times \text{Material Mass (Kg)} = \text{Embodied Carbon Value (KgCO}_2(e))$$

The RSSB RCT will be used in conjunction with templates, which are guidance documents for users when adding products and construction processes to the tool (Network Rail, 2021e). Data will be collected for input to the tool via a novel carbon calculation data form, providing a template for data collection to be provided for rail infrastructure owners to use to capture the data required in a consistent format for input into a carbon calculation tool, the RSSB RCT for this thesis.

These carbon footprints of the case studies will be analysed disaggregated by lifecycle stages A1-3 (materials), A4 (transport) and A5 (construction processes) to enable identification of carbon hotspots within these stages for the differing types of earthworks and intervention type.

For this thesis the NR PAS2080 aligned templates in the RCT have been utilised. This has enabled input of data against each of the detailed lifecycle stages, A-D. Initially A1-3, A4 and A5 data, as previously illustrated in Figure 1.3, was collated and input into the tool to create the BAU footprint scenario.

The second aim of this thesis will be met via meeting objectives 3 to 6.

Objective 3 will be met via a literature review of CO₂e reduction methods with potential applicability to railway earthworks identified in Objective 1.

Objective 4 will be met via a further review of literature on the applicability of CO₂e offsetting methods, such as sequestration via vegetation and the enhanced weathering of minerals, to railway earthworks, identified in Objective 1.

Objective 5 brings together the outputs from the two literature reviews conducted in meeting objectives 3 and 4 regarding emissions reduction and offsetting, and applies them to expanded lifecycle case studies to answer the question of whether the combination of CO₂e reduction and offsetting methods may be able to balance the CO₂e account (to reach net zero) on a case study (project) basis. The case studies will be expanded using methods as outlined in the method section from the literature to expand the A1-5 lifecycle into B use and C end of life (EOL) stages, along with methods in the D stages to then offset these residual emissions once emissions reductions have been applied. With offsets being provided in the field of CDR overviewed in Chapter 6 with a specific focus on AR and EW. In addition to the project-by-project basis of achieving net zero, the potential for emission reductions and emission offset utilising NR's land assets' potential for carbon sequestration, is calculated, surmising the theoretical potential for the whole NR estate in terms of carbon reduction and carbon offset, based on optimum use of these assets.

Objective 6 is met via analysis of sustainability co-benefits of CO₂e offsetting and application of these in a railway context.

1.4 Scope of Thesis

The scope of this thesis is the three earthwork types of embankments, soil cuttings and rock cuttings, see Figure 1.4, excluding mining, falling outside of above ground interventions, see Figure 1.5.

The following is the NR definition of an earthwork and sets the scope for the case studies (Power *et al.*, 2016):

An earthwork is defined as a cutting, embankment or natural slope segment up to 100m long lying within the NR boundary that is equal to, or greater than, 3 metres high, or if less than 3m high, whose failure could pose an unacceptable risk to the safe operation or performance of the railway infrastructure. The earthworks that NR manage are categorised into the asset types of embankments, soil cuttings or rock cuttings.

(Power *et al.*, 2016)

From this definition the beginnings of the boundary definition for the case studies is found, in the earthwork definition of a rock or soil cutting, embankment or slope up to 100m long, see Figure 1.4. Further definitions of earthworks can be found in the thesis glossary.

A cutting is an excavation to enable the track to run on a more level gradient, and an embankment is a build-up of material to enable the track to run on a more level gradient over lower lying ground. A soil cutting is made through surrounding ground that is predominantly made up of soil, and a rock cutting, predominantly through rock (Network Rail, 2022b).

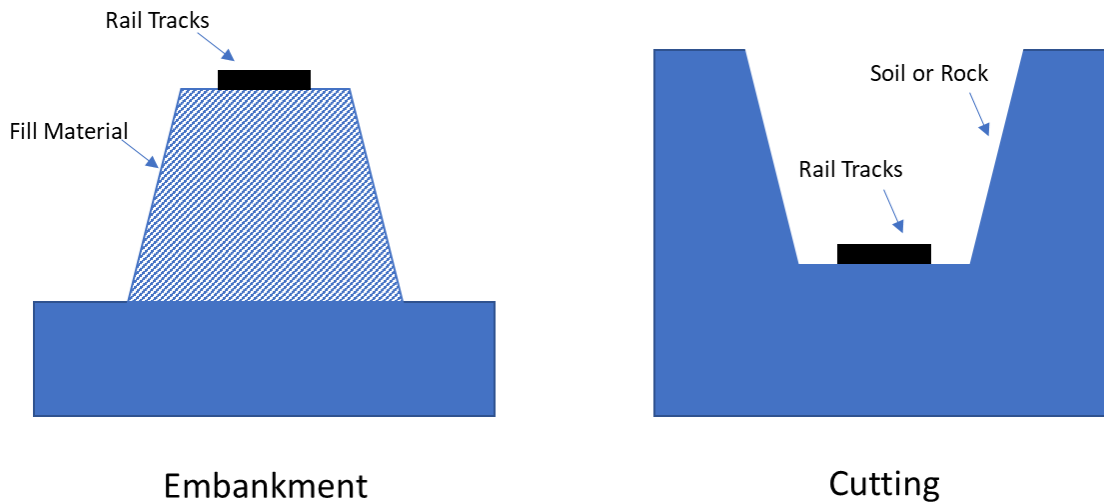


Figure 1.4 Visualisation of Simple Embankment and Cutting, amended from Lesley (2009, p.41)

These railway infrastructure earthworks are investigated via a collection of case studies encompassing the intervention options under the remit of maintenance, refurbishment, and renewal of earthworks (Network Rail, 2017b), see Appendix A.1.

The earthwork intervention options detailed in Appendix A.1 are categorised using definitions in the literature, namely:

“Maintenance (light rapid activities such as clearing drainage), refurbishment (heavier maintenance, such as scaling of rock slopes) and renewal (major engineering activities, such as the installation of sheet piling or soil nails)”

(Power *et al.*, 2016, p.731)

All 50 of the case studies in this thesis are from the GB mainline railway, see Section 3.4.1 for details of earthworks’ identification and locations.

These earthworks are investigated under the three expected intervention lifespans: Maintenance two years, refurbishment 20 years, and renewal at 120 years, see Figure 1.5. Figures from 2020 (issued before the Integrated Rail Plan (IRP) (DfT, 2021c) was released, curtailing HS2 planned track miles), show that NR manages the infrastructure slopes that enable some 20,000 miles of track on the GB mainline railway (Network Rail, 2022b), which encompasses 190,000 earthworks assets (Network Rail, 2018b). The UK has some 113km of High Speed (HS) lines in operation and 225km HS

lines under construction (UIC, 2023). The CO₂e benefits found via this thesis could have the potential to be realised throughout these mainline and HS networks, as the need for maintenance, refurbishment and renewal activities arise on these lengths of tracks currently in use.

LCA has been introduced in Section 1.1 where PAS2080 lifecycle stages have been illustrated in Figure 1.3. LCA is concerned with evaluating the environmental impacts from raw material extraction through construction processes and use, to EOL disposal and recycling (Vieira, Calmon and Coelho, 2016), providing a system boundary for the work. Carbon emissions are just one of a variety of environmental impacts that can be assessed using this methodology. Other environmental impacts include human toxicity, eutrophication, acidification and summer smog (de Bortoli, Bouhaya and Feraille, 2020). The need to investigate embankments and cuttings and to include further footprint family items, such as carbon, energy, water, materials, and land, to give “a complete picture of the environmental impact in HSR construction,” is noted (Cheng et al., 2020, p.2). See Section 2.6 for a discussion on LCA and Section 1.5.2 for a discussion on footprint families.

The main focus of this thesis is emissions reduction (ER) and offsetting, with ER divided into three discrete areas of transport, construction and materials to align with the PAS2080 A1-5 lifecycle stages (see Figure 1.3), and also aligning to carbon hotspots found in Chapter 4. Changes which fall outside of quantifiable emissions factors for use in the RSSB RCT such as those which require behavioural change or changes to working practices fall outside the scope of this thesis.

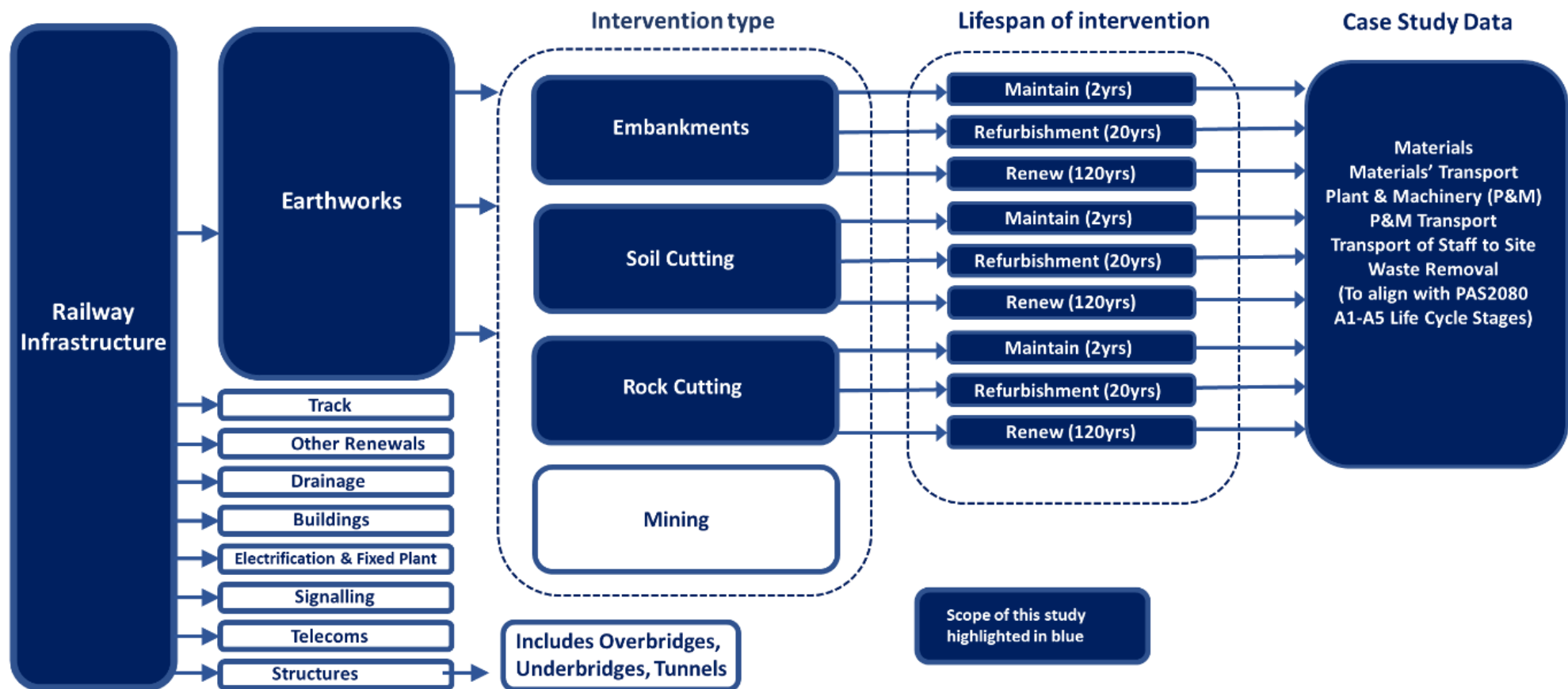


Figure 1.5 Scope of Earthworks for this Thesis, amended from (Network Rail, 2021a)

1.4.1 Equating Differing GHG Gases with CO₂ and GWP100

This thesis is solely measuring carbon dioxide equivalent (CO₂e) in earthworks, other footprint family items are out of scope. CO₂e is a method of equivalencing and summing up different GHG gases into one CO₂ equivalent gas to allow for ease of comparison. CO₂e is used owing to the prevalence of CO₂ in the atmosphere compared to the other gases. A more detailed definition of CO₂e can be found in the glossary, see also Section 1.4.1, and further exploration of timeframes in the form of Global Warming Potential (GWP) is given in Appendix A.2. GWP is dimensionless and compares the ability of differing GHGs to absorb infrared radiation over a period of time relative to the ability of CO₂. The factors used to equate differing GHG gases with CO₂ are provided by the IPCC and differ depending on the GWP timeframe assigned to them of 20, 100 or 500 years (IPCC, 2021), with 100 years being the most commonly considered time interval (Shillaber, 2016, p.24; EPA, 2017). The use of GWP100 has also been standardised by the international community at the 24th Conference of the Parties (COP24) to standardise reporting under the Paris Agreement (Climate Change Committee, 2020b).

For this thesis GWP100 (the most common factor) will be utilised where possible, and any other GWPs used will be indicated where this information is provided in the literature.

The use of CO₂e as a measure is contentious, with Shillaber (2016) calling for the use of CO₂ alone and not CO₂e due to inherent errors in tallying CH₄ into CO₂e, and how this changes over the differing GWPs, as this will differ for each different GHG.

There are different multipliers applicable for the main GHGs over selected lifetimes, with two selected gases, Methane (CH₄) and Nitrous Oxide (N₂O) having GWP factors of 81.2 and 273 for GWP20, and 5.38 and 233 for GWP100. These differing multipliers clearly indicate that GWP will have an impact where CO₂e is utilised. Further details of weightings for these selected GHGs can be found in Appendix A.2.

Wright, Kemp and Williams (2011), due to the variability of differing GHGs over temporal and spatial levels, rationalise their carbon footprint into CO₂ and CH₄ only. They take this posture as these are two most prevalent GHGs, and account for most of the radiative forcing. A graph illustrating this is given in Appendix B.5.

In agreement with use of GWP100 as a suitable time horizon, Kolosz *et al.*, (2017) cites LCA as paying a key role in determination of emissions in cradle-to-grave, in that all the GHGs must be included and converted to CO₂e based on a GWP of a “particular time horizon of 100 years” (Kolosz *et al.*, 2017, p.79). Detailed calculations and analysis of GHGs using these differing metrics are outside of the

scope of this thesis, however additional details and guidance can be found in the IPCC AR6 report in equations 7.SM.5.1, 5.2 and 5.3, along with the full table 7.SM.7 (IPCC, 2021).

1.4.2 System Boundary

A challenge found with transport infrastructure is the notion that some of the fundamental assumptions of LCAs, such as them having a definitive EOL, may not hold true, or that they may not be within a temporal boundary of interest to the infrastructure maintainer. This thesis addresses the issue of EOL and maintenance via expansion of the BAU scenario in whole lifecycle footprints as it is noted that “end-of-life or long-term maintenance needs of infrastructure are often ignored, as transport infrastructure is rarely fully decommissioned” (Saxe and Kasraian, 2020, p.1033). Leaving earthworks in situ is therefore one of the routes explored in the renewal expansion scenarios in Chapter 4.

With rail routes, decommissioning seldom occurs, a notable exception being the cuts arising from the Beeching Report (British Railways Board, 1963). The Beeching Report led to around one third of the railway network mileage in 1963 being lost to passenger and freight (White, 1963), although even here decommissioning did not always occur, with several lines being incorporated into the national cycle network (Di Ruocco *et al.*, 2017) or left derelict with “no plans for reuse or redevelopment” (Wikipedia, 2022). Most of the railway network lines remain operational via routine maintenance for extended periods of time, over 175 years in some instances (Sang-lam, Smethurst and Powrie, 2022), and, as such, materials used for earthworks cannot be salvaged for reuse (Lokesh, Densley-Tingley and Marsden, 2022a). Whereas track does tend to be completely renewed at about 30 year intervals (17-40 year service lives have been found (Milford and Allwood, 2010)), with the rails and fastenings materials salvaged for steel recycling (UIC, 2021). Sleepers have a varying service life depending on material used, 24-60 years for concrete, and softwood and hardwood of 10 to 36 and 15 to 36 years respectively (Rempelos, Preston and Blainey, 2020, p.4).

Rail infrastructure’s life is often extended, and as such rebuilt in essence in the same place, via use of maintenance, refurbishment and renewal, which impacts what the lifespans of these assets are (Saxe and Kasraian, 2020). These differing intervention lifespans are compared in this thesis via a functional unit, see Section 4.1.3.

The system boundary is of consequence as this defines what will and what will not be included within the footprint at various levels, therefore close attention needs to be made to any caveats of works that are analysed to ensure consistency of boundaries and that “like for like” is being compared. The system boundaries used here are the lifecycle stages of PAS2080, see Figure 1.3 and Section 4.3.2 for parameters assessed in this thesis to ensure comparability when comparing results to the literature.

See Appendix A.4 for further definitions of differing PAS2080 boundaries and Appendix A.3 for further details of scopes and streams.

1.4.3 Operating Carbon

Sensitivity analysis applied to Portuguese HSR using different country's energy mix (Jones, Moura and Domingos, 2017) indicate that as the UK energy mix moves towards greater use of renewables, operating carbon costs will reduce for UK railway infrastructure, see also Future Energy Scenarios framework which indicates the UK grid steadily decarbonising up to 2050 (UK National Grid, 2020, p.12). It is noteworthy that operating carbon is not applicable to earthworks as they have zero energy requirements when in use, and these are therefore excluded from the scope of the case studies' carbon footprints.

1.5 Key Terminology

Several items of key terminology are provided below, deemed essential to the reader in clarifying the position taken with respect to these for this thesis. Throughout, other key definitions, where not explained fully in the text, can be found in the Glossary of Terms.

1.5.1 Carbon Neutral/Net Zero

For this thesis net zero is defined using the IPCC definition (see glossary) and will include all GHGs to allow for CO₂e to be used, also aligning to the ISO IWA42 definition (see glossary). CO₂e is the metric used in the RSSB Rail Carbon Tool (RCT), used for creating the carbon footprints for this thesis. Carbon neutrality, due to its limited scope, is not used in this thesis. See Appendix A.3 and A.5 for further clarification on these terms.

1.5.2 Carbon Footprinting and Carbon Accounting

Given the ambiguities surrounding the term carbon footprint, along with the lack of a universal understanding of it at differing levels, in this thesis the term carbon footprint will be used to indicate the amount of CO₂e in each case study under each differing scenario. The carbon footprint to be used in this research will include all the gases in the Kyoto basket including the Doha Amendment and, as such, using the inventory boundaries outlined in Appendix A.6. These footprints would therefore be classified as climate footprints rather than carbon footprints by Williams *et al.* (2012).

Chapter 2 Literature Review

2.1 Introduction

An outline of selected environmental legislation, from international down to UK initiatives in Section 2.2, sets the general policy and legislative context. This is followed by exploration of research in rail infrastructure focusing on carbon footprints and where carbon is in the UK mainline rail and NR in Section 2.3. This chapter then provides an overview of the NR perspective including low carbon initiatives to date in Section 2.4 and continues with analysis of the literature in the area of circularity, and how NR is implementing the circular economy (CE) in Section 2.5. LCA with specific focus on literature relating to LCA of railways and transport is given in Section 2.6, followed by transport and rail carbon accounting processes in Section 2.7.

2.2 Policy and Legislative Initiatives

This section provides an overview of pertinent UK government commitments in the climate sphere, followed by a chronological discussion of the evolution and interconnectivity of policy and legislation in: International, UK national, and UK rail initiatives, regarding the environment, biodiversity, and climate change.

2.2.1 International Initiatives

Between 1976-2016 a plethora of international and national commitments were made by the UK government in the environment sphere (see Appendix B.1). The most pertinent to this thesis are the UNFCCC, the Kyoto Protocol, the UK Climate Change Act, and the Paris Agreement.

The UNFCCC (enacted 1992), one of the first global international treaties, (Nachmany *et al.*, 2014) acts as a framework for international cooperation to combat climate change (RSSB - Rail Industry Decarbonisation Taskforce, 2019). The Kyoto Protocol (agreed 1997) extends the UNFCCC, committing state parties to reducing their GHG emissions based on scientific consensus. Carbon sequestration via afforestation, reforestation (AR) and land use change (LUC) are explicitly mentioned in the Protocol as actions for countries in meeting their CO₂ emissions commitments (UNFCCC, 1998), aligning with Objectives 4 and 5, see Chapter 6. Holding the increase in global temperatures to well below 1.5°C was at the crux of the Paris Agreement, agreed at COP21, and a pivotal moment for climate change legislation, illustrating the UNFCCC trajectory (UNFCCC, 1992), and aligning with the pathways to net zero detailed in the Sixth Carbon Budget (see Appendix B.7.1)

and the SBT trajectory for NR (see Figure 2.13). Following the Paris Agreement, NDCs are set by each country, SBTs are then formulated from the NDCs. The SBTi was set up to enable companies to set their own science-based emissions targets congruent with the pledges made by signatories to the Paris Agreement, with the SBTi providing guidance to ensure compliance (SBTi, 2021b), see also UK Government (2020) and Section 2.2.2.

In tandem with these international climate change agreements are UN Sustainability Development Goals (UNSDGs), 17 interlinked global goals (UN General Assembly, 2015a) designed as a “blueprint” to achieve “a safer, more sustainable and equitable path” (UN Secretary-General António Guterres, 2020). Alignment of net zero strategy with the UNSDGs is also advocated in ISO IWA 42 (ISO, 2022). The UNSDGs, introduced in the 2015 UN General Assembly (GA), provide a framework for promoting sustainable development by 2030 (see Appendix B.2) (UN, 2021). Goal 13 on climate action is reflected in WRACCA guidance, see Section 2.4, where the need to allow for climate change in design is documented and also advocated in EFFC (2022), alongside Goal 7 affordable and clean energy. Goal 15 pertaining to life of land align with this SDG (UN General Assembly, 2015b) via the additional co-benefits of sequestration, assessed for Objective 5. The outcomes of this thesis are assessed against these goals in Chapter 7.

2.2.2 UK National Initiatives

The legislative perspective now shifts to a UK lens. The journey towards net zero for the UK at national level is comprised of a succession of interwoven policies and legislation, see schematic Figure 2.2, and also the timeline aligned to NR initiatives, Figure 2.1.

The Stern Review (Stern, 2007) was the catalyst for national climate change legislation, assessing the scientific evidence relating to the economics of climate change. It concluded that an urgent response, was needed, noting that the cost of prompt action would be far lower [than not], a message reiterated by the IPCC (IPCC, 2019).

The UK became the first country to introduce world leading legislation on climate change via The Climate Change Act 2008, incorporating statutory GHG reduction targets (Nachmany *et al.*, 2014) (later amended to net zero by 2050 (HM Government, 2019a)), alongside 5 year short-term carbon budgets (NDCs) (Nachmany *et al.*, 2014). Independent oversight is provided to the Government’s plans, via the Committee on Climate Change (CCC) (see Figure 2.2).

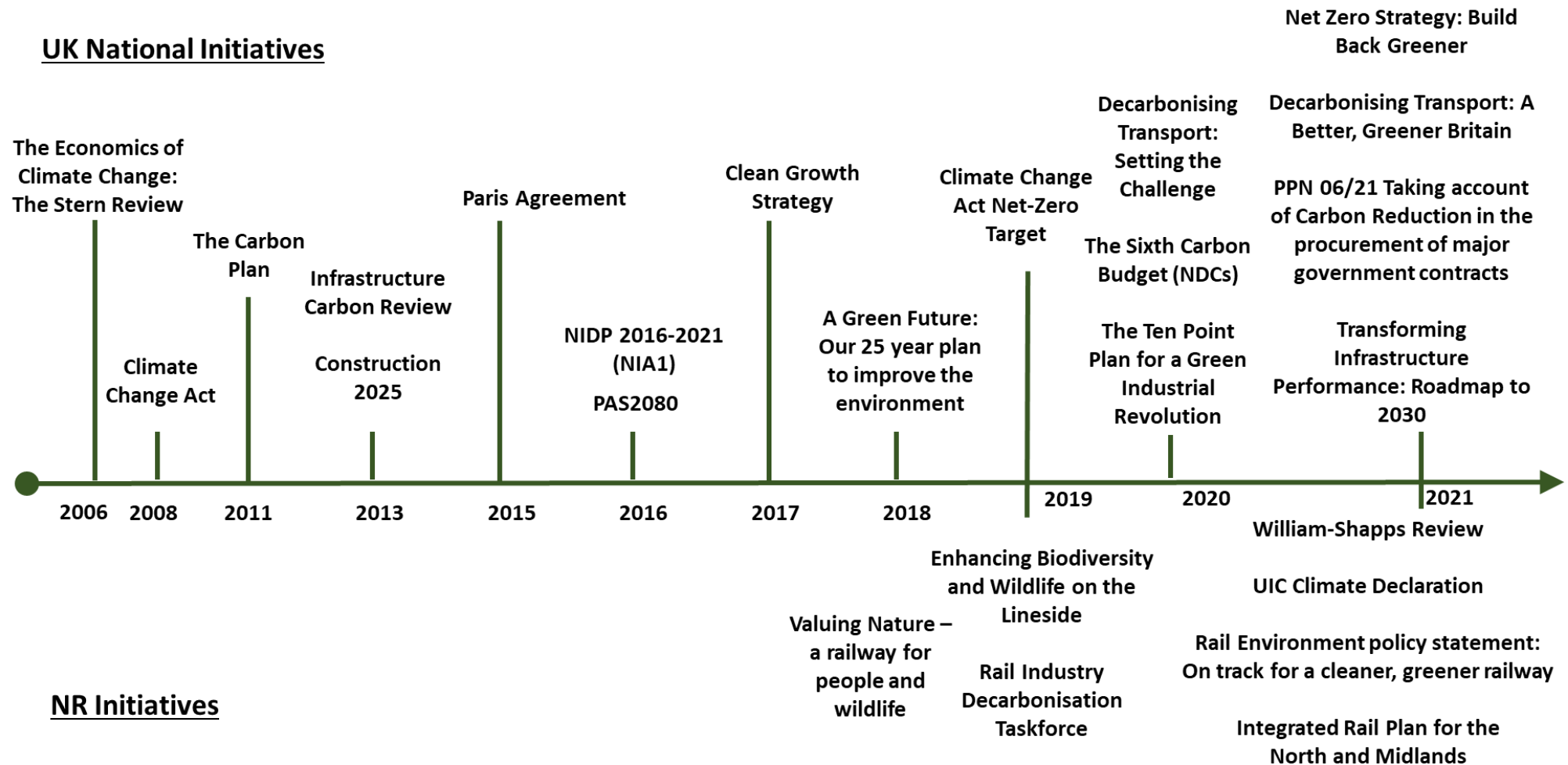


Figure 2.1 Timeline of UK National and NR Initiatives amended from (Ellis, Manidaki and Pantelidou, 2020)

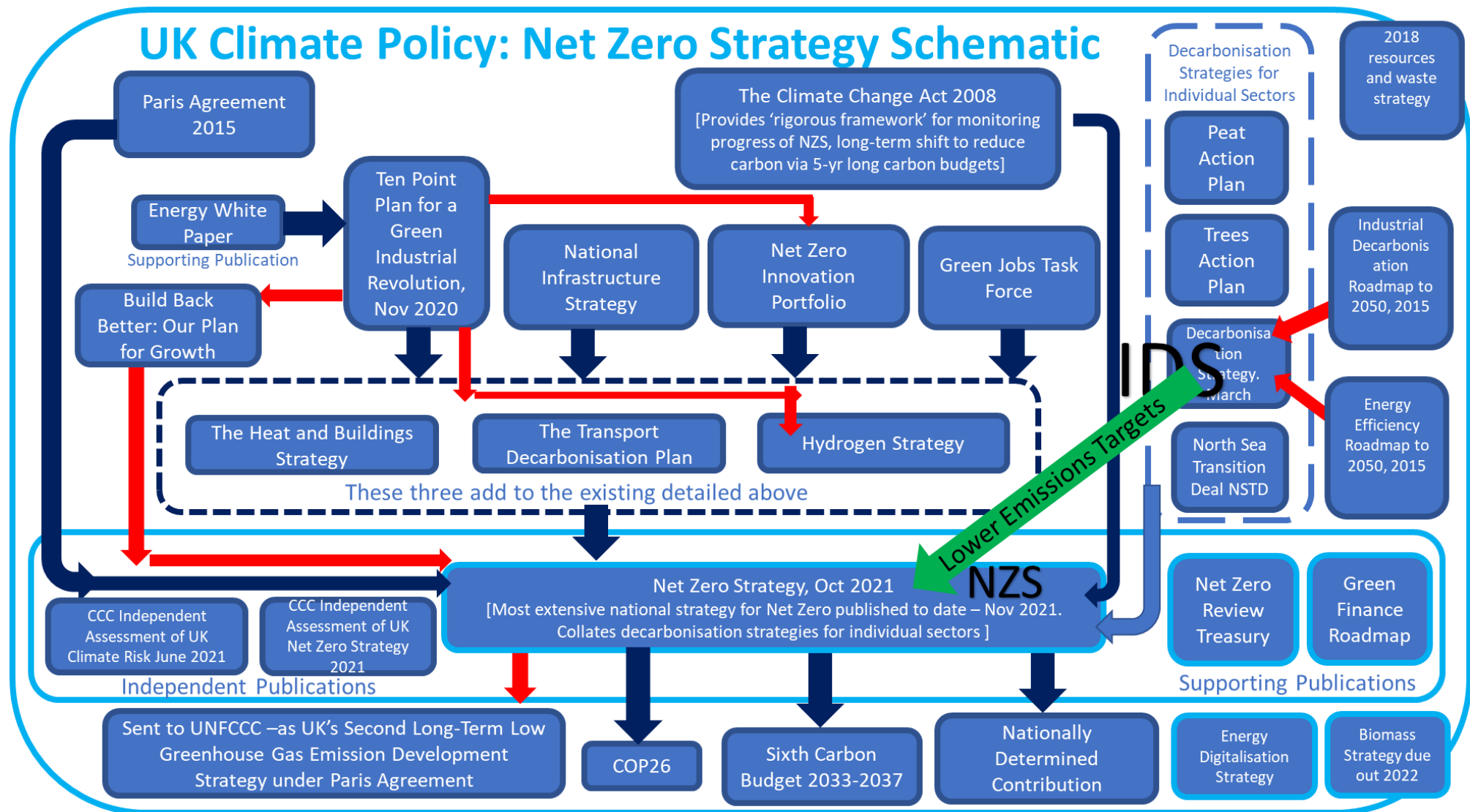


Figure 2.2 Summary of UK Climate Policy Net Zero Strategy Schematic

The Carbon Plan set out the UK Government's plans for achieving GHG emissions reductions, along with NDCs (HM Government, 2011a). The Infrastructure Carbon Review (ICR) describes the UK Government's plans to address carbon reduction in infrastructure, specifically construction operation and maintenance (HM Treasury, 2013). The ICR indicates that as the grid decarbonises the emissions relating to capital carbon will have an increasing relative percentage contribution to construction carbon from 2010 to 2050, as the total itself reduces (see Appendix B.3). The ICR promotes early intervention in the project lifecycle to have the most carbon reduction potential, and presents key terminology for the intervention strategies and their potential carbon reduction potentials, see Figure 2.3.

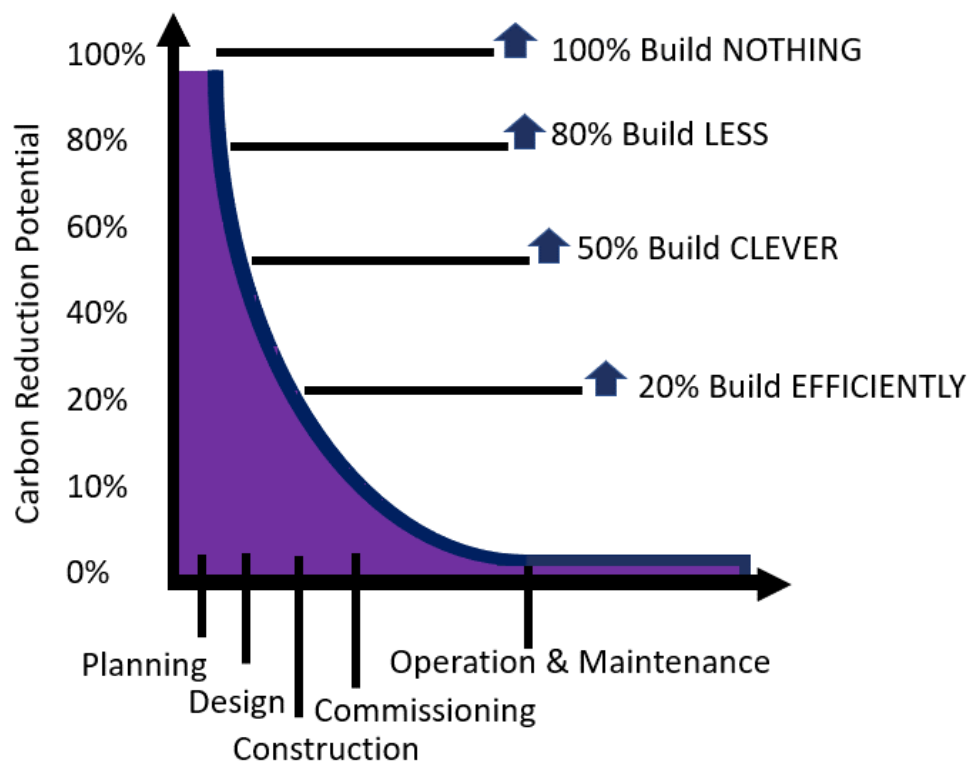


Figure 2.3 Carbon Reduction Curve, amended from (HM Treasury, 2013)

The general shape of the curve in Figure 2.3 is mirrored in the influence of the environmental impact curve applied to the differing design stages of design, manufacturing, provision, use and EOL (BSI, 2017).

The ICR highlights the practical challenges to carbon reduction of the “assortment of carbon models, tools and standards” which “is confusing” (HM Treasury, 2013, p.17), also highlighted in Procurement Policy Note (PPN) 06/21, where no one (carbon) tool is advocated (Cabinet Office, 2021). Clear and concise guidance along with consistency for NR is proposed via use of the RSSB RCT and associated PAS2080 templates advocated in this thesis.

Chapter 2

The Clean Growth Strategy 2017 (HM Government, 2017b) aims to deliver increased economic growth while decreasing emissions. It comprises investment in low carbon innovation including GHG removal technologies, or negative emission technologies (NETs), alongside the clear coupling of UK GDP growth with UK emissions reductions (HM Government, 2017b), reinforcing the message of the Stern Review. The Strategy includes policies for the establishment of new forests, support for peatland, and investment in GHG removal technologies.

The UK government's 25 Year Environment Plan, A Green Future (HM Government, 2018), forerunner to the Varley Report, outlines sustainable use of land, along with nature recovery, as key goals to improve the environment. It explicitly states that trees not only provide additional habitats for wildlife, but they also "reduce carbon dioxide levels and [they] can reduce flood risks" (HM Government, 2018, p.7), providing a clear link between sequestration benefits of nature based solutions (NbS) and potential co-benefits of increased biodiversity. These co-benefits are explored further in this thesis, see Chapter 6.

Following the Paris Agreement (see Section 2.2.1), NDCs are set by each country, 68% reduction of GHGs by 2030 (on 1990 levels) for the UK and NI (UK Government, 2020). This NDC level is consistent with the CCC and the Paris Agreement's 1.5 °C goal (Climate Change Committee, 2020a), see Appendix B.7.

Transport emissions account for around a quarter of all UK emissions (see Table 1.1), with policies in place to begin tackling these (DfT, 2020), including development of a universal metric for comparing CO₂ in differing modes of transport over a given distance. This thesis makes inroads to address this via a functional unit to allow comparison of differing size and lifespan case studies (see Section 4.1.3).

Government policy for the UK advocates use of NETs for the UK to remain within its NDCs, in line with reaching net zero, along with natural environment protection to increase wildlife rich habitats. Harnessing "Mother Nature's ability to absorb carbon" via tree planting is also advocated in the plan (HM Government, 2021e, p.3), aligning with sequestration strategies in Chapter 6.

Procurement policy lists carbon footprint tools (including Carbon Trust SME Carbon Footprint Calculator, but not the RSSB RCT), although these are not officially endorsed by government. Use of such tools in the procurement of major government contracts via high level reporting of GHGs for contracts >£5 million could help to reduce carbon, alongside other actions such signing up to the SBTi or other certified schemes (ISO14001 or PAS2060) (Cabinet Office, 2021).

The UK's Sixth Carbon Budget recommends the route to net zero being achieved via the balanced pathway scenario (akin to the Very Low pathway in Figure 1.2). GHG removals in the balanced

pathway model by 2050 show 8 times more CO₂ being removed via NbS compared to DACs. Chapter 5 explores use of NbS which could help the UK achieve ambitious global carbon reduction targets (as part of the UK's Sixth Carbon Budget) to meet the goals of the Paris Agreement (Climate Change Committee, 2020b) alongside business actions of “measure, disclose, target, act, adjust” (Climate Change Committee, 2020b, p.393).

The Sixth Carbon Budget provides a multitude of choices for net zero in both reductions and removals (via LULUCF plantings of woodland and peatland restoration) of CO₂, highlighting that the 2020s must be the “decisive decade” on action (Climate Change Committee, 2020b, p.5). Accordingly, “learning-by-doing” (Climate Change Committee, 2020b, p.14) is the best route to cost reductions. Further policies impacting NR include the shift from fossil to zero emission vehicles (such as BEVs), lowering travel to site emissions, and the movement of HGVs to alternative fuels, along with reducing emissions from site machinery and targeted reduction in construction materials contributing towards lower material emissions. This route is galvanised further via funding issued to the Greenhouse Gas Removal Demonstrator (GGR-D) projects, assessing the viability of five innovative methods of large-scale atmospheric GHG removal (peatland, enhanced rock weathering, biochar, afforestation, bioenergy crops) (UKRI, 2021). Use of PAS2080 to detail emissions from creation and modification of infrastructure transport is also advocated via DfT (2021a).

Current siloed approaches to biodiversity, carbon, and climate resilience are highlighted in policy (Climate Change Committee, 2021), see Figure 2.4, indicating a move away from such practices via integrated solutions is required (see Chapter 6).

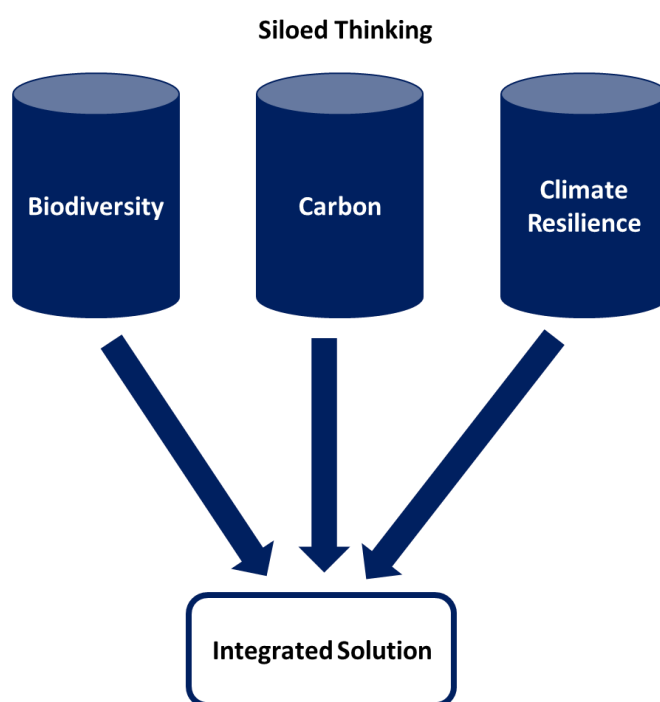


Figure 2.4 Movement Away from Siloed Thinking

The carbon reduction curve headings, see Figure 2.3, are mapped in a White Paper (Mi-ROG, 2020) onto CE thinking terminology, see Appendix B.4. The use of the 9 R's (or closely aligned synonyms) here, see Section 2.5, re-iterate the increased circularity found with the R0-R2 R's, aligning with the Build Nothing theme. The use of Re-Think, an R1 term, is also found in the Build Clever theme, where its use at later design stages can be initiated to ensure carbon savings here also.

Guidance on sourcing public works projects expands on CE thinking in carbon reduction, advocating creating collaboration and reducing waste via standardisation of design and components. This guidance further advocates achieving sustainable outcomes such as sustainable development and delivering on UNSDGs (see Section 2.2.1), which should also be considered alongside net zero goals (HM Government, 2020a).

2.2.3 UK Rail Initiatives

This section shifts down to the UK rail sector and investigates selected rail policy and initiatives, see Figure 2.1. In Varley (2018), clear guidance for NR is set out with respect to vegetation management, especially lineside vegetation (16,000 miles) being managed as an asset, along with increased biodiversity of the large NR natural capital (52,000 ha of land, 6.3 million trees) (Varley, 2018). A further policy document (Enhancing Biodiversity and Wildlife on the Lineside) addresses the position for NR in delivery for the environment (DfT, 2019). A vision for rail industry decarbonisation is presented in the Final Report to The Minister for Rail of the Rail Industry Decarbonisation Taskforce (RSSB - Rail Industry Decarbonisation Taskforce, 2019), see Figure 2.5.

The division of carbon sources and the inclusion of plans and strategies to mitigate these are shown in Figure 2.5. Several of these interrelationships are also included within this thesis. The next step for the rail industry is conversion of these high-level aspirations into tangible results on the ground, which the Objectives of this thesis aid with, see Chapter 7.

The Williams-Shapps Plan for Rail identifies six key problems with the current railway system. NR's need to set "clear commitments" (DfT, 2021b, p.89) on several environmental parameters is clearly stated within this report. One of NR's key problems is that "it struggles to innovate and adapt," (DfT, 2021b, p.18), a key consideration when trying to embed a low carbon culture into NR. The plan's conclusion for the six key problems identified was: "A revolution was clearly needed" (DfT, 2021b, p.18).

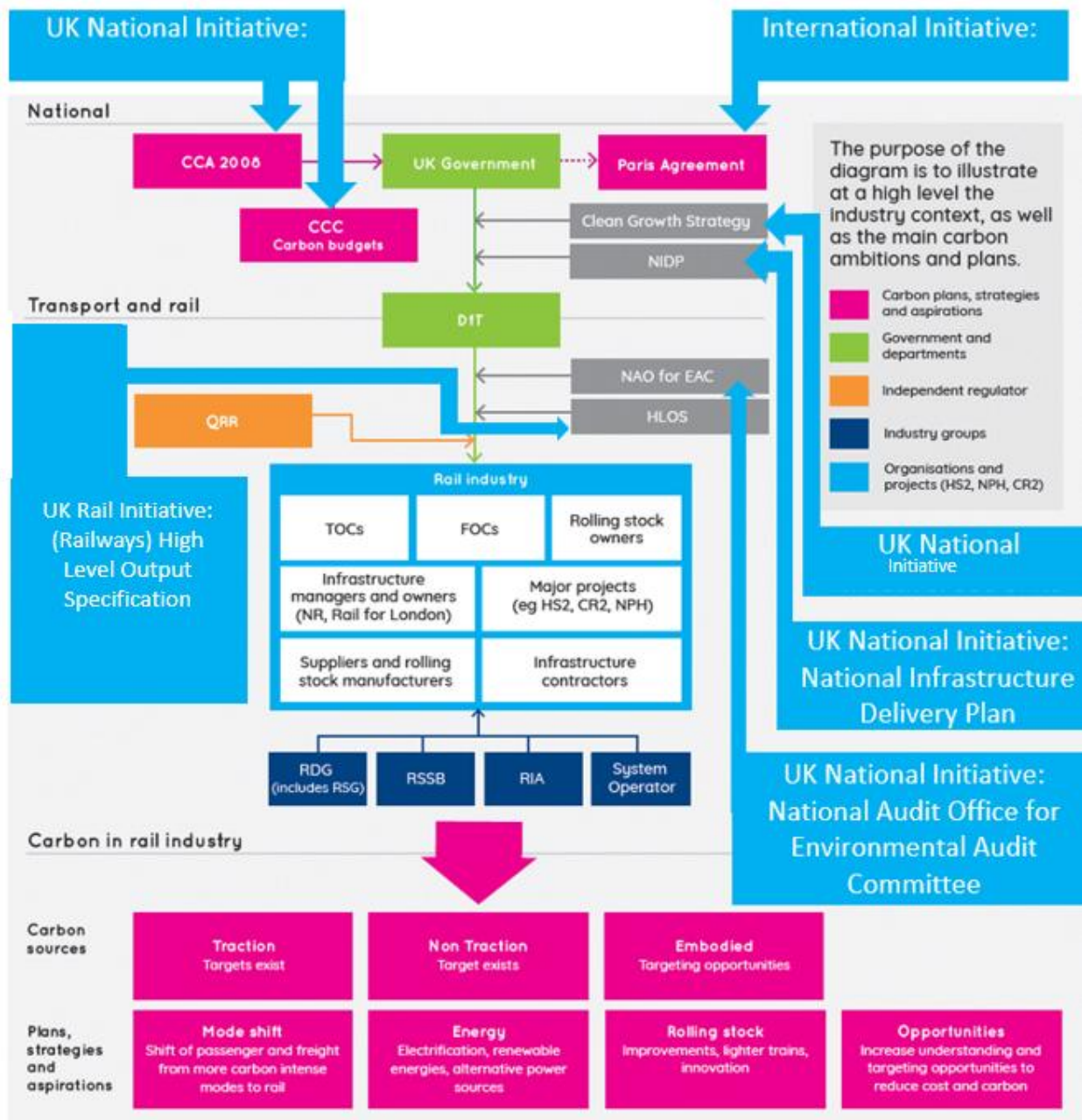


Figure 2.5 High Level Map of Industry Context, Main Carbon Targets and Plans , amended from (RSSB - Rail Industry Decarbonisation Taskforce, 2019)

The key lexicon of “decarbonisation” and “greater biodiversity” (DfT, 2021b, p.23), along with commitment 53: “Rail can and will do more....by...improving rail’s own environmental impacts and helping to restore our natural environment” (DfT, 2021b, p.89) are noted in this plan. This Plan sets a clear green mandate for NR that this thesis directly addresses, with strategies for the emissions reduction of earthworks, see Chapter 5, and the addition of vegetation via AR as part of a taxonomy of carbon offsetting solutions, see Chapter 6.

The need for “a single measurement methodology for carbon” in construction and maintenance in railways is also highlighted in this Plan (DfT, 2021b, p.90). This requirement has not been highlighted

in the literature previously, and is addressed via the method applied in this thesis, (via the novel carbon data calculation form) to aid in the completion of the PAS2080 (and PACE) aligned templates within the RSSB RCT that can be utilised by all NR staff to allow for consistent and comparable carbon accounting of projects, see Section 3.2. The need to accelerate tree-planting on the NR extensive estate amongst other green initiatives to reduce GHGs emissions and improve biodiversity is also highlighted in this plan, and is explored in offsetting via AR, see Chapter 6.

The Rail environment policy statement: On track for a cleaner, greener railway (DfT, 2021d), builds on the Williams-Shapps' review, and cites the publication of a 30-year strategy in 2022 which will "establish rail as the backbone of a cleaner future transport system" (DfT, 2021d, p.5). This policy statement also discusses how 100% of NR cars and vans will be zero emission by 2027. A change to EVs is explored in Chapter 5, quantifying its outcome to NR.

The Sustainable Rail Strategy: Prototype (RSSB, 2022) contains route maps for reaching net zero, see Appendix B.8, however these are yet to have percentage reductions in line with SBTs and NBCs added.

In this section a chronological overview of the international environmental legislation has been presented, followed by pertinent national legislation. This was followed by the rail specific policy, proposals and initiatives on two themes of biodiversity and carbon reduction via the Varley report and the Rail industry decarbonisation taskforce. The evolution and interlinking of these differing policies have been summarised in this holistic overview.

2.3 Research in Rail Infrastructure

In this section an outline of infrastructure and transport carbon precedes an overview of rail infrastructure research. A focus on the carbon footprint of rail infrastructure is then given in Section 2.3.1. This is followed by an overview of offsetting carbon and payback time in Section 2.3.2 along with details of the UK whole industry footprint in Section 2.3.3 and a discussion on where the carbon is in NR in Section 2.3.4.

At the top level, carbon in infrastructure, the ICR (see Section 2.2.2) cites 53% of UK emissions as occurring in infrastructure, and predict this to reach 80% by 2025 (HM Treasury, 2013, p.9), indicating the substantial weight of carbon in this sector. Transport accounts for 27% of total UK carbon emissions (2019 data set (BEIS, 2021)), see Section 1.1, and carbon in transport infrastructure resides within this substantial amount.

This thesis focuses on GB mainline railway geotechnical infrastructure. Earthworks are investigated specifically, as these are an area where there is an apparent lack of granular detail, especially in the

field of embankments and cuttings as the existing literature focuses predominantly on rail track rather than earthworks (Milford and Allwood, 2010; Rempelos, Preston and Blainey, 2020), or on track substructures (Pons *et al.*, 2020).

Other focuses of the literature are tunnels (Kjerkol and Kalager, 2011; Pritchard and Preston, 2018), and bridges (Lee *et al.*, 2014; Lee, 2016; Cheng *et al.*, 2020), with limited research focusing predominantly on existing older rail infrastructure (Lee *et al.*, 2014). A lack of data availability in the construction stages is also noted (Cuenot and Hernandez, 2016; Lee, Lee and Chun, 2020). Where railway maintenance activities have been investigated, these investigations have evaluated emissions from resurfacing in ballasted track bed maintenance activities (Krezo *et al.*, 2018), plain line renewals (Krezo *et al.*, 2016) or ballast, sleepers and rail (Araujo *et al.*, 2019). In depth studies of carbon footprints of high-speed rail and rail infrastructure are well documented in the literature, including in China (Lin *et al.*, 2019; Cheng *et al.*, 2020; Kaewunruen, Sresakoolchai and Peng, 2020), Korea (Lee, Lee and Chun, 2020), Spain (Kortazar, Bueno and Hoyos, 2021), and the UK (HS2 Limited, 2013b).

There is a broad consensus in the literature that engineering structures such as bridges have some of the largest carbon footprints on a given line (Baron, Martinetti and P  pion, 2011; Chang and Kendall, 2011; Lin *et al.*, 2019). Other engineering structures such as tunnels and viaducts, affect a line proportionally, with the greater the share of these features on a line, the higher the overall emissions (Baron, Martinetti and P  pion, 2011). For earthworks a significant share of the emissions are from the use of cement for soil stabilisation (Baron, Martinetti and P  pion, 2011).

2.3.1 Carbon Footprints of Rail Infrastructure

Specific research in carbon reduction in railway infrastructure can be found in work by Aubrat and Lemer   (2018). In their research on the 182 km of new HSR line Bretagne-Pays de la Loire running between the cities of Le Mans and Rennes in France, they note that this project “pioneered the use of an environmental mitigation hierarchy” (Aubrat and Lemer  , 2018, p.402). This hierarchy of avoid, minimize, and offset impacts to the environment, was adhered to rigorously by all parties throughout the design and construction phases, and enabled the “worksite footprint to be reduced by 8% and avoided emission of 4.5% of greenhouse gases associated with the line’s construction” (Aubrat and Lemer  , 2018, p.402). During this project the team went “beyond regulatory obligations and contractual provisions for sustainability, particularly regarding biodiversity and carbon dioxide emissions” (Aubrat and Lemer  , 2018, p.402), to achieve the above reductions. Aubrat and Lemer   (2018) show that via intervention at the very earliest lifecycle stages of a project (those interventions at the top of the asset hierarchy or beginning of the CE curve, see Figure 2.3, which in NR rail terms would be the GRIP 2 or the equivalent PACE stage), real savings can be made in terms of carbon

emissions. Savings can also be made via mitigating biodiversity loss, which is an area where carbon offsetting can be introduced as an additional measure by NR to further decrease their carbon footprint, see Section 6.5.

All transport emissions need acknowledgement (Marsden, Lokesh and Densley-Tingley, 2022), with a need to “pay off” transport emissions via a “payback” period, although these “payback” periods are fraught with ambiguities and inconsistencies (Marsden, Lokesh and Densley-Tingley, 2022, pp.2&8). In HS2 documents regarding route wide effects, a hypothetical motorway of equivalent carrying capacity to the proposed HS2 line is proposed as a comparator (HS2 Limited, 2013a).

Two seminal works regarding carbon footprints of rail infrastructure are the UIC Carbon Footprint of High-Speed Rail in 2011 (Baron, Martinetti and Pépion, 2011) and the 2016 UIC report of Carbon Footprint of Railway Infrastructure (Cuenot and Hernandez, 2016). The 2011 report (Baron, Martinetti and Pépion, 2011) highlights the role of infrastructure and rolling stock emissions (both embodied emissions in the construction of the rolling stock, and the rolling stocks’ operational emissions) on the carbon footprint of four (newly built at the time) HSR lines in France (LGV Méditerranée and South Europe Atlantic-Project), Taiwan (Taipei to Kaohsiung line), and China (Beijing-Tianjin line). This UIC report further questions whether inclusion of these emissions, and a move towards a lifecycle approach to emissions calculations, changes the picture of the carbon footprint. The UIC report results show that inclusion of rail, tunnels, bridges, and earthworks does increase the carbon emissions, indicating that bridges and viaducts can account for large proportions of the construction emissions compared to other construction areas, such as conception (design stage) and rail emissions, which is to be expected due to the large quantities of cement and steel, which are inherently large carbon footprint items, used in such structures. When construction emissions are compared to rolling stock and operational carbon, the total construction footprint accounts for a larger proportion of the total CO₂ per passenger km in the SE-Atlantic and LGV Méditerranée HSR lines, compared to the Taipei-Kaohsiung and Beijing -Tianjin HSR lines. This is attributable to the greater quantity of bridges and viaducts on the SE-Atlantic and LGV Méditerranée lines.

The 2016 report compares ten differing emissions reporting methodologies of railway infrastructure (Cuenot and Hernandez, 2016), see Section 2.7.1. This report gives an overview of the methodologies available at the time and highlights some of the issues, including lack of consistency in system boundaries and elements assessed, and differing standards being used (where disclosed) as part of the carbon footprint leading to difficulties in making comparisons between differing footprints, which is where use of PAS2080 lifecycle stages will allow for robust, like-for-like, comparisons to be made.

Adoption of PAS2080 stages, see Figure 1.3, or other equivalents such as UNI EN ISO 14064-1:2019, has been seen in work by HS2 (HS2 Limited, 2022d) and Italferr (Antonias *et al.*, 2022).

The Rail Industry Decarbonisation Taskforce called for a “comprehensive understanding of the carbon impacts of the railway” in their final report to the minister in 2019 (RSSB – Rail Industry Decarbonisation Taskforce, 2019, p.26). This was presented in the form of DECARB: Carbon Measurements T1197 by the RSSB (RSSB, 2021a) which provided a scope based analysis of emissions by stakeholders, as well as a breakdown of embodied emissions, including construction and track. This breakdown shows the large proportion of CO₂e allocated to construction activities, forming the second highest category of embodied carbon emissions, indicating that railway infrastructure emissions require attention. Project DECARB continues with a further report, T1198, highlighting recommendations for implementing and managing rail industry decarbonisation targets (RSSB, 2021b). This report highlights the large proportion of CO₂e in the embodied carbon section at 5,194,970 tCO₂e, accounting for 55% of the total footprint, with operational and traction carbon at 8% and 37% respectively. Furthermore, it shows embodied carbon in materials, products and services procured from third parties are “an area where there is uncertainty in the industry” (RSSB, 2021b, p.7). Aim 1 of this thesis quantifies the BAU carbon of materials and processes of mainline railway geotechnical assets thereby providing clarity to the railway industry.

Additional carbon data collection and reporting guidance is found in T1228 (RSSB, 2024c), highlighting the focus on operational traction emissions in key strategy documents in rail decarbonisation, such as the Transport Decarbonisation Plan (DfT, 2021a) Traction Decarbonisation Network Strategy (Network Rail, 2020e) and the William Shapps Plan for Rail (DfT, 2021b). See Section 2.2.2. T1228 further highlights the need for a “template” to be developed in support of data collection for carbon assessments, alongside consideration of how the RCT could be used for carbon assessments to “support a consistent approach to carbon assessment” (RSSB, 2024b, p.45). This is where the novel carbon calculation data form created and used in this thesis fills this gap. T1228 further notes that knowledge gaps in data collection are a “significant barrier” in achieving a comprehensive carbon account (RSSB, 2024b, p.68).

An industry perspective of the carbon emissions in the UK rail sector has been provided by Akponeware *et al.* (2022). This perspective stems from an empirical analysis of 14 semi-structured interviews, and outlines a framework for integration of standard based carbon assessment across the industry via a proposed rail carbon knowledge model. This rail carbon knowledge model (see Appendix B.9.1) includes “policy, process, people, and technology dimensions” (Akponeware *et al.*, 2022, p. 1). Use of this model, along with development of standardised GHG methodologies, will enable provision of “reliable baselines” for measuring GHG reductions (Akponeware *et al.*, 2022,

p.315), with specific models proposed for whole life carbon of switches and crossings (Rempelos, 2023), see Chapter 4 for comparison.

Limited data on geotechnical aspects of the railway is found in the literature. One example is the Austrian railway footprint, highlighting the GHGs as CO₂e in this as a discrete item accounting for under 10% of the total Austrian railway infrastructure cradle-to-gate emissions, and also discussing service life of assets (Landgraf and Horvath, 2021). Landgraf and Horvath (2021) use a novel approach to assess life-cycle costs to serve as input for evaluating environmental impacts similar to the proxy costings used to evaluate carbon in the NR NW&C carbon report (Mott MacDonald, 2021) to fill gaps in data.

Carbon accounting knowledge is “immature” in contrast to the field of energy efficiency (Kadefors *et al.*, 2021, p.614), with increased knowledge, for example via carbon literacy training; see Section 2.4.5. This is an area that both the DfT (Sherriff, 2022), NR (ICWG, 2021), and HS2 (Ellis, Manidaki and Pantelidou, 2020) are pursuing. Key guidance in carbon accounting in infrastructure is provided via PAS2080, emanating from carbon policy, see Figure 2.2, and via the UK Government’s Construction Playbook (HM Government, 2020a). Application of CE principles in infrastructure in pursuit of net zero carbon are highlighted by Mi-ROG (2020). Mi-ROG apply CE approaches to the carbon reduction curve, see Figure 2.3, stages of build efficient, clever, less, and nothing. Furthermore, they advocate use of CE principles to address design problems, rather than focusing on waste. Early action, such as curtailing the (carbon) problem before it begins, will enable good progress and “take you a very long way on your net zero carbon journey” (Mi-ROG, 2020, p.2).

To date, limited literature is available in carbon in rail earthworks, with even less useable data in the form of quantifiable amounts of carbon in earthworks such as embankments and cuttings. One notable exception provides granular details of standardized units for embankments and cuttings in relation to LCA (Morita *et al.*, 2011), see Table 2.5, Section 2.6.3. This thesis provides additional data to enable policy makers and linear infrastructure asset owners to make informed choices regarding implementation of maintenance, refurbishment and renewal interventions for embankments and soil and rock cuttings using the PAS2080 templates in the RSSB RCT, along with the ER and offset guidance given in Chapter 5 and Chapter 6.

The literature reviewed above has highlighted the gap in data around construction of railway earthworks, pointing towards accurate data collection and subsequent carbon footprinting being the starting point. For additional details of errors in footprinting see Appendix B.9.

2.3.2 Offsetting Carbon and Payback Time

Whether HSR (during operation) can offset its emissions is explored by Westin and Kågeson (2012). They analysed embedded emissions with respect to future transport demand and conclude that “traffic volumes of more than 10 million annual one-way trips are required to offset the CO₂ emissions from the construction of the high speed line” (Westin and Kågeson, 2012, p.10). This demonstrates the need to assess the lifecycle carbon and to choose a suitable metric when assessing the carbon account of a project and when comparing with existing research. Baron, Martinetti and Pépion (2011) in their UIC report note that the payback time for the French network was 5.3 years, illustrating that using this approach to calculate pay-back time the HSR line can ‘payback’ or offset its emissions (within the time frame noted). Dalkic *et al.* (2017) focus on ridership of routes and specifically exclude carbon from infrastructure construction and maintenance. Whereas Yue *et al.* (2015) find that vehicle operation dominates the lifecycle impact categories, and vehicle manufacturing and infrastructure construction contribute significantly to mineral consumption.

Limited research has been carried out concentrating specifically on the interrelations between HSR, carbon and biodiversity. Cornet, Dudley and Banister (2018) discuss this interrelationship, citing the HS2 environmental assessment and explore the two central issues of the carbon footprint from HSR and local environmental issues regarding biodiversity and habitat loss resulting from HSR. They concluded that line speed and costs to build take priority over carbon and biodiversity costs (Cornet, Dudley and Banister, 2018).

The earliest indications in the literature towards counting deforestation and carbonation (via CO₂ uptake in concrete) with the GHG footprint are found in an assessment of the Bothnia line, where the infrastructure material CO₂ accounts for over half of all the emissions (Stripple and Uppenberg, 2010, p.8).

According to the literature rail (along with other linear infrastructure such as highways) has an abundance of opportunity to utilise its (linear) assets and via “careful plant selection” it can green the rail corridor to offset CO₂ emissions and improve other areas of sustainability such as “carbon storage and sequestration and air pollution and storm water reduction” (Blair *et al.*, 2016, p.1723). This is alongside additional benefits gained from increased biodiversity along the rail corridor land assets (explored in the HS2 environmental assessment review by Cornet, Dudley and Banister (2018)), see Section 6.6.1.

2.3.3 UK Mainline Railway Whole Industry Carbon Footprint

Rail accounts for 0.5% of UK emissions, see Section 1.1. This sub section will begin with an overview of the UK Mainline Railway whole industry carbon footprint to give the baseline.

Two UK mainline railway carbon footprint reports, commissioned from Carbon Intelligence, T1197 (RSSB, 2021a) and T1198 (RSSB, 2021b), build on T913 (has limited scope to T1197) and T1145 (emphasis on traction, in-use carbon only).

T1197 and T1198 were commissioned following recommendations of the Rail Industry Decarbonisation Taskforce, set up to independently respond to the challenge from the Minister for Transport in 2018 to provide a “vision” for decarbonisation of the rail sector alongside removal of all diesel-only trains by 2040 (RSSB - Rail Industry Decarbonisation Taskforce, 2019, p.4). The taskforce gave five key recommendations in their report on these issues (RSSB - Rail Industry Decarbonisation Taskforce, 2019), see Section 2.2, the most pertinent being:

- Delivery Plan – NR (along with other key stakeholders) should set out plans to deliver against the long-term plan and targets to support the decarbonisation of rail to reach net zero by 2050.
- R&D – 5-year periodic research plans should be set out which will increase “the ability to model and measure system wide carbon emissions, arising from both operational and capital works” (RSSB-Rail Industry Decarbonisation Taskforce, 2019, p.7).

The taskforce’s main recommendation was the development of a “single, consistent methodology for collecting, collating, and reporting GHG emissions data” (RSSB - Rail Industry Decarbonisation Taskforce, 2019, p.26). The issue of a single and consistent methodology is an important issue, addressed via advocacy of use of PAS2080 lifecycle stages for footprint creation following data collection using the novel carbon data collection form advocated in this thesis. Accurate comparisons are required to ensure comparative analysis between case studies and to avoid skewing of figures, see Chapter 3.

Decarbon8 provide two technical reports on measuring rail (Lokesh, Densley-Tingley and Marsden, 2022a) and road (Lokesh, Densley-Tingley and Marsden, 2022b) infrastructure carbon. These sit alongside their policy document (Marsden, Lokesh and Densley-Tingley, 2022) forming a suite of documents illustrating the significant contribution of carbon from construction, operation, and maintenance of the roads and railways, aligning with the figures found and overviewed in this section of the thesis. These documents are now explored.

Railways are generally an “environmentally-friendly” mode of transportation (Morita *et al.*, 2011, p.1), even when taking into account the emissions from the construction of railway infrastructure, although it is noted that there is still “significant room for improvement” (RSSB, 2021a, p.1). T1197 (RSSB, 2021a) provides an estimate of the whole industry carbon footprint for 2019/20 at 9.5 MtCO₂e of which embodied carbon accounts for over half of the footprint at 4.9 MtCO₂e.

The methodology used in T1197 follows the GHG protocol (World Business Council for Sustainable Development and the World Resources Institute, 2004) see Figure 2.6. This methodology highlights the need to move away from BAU carbon reductions and to explore and implement novel forms of carbon reduction to meet the reduction ambitions outlined in Table 2.3 and in NRs SBTs, Figure 2.13.

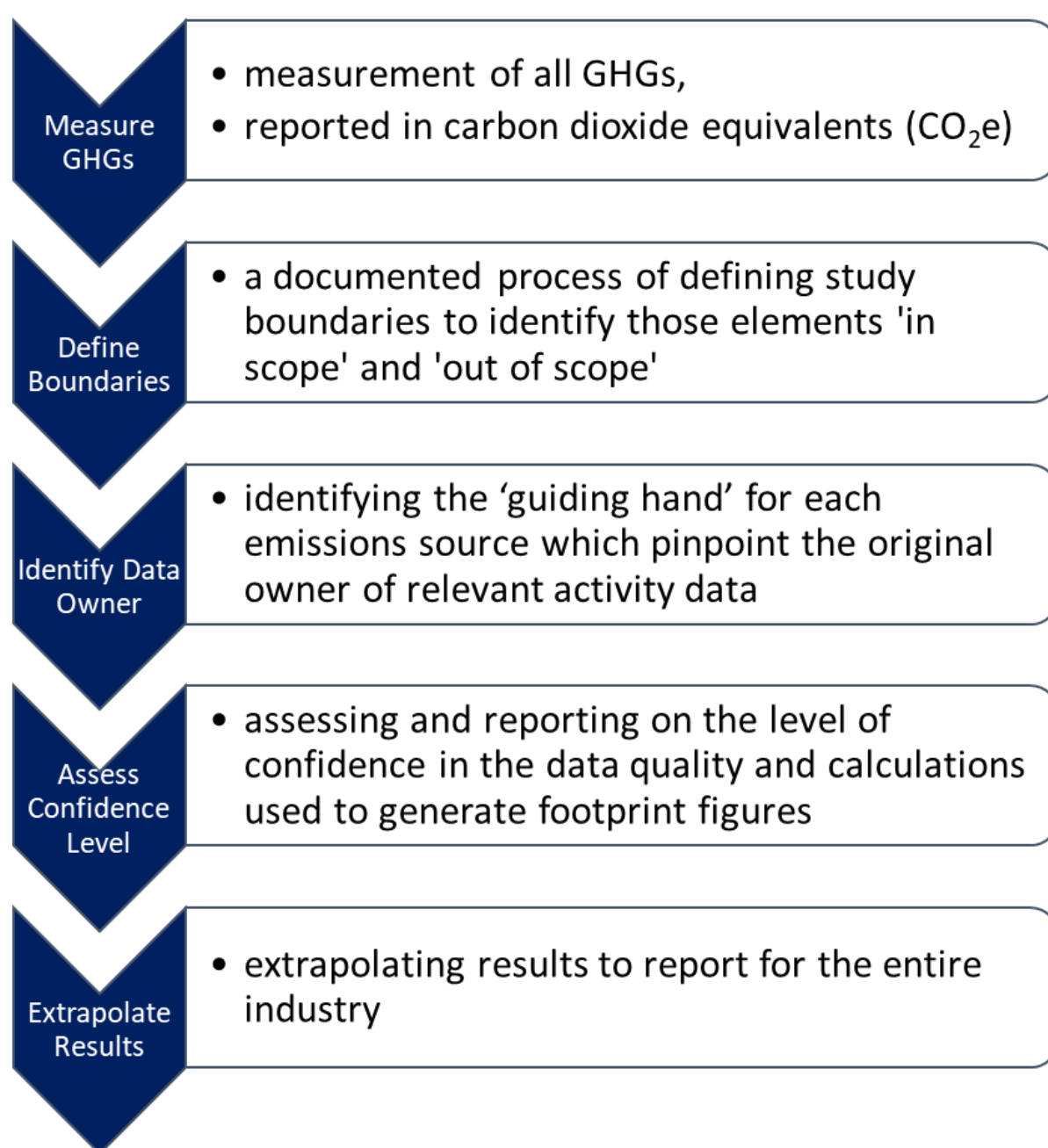


Figure 2.6 Key Elements of T1197 Methodology, amended from T1197 report, RSSB (2021a, p.21)

Report T1197 also provides guidance on how reporting could be improved in the sector. The top-line figures presented in this report are illustrated in Figure 2.7, Figure 2.8 and Figure 2.9.

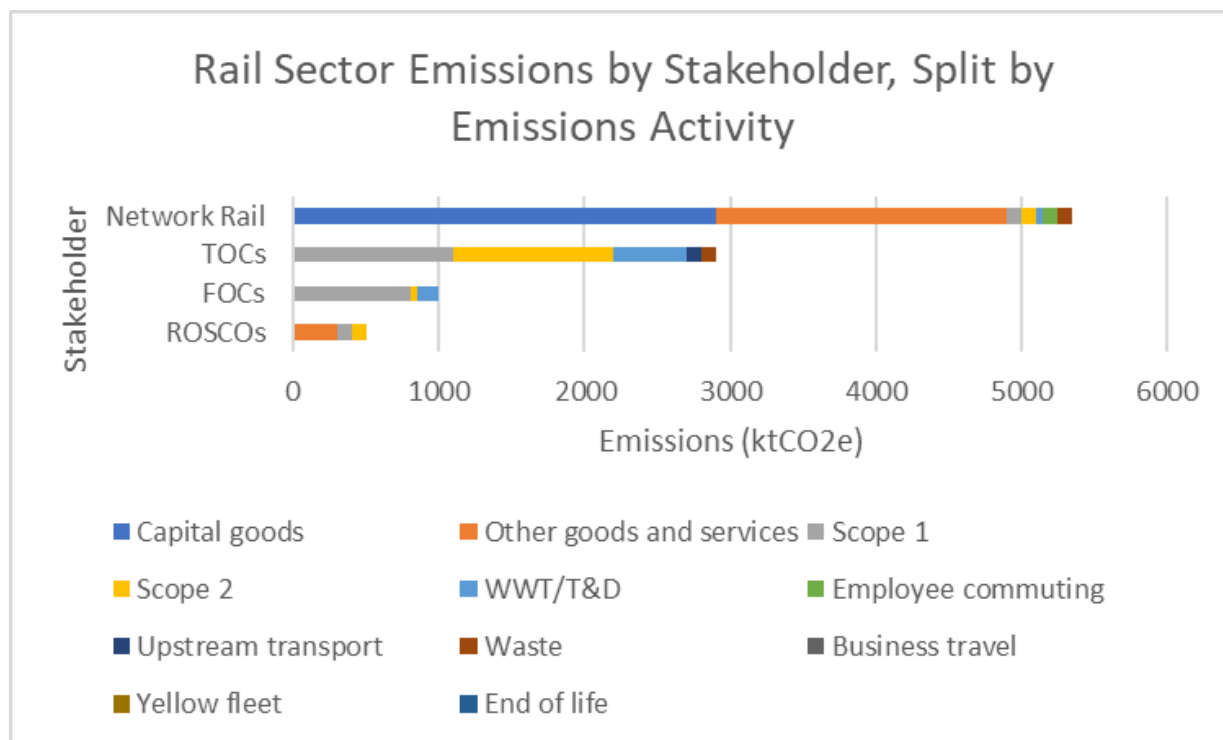


Figure 2.7 Emissions by Stakeholder, Split by Emissions Activity, amended from T1197 Figure 5, (RSSB, 2021a)

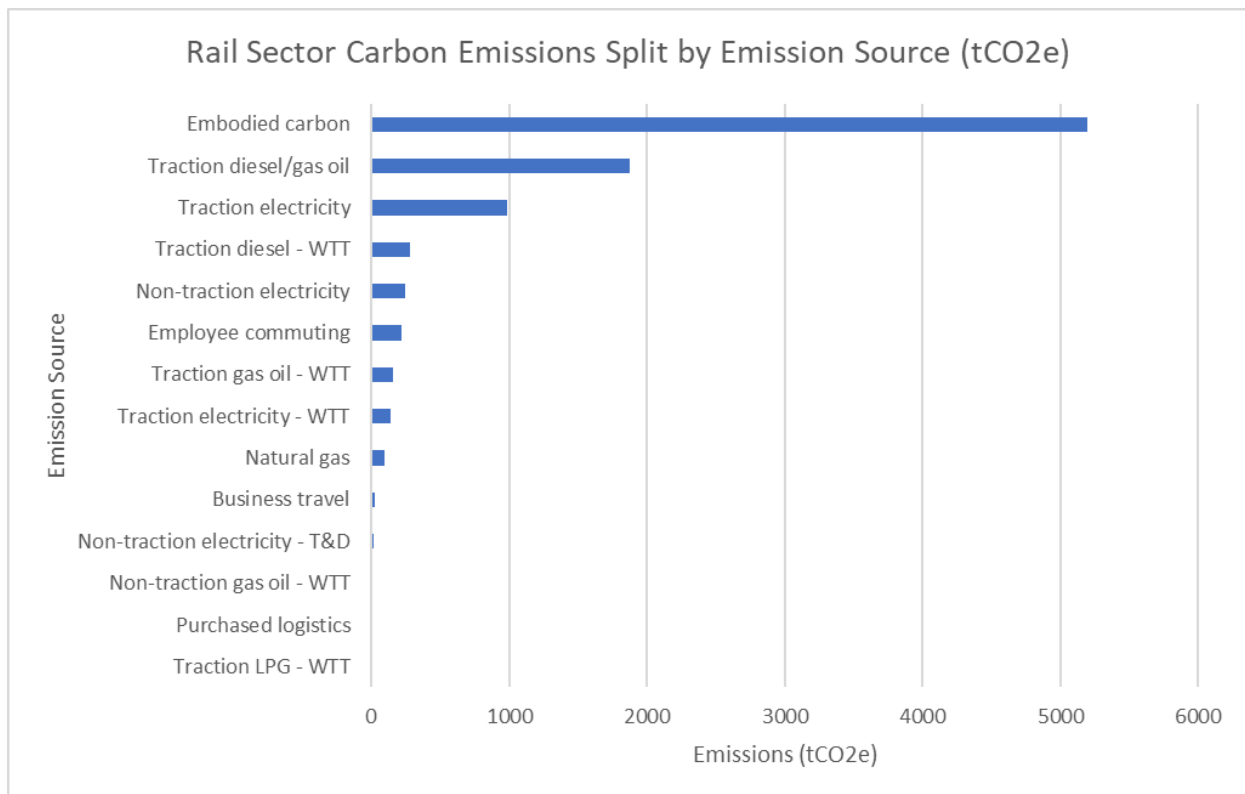


Figure 2.8 Rail Sector Carbon Footprint Split by Emission Source in tCO₂e, amended from T1197 Figure 6, (RSSB, 2021a)

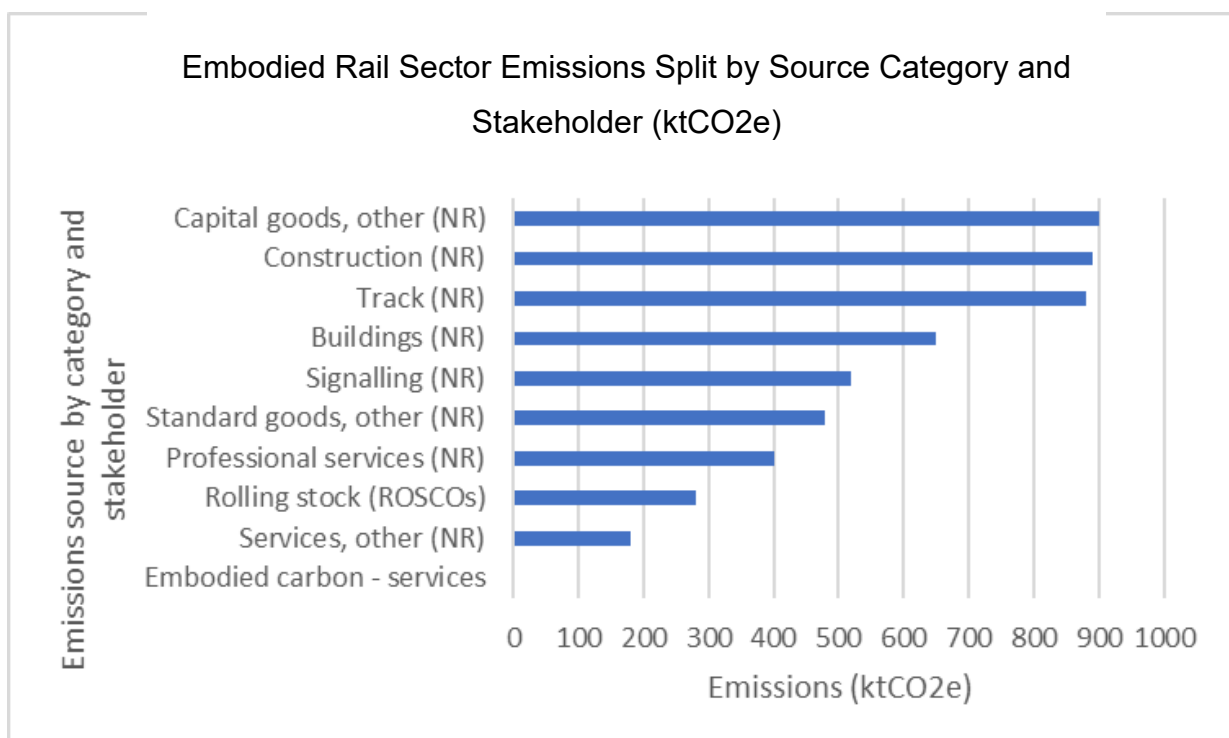


Figure 2.9 Embodied Emissions Split by Category and Stakeholder in ktCO₂e, amended from T1197 Figure 7, (RSSB, 2021a)

Chapter 2

These three figures highlight that the largest portion of the whole UK mainline railway carbon footprint is attributable to NR activities, at 57%, with capital goods and other goods and services dominating NR's portion of the footprint, see Figure 2.7. They further show that by emissions source over half of the footprint is attributed to embodied emissions, see Figure 2.8, and that capital goods and construction are the two dominant emissions sources emitted by NR, with track being the third dominant, see Figure 2.9.

These three figures highlight the carbon "hotspots" within the UK mainline railway (embodied carbon), and specifically NR (capital goods and construction). These "hotspots" provide steering on which areas require the most attention in carbon reduction for NR, see ER scenario in Chapter 5, resulting in the materials carbon A1-3, transport A4 and construction A5 stages being assessed in depth.

T1197 makes four key recommendations and 28 supporting recommendations to improve the accuracy of carbon footprints. Two of the key recommendations, and nine of the supporting recommendations are outlined below:

A key recommendation to improve the accuracy of carbon footprints from T1197, is implementation of GHG reporting in adherence to GHG Protocol Standards and ISO 14064 principles. It also highlights that measurement of emissions underpins the management of emissions and that "this is the first issue that we must solve to effectively reduce emissions in the sector" and is a "priority" for the sector (RSSB, 2021a, p.54). Furthermore, owing to the large percentage of GHGs in the rail sector emanating from embodied carbon (aligning to PAS2080 stages A1-3), this is an area where greater emphasis on reducing this carbon is required, see Chapter 5.

Supporting recommendations from T1197 include the verification of footprints to a standard such as ISO14064-3, future workstream definition to define how to implement 'guiding hand', use of carbon to influence project design rather than "just post hoc carbon reporting,"(RSSB, 2021a, p.66). They also include infrastructure project carbon reported in a more transparent way, embodied carbon reporting extended to include a wider range of projects, investigations to find practical solution to increased use of RCT, carbon hot spots project to be undertaken to look at these hotspots, recommend following GHG protocol when calculating GHG emissions, and providing credibility of footprints via verification to ISO 14064-3.

T1198 (RSSB, 2021b) expands on T1197 providing further guidance on implementing decarbonisation targets in the rail sector, summarising the whole industry carbon footprint, see Figure 2.10.

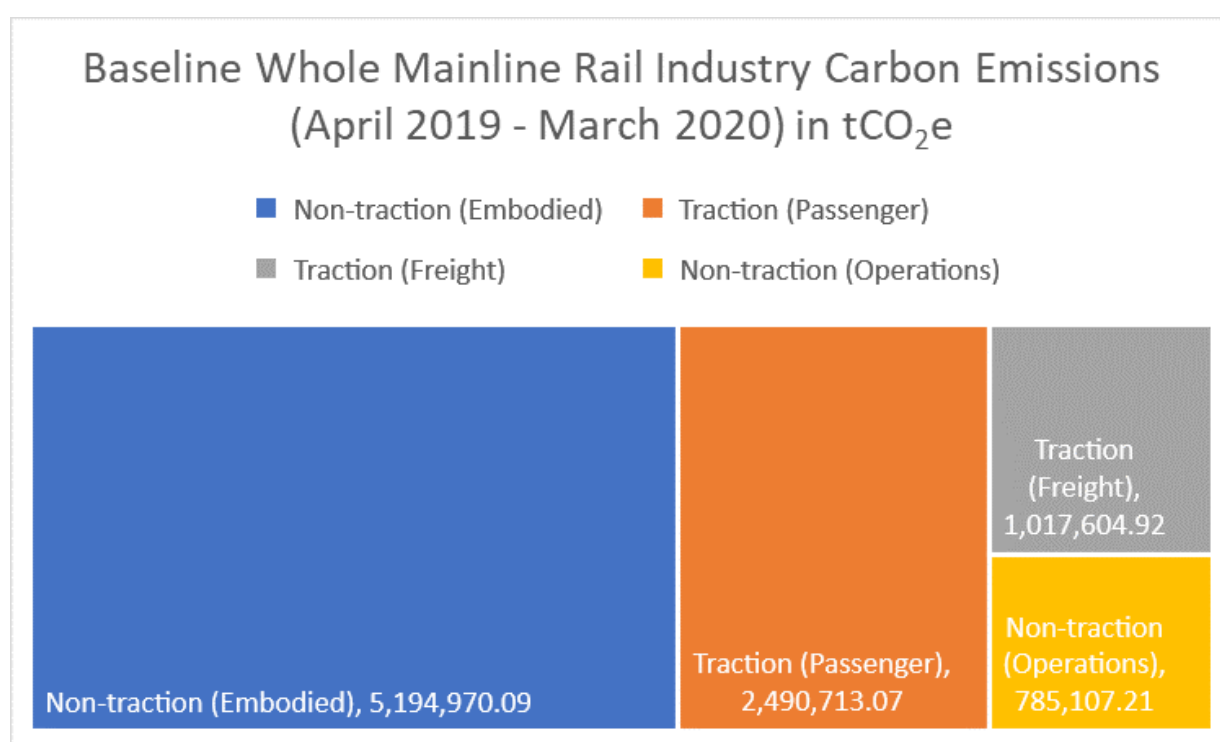


Figure 2.10 Whole Mainline Rail Industry Carbon Emissions Baseline (FY 2019-20) , amended from Report T1198, RSSB (2021b, p.9)

Figure 2.10 illustrates that embodied carbon forms most of the carbon footprint of the rail industry. Table 2.1 details the subcategories which form the emissions categories.

Table 2.1 Details of Selected Emissions Subcategories, amended from T1198, , RSSB (2021b, p.9)

Emissions Category	Subcategory
Operations	Property
	Business travel/logistics/commuting
	Yellow fleet
Embodied	Capital goods – buildings
	Capital goods – signalling and tracks
	Services – professional services, telecoms, infrastructure support services, and contingent labour
	Standard goods – construction, including structures and earthworks
	Standard goods – rolling stock

Table 2.1 indicates that earthworks, including embankments and cuttings, fall under the standard goods subcategory of embodied carbon. Yellow fleet is included within operations due to these plant

being 'on track machines'. It is noted in T1198 that "Other yellow plant (e.g. road-plant or plant with both road and rail capabilities, and lineside generators) are captured within the embodied carbon emissions associated with maintenance and construction materials" (RSSB, 2021b, p.2) with these definitions being developed via consultation between the RSSB and NR. The rationale behind not including Yellow Fleet in 'standard goods – rolling stock' could not be found in the report. These areas (road-plant or dual capability yellow fleet) owing to their contribution to the whole rail footprint, may warrant further exploration in future research projects to determine in more detail their contributions. These may also be able to be broken down further to allow attribution to the construction stage of the PAS2080 lifecycle, A4 and A5 stages. In this thesis all plant and equipment emissions have been attributed to the relevant case study, as project (case study) level accounting has been performed.

Details of the confidence level and magnitude of impact of each subcategory are available in T1198, with the standard goods subcategory of construction, having a low level of confidence against a high magnitude of impact. This low confidence refers to data being provided but with insufficient data regarding its quantification to be confident that the data is complete, and high impact refers here, to more than 10% of the baseline carbon account.

For the standard goods category, NR are answerable in terms of their responsible, accountable, consulted, informed (RACI) matrix position. The level of reporting of embodied carbon emissions in general is limited and ad hoc. Furthermore there is no mandatory reporting structure or data collection period for the industry at this time with it advocated that monitoring the embodied carbon emissions that arise from materials used by NR in construction should take place (RSSB, 2021b).

The division of accountability between the DfT and NR for achievement of embodied carbon emissions reduction targets within the rail industry is defined as the DfT currently provide funding for construction and capital goods purchased. As such they would be "ultimately accountable" for its embodied carbon (RSSB, 2021b, p.21). The DfT and other relevant stakeholders need to be consistently monitoring embodied carbon data, on an annual basis, to enable comparison and verification against the embodied pathway target and the creation of accurate, consistent whole lifecycle carbon footprints of earthworks is the starting point for this data collection. NR would be accountable for reducing emissions that emanate from procured services, and would be responsible for data collection of emissions from traction, operations including yellow fleet, and directly consumed goods and services (RSSB, 2021b).

T1198 advocates use of the guiding principles of the GHG protocol 2004. The results of this thesis can potentially feed into future mainline railway carbon emissions footprints, and as such will be carried out in adherence to the guiding principles of the GHG Protocol, see Figure 2.11.

Report T1198 suggests that embodied carbon within both materials, products and services is an area “where there is uncertainty in the industry” (RSSB, 2021b, p.7), suggesting that this thesis, by providing detailed breakdowns of specific earthwork interventions, will begin to bring clarity to this area of carbon measurement.

Emissions reporting and danger of overlapping emission reporting and items being completely missed off is addressed in this report with several options discussed in the ‘guiding hand’ approach. These options include further development of the RSSB’s environmental reporting tool (ERT), expansion of the ORR data portal’s rail emissions statistics requirements and exploration of other value chain emissions tools which suit the purpose. Findings from Report T1198 highlight the large source of emissions (and convoluted nature of emissions reporting in the rail sector, Figure 2.5) from within the supply chain, and it recommends that this area forms the focus for future work (RSSB, 2021a).

T1197 acknowledges that for the GB mainline railway to achieve full decarbonisation, an equivalent approach to that applied to track decarbonisation will need to be applied to reducing embodied carbon. This aligns with work by Jones, Moura and Domingos (2017) who discuss the need for whole life carbon to be assessed.

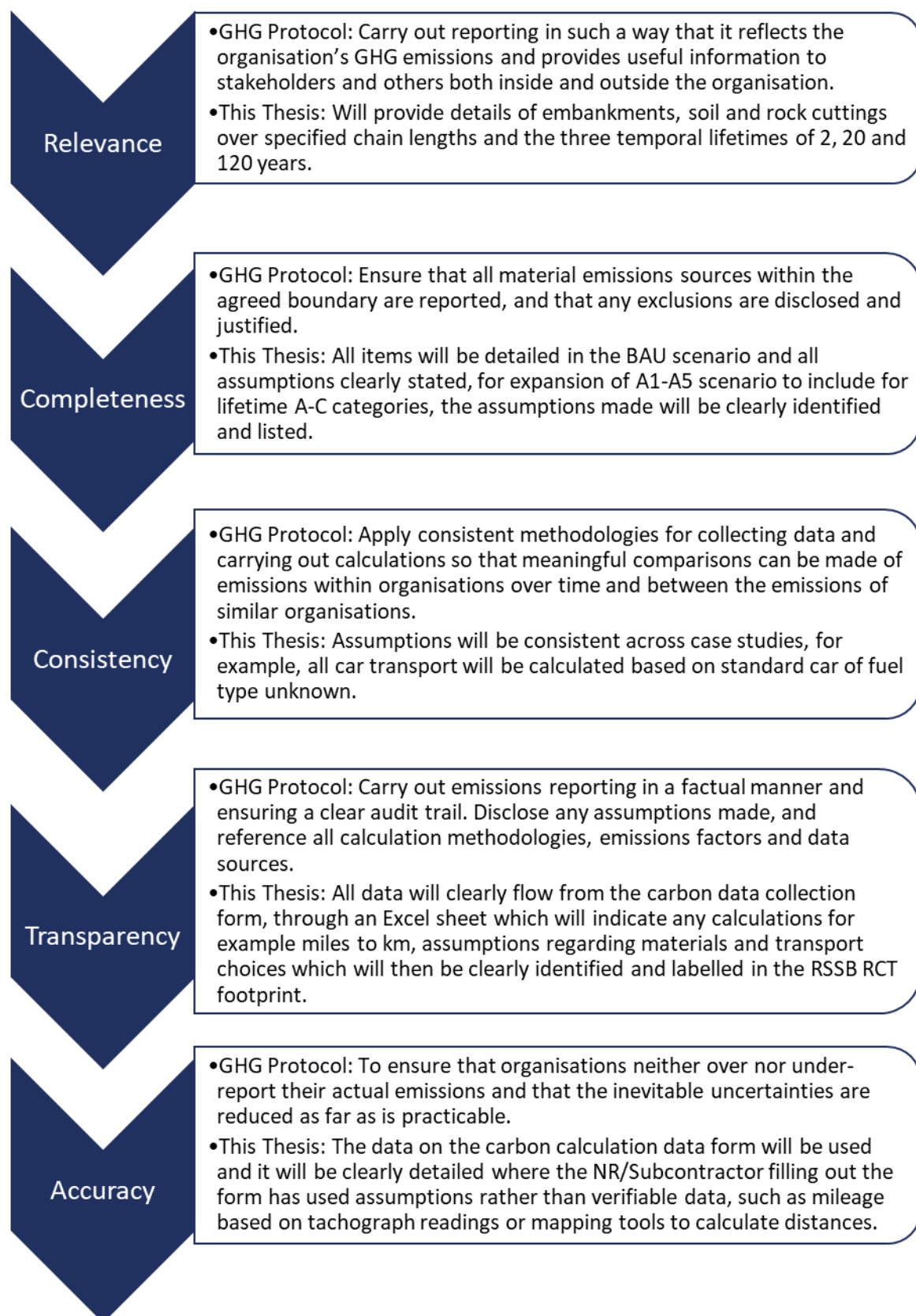


Figure 2.11 GHG Protocol (2004) Relationship to This Thesis, amended from Table 2 of T1198 Report, (RSSB, 2021b, p.5)

As embodied carbon is the greatest source of CO₂e in the whole GB mainline railway footprint (see Figure 2.10) stakeholders should place greater focus on reducing these (RSSB, 2021a).

T1198 provides three specific recommendations for NR:

1. To continue their existing data collection activities with consideration for additional data collection aligned with NR SBTs, such as proportionate emissions data collection for areas they have responsibility for including property, business travel, logistics and commuting.
2. To continue their existing reporting activities which includes energy use data for yellow fleet and potentially data collection of the two discrete types of yellow fleet and plant, owned and rented, with consideration for additional data collection to monitor progress against proposed targets.
3. To consider establishment of contractual arrangements for proportionate calculation and monitoring of embodied carbon including data from the supply chain on number of staff on a monthly basis, using Bills of Quantities (BOQs). EPDs provide standard goods data and by using best practise emission factors calculate the embodied carbon associated with these standard goods.

There is “uncertainty” in the amounts of embodied carbon within materials, products and services provided by third parties in construction activities within the railway industry due to limited user data, and the level of reporting for capital goods and services is classified as “limited” using existing carbon tools and EPDs (RSSB, 2021b, p.7). There is currently no regular or mandated emissions data collection occurring which is where use of a standardised and consistent data collection method prior to footprinting is advocated in this thesis (Najafpour Navaei *et al.*, 2024). A new principle introduced in this RSSB report is the notion of “sunk cost” for embodied carbon in existing assets, with this carbon not needed to be reported annually (RSSB, 2021b, p.7). The proposed focus of annual reporting of embodied carbon should be from new construction or significant refurbishment activities (RSSB, 2021b).

The Everything Counts policy document (Marsden, Lokesh and Densley-Tingley, 2022) re-emphasises several points previously made in the literature. These points being carbon emissions emitted during construction of new transport infrastructure (Aubrat and Lemer, 2018), there is a core of hard to decarbonise emissions which includes cement (Aubrat and Lemer, 2018), and there is a need to understand the payback period and modal shift involved in carbon accounts (Westin and Kågeson, 2012; Baron, Martinetti and Pépion, 2011) [ENREF 22](#).

Marsden, Lokesh and Densley-Tingley (2022) presents findings regarding emissions from maintenance of the existing network not found previously in the literature, and finds that these

emissions are at least as substantial as those emitted from new build activities, with the extrapolation exercise carried out on selected maintenance activities for this thesis also finding that large amounts of carbon are being expended on these so called “small projects,” see Section 4.1.8.

Marsden, Lokesh and Densley-Tingley (2022) also advocates not counting offsets against infrastructure activities due to the difficulties in linking these together (due to debate on whether 1kg emitted is same as 1kg sequestered, see Section 6.1) along with the issue that additional sequestration via tree planting may well be required anyway to fill any CO₂ emissions overshoot as illustrated in the grey zone of Figure 1.2. This later finding is an issue that will also be advocated by this thesis, as planting several trees for example, to offset a small intervention in a particular area, will be shown to not have any significant carbon reduction impact compared to mitigation activities, and whole NR land asset plantings could potentially be the path to pursue for corporate level accounting.

The technical document on reducing rail infrastructure carbon (Lokesh, Densley-Tingley and Marsden, 2022a) once more highlights the challenge of the “stubborn” carbon (Lokesh, Densley-Tingley and Marsden, 2022a, p.7) embodied in the materials of the infrastructure which, as previously noted by Aubrat and Lemer (2018), form a great proportion of the whole life carbon footprint, and are potentially a threat to achievement of net zero carbon by 2050.

Figure 2.12 illustrates the system boundary, where notably decommissioning is outside the boundary owing to the long life-time of these assets and that they may not, due to this extended lifetime, be decommissioned at EOL, but rather have their lifetime extended via routine maintenance.

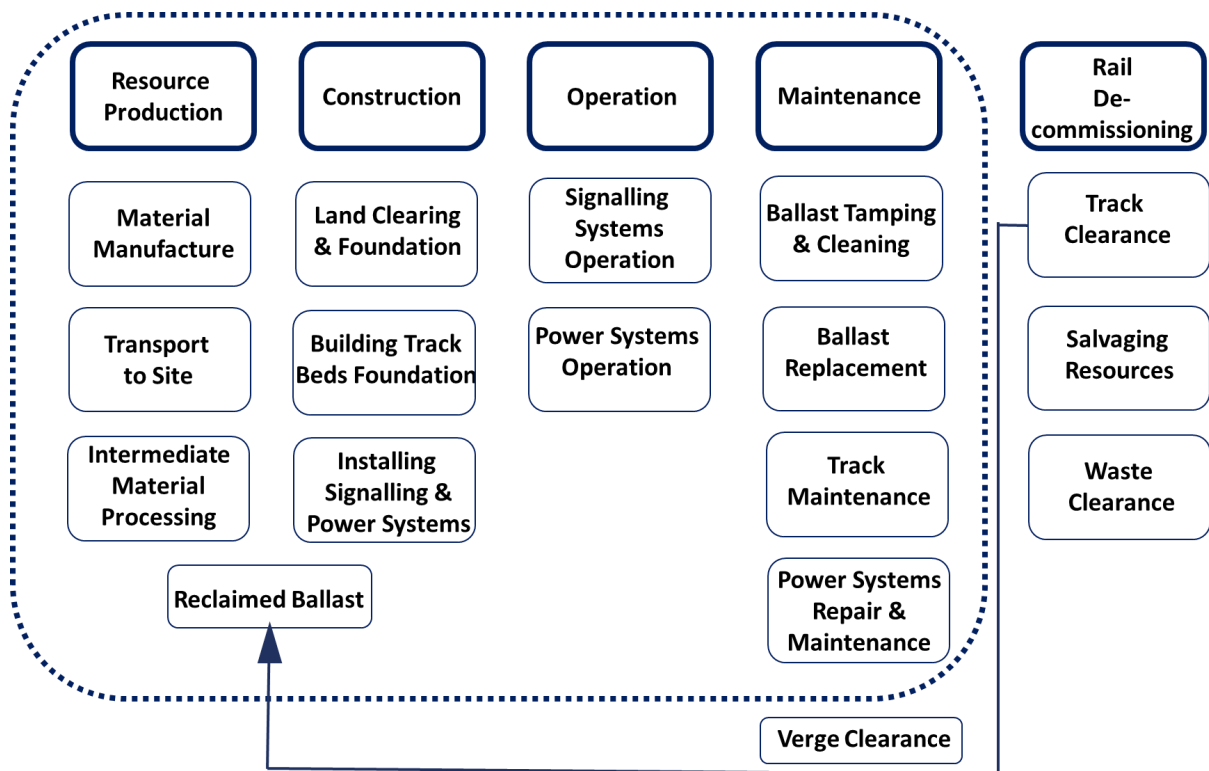


Figure 2.12 System Boundary of Study, amended from Lokesh, Densley-Tingley and Marsden (2022a, p.11)

The exclusion of verge clearance in the maintenance of track, see Figure 2.12, is an area addressed in this thesis. The maintenance interventions of vegetation management, de-vegetation of drains and individual geotechnical tree removal, detailed in Appendix A.1 would all fall under this heading.

2.3.4 Where is the Carbon in NR?

NR has signed up to the SBTi and has committed to reduce their absolute Scope 1 and 2 GHG emissions by 46%, and their Scope 3 (indirect) use-phase emissions by 28%, by 2029, benchmarked against the 2018 financial year in line with reductions required to keep global warming to 1.5°C (SBTi, 2021a). NR also commits to 75% of its suppliers, by emissions, to have SBTs by 2025. These targets are in line with the Sixth Carbon Budget, 68% reduction by 2030 on 1990 levels, and 42% reduction on 2019 levels (Climate Change Committee, 2020b, p.429) with the 2019 levels aligning best with the NR benchmark, 2018. See Appendix B.7 for Carbon Budgets and NDCs. See Chapter 6 for ER reductions plus offsetting, compared to this trajectory. Figure 2.13 illustrates the NR journey to net zero by 2050.

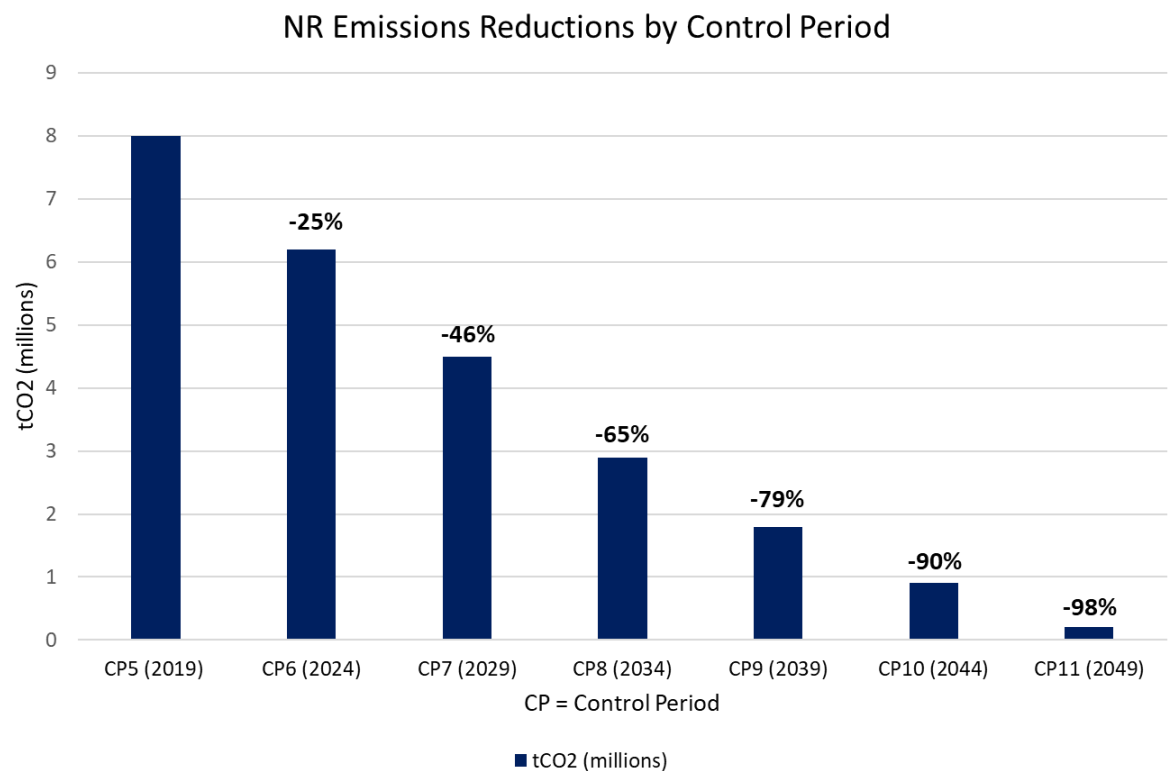


Figure 2.13 NR Pathway to Net Zero, amended from Network Rail (2019, p.3)

The UK’s carbon footprint to 2020, (DEFRA, 2023) will be reviewed to set the context for an overview of carbon in the GB rail industry and its weighting on the UK carbon footprint, detailed in reports T1197 & T1198 (RSSB, 2021b). This is followed by exploring NR’s carbon footprint value via the NR Route Map to Low CO₂e Steel (Expedition, 2020), and quantifying its weighting as both a percentage of GB rail and UK carbon footprint.

Figures for overall UK territorial emissions and transport’s share, introduced in Section 1.1, have been reviewed for 2019 to 2021 using the final GHG emissions tables (HM Government, 2023b) provided by BEIS and the new DESNZ (updated 29 June 2023). Table 1.1 shows that for 2019 UK total territorial GHG emissions were 450.4 Mt, with around 27% accounted for by transport (NC sector classification) and 0.42% by rail (mobile combustion only) (HM Government, 2023b). The T1198 Final Report (RSSB, 2021b) details the GB whole rail footprint for 2019-20 as embodied 5,194,970 t, operations 785,107 t, traction 3,508,317 t, giving a total of 9,488,394 t for the whole of GB rail. See Table 2.2 for comparison of figures.

Table 2.2 2019 GHG Figures for UK, Transport, Rail and NR

All figs in Mt	UK	Transport	Rail	RSSB 2019-20 Figure	NR Footprint (2020)
2019 UK Figures	450.4	123.1	1.9	9.5	8.1
Percentages of UK total	100%	27.33%	0.42%	2.11%	1.80%

Table 2.2 shows that this GB whole rail footprint accounts for around 2.11% of total UK GHG emissions in 2019, almost 4 times higher than the Government figure detailed above, which has rail accounting for 0.42%. Reasons behind this may be that the whole rail footprint for GB includes embodied, operations, and traction, and not just mobile combustion of railways. Due to the aforementioned reasons, there is a requirement for whole LCA to see a clear picture of rail's contribution to the UK carbon footprint.

Although the Route Map is primarily focused on carbon reductions in steel, this map states that the majority of NR's global CO₂e footprint of 8,071 kt lies within Scope 3, the value chain for NR (Expedition, 2020, p.4). This figure consists of 7,824 kt (97%) Scope 3, 51 kt for Scope 1, and 196 kt for Scope 2 emissions. NR's global emissions (8,071 kt) can be expressed as a percentage of the total GB Rail footprint (9,488,394 t), where they account for 85.26% of this figure. When expressed as a percentage of total UK emissions 2019 (450.4 Mt) they are found to account for 1.80% of this figure, which is closer to the RSSB total rail figure of 2.11%. When comparing these figures, it should be noted that they have differing boundaries, the RSSB footprint was for the whole of GB and the NR footprint includes England, Wales and Scotland. These figures illustrate the impact that decarbonisation of NR's footprint can have on not only the GB mainline rail carbon footprint, but also the UK carbon footprint as it progresses along its trajectory to net zero by 2050.

CO₂e percentage reductions against the SBTs are detailed in Table 2.3 alongside control/time periods of NR (Expedition, 2020).

Table 2.3 NR Carbon Reduction Aligned to CP and SBT/IPCC Targets

Control Period/ Time Period	Carbon Reduction Stage	Carbon Reduction Target (Aligned to SBTi to Stay Within IPCC Less Than 1.5°C Temperature Rise)
CP6 2019-2024 CP7 2024-2029	Rapid decarbonisation	By 2030 reduction of 65% embodied carbon vs 2020 levels
CP8 2029-2034 CP9 2034-2039	Normalising decarbonisation	By 2040 85% reduction vs 2020 levels
CP10 2039-2044 CP11 2044-2049	Final push to net zero	By 2050 net zero carbon

2.4 NR Perspective

Following the policy, innovation and legislative overview, and the overview of research in rail infrastructure, the evolution of the NR perspective and approach to this policy and innovation to address carbon reduction and the environment is presented, see Figure 2.14.

The environmental and biodiversity policies highlighted in Figure 2.14 have been identified by NR as the most relevant for targeting carbon reduction. Exploration of the potential for increased biodiversity to deliver offsetting co-benefits is provided in Section 2.4.1. These policies are linked to this thesis, alongside NR waste management and sustainability, see Section 2.4.2, and NR low and whole life carbon initiatives, see Section 2.4.3. These issues are consolidated in Section 2.4.4 and the section concludes in Section 2.4.5 addressing carbon literacy.

2.4.1 Environmental & Biodiversity Policies

WRCCA policy encompasses risk assessment during the Governance for Railway Investment Projects (GRIP) process, to build resilience to weather change into the infrastructure of the railway. This connotes that when maintenance, refurbishment and renewals are implemented the solution utilised needs to have resilience to future climate change built into it alongside low carbon and biodiversity considerations. NR is committed to ensuring the railway becomes resilient to future climate change via “replacing like for better rather than like for like” in the event of catastrophic asset failure due to weather events (Network Rail, 2017c, p.1). This is a form of adaptive capacity built into the system. GRIP has subsequently been replaced with the Project Acceleration in a Controlled Environment (PACE) process. The PACE process is being instigated as part of the Swift, Pragmatic and Efficient Enhancement Delivery (SPEED) project and is one of the markers highlighting when specific PAS2080 stages require completion using the RSSB RCT (Network Rail, 2022c). See Glossary for definitions of GRIP, PACE and SPEED.

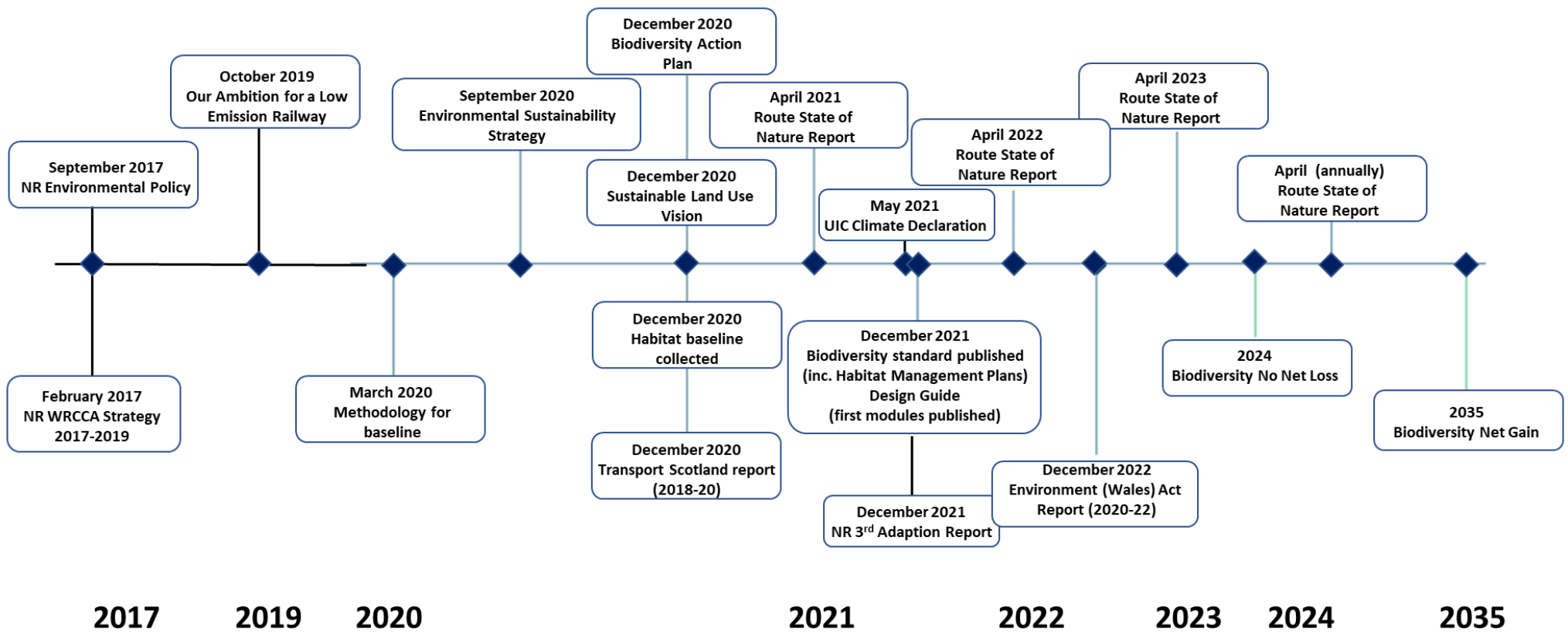


Figure 2.14 Selected NR Environmental & Biodiversity Policies , amended from (Network Rail, 2020d, p.2)

NRs commitment to the environment at the highest levels of management is illustrated in their Environmental Policy, indicating that they will sustainably manage their land assets and consider the impacts of their actions on biodiversity (Network Rail, 2017a). This also shows alignment with government guidance on vegetation management (Varley, 2018), see Section 2.2.3. Furthermore NRs commitment to meeting the requirements of a 1.5°C warming scenario (mirroring the IPCC 1.5°C warming limit set in 2018) via the setting of SBTs, see Figure 2.13, is given in “Our Ambition for a Low Emission Railway” (Network Rail, 2019). In this bold document the first three CPs have the most ambitious targets, indicating that the (perceived) easily accomplished wins in terms of CO₂e being made first, with the harder to decarbonise aspects of embodied CO₂e coming later.

To “go beyond embodied carbon assessments” (Network Rail, 2020b, p.19) and achieve “no-net biodiversity loss” (Network Rail, 2020b, p.9) and “net zero carbon” (Network Rail, 2020b, p.20) are the headline goals of The ESS, (Network Rail, 2020b) outlining NR’s plans for the coming decades. Within the low-emission railway, a core priority is carbon accounting, with a key milestone being that by 2027, to support infrastructure projects, these will “go beyond embodied carbon assessments to whole life carbon assessments” (Network Rail, 2020b, p.5). This thesis aids NR in meeting this milestone as the renewal case studies have been expanded to whole lifecycle covering PAS2080 stages A0-C4, plus the calculation of sequestration (see Chapter 6) to offset each one’s CO₂e. The ESS demonstrates that NR’s commitment to wider SDGs (Network Rail, 2020b, p.4), and the alignment of this thesis to UNSDGs 9, 11 and 13, see Section 2.2.1 aids in meeting this commitment. NR has signed up to the International Union of Railways UIC Climate Declaration accord (which has goals and targets aligning with NR’s SBTs,) (Network Rail, 2021c) reiterating NR’s commitment at international level towards meeting climate goals.

In their proposed circular framework for LCA, see Figure 2.19, Saxe and Kasraian (2020) cite PAS2080 (2016) and highlight the “special module” created in the PAS, lifecycle stage ‘D,’ in an attempt to acknowledge those costs and benefits which lie outside the usual infrastructure boundaries, such as offsetting via sequestration.

One of the issues highlighted by this thesis is the viewpoint that reaching net zero by 2050 is a time horizon beyond the future planning of most people (Simpson, 2022) and, even with SBTs graphically illustrating the journey to net zero for NR (aligned to 5-year CPs over a 30-year lifecycle), see Figure 2.13. The concept that imminent action is required today, in pursuit of this distant goal, is yet to be embraced by all.

Net biodiversity gains have recently been mandated in UK law (HM Government, 2020b; Network Rail, 2020d). The NR ESS also encompasses biodiversity with no net loss by 2024 and net gain by 2035

(Network Rail, 2020b), see Figure 2.14. Nonetheless, an alternative strategy to biodiversity goals alone is investigating the co-benefits of biodiversity for plantings made for maximised sequestration, such as those to offset earthworks interventions, see Chapter 6 and Figure 2.4 illustrating the mind set shift that is required.

Re-use and re-deployment of materials (see Chapter 5) and the CE (see Section 2.4.2), both key metrics in decision making (Network Rail, 2020b), are factors that need to be considered when calculating CO₂e in geotechnical solutions to ensure the lowest embodied CO₂e materials are used, and that materials can have a secondary life via re-use, repair, and re-purposing.

The NR Biodiversity Action Plan, BAP, (Network Rail, 2020d) see Appendix B.6, in response to (Varley, 2018), see Section 2.2.3, and developed in line with Defra's 25-Year Environment Plan (DfT, 2021d), see Section 2.2.2, highlights the interlinkage between sustainability and biodiversity in environmental policy.

The Network Rail Third Adaptation Report has a focus on embedding resilience to climate change in the railway (Network Rail, 2021d). This is alongside engagement to consider NbS owing to the links between CO₂e solutions and biodiversity, while acknowledging that earthworks "cannot be future-proofed quickly" (Network Rail, 2021d, p.18). This Adaptation Report advocates embedding this resilience at both new construction and renewal, aligning to the renewal of earthworks analysed in this thesis. Furthermore, impacts of storm and wind on vegetation are highlighted in this Adaption Report, driving the move towards use of non-leaf drop trees, such as coniferous trees, being preferable on NR land, see Chapter 6 for the broad tree classifications used in this thesis.

2.4.2 Waste Management & Sustainability

The CE material lifecycle (see Figure 2.18) and Waste Management Hierarchy (see Figure 2.21) demonstrate the need for these issues to be explored in tandem. R0-R2 align with prevention, R3-R6 with preparing for re-use, and R7-R9 with recycling, recovery, and disposal at the bottom of the hierarchy. The CE principles are highlighted in the REUSE project, emphasizing the need to adopt these to enable reduction of a "significant proportion" of the 45% of GHGs that will remain after GHG reduction activities such as "energy efficiency and switching to renewable energy," addressing 55% of the global GHGs (UIC, 2021, p.6). Over one third of all waste in Europe comes from construction and demolition waste (CDW), and with both construction and maintenance of railway assets contributing "a lot of waste" towards this figure, there is a clear requirement for further attention and focus on CE principles when looking for GHG savings (UIC, 2021, p.9).

Use of progressive steps to move towards a CE (BSI, 2017), align to the “baby steps” suggested in the REUSE project (UIC, 2021, p.19), and SNCF suggest this approach to their strategy of reuse or recycling 100% of selected rail components by 2025, using small scale projects which can be scaled up as appropriate. This approach aligns to the extrapolation exercise conducted in this thesis, illustrating scaling up of both CO₂e expended in case studies (see Section 4.1.8), and scale up of sequestration efforts in Chapter 6 to a theoretical maximum.

NR, via use of their internal stock market app, “SURPLUS app” (UIC, 2021, p.24) which reduces waste to landfill via re-use in other areas of the business (aligning with R3, see Figure 2.18), have begun to instigate use of CE principles into BAU, alongside collation of metrics on Reuse, Recycled and Recovered materials in the regions (NR W&W Region, 2022).

The UIC advocate renting rather than buying in their REUSE report (UIC, 2021), and this philosophy could be applied to the construction equipment required for earthworks, owing to the potential for this practice to “incentivise the suppliers to provide products with higher lifespan” (UIC, 2021, p.22). Use of rented equipment with longer lifespans could reduce overall lifetime embodied carbon in this machinery.

2.4.3 Low & Whole Life Carbon Initiatives

NR have a multitude of policies to assist them in embedding carbon reduction and biodiversity increase in their BAU scenario alongside managing whole life carbon. NR is currently implementing carbon reduction via Workstream 13 (Network Rail, 2020a) and use of PAS2080 aligned templates in the RCT (Network Rail, 2022a). Further details of these low and whole life carbon initiatives are provided in Appendix B.9.

The Capital Carbon Guidance Note (Network Rail, 2018a), advocates measurement of capital carbon only for projects greater than £1m, demonstrating NRs current top-down approach to carbon measurement. The key elements of capital and operational carbon are outlined in terms of design and construction, operation and EOL in Figure 2.15. The extrapolation exercise conducted in Section 4.1.8 illustrates the potential carbon amounts in the case studies, all less than £1m, and illustrates examples of total quantities when scaled up, 2,598 tonnes CO₂e, highlighting the need for NR to account for these seemingly small amounts of carbon.

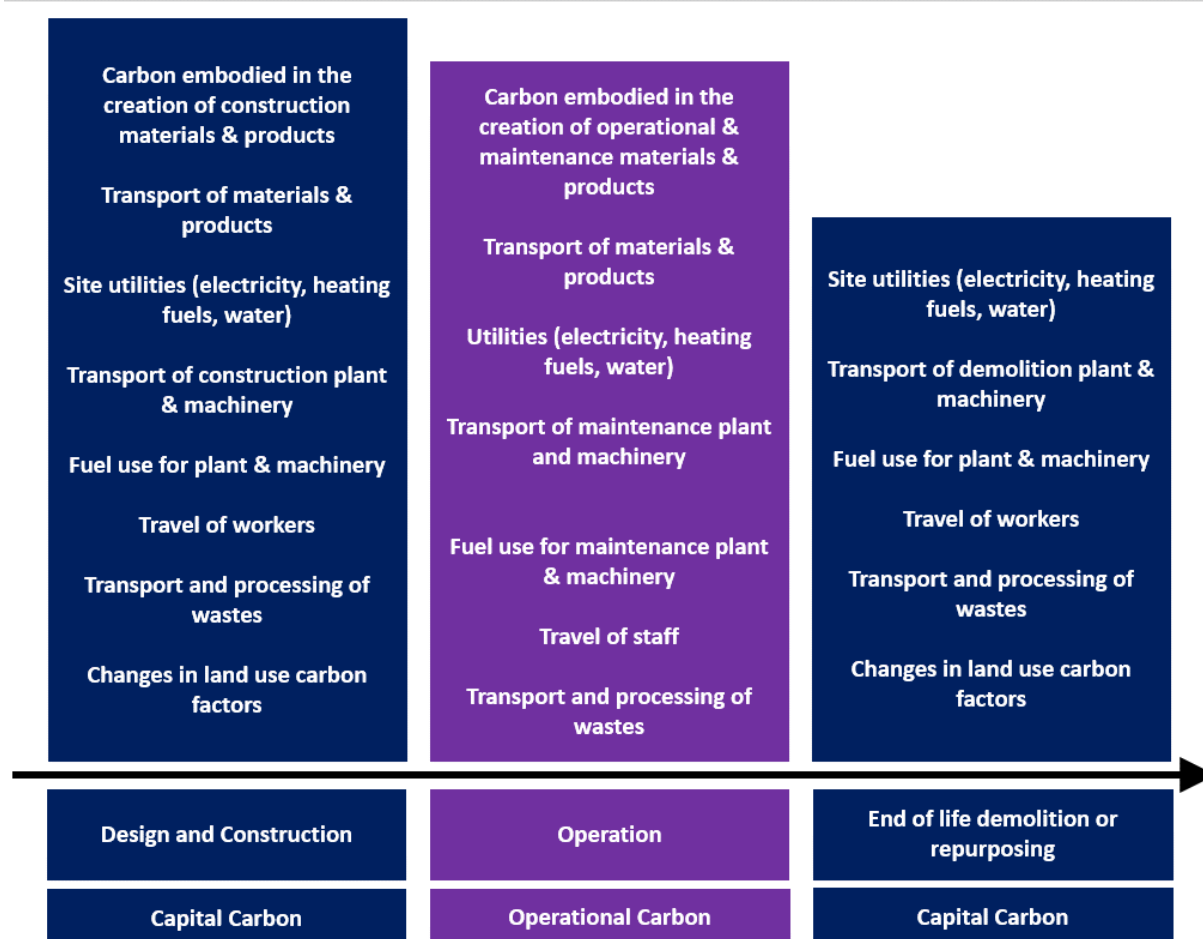


Figure 2.15 Key Elements of Capital and Operational Carbon, amended from Network Rail (2018a, p.1)

The capital carbon guidance note has been superseded by a guidance document with greater scope, for managing whole life carbon in infrastructure, NR/GN/ESD07 (Network Rail, 2022c).

NR's advocacy, and mandating the use of this template via required and optional data inputs could indicate greater comparability of results between differing projects, see Table 3.1. Use of PAS2080 aligned templates within the RSSB RCT is a positive change for NR and provides a consistent structure for carbon footprints to be input into the RSSB RCT, to achieve alignment with PAS2080.

2.4.4 Consolidating Issues & Outlining Problems

The NR Railway Sustainability Design Guide draws the majority of the documents reviewed in Section 2.4 into one comprehensive, easily accessible digital document (Network Rail, 2022e). An overview of the document hierarchy within NR and its links to the Digital Design Guide, from Volume 1, is illustrated in Figure 2.16.

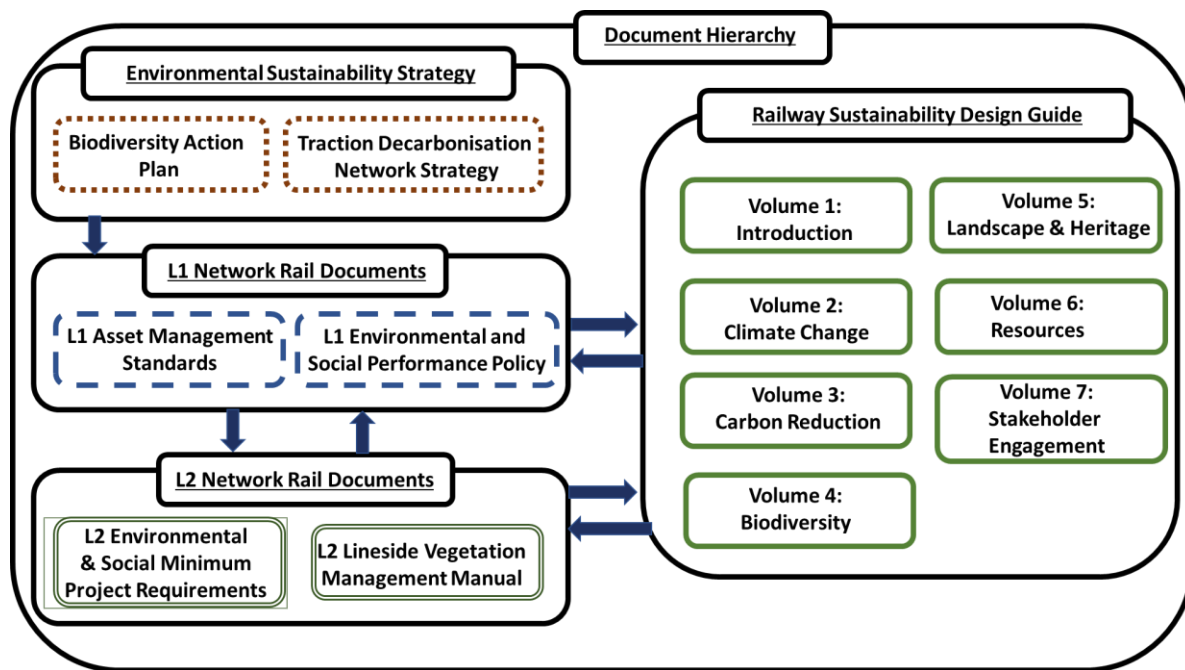


Figure 2.16 NR Document Hierarchy, amended from Vol 1 of Network Rail (2022e)

Figure 2.16 illustrates links between the digital design guide at all levels of NR from strategy documents down to working manuals and the interlinkage between Environmental Policy and the Sustainable Design Guide, particularly Carbon Reduction and Biodiversity, two key areas explored in this thesis. Volume 3 in particular notes the opportunities to offset residual carbon via use of land to store carbon, such as tree planting (Network Rail, 2018c, p.11). In the design guide NR has adopted the National Infrastructure Commission's (NICs) four guiding principles for infrastructure design (Network Rail, 2018c, p.14), namely:

1. Mitigate GHG emissions and adapt to climate change.
2. Reflect what society wants and share benefits widely.
3. Provide a sense of identity and improve our environment.
4. Achieve multiple benefits and solve problems well.

To enable delivery of these principles the NIC recommends all projects appreciating the wider context, engaging meaningfully and continually measuring and improving.

The third enabler for delivery, which is measurement and improvement, aligns with this thesis. This is the first attempt to explore the BAU scenario, and accurately measure the carbon in NR's earthworks. From Volume 3 Low Emissions of Railway Sustainability Design Guide it is noted on the NR time line of actions to 2050 that by 2027 all infrastructure projects must assess Whole Life Carbon, which this thesis aids NR in reaching. From Volume 4 Biodiversity of the Railway Sustainability Design Guide an overview of the hierarchy of NR documents in the biodiversity field is presented in Figure 2.17, illustrating the interconnectivity between strategy and working manuals.

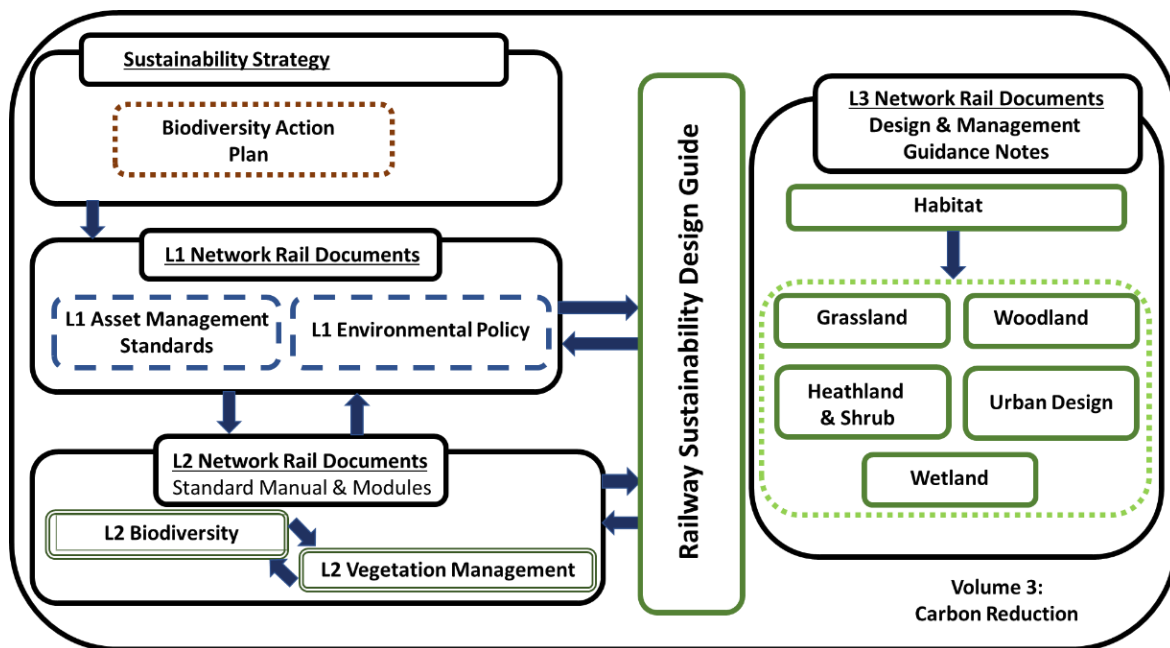


Figure 2.17 NR Biodiversity Documents Hierarchy, amended from Vol 4 of Network Rail (2022e)

The balance between biodiversity and carbon sequestration must be found, as illustrated in the balanced carbon scales, Appendix A.5.2. Lowering embodied carbon must always be the first priority and avoided biodiversity loss falls within the mitigation side of the scales (Axelsson *et al.*, 2024) see Figure 6.12; and off-setting must not become the norm, but, where it does occur, the impact on biodiversity should be assessed. This viewpoint is echoed in the IPCC's comments in their special reports where offsetting not being the primary course of action is noted (IPCC, 2018). Balancing environmental and biodiversity, waste, carbon, and WRACCA policies, see Figure 2.16 and Figure 2.17, needs to be achieved, and the co benefits between these policies (see Chapter 6) need to be highlighted and exploited for mutual benefit of NR and other stakeholders. This section concludes by weighing up selected NR issues via reference to the above outlined policies.

The main issues with the assessed earthworks (existing mainline GB rail infrastructure), is that to remain operational "continual maintenance and renewal" interventions, to mitigate any deterioration that occurs and remedy any earthworks failures as and when they arise, is required (Briggs, Loveridge and Glendinning, 2017, p.107). This leads to the three distinct intervention types, with differing expected lifespans, see Figure 1.5, explored via the case studies.

The NR issues related to implementation of methods used in this thesis that have been identified are two-fold, carbon data capture and carbon footprinting. Issues with data capture highlighted include a lack of comprehensive or cohesive record keeping, or consistent data collection format being found across all regions at NR. Data unavailability tending to be due to lack of initial capture (in the case of staff mileage or material mileage to site) or having convoluted reporting chains (via the supply chain and multiple contractors for example) making the data capture extremely difficult. This gap in record

keeping provides an opportunity for improvement in a format conducive to future input into the RSSB RCT for carbon footprint calculation aligned with PAS2080 and PACE stages. The novel carbon data collection form used in this thesis aims to fill this gap, see Appendix C.3.

Issues with carbon footprinting stem from the current mandate of only projects greater than £1m requiring footprints. Evidence of the tools' limited use is found via a brief perusal into the footprints stored in this tool, where there is very limited visibility of projects, with many footprints behind security firewalls, meaning that transparency of data, where it exists, is also an issue. NR have issued a carbon communication (Network Rail, 2022a) with further guidance on which projects require this data to be collected and filename conventions, however the £1m limit remains (Network Rail, 2022c, p.9).

Data capture plays a pivotal role in this thesis, establishing the BAU baseline for the selected earthworks is a crucial first step on NR's net zero path. NR need accurate, detailed data to begin their emissions reduction journey in line with their SBTs. The whole industry mainline carbon footprint, see Section 2.3.3, provides an overview of the scale of the carbon problem for NR as a proportion of the whole mainline GB railway.

2.4.5 Carbon Literacy

Given the 2050 decarbonisation target, carbon literacy forms an integral part of decarbonisation efforts in the rail industry. Equally, an in-depth working knowledge of PAS2080, and a carbon calculation tool, such as the RSSB RCT, is vital for those directly responsible for carbon footprinting. These combined actions will enable NR staff to calculate their carbon footprint for a given project, as well as analysing, reporting, and applying carbon reduction measures via evaluation of low-carbon options using the embedded carbon factor data in the tool (Expedition, 2020) along with ER measures outlined in this thesis, see Chapter 5. Carbon literacy equips staff implementing PAS2080 with the terminology and concepts needed to progress their net zero thinking and apply this to their projects (Carbon Literacy Project, 2023). The Carbon Literacy for Rail tool from RSSB, certified by the Carbon Literacy Project, demonstrates the burgeoning implementation of such knowledge for those within the rail industry (RSSB, 2024a).

This section has provided an overview of the NR perspective towards the environment, carbon, climate, and biodiversity issues discussed in the legislation section and pointed out the NR policies and management processes to navigate these. Issues with data collection and carbon footprinting have also been highlighted along with carbon literacy in NR.

Section 2.5 will discuss the CE, which feeds into decarbonising efforts by means of reuse and recycling to further reduce carbon emissions.

2.5 Circular Economy (CE) and Waste Hierarchy

The prevalence of research in the area of circularity, encompassing cradle-to-cradle thinking, see Section 1.5.2, along with other schools of thought including the blue economy, performance economy, biomimicry, natural capitalism, industrial ecology and symbiosis, and regenerative design, (BSI, 2017) has increased in recent years (Baker-Brown, Gowler and Arnold, 2023; CENTS, 2023; O'Leary, Osmani and Goodier, 2024).

The British Standard framework for implementing the principles of the CE in organisations points to circularity moving away from the traditional and, crucially, linear “take, make, use, dispose” (or “cradle to grave”) economic model,” see Figure 2.18, which is now “potentially reaching its limits and the availability of cheap, easily accessible materials and energy can no longer be taken for granted” (BSI, 2017, p.3).

Increasingly circular options occur early in the product lifecycle, design stage, and these have the greatest impact, in terms of circularity, see Figure 2.18. Conversely, increasingly linear options occur later in the lifecycle, disposal stage (BSI, 2017). The circular lifecycle of a product aligns to the hierarchical nine “Rs,” detailed by UIC (2021), see Figure 2.18. These hierarchies can be applied to existing knowledge in this area, see Mi-ROG (2020), who elucidate alignment of CE principles with the Green Construction Board’s, Carbon Reduction Curve, see Figure 2.3. Furthermore Baker-Brown, Gowler and Arnold (2023) also highlight the importance of early engagement in decision making for embedding CE principles into construction in their decision-making timeline (Baker-Brown, Gowler and Arnold, 2023, p.54). The carbon reduction curve lexicon; “build nothing, build less, build clever and build efficient,” see Table 2.4, also aligns to the principles outlined in Figure 2.18. “Nothing”, “less” and “clever” cover, planning, and designing of carbon reduction measures. These are where potentially the most impact can be made. “Efficient” aligns with construction carbon, and has comparatively less impact on a project. The ISO IWA42 Guidance also points towards organisations focusing on value chain reduction of emissions, and when consideration of an earthwork, for example, are made, applying the CE and “build less” approach (ISO, 2022, p.18).

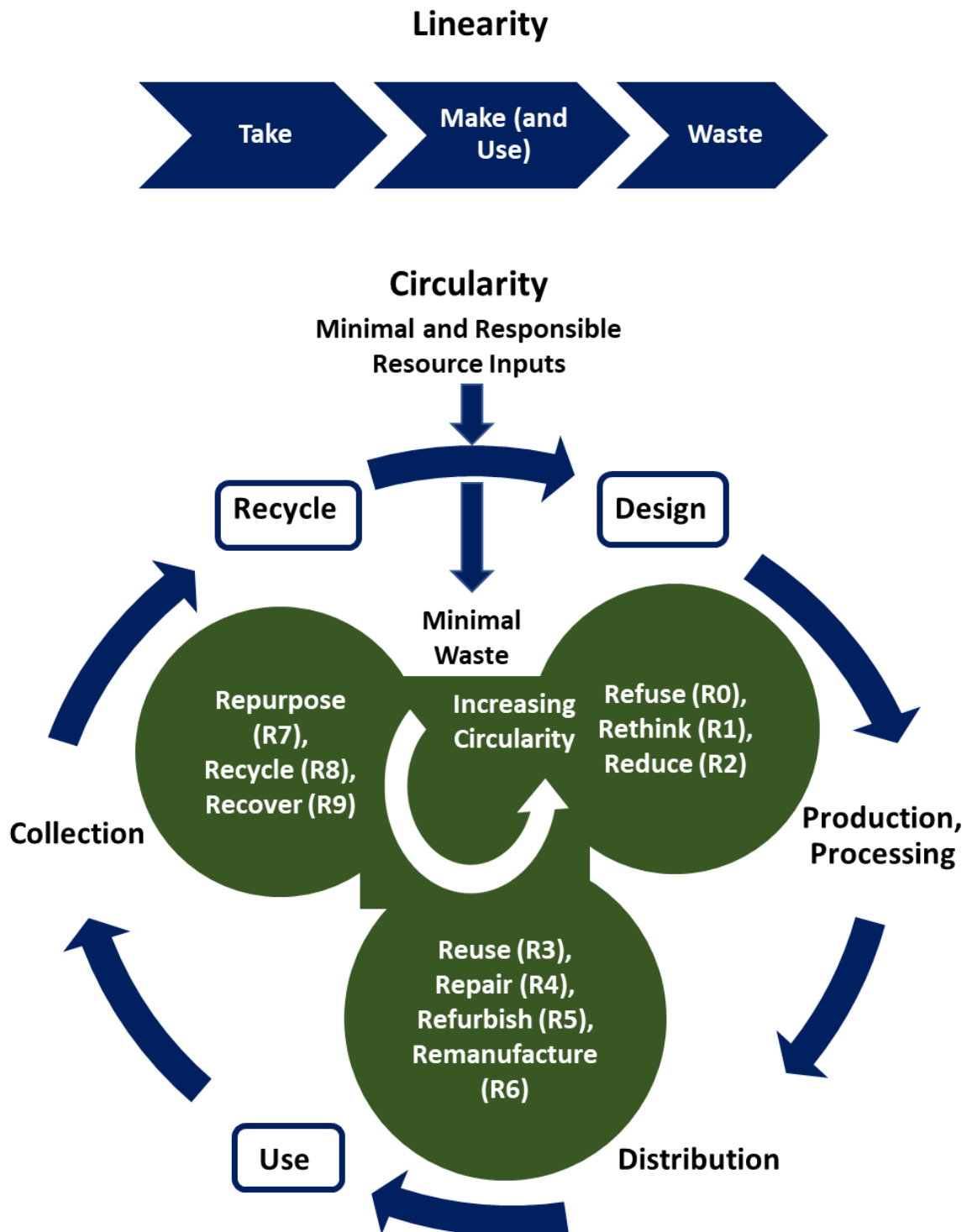


Figure 2.18 Movement from Linearity to Circularity , amended from (UIC, 2021) and (BSI, 2017)

CE thinking, as part of a step change from the linear to circular, is demonstrated in LCA for other linear infrastructure (Harvey *et al.*, 2016, p.2-2), where at EOL, materials can feed back into the lifecycle at earlier stages in discrete loops, via recycling back into materials processing, remanufacture back into the manufacturing process, and reuse back into the use phase. These loops from EOL to earlier stages bearing a clear resemblance to those of the right hand side of the butterfly diagram from Ellen MacArthur (Ellen MacArthur Foundation, 2019). The butterfly diagram shows

multiple loops in the technical cycle (on the RHS of the butterfly) whereby products are kept in circulation via maintenance to prolong use, reuse, then refurbishment, and finally recycling.

The CE frameworks overviewed thus far have had a product focus, however a new CE framework for construction projects has been proposed in Medina and Fu (2021). This framework aligns to five key intervention points in the construction lifecycle, which also align to PAS2080 A-D stages used in this thesis of production/manufacturing, consumption/operation, waste management, recovery/circularity, and innovation (Medina and Fu, 2021, p.306). It is in these discrete stages that carbon hot spots are identified for the case studies in Chapter 4, and then targeted ER strategies explored in Chapter 5. A CE Framework of LCA Stages specifically for transport infrastructure is proposed by Saxe and Kasraian (2020), see Figure 2.19.

Circular Framework of LCA Stages for Transport Infrastructure

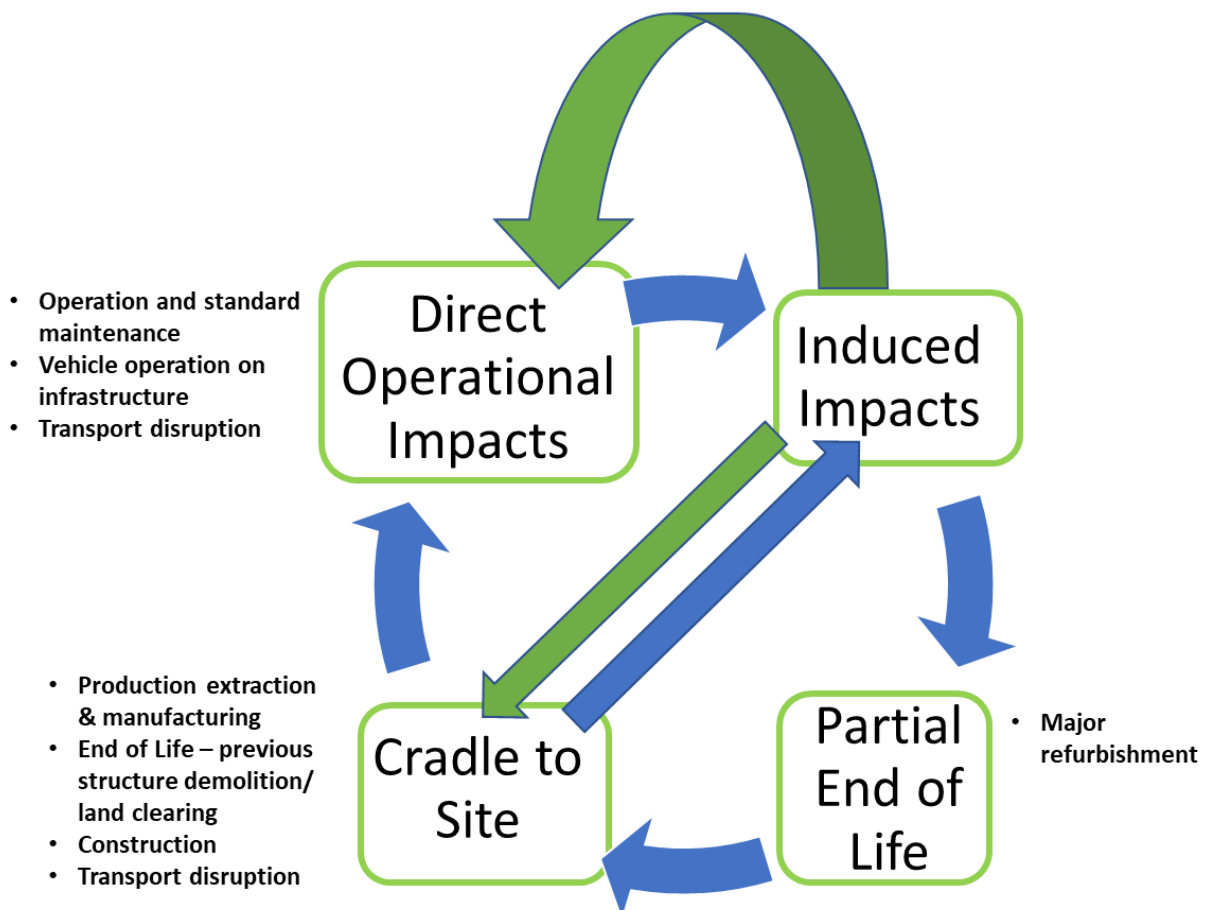


Figure 2.19 Circular Framework of LCA Stages for Transport Infrastructure, amended from (Saxe and Kasraian, 2020, p.1040)

The Saxe and Kasraian (2020) LCA stages, see Figure 2.19, has parallels to the proposed circular framework concept, see Figure 2.20, particularly in terms of demolition and recycling/reuse in stage C feeds back into stage A, mirroring that of the partial EOL in Figure 2.19, feeding back into cradle-to-

site activities. The Medina and Fu (2021) CE framework for construction projects looks at each stage, aligned closely to the PAS2080 stages, but does not encompass the partial EOL acknowledged by Saxe and Kasraian (2020) in their framework as being pivotal for transport infrastructure projects. Saxe and Kasraian (2020) acknowledge that these infrastructure do not have a defined EOL, but have their life extended at this point via maintenance, refurbishment and renewal activities.

The Saxe and Kasraian (2020) circular framework in Figure 2.19 has several key parts:

- Recognises the impact from land clearing at the start of a project.
- Acknowledges the “tightly linked external impacts that transport infrastructure induces” (Saxe and Kasraian, 2020, p.1031). These external impacts include travel behaviour, and LULUCF.
- Crucially, it recharacterizes “end-of-life” as “partial end-of-life”, in recognition of the widespread “indirect impacts from transport infrastructure” (Saxe and Kasraian, 2020, p.1031 & p.1038).
- Induced impact of LULUCF is where the revegetation and reforestation activities, proposed as part of the offsetting, covered under the D stage lie.
- Addresses the issue of differing boundaries being used by practitioners, due to the fact that they are trying to fit an infrastructure process into a production process framework, and it “does not quite fit” (Saxe and Kasraian, 2020, p.1032), leading to extensive assumptions and caveats, such as excluding all EOL processes.
- Detailed data collection is cited as being “rare” for “maintenance needs” (Saxe and Kasraian, 2020, p.1037).
- Notes that “many transport LCAs have been significantly temporally and spatially truncated” (Saxe and Kasraian, 2020, p.1032).

This final, temporal, issue is explored further in this thesis in the proposed CE concept, see Figure 2.20, where the temporal scales are addressed in the progressively larger circular outlines illustrating the differing expected lifespans of the earthwork interventions at 2, 20 and 120 years.

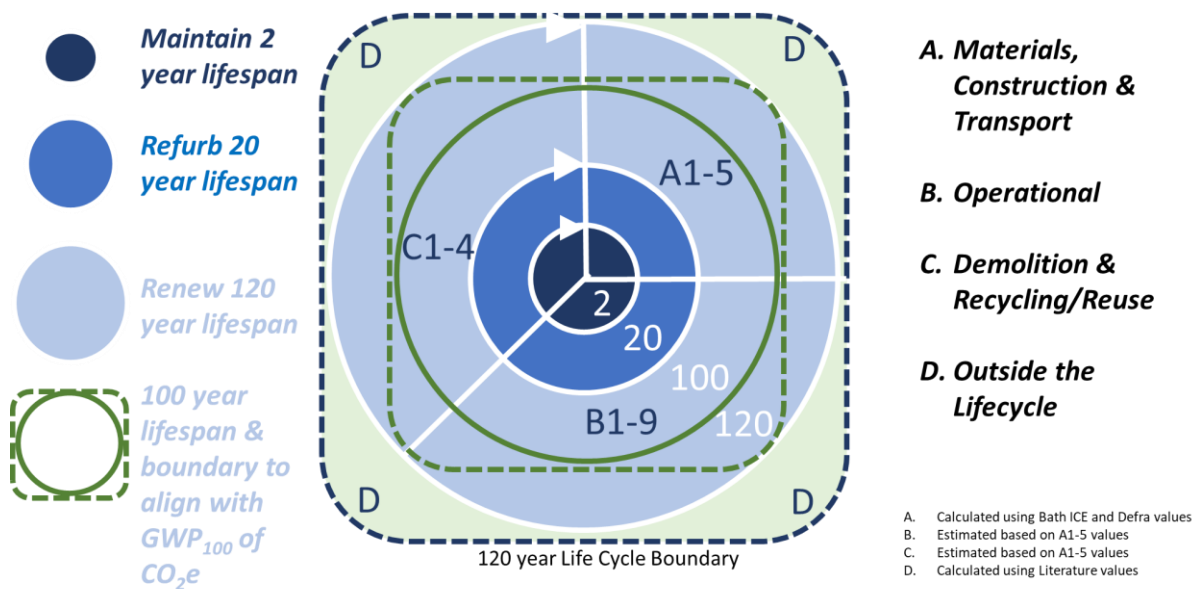


Figure 2.20 Circularity of PAS2080 Lifecycle CO₂e Footprints , previously published (Navaei *et al.*, 2022)

This circular framework, see Figure 2.20, aligns the PAS2080 A-C stages within the temporal boundaries (expected lifespans) of maintenance two-year, refurbishment 20 years, and renewal 120 years, alongside a second limiter of the GWP100 factor. This allows for comparison, via annualization between the three. The PAS2080 D stages lie outside the lifecycle temporal boundaries. The circularity of PAS2080 stages is illustrated in Figure 2.20. Each lifecycle stage from A through to C gets progressively larger with respect to time for each intervention type, bounded by the D stages, outside of the lifecycle. Figure 2.20 aligns well with embodied carbon figures in the literature with the differing lifecycle phases move around in progressively larger loops, although the D stages have been found to feed back into A1-3 (LETI, 2023) and to align to CE principles of waste as food (Ellen MacArthur Foundation, 2019).

The CE is examined more broadly as a framework, investigating CE and net zero carbon using the carbon reduction curve and their “asset hierarchy cascade” (Mi-ROG, 2020, p.8). Similar to carbon footprint, there is little consensus on an accepted definition for CE (Adams *et al.*, 2017). “CE thinking” in construction is in its “infancy” (Adams *et al.*, 2017, p.15), and so far its implementation has been “largely limited to construction waste minimisation and recycling” with “little research...from a systems perspective” (Adams *et al.*, 2017, p.15). Alongside this, losses in circularity of the materials are caused by downcycling as opposed to re-use or upcycling in the system (Walsh, (2012) as cited in (Adams *et al.*, 2017). Use of Building Information Models (BIM) may enable increased use of CE, LCA and carbon footprinting (Adams *et al.*, 2017). The waste hierarchy, see Figure 2.21, is a concise visualisation of the differing interventions available, with those at the top of the inverted pyramid

being preferred to those at the bottom, and with loss of material's value as it progresses down the hierarchy (Adams *et al.*, 2017).



Figure 2.21 Waste Hierarchy, amended from (HM Government, 2019b) and (BSI, 2017)

2.5.1 NR Implementation of CE

Here the implementation of the CE by NR will be overviewed. CE principles followed by lowering emissions will be presented first. Then implementation in practice, and an overview of outcomes of the UIC Sustainability REUSE project. This is then contextualized via achievements of NR to date using NR's reuse, recycling, and recovery (RRR) rates from the Wales and Western (W&W) Region.

Application of CE principles to construction projects can have positive impacts for both carbon emissions and costs. However, there is an inherent “tension” between CE and whole LCA which needs to be acknowledged and understood (Baker-Brown, Gowler and Arnold, 2023, p.20) as the extension of lifecycles may incur additional upfront carbon, increasing the whole lifecycle carbon. A pilot study evaluating the feasibility of implementing the CE in construction projects found that changes to materials for lower emission varieties yields embodied CO₂e reduction at production and manufacturing stages (Medina and Fu, 2021). Five key phases of the construction process (production, consumption, waste management, recovery/circularity and innovation) were

investigated, acting as key intervention points in emerging sustainability and circular strategies (Medina and Fu, 2021, p.306). CO₂e reductions of around 6% were found from the baseline scenario to their circular scenario, as well as cost savings of around 38% between these scenarios (Medina and Fu, 2021, p.311). Most items, such as concrete, steel and asphalt, were considered as being recycled in the CE scenario, as opposed to a higher level of re-use on the waste hierarchy. None were considered as being disposed of, which is a level below recovery and recycling on the waste hierarchy, see Figure 2.21. To implement CE in businesses, guidance documents are available in the form of British Standards (BSI, 2017) and in BRE Environmental and Sustainability Standard issue 4.0 (BRE, 2022) overviewed next.

BS8001:2017 presents a framework for implementing the principles of the CE and outlines the expansion of cradle-to-grave to cradle-to-cradle, in line with circular thinking, and harmonized with the circularity of PAS2080 lifecycle footprints. Practical applications of the CE for NR are found in the 3rd ARP report (Network Rail, 2021d). This report highlights the quick replacement of some parts of infrastructure (track/signalling), compared to the longer term replacement of others, such as earthworks which may take “years to achieve” (Network Rail, 2021d, p.18). This concept links back to the lack of a defined EOL highlighted by Saxe and Kasraian (2020).

Actions which go above CE thinking, such as long term weather and climate change reliance, can be achieved via “replace like for better rather than like for like” and “adapt at construction and at asset renewal” (Network Rail, 2021d, p.35), see also Section 2.4.1. These actions point to the renewal interventions outlined in the case studies not only being opportunities for emissions reduction but also opportunities to embed weather and climate change resistance into the railway infrastructure. Embedding these WRACCA opportunities into railway infrastructure could potentially expand the lifetimes of assets (via greater resilience to climate change), which could potentially lead to lower carbon footprints for the whole life of these assets.

The BRE Environmental and Sustainability Standard (BRE, 2021;2022) provides a framework for responsible sourcing, specifically outlining climate change and energy and waste management activities as areas where responsible sourcing should be directed. It advocates the reduction of fossil fuels and utilisation of renewable sources of energy, along with the use of the waste reduction hierarchy, see Figure 2.21, to prevent waste being disposed of (either via landfill or incineration) without any additional energy or material recovery plans being put into action.

NR is actively monitoring its RRR of materials, aligned to the middle 3 actions of the waste hierarchy, and to its own zero waste, from rail activities and passengers, to landfill by 2025 (DfT, 2021d). Figures for RRR for W&W are now discussed in terms of absolute tonnage of 82,715 t. These figures have scope for extrapolation to determine what the benefit to NR as a whole would be of roll out of these

measures, assuming similar percentages of RRR were to be achieved. An extrapolation has been performed via a simple multiplication by the 5 regions which results in approximately 41 kt of total waste split by the various waste hierarchy routes thus: 340 kt reused, 54 kt recycled, 12 t recovered and 4 t disposed materials, see Figure 2.22 indicating a tentative fit to the waste hierarchy shape given in Figure 2.21. Figure 2.22 illustrates that NR's current actions are keeping a large percentage of waste in the upper levels of the waste hierarchy, and that the lower-level waste hierarchy actions are minimal compared to these. The view that CE principles are important for reduction of both embodied and operation carbon to net zero are found in more recent literature on CE implementation in railway infrastructure projects (O'Leary, Osmani and Goodier, 2024).

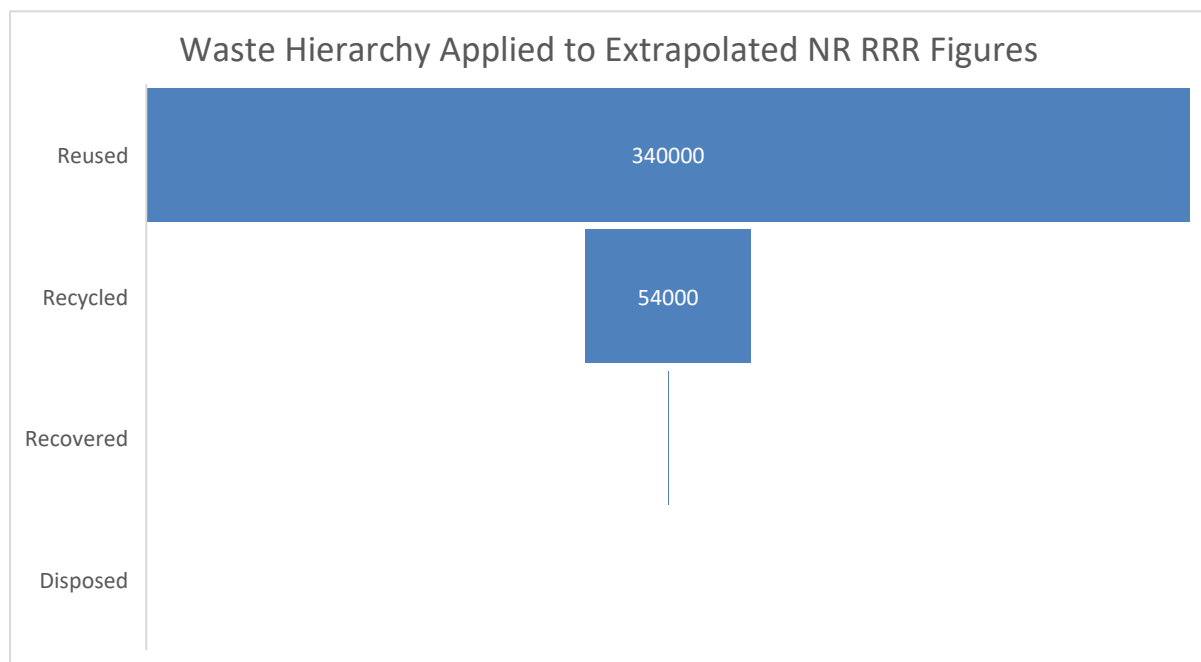


Figure 2.22 Waste Hierarchy Shape Illustrated with NR Extrapolated RRR Figures

Having carbon related targets and policy in place for suppliers is fast becoming a requirement for a contract, rather than just a “nice to have”, and it is envisaged this will have the effect of encouraging and incentivising new (lower carbon) practices in construction of infrastructure (Kadefors *et al.*, 2021) which NR, along with other rail infrastructure operators, can take advantage of.

Mi-ROG (2020) expand the CE principles and the 9 R's (see Figure 2.18), and aligns the carbon reduction curve approaches given in Figure 2.3 with those of CE thinking, illustrated in Table 2.4 along with the Better Value Rail Toolkit (BVRT) hierarchy of options. This hierarchy of options can also be seen in the pyramid of options provided in the BVRT (DfT & ORR & NR, 2021) where by the first option is given at the bottom of the pyramid, change the timetable, and only when all other options have been explored is the option to change the infrastructure examined. Table 2.4 shows the top and bottom options in the BVRT hierarchy aligning well with both the Carbon Reduction Curve and CE Thinking.

Table 2.4 CE Thinking Aligned with Carbon Reduction Curve and BVRT, amended from (Mi-ROG, 2020) and BVRT from (Department for Transport and the Office of Rail and Road and Network Rail, 2021)

Carbon Reduction Curve	CE Thinking	BVRT Hierarchy of Options
Build nothing	Retain	Change the timetable
Build less	Re-use, reclaim, re-cover	Trade off in the timetable
Build clever	Re-think	Change the rolling stock
Build efficiently	Optimise	Change the infrastructure

Table 2.4 shows what practical solutions from CE thinking can be applied to meet the four carbon reduction curve approaches, it also maps the top and bottom of these solutions onto the BVRT hierarchy of options, linking these carbon reductions and circular thinking to rail focused interventions. This provides rail asset managers with a hierarchy of interventions to consider when implementing carbon reduction actions.

Similar principles to this hierarchy of interventions are also advocated by Mi-ROG (2020) who outline the principle of an asset hierarchy, with complete assets such as a railway route or station being at the top of the hierarchy, and materials used within products, or components that make up the route, being at the bottom. A similar hierarchy principle is illustrated, aligned with CE Thinking, using inverted pyramids, see Figure 2.23.

Figure 2.23 illustrates the similarities in approach between the differing levels of the CE hierarchy and the asset hierarchy. At each level of the asset hierarchy pyramid the CE principles can be applied. The biggest savings in carbon can be made using the options at the top of the first inverted pyramid, assets, for CE principles applied to the top of the second inverted pyramid, re-use and so on, applying the CE principles to each level of the asset hierarchy with potential for carbon savings reducing as you work down each level of the CE principles, and each level of the asset hierarchy. A similar multi step inverted pyramid is seen in the CE sphere whereby the use less top of their pyramid is composed of a further inverted pyramid containing build nothing, less, clever, efficiently and minimise waste (Baker-Brown, Gowler and Arnold, 2023, p.15). Use of these pyramids highlights the close alignment of concepts in carbon and CE in terms of strategies for reduction of carbon and increase in circularity.

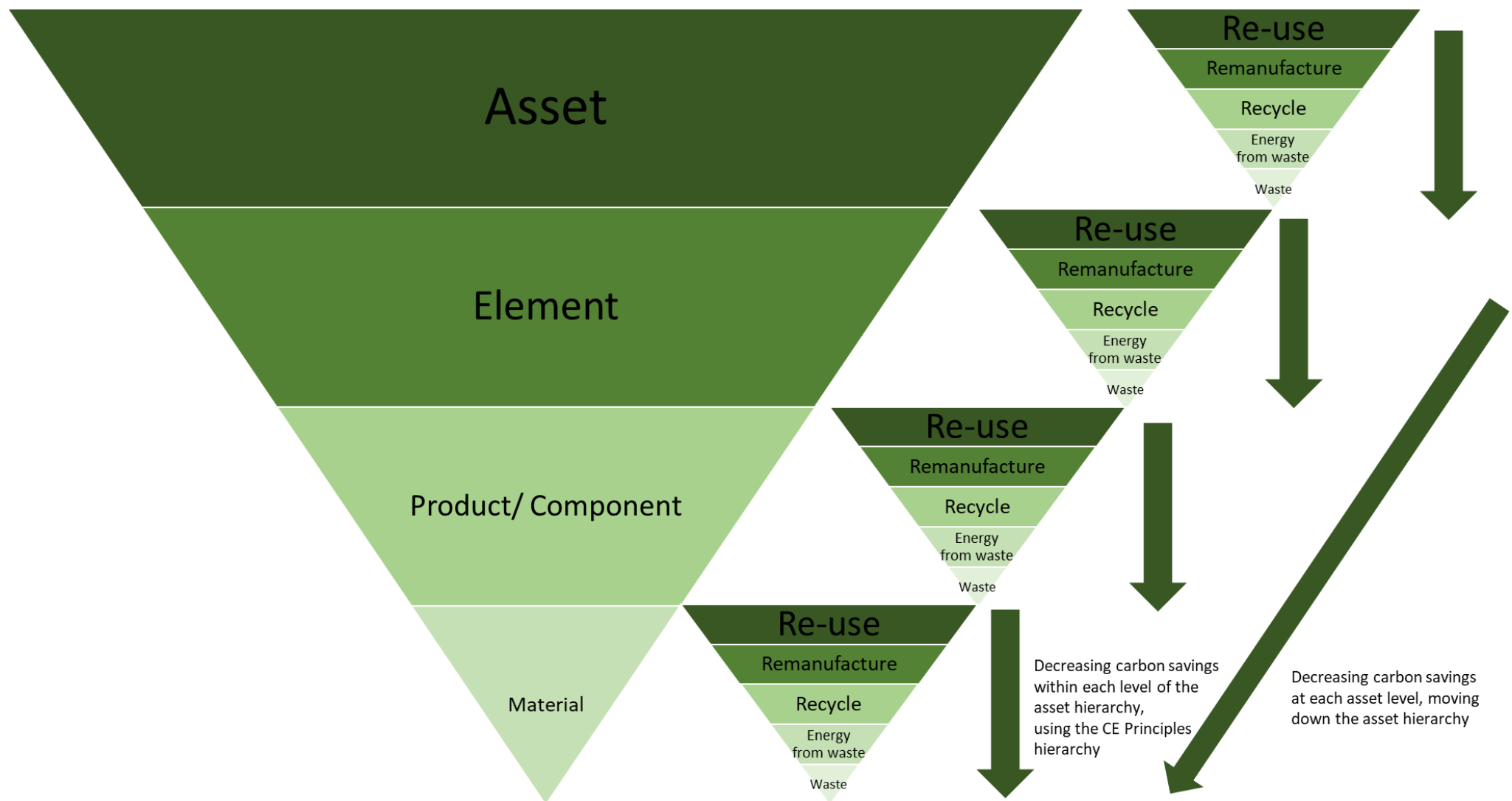


Figure 2.23 CE Principles Mapped onto Asset Hierarchy, adapted from Mi-ROG (2020, p.8)

2.6 Lifecycle Analysis (LCA)

Use of LCA to calculate whole life carbon has been noted in Section 1.1, and the link between CE and LCA is explored in Section 2.6.1 along with literature pertaining LCA of railways in Section 2.6.2.

Boundaries and phases of LCA in the literature are overviewed in Section 2.6.3 along with literature relating to LCA of railways.

2.6.1 Link Between CE and LCA

In this section similarities between CE and LCA are demonstrated. Conception of products so that at the start of their lifecycle their raw materials contain recycled waste and at the end of their lifecycle they can be recycled and reused as raw materials once more is advocated by Vieira, Calmon and Coelho (2016), aligning with CE thinking such as the Butterfly diagram (see Section 2.5) advocated by the Ellen MacArthur Foundation (2019).

CE (see Section 2.5) is a concept that NR wishes to embed into the rail industry by 2035 (DfT, 2021d) and is advocated as a necessary part of the path to net zero for the UK built environment sector (UKGBC, 2022, p.4). The burgeoning of the CE approach to carbon reduction in infrastructure is also found in DfT (2021d) via the advocacy of prevention of “waste of valuable resources at source” (DfT, 2021d, p.20). This CE approach is also advocated in the literature along with scientific and advisory bodies (Adams *et al.*, 2017; Mi-ROG, 2020; Medina and Fu, 2021). The concept of circularity is cited in the report on multi-functionality and sustainability in the EU’s forests (European Academies Sciences Advisory Council, 2017), as well as in the ICE briefing sheet on Carbon Capture and Storage (Institute of Civil Engineers, 2019), where ICE advocate the use of stored carbon to promote a CE.

Circularity principles align well to lifecycle stages where product, construction processes, use, and EOL are the four distinct stages outlined in BS EN 15978 (BSI, 2011), see PAS2080 stages in Figure 1.3, with stages A-D aligning to those of the case studies’ carbon footprints in this thesis.

Lifecycle stages aligned to BS EN 15978 and PAS2080 are also found in the five lifecycle stages in construction outlined by Medina and Fu (2021), where CE principles can also be applied. The five stages of production/manufacturing, consumption/operation, waste management, recovery/circularity, and innovation showing the alignment between carbon reduction measures and the CE.

These stages are evaluated and quantified in the case studies as part of the methodology for illustrating the BAU scenarios for each case study, and assessing the potential for emissions

Chapter 2

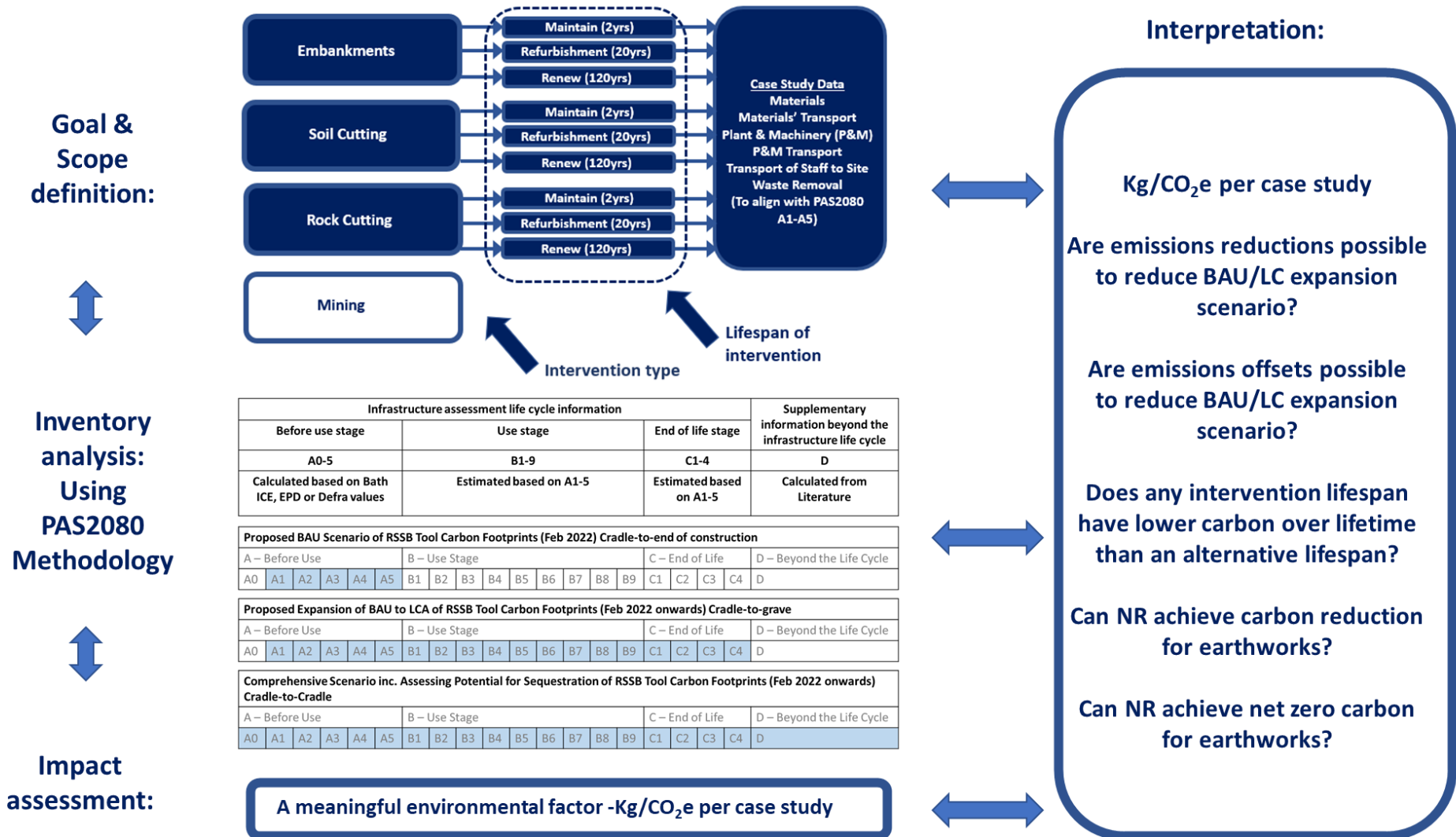
reduction and emissions offsetting for each case study, aligned to these differing stages, illustrated in Chapter 4 to highlight which stages the carbon hotspots are found in.

The four distinct phases of LCA, adapted from ISO 14040, are illustrated in Vieira, Calmon and Coelho (2016) in their review of LCA applied to manufacturing of common and ecological concrete, described in greater detail in Harvey *et al.* (2016) in their pavement LCA framework, and also illustrated in the flow diagram of the process of LCA from Kaewunruen, Sresakoolchai and Peng (2020), and are expanded in Figure 2.24.

The LCA illustrated in Figure 2.24 is used in this thesis. This process has four stages, each stage flowing into the next. The two-headed arrows show the flow of information in both directions illustrating the iterative procedures that take place between the differing phases, 1 and 2, 2 and 3, and 1, 2, and 3 with 4, the interpretation phase (BSI, 2020). In the literature an alternative interpretation of ISO14040 LCA phases, is given by Harvey *et al.* (2016) who show data flow from stages 1 to 2 and 2 to 3 in one direction, with data flow in both directions between 1, 2, 3 and 4 only. For this thesis the data flows from 1 to 2, then 2 to 3 and then 3 to 4, but with the caveat that resultant data can feed back into the flow as per ISO14040 to improve and refine the results as necessary. In this thesis the ER scenarios footprinted are fed back from stage 4 to 2, altering the inventory via revised EFs to produce the new ER scenario footprints which then feed into stage 3 where new functional units are produced from these revised values. These ER scenarios then feed back again, as described above, following application of expansion to A0, B and C stages for the renewal case studies, creating expanded ER footprints for offsetting of residual carbon emissions via offsetting measures, see Chapter 6.

The central section of Figure 2.24 indicates the 3 scenarios to be footprinted. 1) BAU (for all case studies), 2) Lifecycle expanded to B and C stages (for renewal case studies), and 3) Lifecycle expanded to B, C and D stages plus A0 (for renewal case studies), see Appendix A.4.1 and Table 3.6. For all case studies the ER scenario is also footprinted following on from the ER exercise, see Chapter 5.

The starting point for the LCA is goal and scope definition, outlining the purpose of the LCA and what is included/excluded from the study, as caveats with each footprint produced. The boundary detailed in Figure 2.24 aligns well with that provided in the GHG analysis performed by Lee, Lee and Chun (2020) on HSR infrastructure construction in Korea, whereby all materials (aligning with A1-3 stages) and construction processes (aligning with A5 stages) are included for each intervention.

Figure 2.24 LCA Phases Used in this Thesis (adapted and expanded from BSI (2020) and (Harvey *et al.*, 2016))

The inventory analysis stage follows on from the goal and scope definition. Due to the iterative nature of the LCA process, data found here can affect the goal and scope definition and boundaries may require re-definition following this stage. The inventory analysis is produced using PAS2080 methodology and the NR templates situated in the RSSB RCT for this purpose. This stage will track the inputs and outputs to the system under the relevant stages, A-D, for each of the three proposed footprint scenarios: 1) BAU – cradle-to-end of construction, 2) expanded – cradle to grave, and 3) comprehensive – cradle-to-cradle.

The impact assessment follows the inventory analysis and is where the figures obtained in the inventory analysis are converted to a meaningful environmental figure, the functional unit, for comparison, such as kgCO₂e. On completion of the impact assessment, the interpretation of the results found in the impact assessment are assessed against the goals outlined in initial definition of the LCA, which are shown here as a series of questions. These questions are returned to and addressed in Chapter 7.

These questions can then be used to assess the resultant LCAs and guide the intended end user towards the intervention which best meets its specific requirements as the type of study undertaken will have a specified intended output. For this thesis an environmental indicator in the form of a functional unit of kgCO₂e per volume/per year will be produced for each case study to allow for comparison between both different intervention types and lifespans within a single intervention type (Harvey *et al.*, 2016). As such, the LCAs to be conducted for this research are to be comparative consequential studies with a definition provided for comparative consequential studies by Harvey *et al.* (2016) of “comparing the changes in flows and impacts within and beyond the system boundary due to alternative decisions” (Harvey *et al.*, 2016, p.3-4). These comparative consequential studies are intended to assist NR in choosing the lowest whole life carbon intervention when undertaking maintenance, refurbishment or renewal of earthworks (Harvey *et al.*, 2016).

The type of LCA used in this thesis has a focus on the environmental aspects of GHG emissions in the form of CO₂e, and sustainability co-benefits of carbon offsetting are explored further in Section 6.6.

2.6.2 Literature Relating to LCA of Railways

Many studies have been performed investigating LCA of emissions of railways over the past decade, including de Bortoli, Bouhaya and Feraille (2020) Banar and Ozdemir (2015), Baron, Martinetti and Pépion (2011), Chang and Kendall (2011), Cornet, Dudley and Banister (2018), Morita *et al.* (2011), Kiani, Parry and Ceney (2008), Lin *et al.* (2019), von Rozycki, Koeser and Schwarz (2003), Tuchschnid *et al.* (2011), Cuenot and Hernandez (2016), and Westin and Kågeson (2012).

More recently, de Bortoli, Bouhaya and Feraille (2020) give a comprehensive overview of 15 LCA studies on HSR and standard track (ST). These are discussed and analysed with respect to the track features, boundaries of LCA, and modal shift to rail, along with analysis of the recently updated ISO standards on environmental management LCA principles and framework (BSI, 2020), and the requirements and guidelines (BSI, 2018), with respect to railway infrastructure. The predominate focus of the case studies in this thesis is conventional rail (CR) since HSR in the UK does not form part of NR's portfolio (HS1 and HS2 managed by their own parent companies), however the majority of the literature review pertains HSR as this is the predominate focus of the literature with very few articles being found concentrating solely on CR.

Work by Banar and Ozdemir (2015) assessed the passenger railway transportation system in Turkey from an environmental view point via LCA and from the economic view via Lifecycle Cost (LCC) methodologies using the system boundary of cradle-to-grave. Banar and Ozdemir (2015) performed their LCA based on CML2 baseline 2000 method for a selection of the impact categories including railway vehicles, infrastructure and energy, using SimpPro 7.3.3 PhD version.

Banar and Ozdemir (2015) performed their LCC assessment in three steps, the first two mirroring those used in this thesis:

1. Goal and scope definition.
2. Lifecycle cost inventory analysis.
3. Lifecycle costs assessment using the LCC method.

Banar and Ozdemir (2015) calculated LCC by creating a new economic method for internal cost to include energy, materials and transport categories. The external costs include pollutants, accidents and noise categories, all within the same piece of software. It is under this category of pollutants that a monetary cost is attributed to global warming and, using kgCO₂eq per 1 passenger-km of HSR and CR, a figure is given for global warming via kgCO₂eq per 1 passenger-km as part of the railway infrastructure costs, with the HSR figure being 1.1E^{-2} and CR being 8.6E^{-3} . Figure 2.25 illustrates the LCA/LCC integrated model framework used by Banar and Ozdemir (2015).

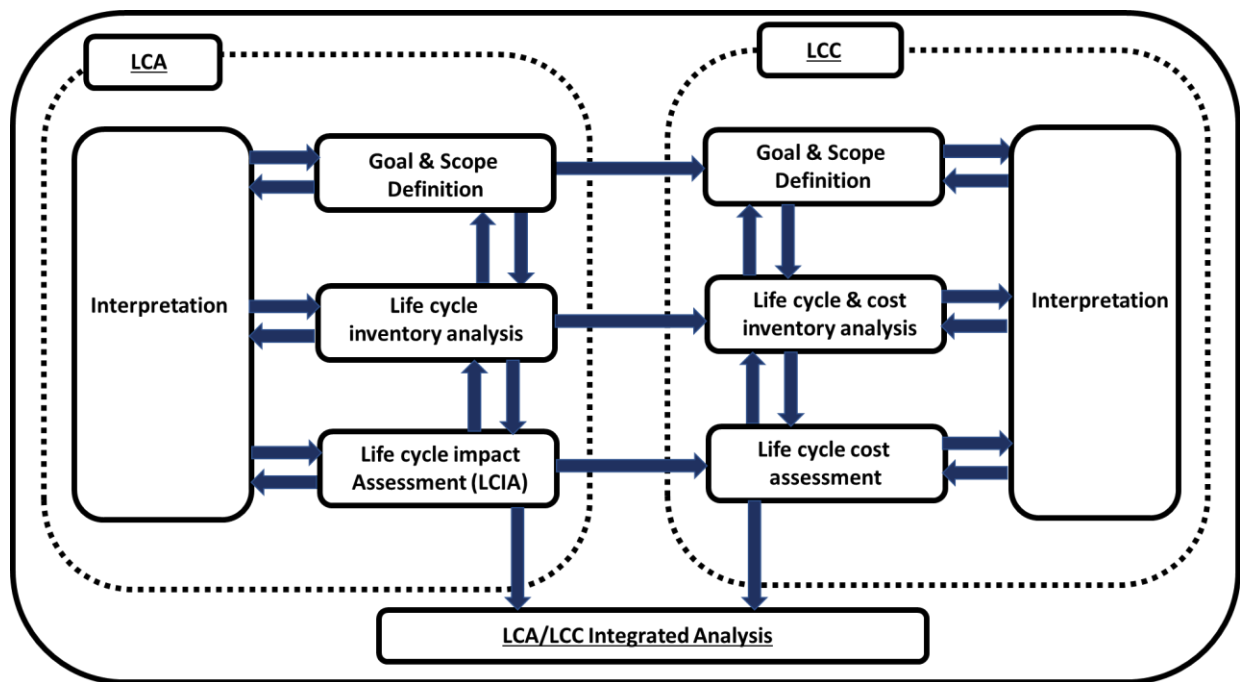


Figure 2.25 LCA/LCC Integrated Model Framework, amended from Banar and Ozdemir (2015, p.90)

Figure 2.25 highlights the similar methodologies applied to LCA and LCC analysis. Figure 2.26, outlines what Banar and Ozdemir (2015) include in their rail infrastructure and transport boundaries, noting their functional unit of 1 passenger-km of rail transportation for both HSR and CR.

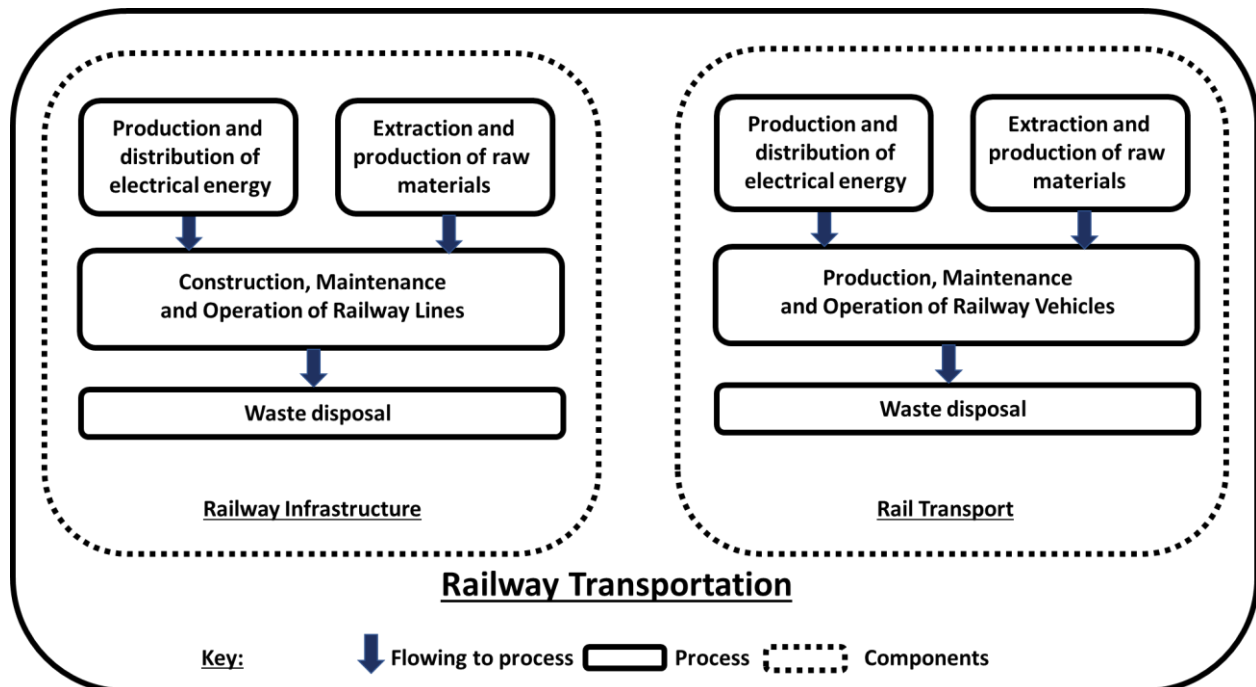


Figure 2.26 LCA/LCC System Boundaries, amended from Banar and Ozdemir (2015, p.90)

Figure 2.26 also highlights that caution must be taken when comparing these results with the literature, due to the inclusion of operating energy and materials within the railway infrastructure boundaries.

The extended LCA (modal shift taken into consideration (Morita *et al.*, 2011)), is the next step to extend the physical lifecycle stages (material extraction, construction process, uses and EOL). HS2, in their route wide effects document (HS2 Limited, 2013a), extend their lifecycle and take the modal shift from cars into consideration in their carbon accounting, including a hypothetical new motorway for comparison, which gave, around 10 times more carbon than HS2.

Examination of HS2 carbon emission assumptions data identifies gaps, particularly in construction, movements of excavated material, and maintenance. The maintenance gap, described as “partial” and the extent of the missing data for the construction and movements of excavated material, described as “full” (HS2 Limited, 2013b, p.23), illustrating the research gap filled by this thesis.

Further gaps highlighted by Lee, Lee and Chun (2020), in their analysis of HSR construction GHG emissions in Korea, using a Bill Of Material (BOM) based approach, find “poor relevant data” in construction waste, both to and from construction sites, and therefore exclude this item (Lee, Lee and Chun, 2020, p.4). Interpretation and comparison of their work is difficult as all material transport was allocated to the civil engineering works, encompassing earthworks, tunnels, viaducts & bridges & crossings, secondary work & temporary facilities, with no additional breakdowns provided.

A hierarchy of options are used by HS2 to reduce its carbon (HS2 Limited, 2017b), in line with the output of this thesis (hierarchy of lifecycle stages for ER actions). The HS2 hierarchy has calculating carbon first, then reducing embedded carbon in construction materials and works, followed by reducing energy requirements, and then use of low carbon energy and finally sequestering of carbon.

2.6.3 Boundaries and Phases of LCA in the Literature

Lin *et al.* (2019) find differing factors behind the major portions of the whole LCC for railways in their carbon footprint analysis of the Beijing-Shanghai HSR line, and von Rozycki, Koeser and Schwarz (2003) also find these in their LCA case study of the Hanover-Wuerzburg line. These carbon costs vary considerably, ranging from operating carbon playing a major part in the Beijing-Shanghai HSR line at over 71% (Lin *et al.*, 2019), to operating carbon costs accounting for 80% of the environmental footprint in work by von Rozycki, Koeser and Schwarz (2003) as cited in Baron, Martinetti and Pépion (2011). This 80% figure has not been validated, as cited in Baron in the source paper of von Rozycki, Koeser and Schwarz (2003), finding instead reference to Cumulative Energy Demand (CED) of the infrastructure for the Hanover-Wuerzburg line contributing “13% to the total CED per 100 person kilometres” and the CED of traction being the dominant feature of the lifecycle (von Rozycki, Koeser and Schwarz, 2003, p.83). Lin *et al.* (2019) have also investigated contributions towards the whole lifecycle footprint, with construction and maintenance contributing 20% and 9% respectively. A direct

comparison between two carbon footprints in the literature is therefore not always possible due to differing scopes, boundaries, and asset types.

Where comparisons between the literature are made, care needs to be taken due to boundary differences, scope of emissions (carbon only, or all GHGs) and the asset type, building, versus geotechnical asset. When comparisons are made in this thesis a review of parameters has been undertaken, see Section 4.3.2, to ensure like-for-like comparisons are made.

Limited data is available in the literature showing a granular break down of the differing lifecycle emissions for railway infrastructure, however some examples, in varying levels of granularity are found. Morita *et al.* (2011) show measurement of railway emissions through the A-D stages using “standardized elements” (Morita *et al.*, 2011, p.2), (discussed below). Lokesh, Densley-Tingley and Marsden (2022a) in their LCA of infrastructure and rolling stock created detailed footprints of ballasted and non-ballasted track, however they did not break these down to earthworks level, they also exclude EOL and circularity of materials from the construction phase. In contrast Lee, Lee and Chun (2020) excluded workforce transit emissions (A4 stage). Lack of granularity and differences in system boundaries causes issues with comparison between footprints in the literature, and both Olugbenga, Kalyviotis and Saxe (2019), (who themselves did not categorise earthworks as a separate entity), along with Tuchschnid *et al.* (2011) cite limitations due to differences in system boundaries, which Olugbenga, Kalyviotis and Saxe (2019) further noted were impeding hot-spot detection. Hot-spot detection is vital to ensure that the largest carbon emitting sources are identified, see Objective 3, as this is where the first wave of mitigations must intervene to make the largest difference in the shortest time, aligning to NR reductions targets, see Figure 2.13. As the move towards net zero carbon progresses each kg of carbon matters (progressively more as the NDCs reduce with time) and must be mitigated. Offsetting must only be utilised after all mitigation efforts have been deployed as per the offsetting hierarchy (Axelsson *et al.*, 2024).

Morita *et al.* (2011) show how to measure emissions from railways covering the whole lifecycle from cradle to grave (A-D stages of PAS2080). Due to the way this data is presented embankments and cuttings are classified as structure items under the general heading of construction items and therefore align with PAS2080 A1-5. They also introduce the extended LCA concept outlined in Section 2.4.5, taking into account modal shift. Morita *et al.* (2011) note that their data is from the planning phase, which may not be as detailed as that utilised in this thesis (ex-post construction). Using planning phase data they have applied a simpler measurement unit in the form of “standardized elements” (Morita *et al.*, 2011), see Table 2.5.

Table 2.5 Standardised Units for Study , amended from (Morita *et al.*, 2011)

Item			Basic Unit	Unit
Structure	Viaduct		7.21	ton-CO ₂ /m
	Bridge		3.10	ton-CO ₂ /m
	Shield Tunnel		8.85	ton-CO ₂ /m
	Embankment (W=10.7m, H=6.0)		6.02	ton-CO ₂ /m
	Cut (W=10.3m, H=6.0)		3.29	ton-CO ₂ /m
	Slab Track		0.292	ton-CO ₂ /m
	Ballasted Track		0.356	ton-CO ₂ /m
	Elevated Station		3.81 x 10 ³	ton-CO ₂ /station
	Underground Station		3.12 x 10 ⁴	ton-CO ₂ /station
	Depot		5.88 x 10 ³	ton-CO ₂ /site
Maintenance	Rail		14.4	ton-CO ₂ /million.car.km
	Aerial Line		0.152	ton-CO ₂ /million.car.km
Rolling Stock	Aluminium Body	Manufacturing	93.9	ton-CO ₂ /car
		Disposal	0.662	ton-CO ₂ /car
	Stainless Body	Manufacturing	66.8	ton-CO ₂ /car
		Disposal	0.662	ton-CO ₂ /car

Table 2.5 gives a basic unit of 6.02 tCO₂/m for the given embankment size and 3.29 tCO₂/m for the given cutting size. This is one of the very few examples of detailed data for a railway embankment or cutting, however the background data for compiling these standardized measurements could not be located within the paper. A further example of detailed data for earthworks is found in the FOI request to HS2 (HS2 Limited, 2022a) where data for embankments and cuttings between London and Old Oak Common, split into lifecycle stages congruent with PAS2080, have been sourced and analysed against the case studies (see Section 4.3.3). To evaluate the accuracy of these standardized measurements they have been compared to both the case studies in this thesis and HS2 earthwork data (see Section 4.3.3).

In Morita *et al.* (2011, p.3) their “Elements for the calculation of emission” indicate that only the fuel used by construction equipment has been accounted for in construction emissions. Future studies would be more comprehensive if they include proportional allocation of emissions from the manufacture of the construction machinery itself (aligning to stage A1-3), as in this thesis (see Appendix C.12).

Lokesh, Densley-Tingley and Marsden (2022a) provide indications on the scale of emissions from construction and management of infrastructure and rolling stock. Lokesh quantifies the embodied and operational carbon in rail-based transport infrastructure, and provide detailed analysis and

footprints of ballasted and ballasted track. Lokesh does not break this down further into embankments and cuttings. Lokesh acknowledges that the his study is “exploratory,” to gauge the significance of differing infrastructure, and that the case studies are “speculative in nature” (Lokesh, Densley-Tingley and Marsden, 2022a, p.17). Lokesh also acknowledges, in line with Lee, Lee and Chun (2020), that there is “little to no information” regarding some aspects of the LCA, material specifications, and sources of materials in the case studies (Lokesh, Densley-Tingley and Marsden, 2022a, p.17). Lokesh has therefore assumed travel distances to site for materials, and has excluded emissions related to workforce transit, both of which form part of PAS2080 stage A4 and both of which are included in the calculations for the case studies for this thesis. See Section 4.3.6 for a comparison of results against Lokesh, Densley-Tingley and Marsden (2022a).

One of the most comprehensive reviews of embodied emissions in rail infrastructure found to date is that of Olugbenga, Kalyviotis and Saxe (2019). In their critical literature review of embodied emissions in rail infrastructure, which covered a comprehensive array of differing rail types including intercity, commuter, light rail, metro, and freight. In their review they identify 22 publications and 57 case studies from the decade prior to publication (2009 -2019), spanning 3 continents. Their critical literature review aimed to provide a model for producing an estimate of the embodied GHG emissions per km of rail. Their critical review has infrastructure compartmentalised into trackbeds, stations, bridges, and tunnels, however earthworks are not drawn out as a separate entity.

Their functional unit, GHG emissions per km of rail, is a good starting point for future comparison with other literature (however their data did not meet the parameters for comparison with this data set, see Section 4.3.2), to build up the repository of data for embodied GHG emissions in rail infrastructure. It should be borne in mind that their comments regarding there being insufficient data to allow for standardisation of boundaries between papers and that this was therefore a “key limitation” of the literature in this field, along with a lack of standardisation in reporting which is impeding carbon hot-spot detection in rail infrastructure (Olugbenga, Kalyviotis and Saxe, 2019, p.9).

One of the findings of Olugbenga, Kalyviotis and Saxe (2019) aligns with that of this thesis, the type of construction, at-grade, underground, elevated is a key determiner of the embodied GHG level. As part of this thesis the embodied GHGs in the form of CO₂e of maintenance, refurbishment and renewal interventions of cuttings and embankments are compared to provide further knowledge of how these differing interventions drive the embodied CO₂e levels of the different earthworks.

When conducting a comparison between differing case studies, similar to that detailed above for Olugbenga, Kalyviotis and Saxe (2019), a like for like comparison of one study with another prior to fully analysing the details of the boundaries of the study will not be accurate. Tuchschnid *et al.* (2011) also found this issue when reviewing differing studies in their UIC report on carbon

footprinting of rail infrastructure, which at the time was excluded from the carbon calculators they investigated. They found that although methodologies are applicable and comparable, “the system boundaries often differ. This is the reason, why a direct comparison of the values between the studies is not possible” (Tuchschnid *et al.*, 2011, p.3). See Chapter 4 for comparisons with selected works.

2.7 Transport & Rail Carbon Accounting Process Worldwide

There is a lack of standard approaches to boundaries and functional units within transport LCAs, alongside the potential for burden shifting to occur with the use of existing tools (Saxe and Kasraian, 2020). Discussion of rail carbon accounting processes used in the rail industry around the world including SNCF (France) alongside the RSSB carbon footprint of the GB rail industry report (RSSB, 2021a) will now be given. Further details of Carbon Accounting Methods and LULUC can be found in Appendix B.11.

2.7.1 Methodologies for Calculating Railway Infrastructure Carbon Footprints

A detailed examination of ten differing methodologies for carbon footprint calculation for railway infrastructure, by UIC, highlights the differing methodologies available (Cuenot and Hernandez, 2016), see Appendix B.12B.9. This diversity of emissions factors, different elements and boundaries and scopes, alongside differing levels of transparency between these methodologies, causing difficulties for boundaries and scopes alignment, and comparisons to be made, has been highlighted (Cuenot and Hernandez, 2016).

Only two of the methodologies have a good transparency rating, where data is fully available and traceable, across the three areas of: Illustration of calculation and assumption details, Reporting of CO₂ emission factors, and indication of the emission factor data sources (Cuenot and Hernandez, 2016). Half of the methodologies included at least one bad transparency rating, meaning no source or detailed numbering was available, see Appendix B.13.

No single methodology includes all boundary areas which would be required to construct a full LCA (Cuenot and Hernandez, 2016). Two methodologies cover the greatest number of stages, planning to maintenance, and construction to disposal respectively, see Appendix B.14.

Analysing the specific elements assessed within each methodology finds half of the methodologies include all of the elements, see Appendix B.15. One methodology only includes tunnels and bridges, which are excluded from other methodologies, again highlighting difficulties in direct comparisons between studies (Cuenot and Hernandez, 2016).

This detailed examination of these ten methodologies concluded that the IFEU/Tuchschnid methodology, funded by UIC, “is the most transparent, versatile and comprehensive methodology” (Cuenot and Hernandez, 2016, p.30).

UIC04 ITALFERR, is one of the methodologies outlined in the UIC report which has an approach similar to PAS2080, with materials and processes allocated to categories in the inventory, see Table 2.6.

Table 2.6 Allocation of Emissions by Categories and PAS2080 Lifecycle Stages amended from Loffredo, Fedele and Severini (2011)

Category	tCO ₂ for Project (% of project)	Emissions Included	Aligns with PAS2080 Module	Notes
1	57 (0.02%)	Development of the project	A0	
2	190.280 (81%)	Production of building materials	A1-3	
3	12.010 (5.11%)	Transport of materials	A4	
4	30.762 (13.04%)	Operational activities performed at the building site	A5	A5 spans across category 4 and 5 here
5	1.815 (0.83%)	Installations and building site management	A5	A5 spans across category 4 and 5 here
Total of above	234.924 (100%)			
6	2.4	Green works	D	Per annum
7	0	Installation of systems that use renewable energy	Assumed to lie within LC stage D	Per annum

Table 2.6 shows that although this categorisation does encompass much of A0-A5 and some of the aspects that could potentially be included in stage D, it does not encompass the whole lifecycle with the notable absence of B1-B9 and C1-C4 stages. This absence is noted by the authors in their conclusions who state that for whole LCA, maintenance processes and operation, along with closing down of the work is required (Loffredo, Fedele and Severini, 2011). This misalignment re-enforces the argument regarding use of common methodologies (Akponeware *et al.*, 2022), see Section 3.2.1.

The RSSB RCT is not included in the recommendations for a harmonized approach in the UIC report (Cuenot and Hernandez, 2016). The RSSB RCT, along with the SBB Mobi Tool are illustrated in this UIC report as two of the best examples of LCA Eco-Tools. It is also advocated that infrastructure carbon content is added to these tools to “improve the transparency and consistency of the results” over

time, with additional results being added, further refining these in the long run (Cuenot and Hernandez, 2016, p.30).

This thesis provides 50 additional case studies in the RCT, illustrating pathways to decarbonisation using existing technologies and practices, see Chapter 5.

2.8 Summary

This literature review has provided an overview of policy, initiatives and legislation in the carbon sphere detailing the origins of high-level carbon budgets in Section 2.2. A review of literature in the field of carbon quantities in railways and earthworks in Section 2.3 has identified a lack of detailed data regarding carbon in these earthworks, and also a lack of adherence to standardised terminology (such as PAS2080 stages) in describing this. The NR perspective in the carbon sphere has been presented in Section 2.4 along with detailing where NR's carbon lies, clearly charting the trajectory needed in the coming decades to achieve net zero carbon by 2050. The lack of a consistent unit for comparison between railway footprints has also been identified, addressed in this thesis via the inclusion of a functional unit, allowing comparison between differing size and expected lifespan case studies.

The CE and waste hierarchy has been explored in Section 2.5 along with NR's implementation strategy for this. LCA has also been explored in Section 2.6 and differing carbon accounting methodologies worldwide in Section 2.7.

A lack of consistent carbon data collection and limited lifecycle footprints have also been found. The lack of consistent carbon data collection will be met via the creation and use of a standardised and consistent data collection form (Najafpour Navaei *et al.*, 2024) and the limited lifecycle footprints will be expanded from the current BAU of A1-3 to encompass a new BAU of A1-5 before being expanded further to encompass the B and C stages.

The focus of this thesis is accurate accounting of all materials and construction stages in the lifecycle, A1-5 as per PAS2080. This thesis extends the boundaries, by extending the carbon account into the B1-5 Use stages including maintenance activities and C1-4 EOL stages including waste streams' emissions for the selected standard details. The carbon accounts for the case studies focus on representative 5-chain lengths of earthworks (around 100m). The need for accurate and complete records are recommended in the literature for further research (Krezo *et al.*, 2018) and as such accurate and complete records of all A1-5 activities form a critical part of each case study and this includes fuel consumption and emissions from machinery used in the A5 construction processes.

Chapter 2

When comparing case studies a functional unit, introduced in Section 2.6.1 and expanded on in Section 4.1.3, is used to enable comparison of case studies of differing sizes and expected life spans.

Next Chapter 3 will present details of the carbon footprinting method used.

Chapter 3 Carbon Footprinting Method

3.1 Introduction

The literature review has provided an overview of policy, initiatives, and legislation in the carbon sphere. The review outlined the field of carbon quantities in railways and earthworks, along with the NR perspective in this space, identifying the gaps addressed by this thesis. The gaps are a lack of granular data regarding carbon in railway earthworks aligned to PAS2080 stages, lack of consistent carbon data collection, lack of a consistent unit for comparison of data between railway infrastructure projects, and a BAU scenario which does not include for whole LCA.

This chapter will, building on the review and identified gaps, discuss carbon accounting methods, rail accounting tools and methods currently used. The steps that need to be taken to produce a carbon footprint along with details of where errors can occur in footprinting will be given in Section 3.2, followed by an introduction to primary data in the tools in Section 3.3. This chapter concludes with details of the method used in this thesis for case study identification, data collection and carbon footprinting in Section 3.4.

3.2 Carbon Footprinting

In this section the choice of the RSSB RCT is justified, see Section 3.2.1, followed by the steps to perform a carbon footprint in Section 3.2.2. The common errors found in footprinting, alongside mitigation measures used to alleviate these, are then given in Section 3.2.3.

3.2.1 Choice of RSSB RCT as Carbon Tool for Thesis

The RIA report on learning from major rail projects (RIA, 2021) cites the RSSB RCT, as a web-based platform that allows users to calculate and analyse carbon footprints for UK rail projects in order to identify and assess alternative low carbon options, and to select low carbon solutions, along with use of the hierarchy of intervention available in the Better Value Rail toolkit, see Section 2.4 (RIA, 2021).

The UK mainline railway whole industry carbon footprint, see Section 2.3.3, in report T1197 recommends the RSSB RCT to be implemented as part of the ‘guiding hand’ approach for NR to better understand their supply chain footprint. As such projects additional to those currently included (projects with a spend of over £1m on civils, track and OLE) need to be analysed using this tool. This is where the research for this thesis lies as part of the recommendations by T1197 GHG reporting system. This is reaffirmed via the NR guidance document on managing whole life carbon in

infrastructure (Network Rail, 2022c), where further direction on using the RSSB RCT at differing PACE stages is provided, see Table 3.1.

The T1197 report (RSSB, 2021a) indicates the continued use of the RSSB RCT, despite questions regarding its uptake and efficacy by stakeholders. RSSB (2021a) further suggests that the resultant footprints be fed into their recommended carbon reporting system, improving completeness of the rail sector carbon footprint.

Table 3.1 Alignment of PAS2080 Modules to Asset Renewal/Replacement Work, amended from (Network Rail, 2022c, p.13)

Asset Renewal/ Replacement Works			Feb 2022 – Dec 2022	Jan 2023 – Dec 2023	Jan 2024 – Mar 2025
			PCA 1	PCA 1	PCA 1
Before Use	A0	Preliminary Studies	Not Required	Not Required	Not Required
	A1-3	Product Stage	Required	Required	Required
	A4	Transport to site	Required	Required	Required
	A5	Construction/ Installation	Required	Required	Required
Use	B1	Emissions from Installed Materials	Not Required	Not Required	Optional
	B2	Maintenance	Optional	Required	Required
	B3	Repair	Not Required	Optional	Optional
	B4	Replacement/ Renewal	Optional	Required	Required
	B5	Refurbishment	Not Required	Not Required	Not Required
	B6	Operational Energy	Required	Required	Required
	B7	Operational Water	Optional	Required	Required
	B8	Other Operational Emissions	Not Required	Optional	Required
	B9	Operational Energy/Water & Other Emissions	Not Required	Not Required	Not Required
End of Life	C1	Deconstruction	Optional	Required	Required
	C2	Transportation	Optional	Required	Required
	C3	Treatment	Optional	Required	Required
	C4	Disposal	Optional	Required	Required
Beyond Life Cycle	D	Emissions loads/benefits inc. CE & Offsetting	Optional	Optional	Required

Table 3.1 illustrates the move towards whole LCA via use of PAS2080 lifecycle stages. From January 2024 PACE projects greater than £1m in value will require A1-A4, B2, B4, B6-B8, all C stages, and, for the first time, D stage, beyond the lifecycle. B1 and B3 stages remain optional. The A0 stage is 'not required' here and the results of this thesis will provide an indication of the scale of A0 carbon costs for the earthwork types investigated.

Use of whole LCA in assessments of GHG emissions for rail projects is still limited, with the boundary of cradle-to-site or only operational emissions being explored in some studies, such as Saxe *et al.* (2015), with a more holistic understanding of the whole lifecycle being required, encompassing capital, operational and maintenance alongside mode shift, see Appendix B.9.2.

The RSSB RCT utilises the Bath ICE database (updated periodically and currently at V3.0) as one of its main data sources.

The Built Environment Carbon Database (BECD) in 2023, a new free to use online carbon database supported by various institutions including ICE, RICS, IStructE, and BRE, may be of use when comparing various databases. When the BECD was explored it was found to be highly dependent on specific product EPDs. The BECD database will build upon the existing Bath ICE database, and its potential inclusion within future versions of the RSSB RCT could be via updates to new Bath ICE versions. The RSSB RCT is listed in the list of available carbon assessment tools with details of its strengths and weaknesses, see Table 3.2. This assessment was carried out prior to NR PAS2080 templates' inclusion in the RSSB RCT circa. April 2021, using these templates the tool could now be considered as PAS2080 compliant.

Table 3.2 has RAG rated colour coding (Red = no, Orange = partial, Green = yes) to indicate compliance with the various conditions listed. This table shows the two assessment tools (currently available) suitable for use in rail projects, the RSSB RCT and the eTool. The eTool originates in Australia, utilised by HS2 (eTool, 2023) and the RSSB tool originates in the UK and is utilised by NR. Rationale for using the RSSB RCT is that it is part of the list of available tools and that it is suitable for rail projects, and also that it is the tool available for use by NR for this thesis, and for ongoing production of footprints by NR staff, allowing for future comparisons with this data set.

A core intention behind carbon data sharing is communication of lessons learned (with the rest of the rail and infrastructure community), enabling best practice to proliferate throughout the industry. Sharing of carbon data is also advocated by the UIC (2021), however, from Akponeware *et al.* (2022), it appears that many are reluctant to share their data. This view is echoed by the Tiger Team at NR investigating the Net Zero carbon challenge (McCann *et al.*, 2021), where the lack of exemplar projects and carbon skills within the rail sector is highlighted. Within the construction industry, a lack of knowledge and perceptions regarding greener concrete is highlighted by Akan, Dhavale and Sarkis (2017), whereas Scrivener *et al.* (2018) points to lack of knowledge regarding use of magnesium oxides in carbonation of concretes. Where carbon data is available, it is not of sufficient granularity to allow for comparisons to be made. To enable data to be shared it needs validation through benchmarking processes (ICE Workstream 1 of The Carbon Project, 2020).

Table 3.2 Available LCA Software Tools, amended from ICE Workstream 1 of The Carbon Project (2020, p.22)

Carbon Tool	Country of Origin	Applicable to UK?	Project Type	Online/ Offline	Scope Based on BS EN 15978	PAS 2080 Compliant	Whole Value Chain Design Access	Input Cost Data	Transparency	Robust Database	Ability to Update Database
One Click	Finland	Yes	Buildings and civils	Offline software	A-C						
eTool	Australia	Yes	Buildings, civils and rail	Online software	A-C (+D)						
CITT	UK	Yes	Buildings and civils	Online software	A-C						
SimaPro	Netherlands	Yes	Buildings and civils	Online software	A-C						
BREEAM	UK	Yes	Buildings		A-C						
RSSB Rail Carbon Tool	UK	Yes	Rail	Online software	A-C						
Environment Agency	UK	Yes	Buildings and civils	Online	A-C (+D)						
Highways England	UK	Yes	Highways		A-C						
National Grid Carbon Interface Tool	UK	Yes	Power	Offline software	A-C						
H/B:ERT	UK	Yes	Buildings	Online	A-C						
Rapier ECCOLab	UK	Yes	Buildings	Online	A-C						

In line with the sharing of carbon data, is the idea of EPDs for railway infrastructures, advocated by Stripple and Uppenberg (2010) in their LCA of the Bothnia Line. Stripple and Uppenberg (2010) include a discussion on deforestation carbon quantities, listed as biogenic carbon (which could also be counted as LUC carbon and require accounting for in biodiversity loss), along with carbonation due to cement. A rare instance where such granularity of carbon sequestration has been found in the literature, is in an LCA in Stripple and Uppenberg (2010). They provide detailed kgCO₂e for track foundation processes, including earth cuttings and rock cuttings, along with details of the largest contributors to CO₂e by process. These foundation processes included infrastructure material, construction work material transport and operation, however this data was not suitable for comparison, see Appendix D.21, using the parameters outlined in Section 4.3.2.

3.2.1.1 RSSB RCT: Templates, Consistency & PAS2080 Alignment

This section encompasses details of use of templates, consistency, and PAS2080 alignment. For details of how data is input into the tool and details of training see Appendix C.1.

The RSSB RCT is kept up to date in a variety of different ways (Network Rail, 2021e) including updates to the most recent version of Bath ICE (V3.0) and addition of templates to the database of these. The CMWG are currently working on several carbon related projects including a feasibility study to integrate BIM into the tool for whole-life carbon assessment, and a review of templates to assist with provision of carbon baselines (Network Rail, 2021e). Carbon literacy also falls under the remit of the CMWG (ICWG, 2021), see Section 2.4.5. Greater understanding of the embodied carbon in railway infrastructure has been found over the past ten years following NR's policy of using the RCT to aid in carbon reduction in infrastructure project (Network Rail, 2020e, p.181).

This thesis has been aligned with the GHG protocol 2004 guiding principles, see Table 3.3.

Table 3.3 Guiding Principles from GHG Protocol 2004, amended from T1198 (RSSB, 2021b, p.5)

Guiding Principle Area	Guiding Principle Details	How Case Studies Aligns with Guiding Principle
Relevance	Carrying out reporting in such a way that it reflects the organisation's GHG emissions. Providing useful information to stakeholders and others both inside and outside the organisation.	Via use of novel Carbon Calculation Data form aligned with PAS2080.
Completeness	Ensuring that all material emissions sources within the agreed boundary are reported. Any exclusions are disclosed and justified.	Assumptions are as detailed in Appendix C.5 example and DOI document for all 50 case studies.

Guiding Principle Area	Guiding Principle Details	How Case Studies Aligns with Guiding Principle
Consistency	Applying consistent methodologies for collecting data and carrying out calculations. Ensuring meaningful comparisons can be made of emissions within organisations over time and between the emissions of similar organisations.	Via use of novel data capture form aligned with PAS2080.
Transparency	Carrying out emissions reporting in a factual manner. Ensuring a clear audit trail. Disclosing any assumptions made and reference all calculation methodologies, emissions factors and data sources.	Via use of novel data capture form aligned with PAS2080 & Assumptions are as detailed in Appendix C.5 example and DOI document for all 50 case studies.
Accuracy	Ensuring that organisations neither over nor under-report their actual emissions. Ensuring that the inevitable uncertainties are reduced as far as is practicable.	Via use of novel Carbon Calculation Data form aligned with PAS2080.

Other studies which utilises the same methodology as this thesis have been found (Lokesh, Densley-Tingley and Marsden, 2022a).

3.2.2 Steps to Produce a Carbon Footprint

The five general steps to produce a carbon footprint are presented by Williams *et al.* (2012):

1. Identification and categorisation of all emissions sources for the subject of interest.
2. Determination of relevant emissions sources to include in carbon footprint calculation via a decision-making process.
3. Selection of suitable method to translate measurable activities of emissions source to a weight of CO₂e emissions.
4. Gathering of data and application of method selected in (3) to calculate total quantity of CO₂ and CH₄ emissions, expressed as CO₂e.
5. Full documentation of all steps undertaken to allow for future carbon footprints to be comparable.

The above steps are broadly in line with those followed in this thesis, (data gathering is CO₂e only). This thesis follows PAS2080 methodology, and specifically the process requirements, amended from PAS2080 (BSI, 2016):

1. Identification of system boundary.

2. Identification of scope of carbon assessment.
3. Assessment standards and calculation methodology described.
4. Data and tools used to calculate footprints described.
5. Starting point, iterations and frequency noted.
6. Presentation of the results using a functional unit for comparison.
7. Continual improvement via analysis of results and identification of hot spots for mitigation and then offsetting of carbon.

For the case studies, the emissions sources are identified from the Carbon Calculation Data form to ensure alignment with PAS2080 stages. All data entered into the RSSB RCT is classified as “measured” as this data is in the form of mileage for transport/staff distances and kg of materials and waste (BSI, 2016, p.21). Running hours for equipment is provided in hours and subsequently converted into fuel spent. Data collected as per PAS2080 data quality rules shall be the most “representative, accurate and plausible data” for the study and shall be defined in terms of age, geography, technology, methodology and competency and noted for each case study (BSI, 2016, p.20). Data is noted as actual or forecast (assumed data) for each case study. This uncertainty due to data collection has been evaluated and consideration given to whether this might significantly affect the outcome of the given case study footprint. All data is expressed in kgCO₂e via use of emissions factors found in the RSSB RCT repository of data, incorporating Bath ICE and Defra figures and the use of Equation 1 inside the RSSB RCT to perform the carbon footprint for each item in the case study in question for each of the three scenarios BAU A1-A5, A1-C4 and A0-D. Results have been included as functional intensity metrics for comparison to the literature as kgCO₂e per 100m linear earthwork (volume). PAS2080 also states that normalisation of metrics by cost such as tCO₂e per £100k should always be reported. In this thesis these metrics have not been the primary focus instead a simple correlation of the contractors cost estimate against total BAU carbon is calculated and presented in Figure 4.5. Fiscal data has been used as a metric for reverse calculating carbon for the Carbon Assessment metrics obtained for the NR North West and Central Region performed by Mott MacDonald, where this metric was used to obtain carbon data for projects where they had only fiscal data but not carbon data (Mott MacDonald, 2021). Benchmarking has been conducted for the data sets by intervention type and earthwork type via a functional unit of kgCO₂e per volume/per year. See Section 3.3.5 for discussion on data quality for the case studies and Section 3.4 for footprint method, case study identification and data collection method.

3.2.3 Errors in Footprinting

There is the potential for errors when producing carbon footprints (The University of Queensland, 2021), owing to the substantial amount of data collation and input from data collection onto forms,

input to Excel for conversion to factors suitable for input into RSSB RCT, and then data output to Excel and further manipulation into results tables and graphs. Mitigation measures are therefore implemented for the case studies in this thesis, see Table 3.4.

Table 3.4 Common Footprint Mistakes & Mitigation Used in this Thesis, amended from (The University of Queensland, 2021) and (Royal Institution of Chartered Surveyors, 2012)

No.	Common Mistakes in Carbon Footprinting	Mitigation Measures Used in this Thesis to Alleviate Mistakes
1	Incorrect choice of emissions factor.	Correct and consistent choice for assumptions is made and detailed for each case study.
2	Data not converted to appropriate unit before applying EF such as g rather than kg.	Use of appropriate units for data – such as MWh and kWh – reference to the unit used in the tool is made for each item.
3	Incorrect application of energy content factor when converting liquid fuel volumes into gigajoules.	N/A
4	Omission of facilities or entities which should be included.	Consistent exclusion of out-of-scope items.
5	Poor levels of quality control or data management.	Alleviated via use of automated calculations in Excel, mitigated via avoidance of manual calculations and using cell-referenced formulas in a spreadsheet program such as EXCEL to enable avoidance detection and correction of data input errors.
6	Errors in source data – such as database choice global not national data.	Use of ICE database, Defra which sit behind the RSSB RCT, use of EPD where available.

This thesis will be investigating carbon footprints over the BAU and two expansion scenarios. These three stages align well with those detailed in PAS2080 Table B1 for system boundary where data reporting in three boundary conditions is detailed (BSI, 2016):

- Cradle-to-completed construction (A0-A5).
- Cradle-to-grave (A1-C4 ex B9) over 10-year ref study period up to a max as defined in the asset standard.
- Cradle-to-cradle (A1-C4 ex B9 + D) over a reference study period as defined in the asset standard.

3.3 Databases Used by Carbon Footprint Tools: Constraints & Assumptions

This section will discuss the primary data used in the RCT and the Bath ICE database, see Section 3.3.1. This is followed by a discussion of the choice of database, see Section 3.3.2, highlighting

constraints and assumptions that are brought about via the use of these for emissions factors as opposed to EPDs. Verification of primary data sources is addressed in Section 3.3.3. This is followed by an overview of the validity of the data in the tool, see Section 3.3.4, and on data quality, see Section 3.3.5.

3.3.1 Primary Data in RSSB RCT – Bath ICE and DEFRA

Saxe *et al.* (2015) cite use of the ICE database, a cradle-to-site repository of EFs, and that other factors from separate sources would be required to complete a full LCCA, such as energy for construction, operation, and maintenance. In contrast, Akponeware *et al.* (2022) cite the ICE database as a cradle-to-gate repository. There is ambiguity regarding the range of lifecycles that the ICE database covers and careful choice of EF within the RSSB RCT is required, along with clear notation of choices, detailed in the 5 steps of a carbon footprint and the 7 steps to a PAS2080 analysis, see Section 3.2.2.

With regard to emission scopes, see Appendix A.3, the allocation of these sources of emissions (at source or at point of use) by databases, such as DEFRA, is also unclear (Pritchard, 2015). Differences in regional EPDs regarding emission factors for some materials have also been highlighted by Landgraf and Horvath (2021).

Uncertainties in carbon footprints from differences in EPD level via the use of different generic databases was also pointed out by Olugbenga, Kalyviotis and Saxe (2019) in their review of 100 LCA case studies within the railway sector to produce a “sketch model” of estimation for the GHG impact of rail infrastructure (Olugbenga, Kalyviotis and Saxe, 2019, p.15). This uncertainty points to the use of generic databases with caution, and with a clear understanding of where the data set originated from (regional or global data), and whether it is suitable for the intended purpose, which for this thesis is GB mainline railway earthworks.

Hammond and Jones (2008), the ICE database creators, provide a description of the database, an open-access database for embodied energy and CO₂ emissions, developed primarily for the UK construction industry. They explain the majority of the data in the database originated from secondary data resources, with the database originally being populated with materials from the CIBSE guide to thermal properties of buildings and components 2006, and the initial embodied carbon values extracted from Boustead and Hancock’s handbook of industrial energy analysis published in 1979.

Hammond and Jones (2008) explain that data was extracted from peer reviewed literature on the basis of a defined methodology, and the five criteria listed below, with a focus on data for construction materials:

1. Compliance with approved methodologies or standards such as ISO 14040 or 14044.
2. System boundaries of cradle-to-site preferred for embodied data.
3. Country of origin of data (UK data sought where possible due to differences in fuel-related carbon in manufacturing but European or World averages used where this was not possible).
4. Data age was of concern owing to the changing fuel mix in the UK affecting embodied carbon data.
5. Embodied carbon from LCA preferred, but where unavailable substitute values estimated from typical fuel split for the UK industrial sector in question.

Hammond and Jones (2008) overall caveat is that all figures should be used with caution and the exact primary source needs careful scrutiny with comparison to footprints created from other databases, to ensure consistency of boundary conditions and similar assumptions or data set use, such as UK with UK, rather than UK with world or EU average.

Akan, Dhavale and Sarkis (2017) highlight discrepancies between the ICE database and EPDs for products, and use independent sources from the literature to estimate GWP for cement products and found that this estimate provided emissions factors close to that of the ICE database and the UK 2014 EPD for cement products “after allowing for different clinker ratios and estimating procedures”(Akan, Dhavale and Sarkis, 2017, p.1200). Akan, Dhavale and Sarkis (2017) also investigate emissions for transportation based on varying speed and load, discussed further in Section 5.3.4 & 5.8.3.

Other databases have been reviewed. See Appendix C.1.1 for details.

3.3.2 Choice of Database

In choosing the LCI database to use with a carbon footprint tool some country level guidance is available (Lasne, Large and Bruni, 2015) with Base Carbone (Bilan Carbone v7) advocated for France, DEFRA and (Bath) ICE for UK and EPA for USA, and with EFFC-DFI for use in the specific soil nail and pile walls carbon footprint tool (Lasne, Large and Bruni, 2015, p.5).

The country level guidance detailed here affirms the choice of the RSSB with the DEFRA and Bath ICE databases, further evidence towards its use is found in Yan *et al.* (2022, p.227) citing “in the infrastructure category, there is only one tool available (RCT) that provides railway specified LCA analysis of carbon footprint.”

Use of the ICE database is also cited by Saxe *et al.* (2015), stating that this is a cradle-to-site repository of EFs and that other factors from separate sources would be required to complete a full LCCA analysis such as energy for construction, operation and maintenance (Saxe *et al.*, 2015). Furthermore, they comment on the establishment of a database with material and energy use for rail infrastructure, presumed to be the RSSB RCT.

A list of third party life cycle databases are available on the GHG Protocol website including Bath ICE and Defra (GHG Protocol, 2024). Issues with use of Defra database are also highlighted by Pritchard (2015) who point out that it “is not always clear cut...whether emissions are allocated at source, or at a point of use” (Pritchard, 2015, p.11).

Uncertainties, similar to those found in a review of 100 LCAs in the railway sector (Olugbenga, Kalyviotis and Saxe, 2019), owing to the limited number of evaluations on the influence of differing generic databases affecting EPDs, are found in the literature (Landgraf and Horvath, 2021). The use of generic assumptions from distant time periods and other countries, and non-specific data is a major source of uncertainty in carbon footprints potentially affecting their usefulness for implementation of environmental improvements and policy change (Landgraf and Horvath, 2021).

3.3.3 Verification of Primary Data Sources

Around the world various tools and databases, sitting behind the tools, are utilised, and differing standards and methodologies, including ISO and PAS2080, are used by companies to create their own EPDs for products.

The MPA uses GaBi V8.0.0.247 (MPA, 2017), Hanson uses EcoInvent V3.2 (Hanson, 2019) and Marshalls Bricks uses EcoInvent V3.4 (Marshalls Bricks & Masonry, 2021). Differences between the ICE and EcoInvent databases, regarding geopolymers, have been highlighted (Raja *et al.*, 2015) and this difference between databases warrants further attention, particularly regarding whether EPDs would be the optimum route for verification of accurate carbon accounts.

Emissions data is not easily obtainable by designers and engineers in the construction industry (Akan, Dhavale and Sarkis, 2017, p.1026). The call for data from the DfT for carbon data from the RSSB RCT indicates that government is beginning to investigate the methodology behind carbon footprints and is ready to explore further insights for sharing best practice (Coles, 2022). In this thesis access to secondary data has been via the Carbon Calculation Data form, making this a strength of the analysis. Gaps in data have been filled by data from the literature and this has been clearly identified, although due to differences in how the literature arrived at their conclusion could be a weak point for the data set in question. Standardisation of EFs is needed to allow for accurate comparison

between differing studies and this has been achieved for this thesis via use of the same EF factors between studies where applicable, such as such use of HGV unknown in the RSSB RCT.

A focus on reduction of emissions from construction process (aligning to PAS2080 A1-5) is important to “minimise erosion of the anticipated future benefits of greater use of rail” (Hill *et al.*, 2011, p.vi) by beginning an infrastructure project with a large carbon “debt”.

3.3.4 Validity & Justification of Databases Used

For this thesis EPDs are the preferred source of concrete emissions factors rather than the Bath ICE database to ensure the most accurate and up to date data is utilised, as use of credible LCAs (for concrete particularly) is highly dependent on use of credible LCIs (Gursel *et al.*, 2014) .

The use of a pre-populated LCI such as Bath ICE is the practical alternative to compiling a bespoke database of items due to the potential for lifecycles of these items to be composed of hundreds or even thousands of processes, collection of data would be inordinately time consuming (and inordinately expensive), and therefore impractical to carry out (Vieira, Calmon and Coelho, 2016).

Choice of emissions factors database used is also discussed in Lasne, Large and Bruni (2015) where a carbon footprint tool is showcased for soil nails and pile walls and explicit direction is given regarding choice of database with country specific databases recommended for France as the Bilan Carbone v7, for the UK as DEFRA and ICE, which is the case for this thesis via its use of the RSSB RCT, and the USA as the U.S. Environmental Protection Agency (EPA).

3.3.5 Data Quality

A problem highlighted by others in use of these tools, and found in the RSSB Tool via use of the ICE 2.0 database and the Government factors from 2018 in the case studies, is the updating time frame of the emissions factors within them (Shillaber, 2016). Although EFs use a method which has long-term applicability, the factors used are time-dependent in that they themselves require updating as the factors they are comprised of update with technological improvements, for example for machinery, or production methods, or are powered via renewables from the grid rather than fossil fuels, all changing their underlying EF.

Adherence in this thesis to the PAS2080 data quality rules is highlighted in Section 3.2.1. Data quality shall also be aligned with the GHG Protocol (Greenhouse Gas Protocol, 2011) and the following indicators are also considered; technological, temporal and geographical representativeness, completeness and reliability (all having very good, good, fair and poor scoring criteria) (Greenhouse Gas Protocol, 2011, pp.76-77). These parameters are considered when conducting comparisons of

data from this thesis with the literature, see Section 4.3.2, and with the guiding principles of the GHG Protocol followed, see Table 3.3. Common challenges in collecting data include a lack of knowledge (linking with the need to increase carbon literacy throughout the supply chains), lack of capacity in terms of time and people both within company and within their value chain to create the footprint, lack of transparency amongst those in the supply chain (which feeds into data quality), and choice of units used to allow for data sharing, along with confidentiality concerns of suppliers, plus language barriers for those working in global supply chains (Greenhouse Gas Protocol, 2011, p.82).

Due to the fact that the European Federation of Foundation Contractors and Deep Foundations Institute carbon tools (EFFC-DFI) (EFFC, 2023b) utilises the same LCI databases as the RSSB RCT it is not justifiable to perform a comparative analysis using this tool as the results would be similar (Lasne, Large and Bruni, 2015).

3.4 Method: Case Studies Identification, Data Collection & Footprint Method

Owing to the large size of the data collected for this research, selected examples of the data for the case studies presented in this chapter are given in Appendices, detailed as follows, with full data sets available as accompanying material under the DOIs detailed in the List of Accompanying Materials:

- A to Z Case Study Descriptions, see Appendix C.2
- A to Z NR Carbon Calculation Data Completed Forms, see Appendix C.3.3
- A to Z NR Carbon Calculation Data Queries and Responses, see Appendix C.4
- User Manual for Footprint Creation
- NR Carbon Data Calculation Rev 3, see Appendix C.3.1
- A-Z of NR Case Study Assumptions, see Appendix C.5
- A to Z NR Case Study CSV Download (BAU), see Appendix C.6
- A to Z NR Case Study CSV Download (ER), see Appendix C.6

3.4.1 Case Studies Identification

How the case studies were identified, the data collected, and the footprint method used, are presented here.

To convey how the case studies have been identified, an understanding of how NR railway infrastructure is organised is given. NR splits its railway infrastructure into nine distinct areas (see Figure 1.5), of which earthworks are a discrete area. Sitting under earthworks are the different intervention types of embankments, soil cuttings and rock cuttings, forming the focus of this thesis.

Chapter 3

Each intervention type has differing lifespans, maintenance at two years, refurbishment 20 years, and renewal 120 years (Network Rail, 2021a), with these lifespans being aligned to the expected lifespan of the intervention before the next intervention is required. NR further divides its assets into five regions: Scotland, North West & Central (NW&C), Wales and Western (W&W), Eastern, and Southern, see Figure 3.1 (Network Rail, 2022d).

Within each region, NR divides its rail infrastructure areas into “volumes.” For earthworks, the “volumes” are based on a linear measurement of 5 chains (with this being equivalent to an imperial unit of 110 yards or approximately 100m, owing to the railway being originally constructed prior to the introduction of the metric system). These volumes are related to the asset count for the whole network, with over 191,636 earthwork volumes listed in the Cost and Volumes count for 2023/24 Period 01 for embankments, rock cuttings and soil cuttings, see Table 4.11. Details of how volumes are assigned to the different earthworks, and earthwork clarification, is provided in Appendix C.8 (Power *et al.*, 2016, p.727).

For earthworks, upcoming and recently completed maintenance, refurbishment and renewal works on the network are detailed in “workbanks” for NR regions. Using these “workbanks,” supplied in the form of Excel sheets or identified via discussions with NR Project Managers, projects that would be completed within the thesis data collection timeline of January 2021-April 2023, of around one volume, were identified and data requested from NR, see Section 3.4.2 for the data collection process. Differences in lifespan and volume of case studies are incorporated into the functional unit, see Section 4.1.3, allowing for case study comparison.



Figure 3.1 Network Rail Regions 2022 , adapted from (Network Rail, 2022d)

To create a suite of case studies covering a broad range of interventions, a range of case studies were identified from the NR “workbanks”, to include a wide variety of the differing interventions listed in Appendix A.1 to maintain, refurbish and renew earthworks. Cross referencing of the case studies to the categories of intervention, and then extrapolation to the whole of the network is described further in Section 4.1.7, to explore the carbon impact of the most frequent interventions to the whole network. These case studies were aligned to earthworks and then further categorised to specific interventions to provide a data set that NR can use as a baseline as they decarbonise to net zero.

3.4.2 Data Collection via Carbon Calculation Data Form

BOMs were obtained early on in this thesis for preliminary review for potential case studies, however these were found to be lacking the detail required for carbon footprinting. To fill this gap the carbon

calculation data form was created with alignment between its sections and that of the RSSB RCT PAS2080 template.

The data used in this research has been collected from NR contractors in the four regions of: Scotland, North West & Central, Wales and Western, and Eastern (see Figure 3.1) (Network Rail, 2022d). These regions provided data for the case studies identified from their “workbanks,” see Section 3.4.1. Use of local names only have been requested to be shared by NR for these sites, and not the exact mileage on the track, protecting subcontractor confidentiality. Postcodes/Grid References were requested for all sites to enable further investigation of terrain and its impact on carbon footprint and geographic location effect on the footprint is explored and described further in Appendix C.11 via a rural-urban classification exercise.

As a result of interrogation of the “workbanks” provided by NR, case studies were identified based on their meeting the key characteristics of: Suitable size, appropriate earthworks intervention type (see Appendix A.1) and with data being available within the time period for data collection, January 2021 to April 2023.

To capture data in a standardised and consistent manner a novel Carbon Calculation Data form was created (Najafpour Navaei *et al.*, 2024) (see Appendix C.3.1), aligned to PAS2080 stages (see Figure 3.2), with the LCA phases of this study, see Figure 2.24, to enable all the pertinent details required for footprint creation to be captured by the contractor/project manager in a suitable format.

The carbon data capture form used underwent several iterations from R0 to the final version R3 via trial and error during its initial use. The initial form was created in Microsoft Word with alterations made to this version, which proved popular in use by contractors due to its simple and easy to use and navigate format. For evolution of this form see Appendix C.9.

An FAQs document was also created, see Appendix C.3.2, outlining some of the more common areas for clarification to aid in the form’s completion, such as indication of whether staff travelled weekly to site and stayed in accommodation or if plant was left on site for duration or transported/towed back and forth weekly or per shift. Form validation was carried out by using the form in its various revisions and creating footprints for the thesis and amending the form as per the revisions (detailed above) to suit the template.

This strategy of data collection leads to a standardised and consistent data collection method facilitating comparable data collection for carbon accounting purposes, thereby enabling NR to accurately collect data and create footprints for their earthworks and aligns with recommendations from the RSSB related to data collection (RSSB, 2024b). This data collection method is suitable for a range of sizes of case study from the one volume size used in this thesis up to larger interventions

such as a new line (Bothnia line, HS2), with these larger footprints being comprised of a series of smaller projects and thus each having their own footprint which amalgamate into one total.

Regarding data validity, while every effort has been made to check the accuracy of the data used and to control for anomalies, it is impossible to be entirely certain that all raw data supplied by NR and by others is entirely accurate, and this should be borne in mind when considering the results obtained.

Following identification of 72 sites from the “workbanks” the contractors in the regions were then requested, via a remit raised by NR, to complete the carbon data capture form (see Appendix C.3.1) created for this thesis outlined above, for all case studies identified in their region. To aid in form completion the FAQ document was created (see Appendix C.3.2) and sent to contractors along with the exemplar completed form (see Appendix C.3.3). In total 57 carbon data capture forms were returned across the four regions.

On return of these forms via email, several forms were found to be missing data. Given that the accuracy of data is crucial in carbon footprinting, any ambiguous forms received were followed up with queries to the contractor raised on a standardised query form created for this purpose (see Appendix C.4) to provide clarity. The full set of queries and responses can be found in the accompanying data set, see Section 3.4, forming part of the specific assumptions for each case study.

Following resolution of the queries, a suite of 50 case studies covering 4 of the 5 regions in NR were moved forward for BAU footprints to be created. Details of tracking sheet used to track progress of form completion and query resolution is provided in Appendix C.10. These 50 case studies were aligned to earthwork type, lifetime, intervention type as per Cost and Volumes handbook to avoid ambiguity in later analysis, and hereafter described as the case study description, see Appendix C.2.



Figure 3.2 Alignment of Carbon Calculation Data Form with PAS2080 Stages (Najafpour Navaei *et al.*, 2024)

From this master case study description, a breakdown of the full data set of 50 case studies , whereby the number of case studies in each category of earthwork (horizontal rows) and in each expected lifespan category (vertical columns) is presented, see Table 3.5

Table 3.5 Breakdown of Case Studies by Earthwork Type & Expected Lifespan

	Maintenance	Refurbishment	Renewal	Total No of Case Studies by Earthwork
Embankment	14	3	3	20
Rock Cutting	8	3	0	11
Soil Cutting	13	4	2	19
Total No of Case Studies by Expected Lifespan	35	10	5	50

Table 3.5 illustrates that maintenance interventions dominate the expected lifespans of the data set, accounting for 70% of the data, and that embankments and soil cuttings accounted for most of the earthwork types, accounting for 78% (40% and 38% respectively) of the data set. Details of the locations of the 50 final case studies were obtained from NR (for postcode alignment to sites see Appendix C.11), to illustrate their spread throughout GB. The case study locations are superimposed on to a GB map, colour coded by earthwork type, see Figure 3.3, and also colour coded by intervention type, maintenance, refurbishment and renewal, see Figure 3.4.

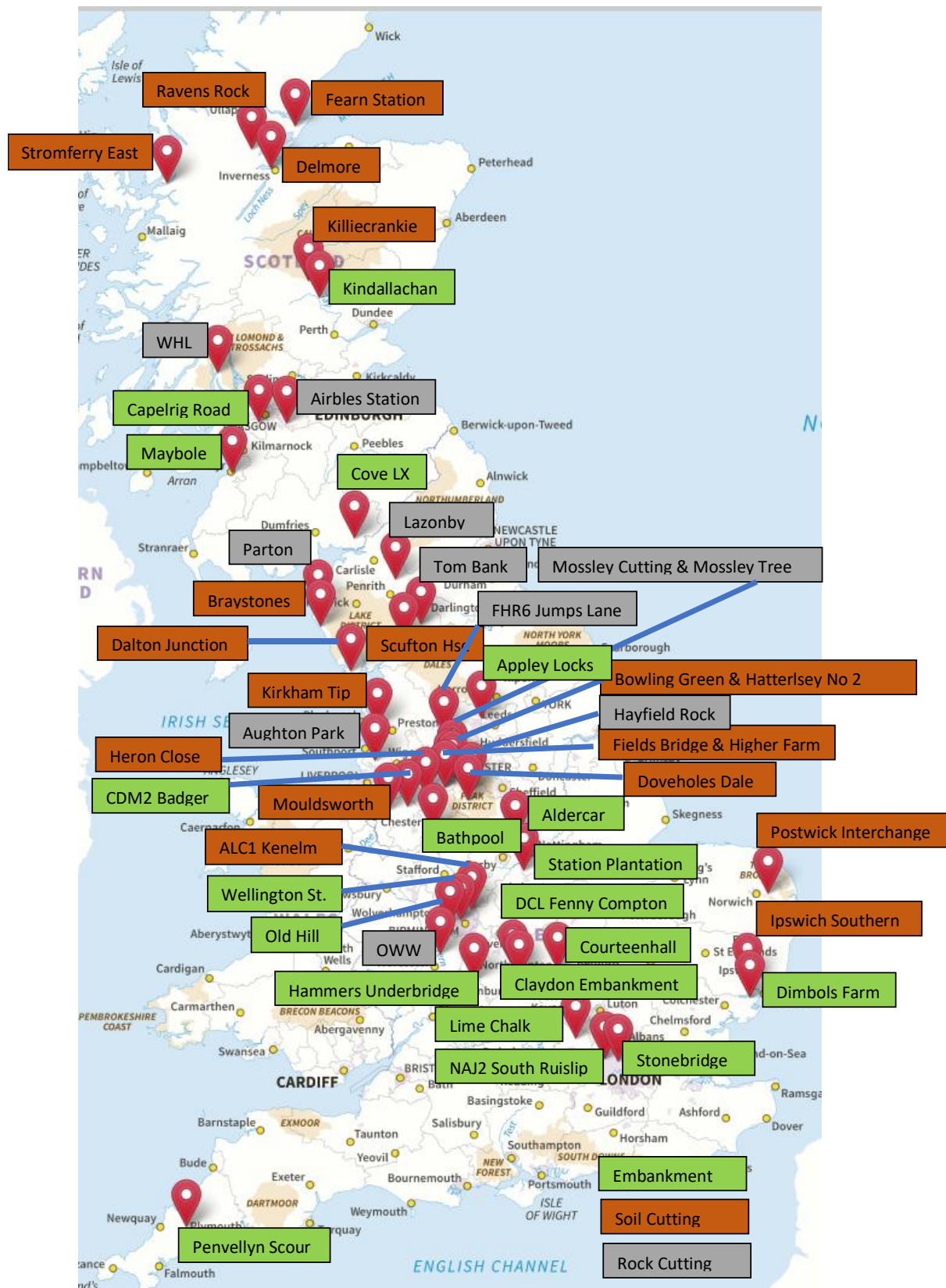


Figure 3.3 Case Studies' Located on GB Map Coded by Earthworks' Type

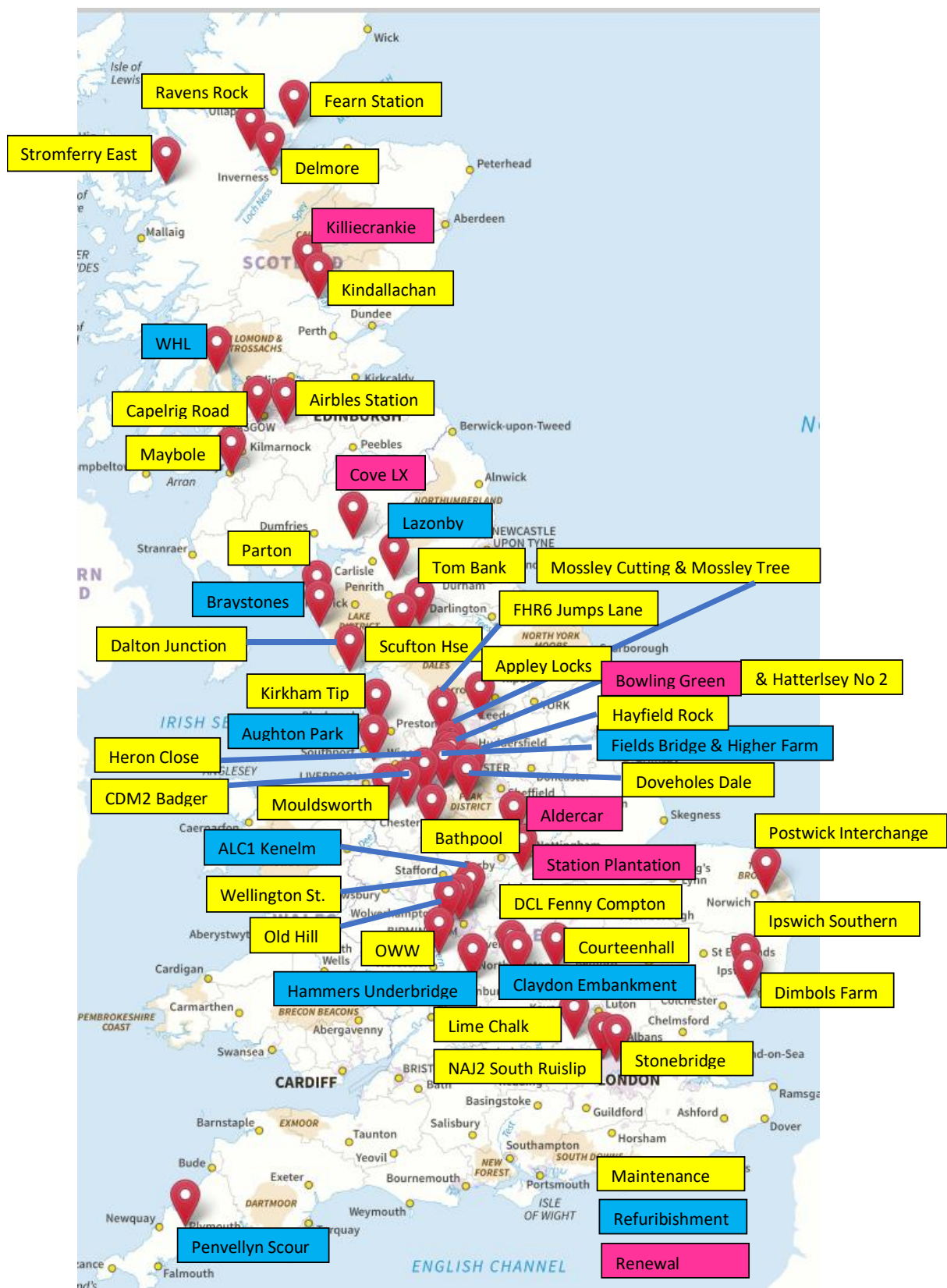


Figure 3.4 Case Studies' Located on GB Map Coded by Intervention Lifespan

3.4.3 Footprint Production

Following identification of suitable case studies (see Section 3.4.1, and completion of carbon data capture form by the subcontractor, along with checking for completeness and resolution of queries, see Section 3.4.2), the next stage of footprint production was undertaken. The RSSB RCT footprint was created for the final 50 footprints which had completed forms and all queries answered or suitable assumptions made.

The RSSB RCT is utilised for production of carbon footprints in all three scenarios of BAU A1-5, expanded EXP A1-C4, and expanded EXP A0-D. All three will be described in their relevant sections in Chapter 4. The NR PAS2080 template, sitting within the RCT, was utilised to input all data into consistent stages to enable meaningful comparison between each other and the wider literature. Instructions for creating a footprint can be found in the guide to this User Manual for Footprint Creation in Accompanying Materials with use of an Excel sheet aligning with newly published research guidance from the RSSB for supply chain carbon data collection and reporting (RSSB, 2024c).

The specific details of materials, plant and equipment, transport mode chosen for each case study, the databases EFs are from, and the EF used for items in the carbon footprint, are all detailed in the .csv data file downloaded from the RCT for each case study, see Appendix C.6.

The inherent error due to weighting of differing GHGs when converting to CO₂e, will be introduced to all items in the RSSB RCT inventory, as these are measured as CO₂e, see Section 1.4.1.

3.4.4 Baseline Carbon Accounts

The progression of this thesis from the BAU scenario of carbon footprints in the RSSB RCT at the start of this project, and the progression of footprint creation to the expanded A0-D scenario over the course of this thesis is illustrated in Table 3.6. The top lines show the limited extent to which footprints were previously being created, the next line shows the BAU expanding into A4 and A5 lifecycle stages and then the next two lines shows the two proposed expansions A1-C4 and A0-D. The final expansion scenario encompasses A0-C4 in the RCT, with the D stages calculated outside of the tool to be offset against this.

Table 3.6 Current and Proposed Footprint Scope

Infrastructure assessment life cycle information																	Supplementary information beyond the infrastructure life cycle			
Before use stage					Use stage									End of life stage						
A0-5					B1-9									C1-4						
																	D			

Current Status of RSSB Tool Carbon Footprints (Feb 2021) Cradle-to-gate																			
A – Before Use						B – Use Stage									C – End of Life				D – Beyond the Life Cycle
A0	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	B9	C1	C2	C3	C4	D

Proposed BAU Scenario of RSSB Tool Carbon Footprints (Feb 2022) Cradle-to-end of construction																			
A – Before Use						B – Use Stage									C – End of Life				D – Beyond the Life Cycle
A0	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	B9	C1	C2	C3	C4	D

Proposed Expansion of BAU to LCA of RSSB Tool Carbon Footprints (Feb 2022 onwards) Cradle-to-grave																			
A – Before Use						B – Use Stage									C – End of Life				D – Beyond the Life Cycle
A0	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	B9	C1	C2	C3	C4	D

Comprehensive Scenario inc. Assessing Potential for Sequestration of RSSB Tool Carbon Footprints (Feb 2022 onwards) Cradle-to-Cradle																			
A – Before Use						B – Use Stage									C – End of Life				D – Beyond the Life Cycle
A0	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	B9	C1	C2	C3	C4	D

Table 3.6 highlights the current limited footprint scope and details how this thesis has significantly extended the scope of NR earthworks' carbon footprints from a narrow A1-3 materials focused footprint to a comprehensive footprint. This comprehensive footprint includes the design stage of before use stages, maintenance in the use stage and deconstruction activities, where applicable in the EOL phase, with residual carbon in the D stage being addressed via the offsetting options overviewed in Chapter 6.

3.4.5 Assumptions in Carbon Footprints

The assumptions for each case study vary pending on which materials, plant and transport are utilised. These are presented in detail in an Excel sheet for each case study, see Appendix C.5. This Excel sheet is populated from the data found in the completed Carbon Accounting Data Collection Form. All case studies had the same general exclusions applied to them for consistency, these are:

- Construction-phase consumable products (excluding fuel & water).
- Fossil fuel use for fixed/static plant & equipment for site operations and welfare.
- Grid electricity use by plant / equipment / services for site operations.
- Welfare and mains water use for site operations and welfare.
- Apportionment of carbon from overheads.

For each case study that encompasses plant and machinery the proportional embodied carbon has been accounted for in the case studies (A1-3), see Appendix C.12 for further details.

3.5 Summary

Steps to produce a carbon footprint, choice of the RSSB RCT and errors in footprinting have been provided in Section 3.2. Background to the databases used by carbon footprint tools was provided in Section 3.3. This was provided alongside verification of primary data sources and validity and justification of the databases available. Conclusions on general data quality, linking back to the carbon footprint steps was also provided. Finally, the method used for case study identification, data collection and carbon footprint production were outlined in Section 3.4. Chapter 4 will present the results of the case studies' carbon footprints.

Chapter 4 Results

The carbon footprinting method for the thesis has been outlined in Chapter 3 via use of the RSSB RCT and primarily the Bath ICE database and government data, along with a description of the case study identification, data collection and footprint method chosen.

This chapter presents the raw results of the BAU (A1-5) footprint of the whole data set. To enable comparison between case studies with differing lifetimes, a functional unit is calculated. The whole data set is also analysed in discrete sections by intervention lifetime and further disaggregated by earthwork type. A detailed method for expansions and the results of the two expansions: BAU EXP (A1-C4) and BAU EXP (A0-C4) for the renewal interventions is provided along with a discussion around uncertainty in the expansion of lifecycles. The quantification of carbon in these case studies and identification of “hot spots” meet Objective 2. This chapter ends with comparisons of the data sets BAU (A1-5), BAU EXP (A1-C4) and BAU EXP (A0-C4) with the literature.

4.1 Results of all 50 Case Studies

Results of the whole data set are presented here, initially as raw BAU, see Section 4.1.1, enabling correlations with other metrics such as mileage, see Section 4.1.2, and then transformed into the functional unit ($\text{kgCO}_2\text{e/Volume/Year}$), to allow for comparison between differing interventions' expected lifespans and sizes of interventions, see Section 4.1.3. The results are presented disaggregated by maintenance, see Section 4.1.4, refurbishment, see Section 4.1.5, and renewal, see Section 4.1.6 and are summarised in Section 4.1.7. A cross-referencing exercise against NR intervention types is then presented disaggregated by maintenance, refurbishment, and renewal interventions, see Section 4.1.8. The section ends with conclusions from all the analyses performed on the BAU scenarios and an overview of the potential impact of case studies of this size on the whole NR network of earthwork assets.

4.1.1 Overview of Whole Data Set

For an overview of the complete data set see Appendix D.1. For descriptions of each case study see example in Appendix C.2 and accompanying materials detailed in Section 3.4.

Appendix D.1 illustrates the range of raw data obtained for the case studies, with the largest and smallest values of 406,120.59 kgCO₂e and 15.39 kgCO₂e respectively, see Figure 4.1.

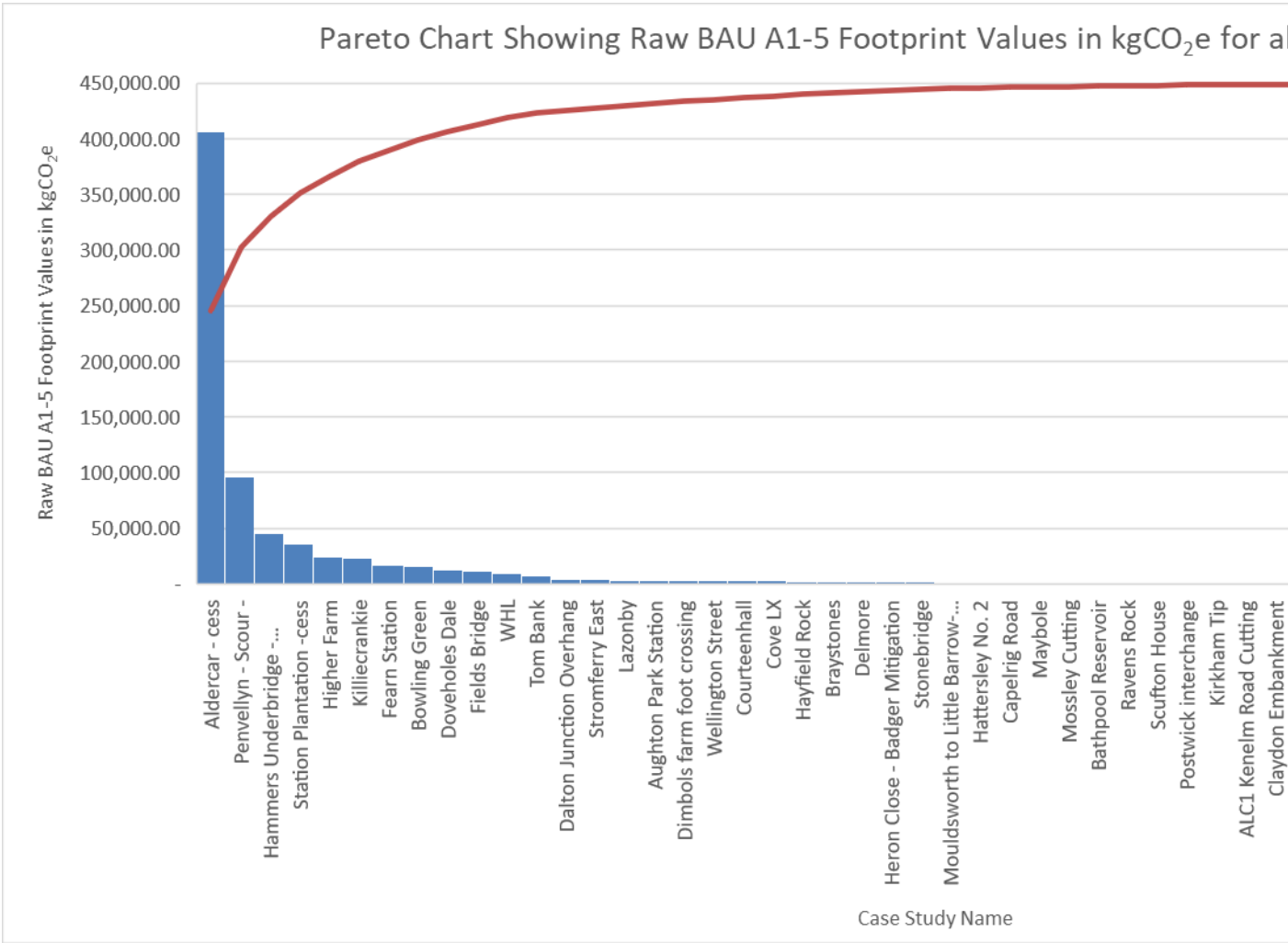


Figure 4.1

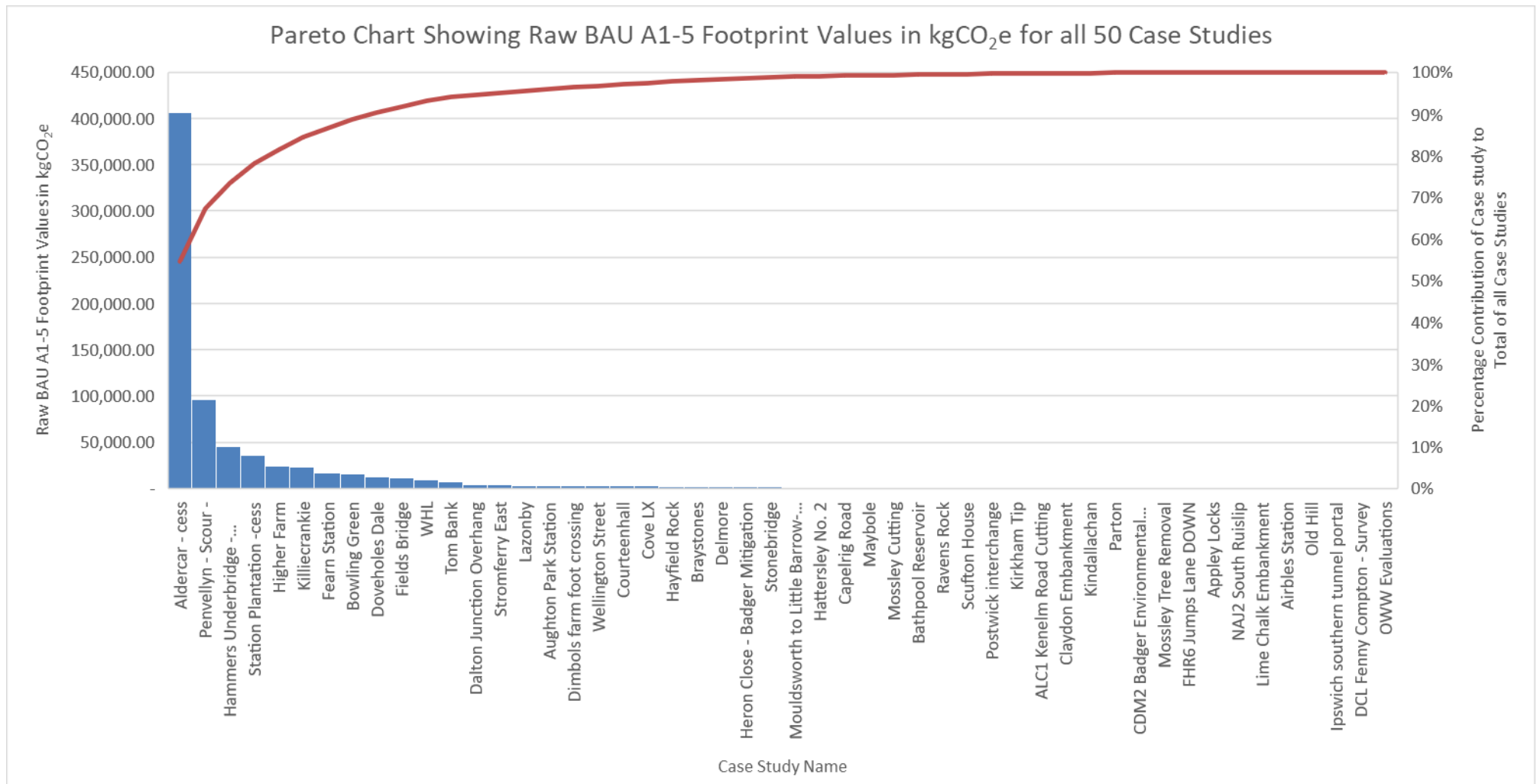
Figure 4.1 Raw BAU (A1-5) Footprint Value (kgCO₂e) for All 50 Case Studies

Figure 4.1 illustrates that Aldercar accounts here for over 50% of the total sum of all footprints, and that the two largest footprints account for over 60% of the total. Aldercar's footprint is four times larger than Penvellyn, the second largest footprint, and Penvellyn is over twice as large as the next largest footprint, Hammers Underbridge.

The far right column in Appendix D.1 shows the raw BAU A1-5 value divided by the size of each case study (number of volumes with each volume being approximately 100m linear length, see Section 3.4.1). Using this divisor, Aldercar, at 135,373.53 kgCO₂e is around 2.75 times larger than the next largest case study, Penvellyn, at 48,004.97 kgCO₂e and Station Planation comes in third largest at 35,572.31 kgCO₂e. Using this divisor, it is clear that such a measure is required to ensure case studies are accurately compared by size, illustrated by the third place ranking of Hammers Underbridge in raw BAU A1-5 value moving to fourth place when the divisor of volume is used.

A ranking exercise was performed split by intervention expected lifespan for the independent variables of total staff hours per case study (total number of staff per shift x number of shifts x length in hours of shifts) and total staff transport mileage in km (mileage per staff member x number of shifts) and for the functional unit (see Appendix D.2). This exercise indicated tentative alignment between these variables and the functional unit, therefore further correlation analysis was performed, see Section 4.1.2, to gauge the impact of these variables.

Statistical analyses of the data set are given in Figure 4.2 in the form of box plots, constructed to illustrate the spread of data and differences in the data between maintenance, refurbishment, and renewal case studies' raw BAU A1-5 kgCO₂e and the two suggested explanatory variables of staff hours and total staff transport mileage (km).

For all three box plots across these suggested explanatory variables, the median for each is progressively higher, which is as expected as each intervention is progressively for a larger expected lifespan. Therefore, it would be expected that a 120-year lifespan intervention would incur greater carbon due to its nature, such as installation of gabion wall for a renewal compared to de-vegetation activities for maintenance interventions, and that more time would be required on site.

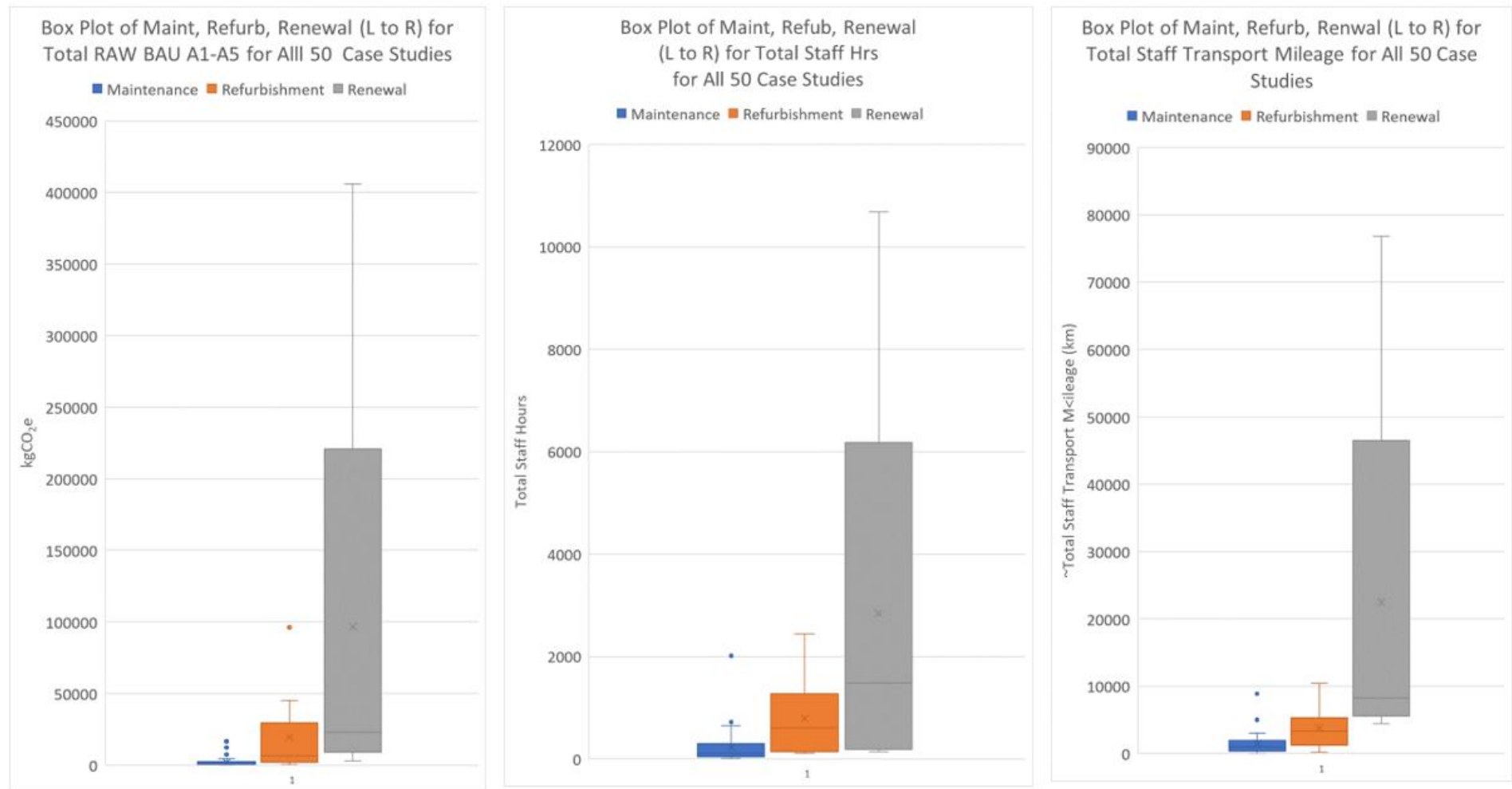


Figure 4.2 Box Plots: Total BAU A1-A5, Total Staff Hrs, Total Staff Transport Mileage for all 50 Case Studies

4.1.2 Correlation Analysis of Whole Data Set

A correlation coefficient of 0.93 (Pearson's R) is found for the raw BAU and number of shifts for the 50 case studies, indicating a positive correlation between length of works and carbon footprint. The number of shifts, and as such the total staff hours, may also be linked to the staff transport mileage, and this may be the factor contributing the most to the carbon value, as the transport of staff to site will increase in line with the number of shifts.

Correlation between length of works, transport mileage and cost with the raw BAU carbon emissions have been calculated and this data is included in comparisons with correlations found the literature, see Section 4.3.7. Scatterplots, using a log-log scale, have been created to illustrate the exponential relationship between these variables and carbon emissions, see Figure 4.3, Figure 4.4 and Figure 4.5.

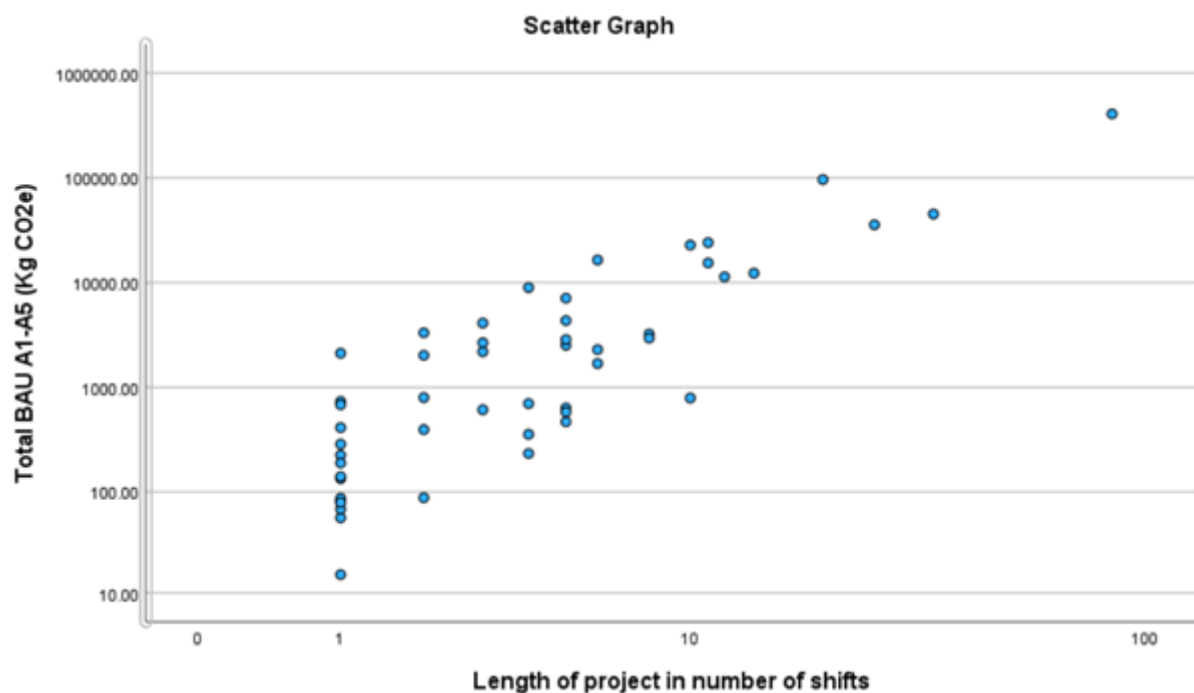


Figure 4.3 Log-Log Scatter Graph: Total BAU A1-5 (kgCO₂e) vs Project Length in Number of Shifts for Whole Data Set

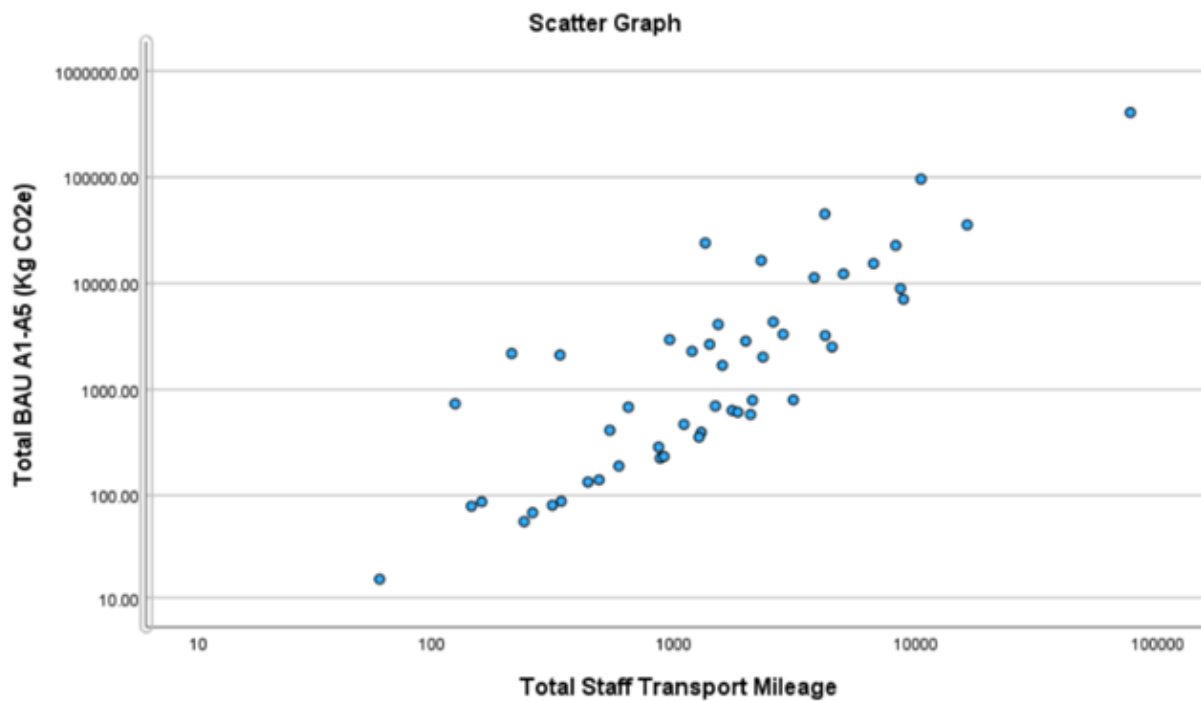


Figure 4.4 Log-Log Scatter Graph: Total BAU A1-5 (kgCO₂e) vs Transport Mileage in km for Whole Data Set

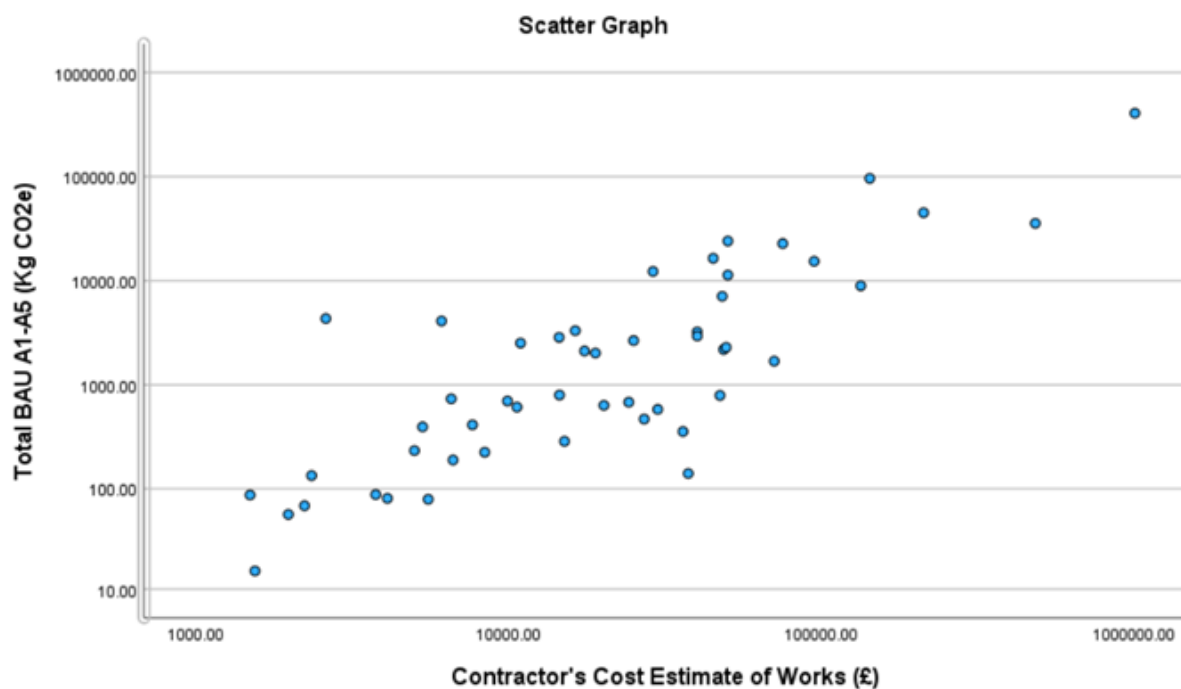


Figure 4.5 Log-Log Scatter Graph: Total BAU A1-5 (kgCO₂e) vs Total Cost (Contractors Estimate of Works (£) for Whole Data Set

These scatter graphs indicate a positive relationship between carbon emissions and length of time on site, total transport mileage, and total cost, indicating exponential growth of carbon as each variable also increases exponentially. Correlation coefficients (Pearson's R) were also found for the three data

sets (of all 50 case studies) with these being for carbon vs time on site (as length of project in number of shifts), total staff transport mileage and contractors cost estimate of works, 0.93, 0.97 and 0.92 respectively, indicating that all three have strong relationships, with staff transport mileage being the strongest of the three. The maintenance data set disaggregated by earthwork type has been further analysed in terms of these correlations in Section 4.1.4.

From the Kurtosis values obtained, the extreme outliers, such as Aldercar, are affecting the shape of the distribution, although they are showing correlations in line with the other values.

4.1.3 Functional Unit kgCO₂e Volume/Year (Vol/Yr)

A functional unit has been calculated (kgCO₂e Vol/Yr) to allow for comparison between different size case studies and constructed by dividing the raw footprint by number of volumes and the intervention's expected lifespan. See Figure 4.6 for functional units, and Table 4.1 for descriptive statistics.

Benefits and limitations of the use of the functional unit kgCO₂e/Volume/Year are outlined below:

Benefits: Ability to compare differing physical size case studies and case studies of differing expected life span.

Limitations: Comparisons on this annual basis do not account for the total footprint of a project during the year in question. The comparison would also mean that carbon spent on a project would not be accounted for in the year it is actually released, but spread out over the total expected life span of the project, such as 2 years for maintenance.

Table 4.1 Descriptive Statistics for All 50 Case Studies' for BAU Functional Unit (kgCO₂e Vol/Yr)
Disaggregated by Intervention Type

Descriptive Statistic Type	50 Case Studies	35 Maintenance Interventions	15 Refurbishment Interventions	5 Renewal Interventions
Mean	550.53	577.08	556.54	352.68
Standard Error	113.82	147.06	235.53	198.93
Median	159.44	143.39	306.53	189.68
Standard Deviation	804.86	870.04	744.80	444.81
Kurtosis	7.16	7.70	4.18	4.03
Skewness	2.43	2.44	2.00	1.96
Sum	27,526.63	20,197.83	5,565.41	1763.40
Largest(1)	4,104.95	4104.95	2,400.25	1128.11
Smallest(1)	7.70	7.70	17.81	21.02

Table 4.1 shows the mean average functional unit value for the complete data set is lower than that for refurbishments and maintenance, yet higher than renewal interventions' mean, indicating that the maintenance interventions' higher functional unit values are driving this figure upwards.

For comparison, the means of the raw BAU A1-5 values for maintenance, refurbishment and renewal are 1,965.27, 19,483.85 and 96,470.95 kgCO₂e respectively (see Appendix D.3 for BAU descriptive statistics). These raw BAU A1-5 mean figures convey the difference in lifespan of these interventions, showing the increase between maintenance to refurbishments as around 10 times larger carbon, aligning well with the difference in expected lifespan from two years to 20 years (10 times larger). The increase from refurbishment to renewal shows an approximate five times increase in carbon where the expected lifespan is increasing from 20 years to 120 years (6 times larger). This aligns well with expectations. Use of the functional unit (kgCO₂e/vol/year) enables a more accurate comparison between differing expected lifespan interventions.

The functional unit values are in line with expectations given the mean BAU values are in line with expected lifespans. So, although a lower mean is given for renewals, this will be every year for 120 years, compared to every year for two years for maintenance interventions, and as such its cumulative carbon impact over its lifespan will be greater.

The large standard deviations seen in the functional units' means indicate increasing variability in the data as it moves from renewals to refurbishment and to maintenance interventions. The Kurtosis value of 7.16 shows that the distribution of the tails of the whole data set is relatively peaked, in relation to a normal distribution. This value drops slightly as you progress along the three differing expected lifespans of the interventions. The Kurtosis values for the data set and the three disaggregated temporal interventions are all greater than 3.0 which indicates Leptokurtic distribution, indicating that there are outliers in the tails of the distribution which distort the distribution curve making the bulk of the data appear in a narrow vertical range. This Leptokurtic Kurtosis in all the data sets indicates a high susceptibility to outliers. The skewness value of 2.43 for the whole data sets showing highly skewed asymmetry of the data distribution. This positive skewness indicates that the functional unit is skewed to the right and that the functional units in the right tail, those with a higher value, are distributed farther out than those values at the lower end of the range which could lead to potential biases in the data analysis. In summary, the data set shows variability, with peaked tails and susceptibility to outliers, and having a right skewed distribution.

The range for this total data set shows that there is a great range between the three expected lifespans and earthwork types, this is described in more detail for each data set in the differing earthwork sections which follow. These descriptive statistics shows that the full data set and the maintenance data set have the same range, as the highest and lowest functional unit values are for

maintenance interventions. The refurbishment and renewal ranges are progressively smaller. The refurbishment data set range is around 1.5 times smaller than maintenance, and the renewal data set range is 3.25 times smaller than maintenance. This shows that there is greater variability in the footprint functional unit value for maintenance interventions than for refurbishment or renewal, and that renewal interventions have the least variability in size. This indicates that these values have a less varied distribution of functional unit which would tend to indicate that this renewal value would be more consistent to use in future planning of carbon emissions than the refurbishment or maintenance values.

Figure 4.6 illustrates the wide range of functional units for the complete data set in descending order. If the same data is plotted as a histogram (see Appendix D.4) with bin width 100 kgCO_{2e} Volume/Year, clustering of data points is seen in the first two bins. The clustering in the <100 bin is 18 case studies, and 10 case studies in the 100-200 bin. This is a similar clustering as that inferred from the previous data sets of Raw BAU A1-5, total staff hours and total staff transport mileage (see Figure 4.2).

The data used in this thesis has not been further categorised by scopes, introduced and overviewed in Appendix A.3, as all of the data being analysed would lie under scope 3, outside NR direct control, as all is categorised as subcontractor emissions – and therefore classed as upstream activities. If NR staff were using NR cars and equipment these would lie under scope 1. However, this data differentiation has not been provided and all data provided by sub-contractors has been assumed to be their data and lying under scope 3.

The case studies have been differentiated by rural-urban classification to explore its effect on footprints, however this is outside the scope of the main aims and objective of the thesis so is included in the appendices (Appendix C.11) for information only.

In the next section the data set will be further divided and analysed in terms of expected lifespan.

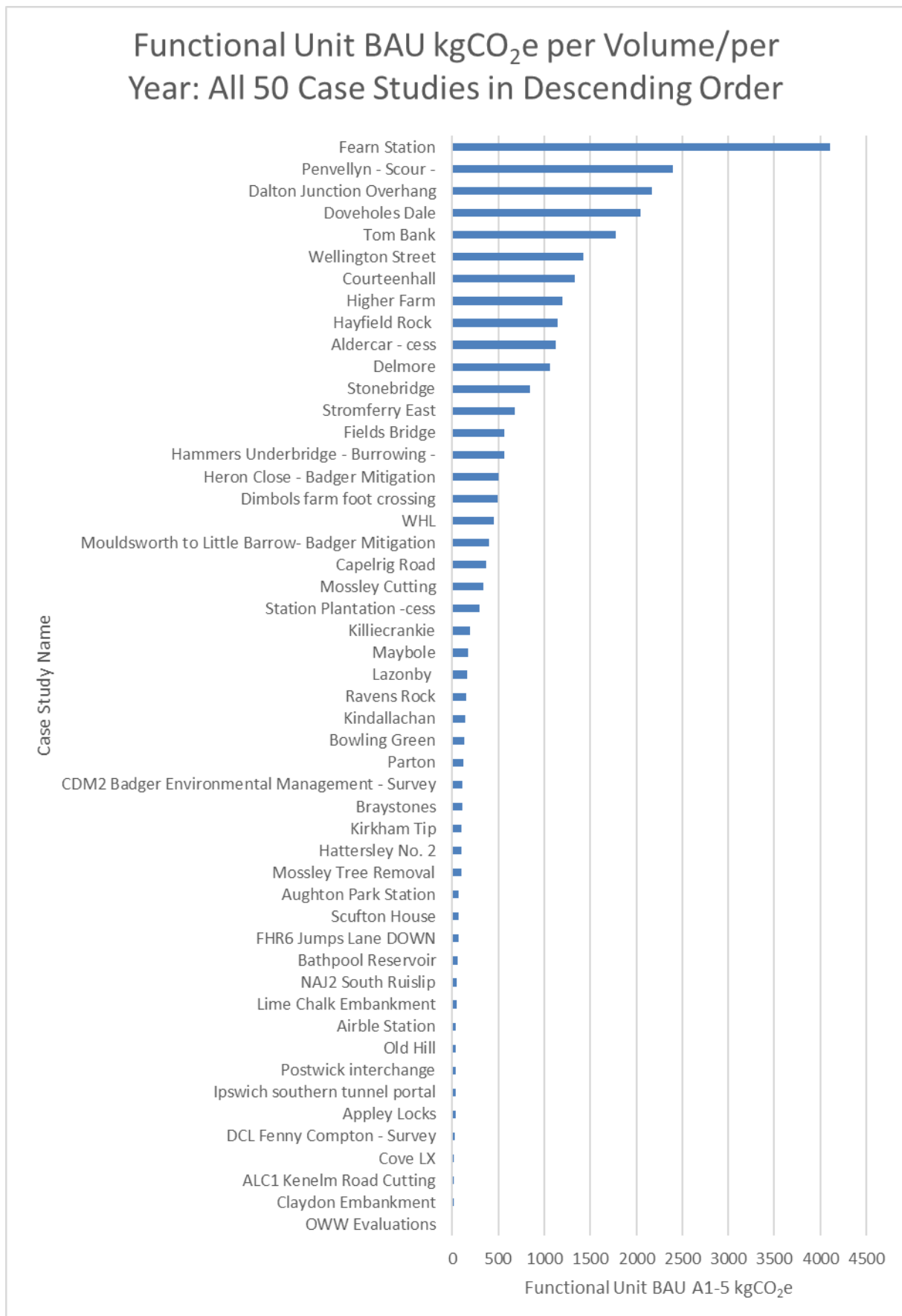


Figure 4.6 Functional Unit BAU A1-5 (kgCO₂e Vol/Yr) for All 50 Case Studies

4.1.4 Maintenance Case Studies

The results of the 35 maintenance case studies are presented here followed by disaggregation by earthwork type. The percentage contribution of each lifecycle stage for the maintenance interventions (grouped by earthwork type as indicated) is given in Figure 4.7. This figure shows that 60% of maintenance interventions have over half of their total carbon from A4 sources, 14% have over half of total carbon from A1-3 sources, and a further 14% have over half of their total carbon from A5 sources. Some 87% have over half of total carbon from A1-3 plus A4 sources. These percentages indicate that the carbon “hot spot” for maintenance interventions is the A4 transport stage, with the exception of Fearn Station, where the hot spot is in the A1-3 stage. This is due to the large amount of stone materials being used in Fearn Station and therefore divided into this two-year intervention.

The maintenance case studies are also presented as a Pareto graph (see Figure 4.8) illustrating the great variety in results across the three earthwork types. This shows that over half of the total carbon from the 35 interventions is from four of the (larger) case studies, and 10% is from 23 of the (smaller) case studies.

The four larger case studies, ranked in descending order of functional unit are Fearn Station, Dalton Junction, Doveholes Dale and Tom Bank. Delving deeper into the data for these four case studies the following rankings description is found, see Appendix D.2. These have been ranked for total staff hours per case study, total staff transport per case study and staff hours per volume, and staff transport mileage per volume. This allows for a like-for-like comparison against the functional unit which is also incorporating this volume divisor.

The rankings given in appendix D.2 illustrate that Fearn Station, although having the highest ranked functional unit at 4,104.95 kgCO₂e, does not have the highest staff hours per volume, sitting at 16th in the ranking with 82.5 staff hours and has the 10th highest ranking for staff transport mileage per volume. Fearn Station sits at 20th place for total staff per shift indicating a mixed picture in the rankings dependent on the metric used. The majority of the carbon for Fearn Station, 66%, is attributed to stone, cement and sand in the A1-3 stage, therefore staff transport mileage is not influencing this footprint to the same extent as the materials.

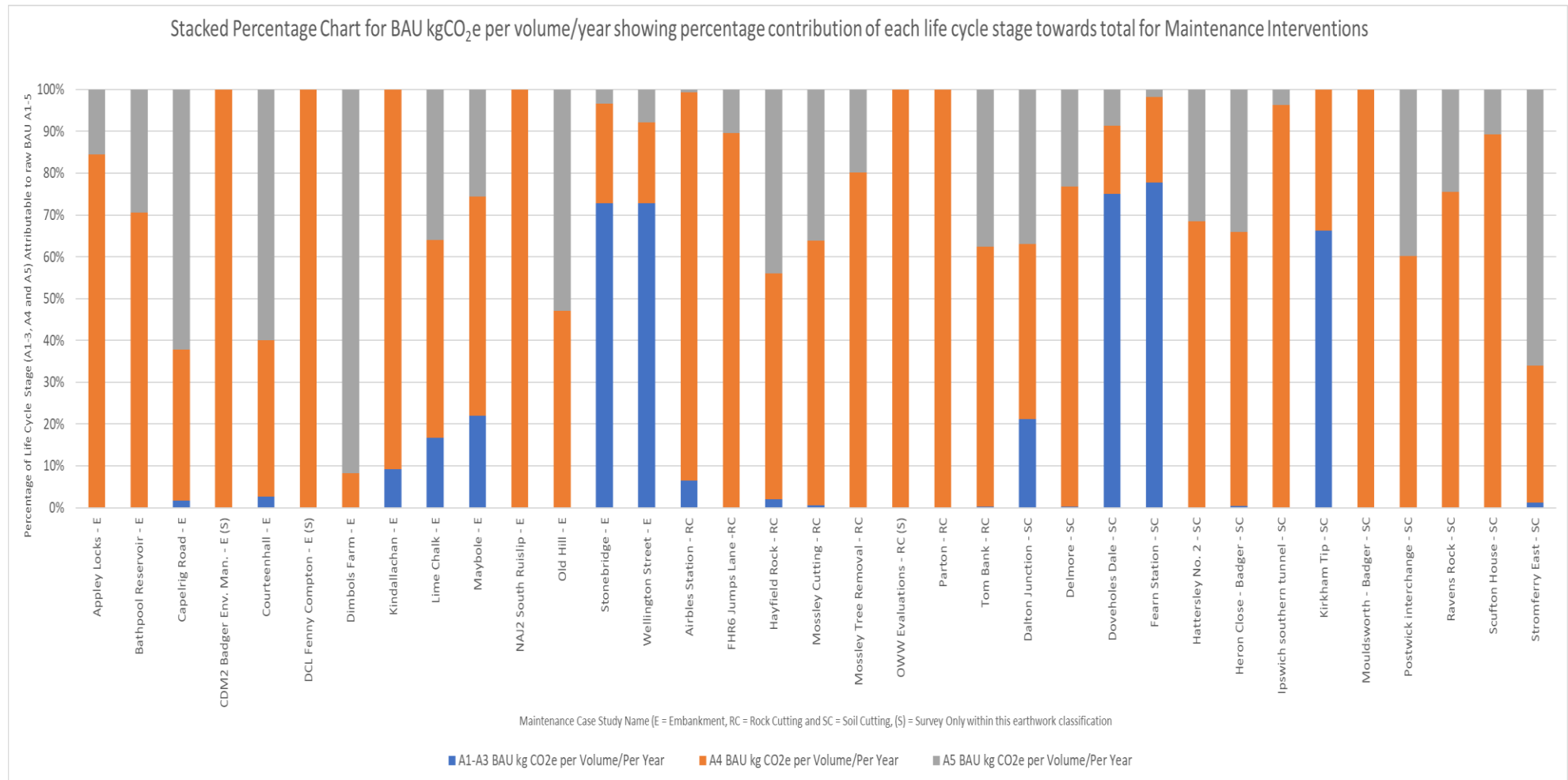


Figure 4.7 Maintenance Interventions Percentage Contribution of Each Stage BAU kgCO₂e, grouped by Earthwork Type

Dalton Junction ranks second highest for functional unit, and third for staff transport and staff hours per volume, and fourth for staff per shift. This shows there is less divergence across the different metrics when compared to Fearn Station, indicating that for this case study the staff transport mileage and staff hours are more closely linked to the functional unit.

Doveholes Dale has the largest number of staff hours per volume, largest number of total staff per shift (16 staff), and fifth largest staff transport kilometres per volume, again indicating closer convergence in the metrics' rankings for this case study. Three of the four metrics lie within the top four rankings, again indicating a tentative alignment between staff transport mileage and functional unit. However, its functional unit is lower than for Fearn Station or Dalton Junction.

Further relationships between the differing lifecycle stages and functional unit are explored in Appendix D.2.4, where a comparative graph of BAU lifecycle stages, total alongside staff hours and functional unit for these four case studies is presented. The graphs indicate the large impact of the materials used in Doveholes Dale and Fearn Station on the total BAU footprint and the impact of the transport and construction stages on Tom Bank towards its BAU footprint, and the impact of the large percentage contribution towards the A1-5 carbon footprint of the materials used in Dalton Junction and Fearn Station on the resultant functional unit. When these case studies are divided by their volume, a more accurate comparison, based on interventions of a similar length can be made, particularly against the functional unit which incorporates this divisor along with lifespan of the intervention.

Tom Bank has the fourth highest total number of staff hours and functional unit, at 495 staff-hrs and 1,773.06 kgCO₂e respectively. It sits at third place for total staff per shift with 11 staff, and it ranked first for staff transport mileage at 8,877 km. Similar to Dalton Junction and Doveholes Dale, Tom Bank shows less divergence across the metrics, leading to the conclusion that Fearn Station may be an anomalous result in terms of metric rankings which appears to be due to the very large proportion of the footprint accounted for by gabion stone. Some 66% of the A1-5 BAU footprint carbon is directly attributable to this stone, thereby skewing the functional unit figure upward as the divisors for this case study are two volumes and two years. This is in contrast to the two renewals which have several tonnes of steel, Aldercar and Station Plantation, which are divided by 120 years and 3 and 1 volumes respectively, or Bowling Green renewal which has 10 tonnes of stone. This case study is then divided by 120 years and 1 volume resulting in a lower functional unit. Tom Bank, similar to Doveholes Dale, has four metrics lying within the top four rankings.

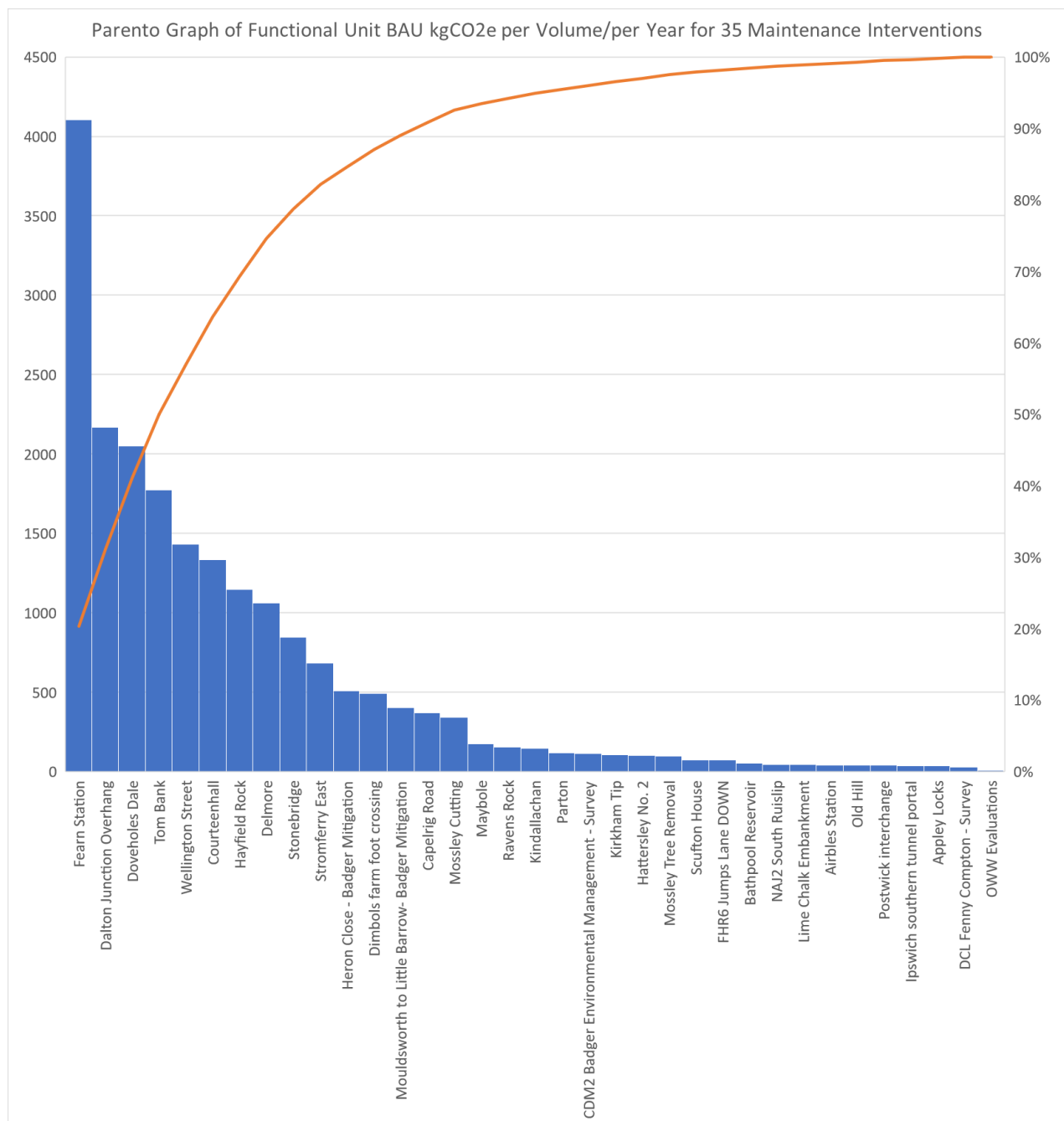


Figure 4.8 Maintenance Interventions Pareto Graph of Functional Unit BAU (kgCO₂e Vol/Yr)

Looking through a different lens, the four case studies, accounting > 50% of the total carbon of the maintenance set, are compared as a group to the other 31 case studies. Descriptions of these four case studies are presented in Table 4.2.

The top four maintenance case studies, by functional unit (see Table 4.2), illustrate that Fearn Station and Doveholes Dale have a substantial amount of their carbon footprint in A1-3 stages (from the 100% stacked chart in Figure 4.7 around 75% of their carbon footprint is in A1-3 stages) which is partly accounted for by the large amounts of stone used in these interventions. Over 120t of gabion stone in Fearn Station and 80t of 6G stone in Doveholes Dale, contributing significantly towards their

rankings in first and second place for total BAU A1-3 at 12,764.3 kgCO₂e and 9,230.98 kgCO₂e respectively.

Dalton Junction and Tom Bank are outside of the top three rankings by BAU A1-3, sitting at 5th and 12th place respectively, with Dalton Junction have around one tenth of the stone used in Fearn Station, and Tom Bank having no materials.

Table 4.2 Summary Table: Four Highest Functional Unit Maintenance Case Studies

Case Study Name	Description of Works	Materials	Plant and Equipment	Vol.	Length of Works	No. of Staff / Vehicles	Total Staff Mileage (km)
Fearn Station - SC	Unblock manhole at crest, unblock UTX, re-connect drainage, remove failed and soft material and stone up slope	120t Gabion Stone, 40kg Cement, 120kg Sand, 160 Engineering Bricks, Terram 180m ² , 9 raising frames, 5 catchpits	3 x Generator, 1 x Stihl Saw, 1 x Cement mixer, 1 x RRV, 4 x Peli lights, 3 x Water pump, 1 x Grinder	1	6 shifts	5 staff/ 4 vehicles	2,292
Dalton Junction - SC	Removal of vegetation overhang.	10t MOT Type 1	3 x Chainsaw, 1 x RRV, 2 x Tower lights	1	5 shifts	10 staff/ 10 vans	2,571
Dove-holes Dale - SC	A mixed soil and rock cutting where a rotational failure of the upper slope occurred. Works consisted of clearing failed material, interim 6G repair of the upper slope and reinstatement of the fence line.	150 x sandbags, 80t 6G, 20t MOT Type 1, 1x roll Terram	1 x 5t excavator, 1 x 13t long reach	3	14 shifts	16 staff/ 16 vehicles	5,014
Tom Bank - RC	Light scaling of rock face to remove loose material that can fall onto the track.	n/a	1 x RRV, 2 x Tower lights	1	5 shifts	11 staff/ 10 vehicles	8,877

Looking in detail into the NR classification of interventions, see Appendix A.1, additional insights into these differences are found. An analysis of the NR classification of interventions using the differing intervention they describe under each earthwork type, a number of classification cross reference exercises have been undertaken (see Appendix D.5), summarised below. NB: more than one intervention may be undertaken simultaneously for the same case study.

Vegetation management dominates the maintenance interventions, followed by debris and refuse clearance. The four top ranked maintenance interventions are classified:

- Fearn Station: drainage maintenance
- Dalton Junction: vegetation management
- Doveholes Dale: debris and refuse clearance
- Tom Bank: regular light scaling

As such, no one intervention type can be identified as having an inherently larger footprint than any other using this classification exercise. The three surveys of DCL Fenny Compton, CDM2 Badger Environmental Management, and OWW Evaluations sit in the bottom four rankings for total number of staff, and DCL and OWW sits in the bottom two rankings for functional unit. These rankings indicate that surveys tend to have lower functional units and less staff, which align with lower staff transport mileages.

Descriptive statistics for the maintenance interventions have been provided (see Table 4.1). These statistics can also be applied to the disaggregated maintenance interventions by earthwork type, illustrated in Table 4.3.

Table 4.3 Maintenance: Descriptive Statistics for Functional Unit BAU A1-5 Disaggregated by Earthwork Type

Descriptive Statistic Type	35 Maintenance Interventions	14 Embankments	8 Rock Cuttings	13 Soil Cuttings
Mean	577.08	367.12	448.77	882.15
Standard Error	147.06	130.52	231.17	336.70
Median	143.39	127.94	105.71	399.30
Standard Deviation	870.04	488.36	653.83	1,214.00
Kurtosis	7.15	1.06	1.53	3.37
Skewness	2.44	1.52	1.62	1.87
Sum	20,197.83	5,139.65	3590.19	11,468.00
Largest(1)	4,104.95	1,430.03	1773.06	4,104.95
Smallest(1)	7.70	28.09	7.70	34.14

Table 4.3 shows the variation in means for differing earthwork types. The mean for embankments and rock cuttings is lower than maintenance interventions and the soil cuttings mean is greater than that for all maintenance interventions.

The data in Figure 4.8 has been extracted from the main data set graph to enable comparison against Figure 4.9 Total BAU kgCO₂e per Hour of Works. For further exploration of correlation between length of works and BAU kgCO₂e see Section 4.1.4.2.

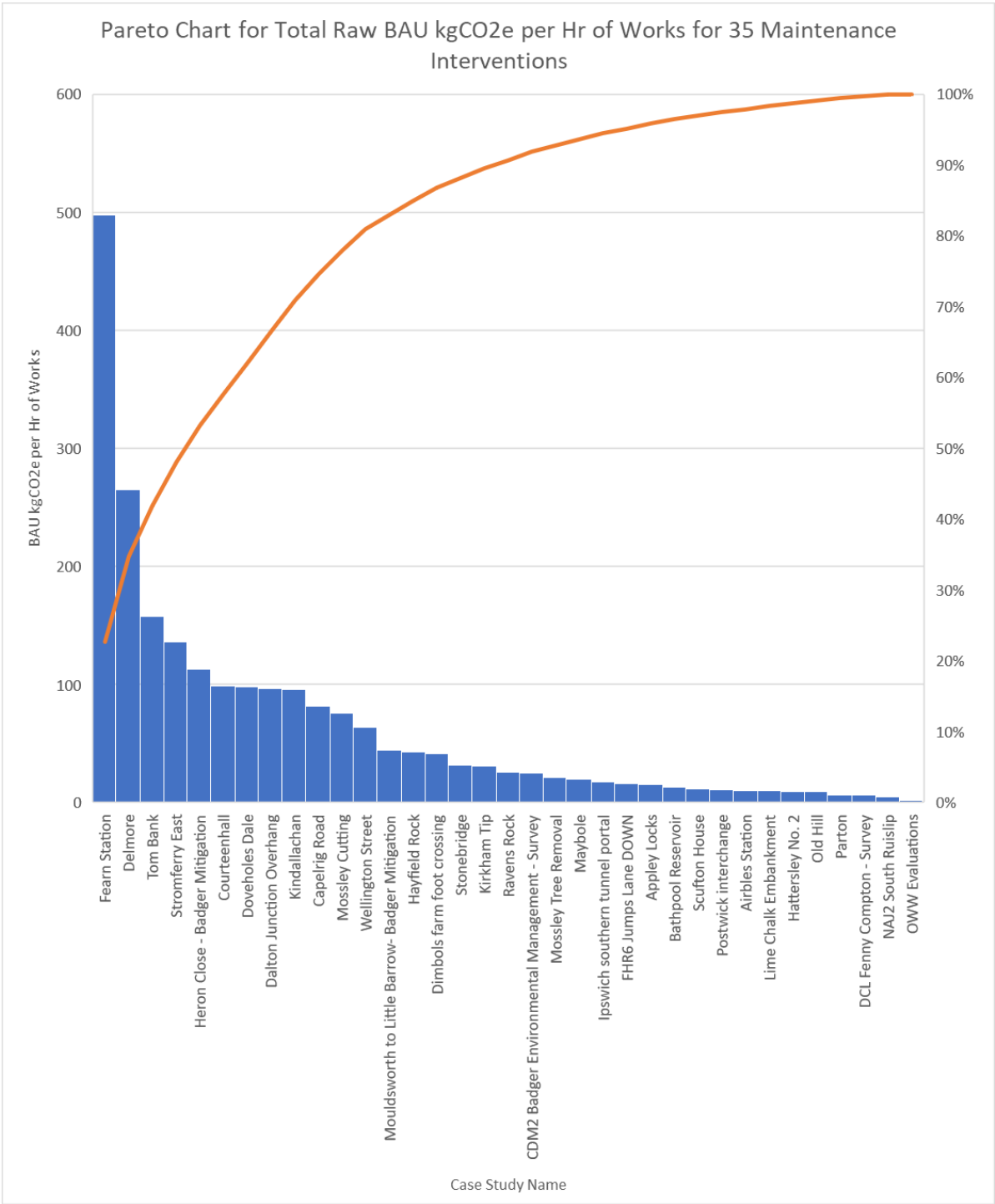


Figure 4.9 Total Raw BAU (kgCO₂e) per Hr of Works for Maintenance Interventions

Figure 4.9 illustrates the range of carbon values for maintenance interventions per hour of works, with the largest value at 497.57 kgCO₂e and the smallest value at 1.71 kgCO₂e, and a mean value of 62.78 kgCO₂e. When compared to the data in Figure 4.8 the highest ranked case study by functional unit, Fearn Station, also has the highest total Raw BAU per hour of works. Dalton Junction and Doveholes Dale, ranked second and third by functional unit do not hold these positions here. Instead, the second and third rankings here are for Delmore and Tom Bank, showing that ranking by carbon expended per hour of works does not align well with the functional unit.

4.1.4.1 Maintenance: Divided by Embankments, Rock & Soil Cuttings

The maintenance case studies illustrated in Figure 4.7 are now further disaggregated by earthwork type into 14 embankments, 8 rock cuttings and 13 soil cuttings and a summary of the percentage contribution of each lifecycle stage to the total footprint are given, see Table 4.4.

Table 4.4 No. of Maintenance Case Studies Within Each Earthwork Type Which Have a Lifecycle Stage Contributing Greater Than Half of the Total Footprint

Maintenance	A1-A3	A4	A5	A1-A3 + A4
Embankment	2/14 (14%)	7/14 (50%)	4/14 (29%)	10/14 (71%)
Rock Cutting	0/8 (0%)	8/8 (100%)	0/8 (0%)	8/8 (100%)
Soil Cutting	3/13 (23%)	8/13 (62%)	1/13 (8%)	12/13 (92%)

Table 4.4 illustrates that the A4 stage dominates for all maintenance earthwork types. Aggregating A1-3 and A4 data the percentage of case studies having over half of their carbon residing within these two stages increases for embankments and soil cuttings, rock cuttings remain at 100%, as all rock cuttings have more than half of their carbon in the A4 stage. This illustrates the greatest potential for ER lies in the A4 stage, which is a clearly identified “hot spot,” for maintenance interventions.

A detailed description of the eight rock cutting maintenance interventions is presented in Table 4.5, and from this further explanation of these differences is elicited. The rock cutting interventions were mainly comprised of works which did not require materials nor were large quantities of plant and machinery used to carry these out, hence the A1-3 and A5 stages did not exceed 50% of the total footprint for any of these case studies. For the three case studies which did have heavy machinery such as RRVs and Excavators (Hayfield Rock, Mossley Cutting and Tom Bank), Figure 4.7 shows that these have the largest A5 contributions to the total footprint.

Table 4.5 Detailed Description of Rock Cutting Maintenance Case Studies

Rock Cutting Maintenance Case Study Name	Description of Works	Plant and Equipment	Number of Staff/Vehicles	Total Staff Transport Mileage (km)
Airbles Station	Remove overburdened materials and reinstate netting.	2 x Battery K9 Peli Lights	6 staff/5 vehicles	314
FHR6 Jumps Lane DOWN	Vegetation removal to facilitate inspection of the rock face.	2 x chainsaws, 2 x hedge trimmers	5 staff/4 vehicles	490
Hayfield Rock	Light vegetation removal and scaling of the rock cutting.	2 x RRV	12 staff/12 vehicles	1,187
Mossley Cutting	De-vegetation to enable inspection – arisings spread locally.	1 x 13T Excavator	10 staff/10 vehicles	648
Mossley Tree Removal	Removal of fallen tree that was at risk of train strike.	2 x chainsaws, 2 x hedge trimmers	7 staff/6 vehicles	592
OWW Evaluation Surveys	These will require walking up and down the slope and taking photos and notes of the condition of the earthworks, to include areas of toe and crest. This remit is to provide track access and support.	Hand tools only	1 staff/1 vehicle	60
Parton	Rock release – 2 No blocks were being held by existing netting. Remit was to release the blocks using hand tools only and retention the cable so that the netting sat flush with the rock.	Hand tools only	4 staff/3 vehicles	910
Tom Bank	Light scaling of rock face to remove loose material that can fall onto the track.	1 x RRV, 2 x Tower lights	11 staff/10 vehicles	8,877

4.1.4.2 Correlation Analysis of Maintenance Interventions

The disaggregated maintenance data by earthwork type discussed above has also been compared by Total Raw BAU kgCO₂e per case study, Functional Unit kgCO₂e per volume/per year, Raw BAU kgCO₂e per £1k spend, and Raw BAU kgCO₂e per Hr of Works in simple bar graphs (see Appendix D.6), with no discernible relationships being seen. As a result and following the whole data set correlations, see Section 4.1.2, the data has been disaggregated for the maintenance interventions (as the largest data category) to delve deeper into any potential relationships between these and specific intervention types, and the following correlations found:

- Total length of works in hours correlated to kgCO₂e per £1k spend for maintenance interventions indicating that 8%, 47% and 3% of the variation in carbon per £1k spend is attributable to the length of works for embankments, rock cutting and soil cuttings respectively (see Appendix D.7).
- Total staff transport km correlated to Total raw BAU A1-5 kgCO₂e for maintenance interventions indicating that 41%, 95% and 29% of the variation in total carbon is attributable to transport mileage for embankments, rock cutting and soil cuttings respectively (see Appendix D.8).
- Total Length of works hrs correlated to total BAU A1-5 kgCO₂e for maintenance interventions indicating that 56%, 45% and 17% of the variation in total carbon is attributable to length of works for embankments, rock cutting and soil cuttings respectively (see Appendix D.9).

The above correlations indicating that staff transport and length of works all play significant roles in determining carbon emissions and that there is a mixed picture for the impact of length of works on the variation of carbon per £1k of works, for different types of maintenance interventions.

4.1.5 Refurbishment Case Studies

See Figure 4.10 for the 10 refurbishment case studies' results by descending functional unit.

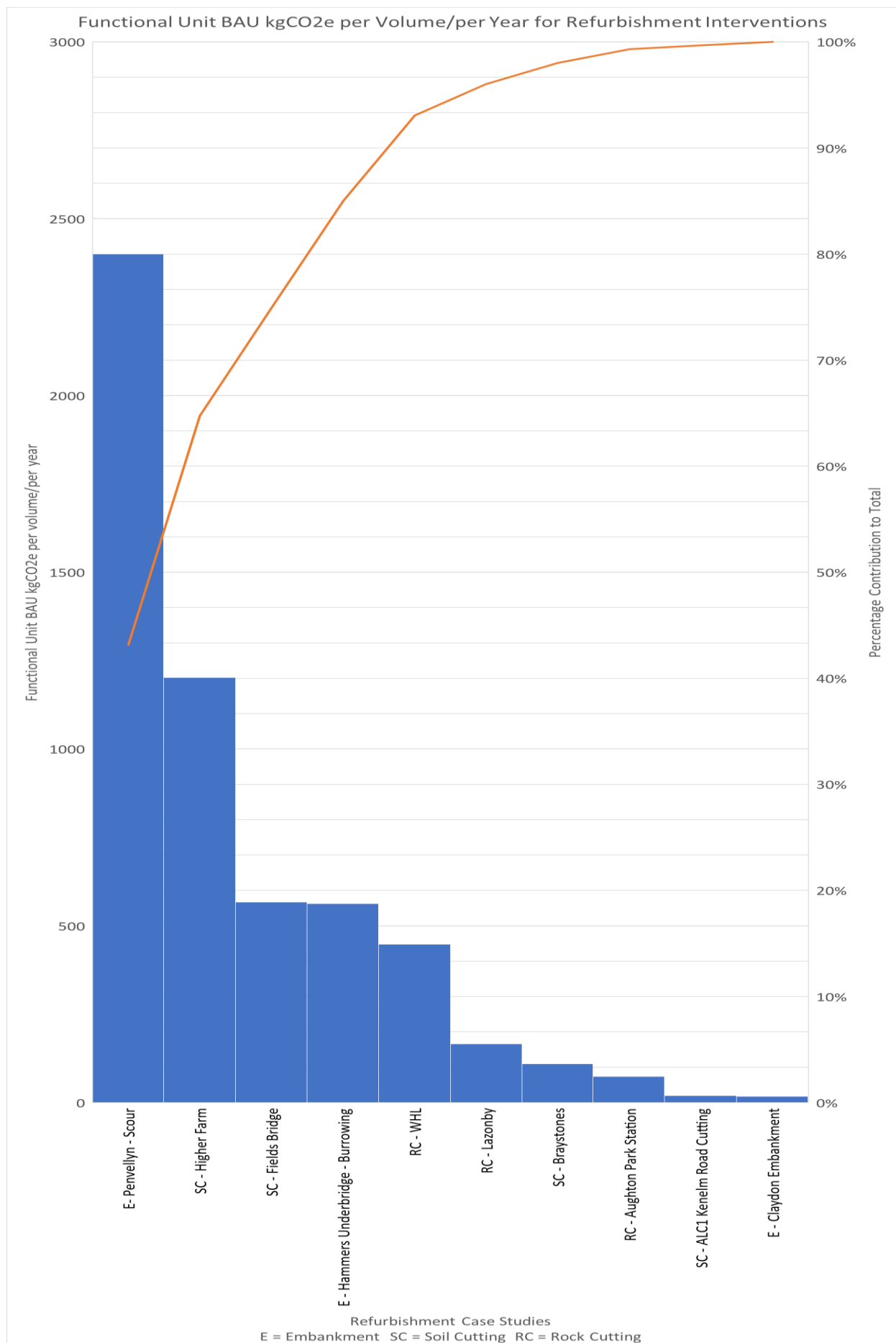
Figure 4.10 Refurbishment Interventions Functional Unit BAU A1-5 kgCO₂e per Volume/per Year

Figure 4.10 shows variety in the results for the functional unit for refurbishment interventions across the three earthwork types, with the refurbishments described further in descriptive statistics (see Table 4.1). Figure 4.10 further illustrates the weighting of the Penvellyn case study, accounting for over 50% of the total when measured in terms of functional unit.

The carbon values per hour of works are now analysed (see Figure 4.11).

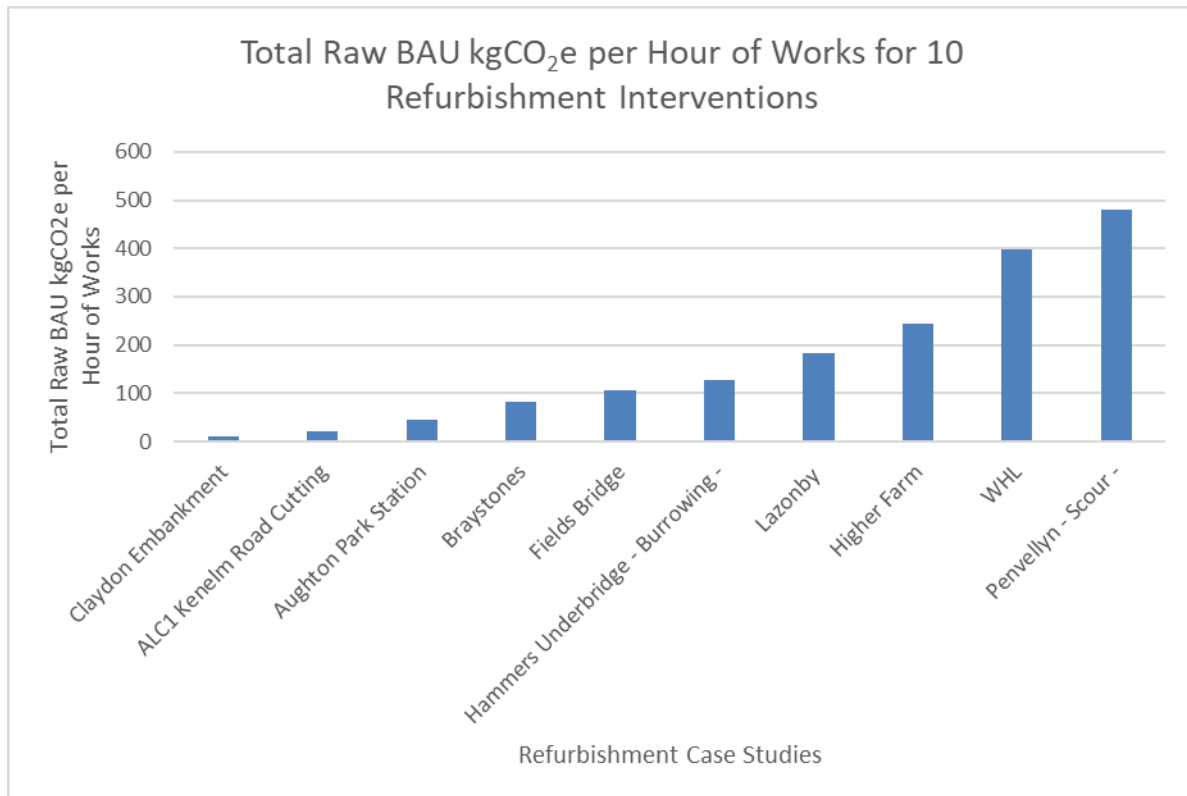


Figure 4.11 Total Raw BAU kgCO₂e per Hour of Works for Refurbishments

Figure 4.11 indicates the range of carbon values for refurbishment interventions per hour of works in ascending order. The largest and the smallest values, illustrating a wide range, are respectively 480.05 and 9.89 kgCO₂e, and a mean value of 169.60 kgCO₂e per hour of works.

Four of the bottom five rankings (Braystones, Aughton Park, ALC1 and Claydon) and four of the top five rankings (Penvellyn, WHL, Higher Farm and Hammers Underbridge) for functional unit, respectively sit in the bottom five rankings and top five rankings for CO₂e per hour of works. These indicate that using this metric of CO₂e per hour of works there is some tentative alignment with the functional unit as the largest and smallest values remain the same.

These 10 refurbishments are also analysed in terms of their rankings against the metrics of functional unit, staff hours per volume, and staff transport mileage per volume (see Table 4.6). The divisor of volume is used as a step towards a more accurate comparison using the functional unit.

Table 4.6 Refurbishment Interventions: Ranking of Selected Metrics against Functional Unit Rankings

Ranking Highest to Lowest	Functional Unit kgCO ₂ e	Case Study Name	Staff Hours / Vol	Case Study Name	Staff Transport Mileage km / Vol	Case Study Name
1st	2400.25	Penvellyn - Scour -	1512.0	Fields Bridge	8619.0	WHL
2nd	1202.22	Higher Farm	1188.0	Higher Farm	5240.0	Penvellyn - Scour -
3rd	566.78	Fields Bridge	612.5	Hammers Underbridge - Burrowing	3795.0	Fields Bridge
4th	562.73	Hammers Underbridge - Burrowing -	504.0	Aughton Park Station	2824.0	Lazonby
5th	447.12	WHL	500.0	Penvellyn - Scour -	2107.0	Aughton Park Station
6th	165.93	Lazonby	196.9	WHL	1347.0	Higher Farm
7th	109.42	Braystones	180.0	Claydon Embankment	1296.0	ALC1 Kenelm Road Cutting
8th	73.39	Aughton Park Station	144.0	Lazonby	1270.0	Claydon Embankment
9th	19.74	ALC1 Kenelm Road Cutting	135.0	Braystones	1050.0	Hammers Underbridge - Burrowing
10th	17.81	Claydon Embankment	108.0	ALC1 Kenelm Road Cutting	213.0	Braystones

Table 4.6 shows Penvellyn at the top ranking for functional unit and 2nd ranking for staff transport mileage per volume. Penvellyn falls to 5th ranking for total staff hours, indicating that functional unit is more closely aligned to transport mileage than total staff hours. Hammers Underbridge is ranked 3rd for staff hours per volume. Hammers Underbridge sits in 4th ranking for functional unit at around one fifth of that of Penvellyn.

The 10 refurbishments now are split into their respective constituent life cycle carbon amounts for further analysis (see Figure 4.12).

Figure 4.12 shows the percentage contribution of each lifecycle stage to the total footprint and are also grouped by earthwork type as indicated. This set of 10 refurbishments is not further disaggregated, to avoid using a very small sample which may not capture the full variability in real life interventions. In addition there has not been any correlation or regression analysis, given that $n=10$ (Bevans, 2023), and $n<20$ (Burmeister and Aitken, 2012, p.8).

This group of 10 refurbishments show that 20% have greater than half of their lifecycle carbon in stage A1-3, 30% have greater than half of their lifecycle carbon in stage A4, and 40% have greater than half of their lifecycle carbon in stage A5 when measured using percentage contribution. These results indicate that the construction stage followed by the transport stage have the greatest effect on the carbon footprint for refurbishment case studies when measured using percentage contribution, and that the carbon “hot spot” lies in the A5 construction stage. When A1-3 & A4 sources are added, 60% of the refurbishment case studies have over half of total carbon from these two stages.

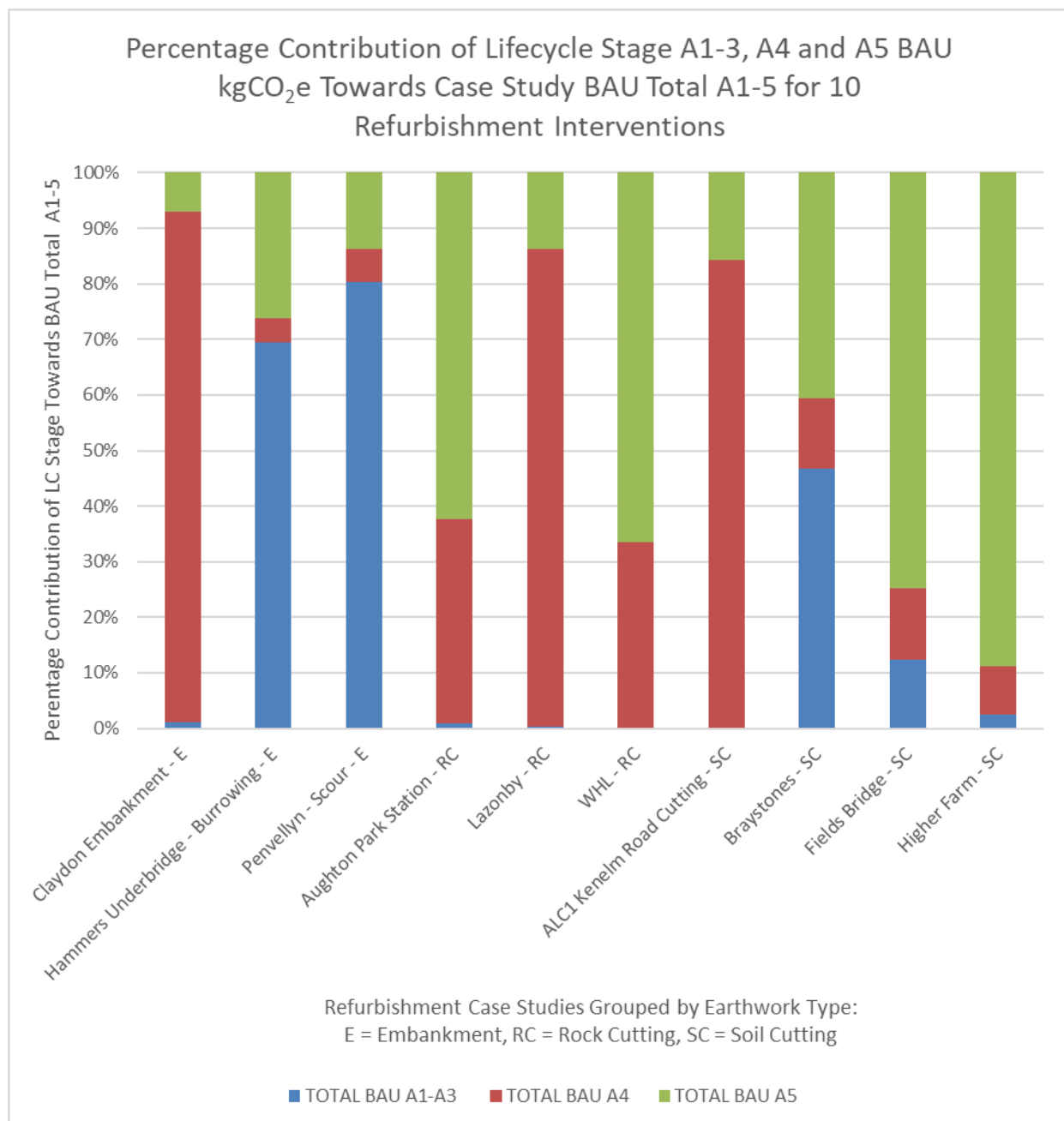


Figure 4.12 Stacked Percentage Chart for BAU kgCO₂e showing percentage contribution of A1-3, A4 and A5 towards case study total for Refurbishment Interventions, grouped by Earthwork Type

Further analysis has also been performed of this data in absolute terms to explore the relative amount of carbon in each lifecycle stage for interventions, alongside an “average” refurbishment case study value (see Figure 4.13).

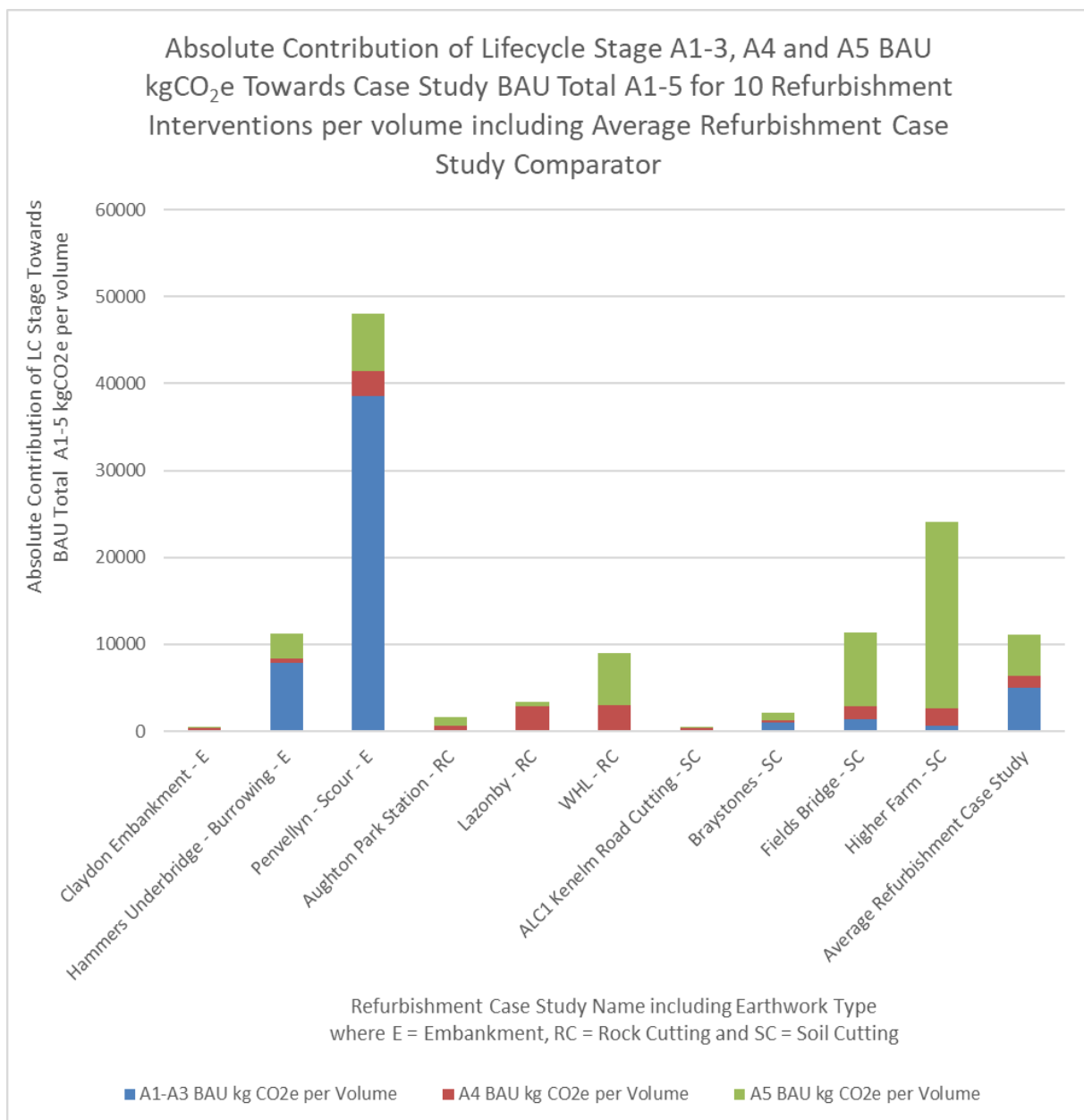


Figure 4.13 Refurbishments: Absolute Contribution A1-3, A4 & A5 BAU kgCO₂e to A1-5 per volume including “Average” Refurbishment Case Study Comparator

When the data is compared using absolute values per volume (see Figure 4.13), and with an “average” refurbishment case study, the majority of the carbon, in absolute terms, lies in the A1-3 and A5 stages, with the A4 transport figure being skewed upwards in the percentage graph by those case studies with no materials. Figure 4.13 illustrates the great value of carbon lying in the A1-3 stages in absolute terms, which is not clearly seen in the percentage contribution graph. Furthermore Figure 4.13 indicates some alignment in the A5 stages to the percentage contribution graph, although indicating that the value of the A5 is not as great in absolute terms as that of the A1-3. These differences are due to the differing constituent parts that make up each case study. When investigated further the great majority of the carbon in Penvellyn, A1-3, is due to the large quantity of granite rocks being used here.

Chapter 4

The majority of the carbon for individual projects is in the A5 stage, seen here for Aughton, WHL, Braystones, Fields Bridge and Higher Farm. Reductions in the A5 stage can reduce the absolute carbon of around 50,000 kgCO₂e for these five projects, in contrast to the large absolute carbon value of around 40,000 kgCO₂e for stage A1-3 for Penvellyn.

When the comparator refurbishment case study is investigated, this comparator has around 4,945 and 4,776 kgCO₂e in stages A1-3 and A5 respectively, and 1,423 kgCO₂e in stage A4. This equates to 44.4%, 12.8% and 42.9% respectively, aligning most closely with Braystones in the percentage contribution chart (see Figure 4.12) and gives a joint carbon hotspot of the A1-3 and A5.

In absolute terms Penvellyn scour's A1-3 stage dominates due to the large quantity of granite rocks, contributing around 40,000 kgCO₂e per volume. Higher Farm has a large absolute contribution per volume in the A4 stage due to extensive running hours of machinery contributing around 19,000 kgCO₂e per volume.

This difference between percentage contribution of stages and absolute carbon contributions for these 10 refurbishment case studies, show that carbon reduction will need addressing on an individual project basis.

It is therefore imperative at the planning stage of refurbishments works to approximate the carbon footprint using estimated figures. To find these figures information about the materials, staff per shift on site (and travel distances), and machinery running times are required. Then an estimated pre-construction carbon footprint can be produce to identify the hot spots to ensure carbon reduction measures are implemented in the most effective manner via the largest lifecycle stage in absolute terms. This footprint could then be refined as the design of the works progresses to ensure carbon reduction measures are deployed in the most effective manner using ER measures outlined in Chapter 5.

4.1.6 Renewal Case Studies

The results of the five renewal case studies are now presented, in descending order, see Figure 4.14.

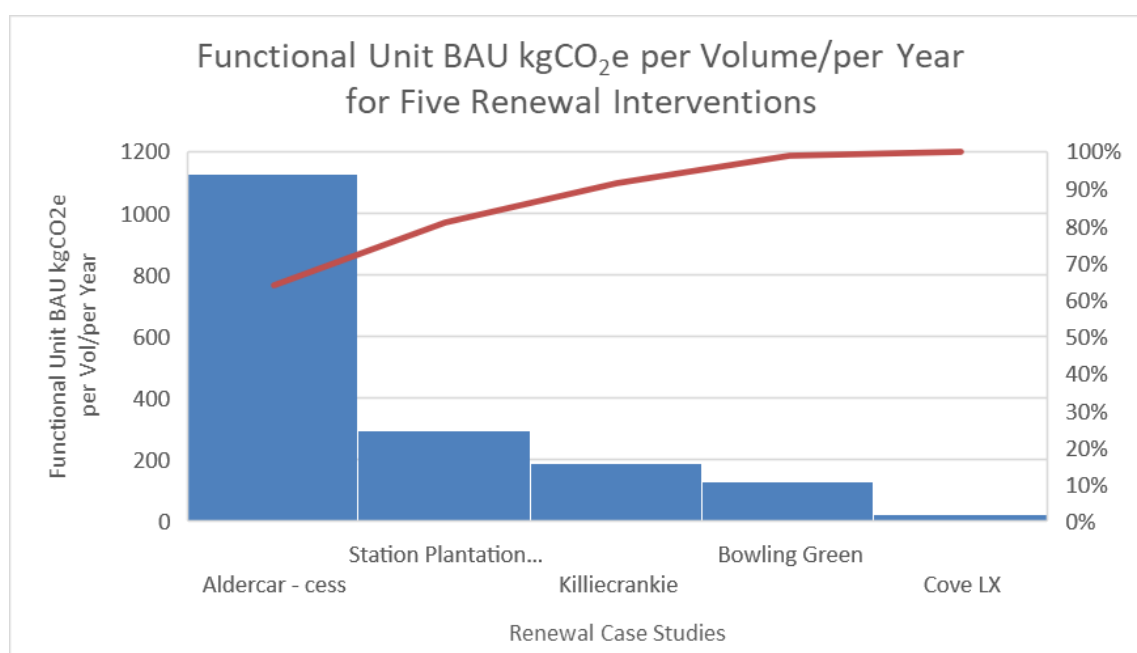


Figure 4.14 Renewals Functional Unit BAU kgCO₂e per Volume/Per Year

Figure 4.14, similar to maintenance interventions (see Figure 4.8), shows a mixed picture regarding the functional unit across the data set. Figure 4.14, illustrates Aldercar dominating in this comparison, with over 60% of the total sum of the functional units of the five renewal case studies, Cove LX lags behind the other three case studies. Station Plantation has twice the functional unit of Bowling Green, and Killiecrankie lies between these two in terms of functional unit size. The rankings for the five renewals are now presented against the functional unit rankings. The other metrics ranked are staff hours per volume, and staff transport mileage per volume to align with the divisor used for functional unit of volume. These are illustrated in Table 4.7.

Table 4.7 Renewals Ranking of Selected Metrics against Functional Unit Rankings

Ranking Highest to Lowest	Functional Unit kgCO ₂ e	Case Study Name	Staff Hours/ Volume	Case Study Name	Staff Transport Mileage km/ Volume	Case Study Name
1st	1128.11	Aldercar - cess	3560.0	Aldercar - cess	25584.1	Aldercar - cess
2nd	296.44	Station Plantation - cess	1680.0	Station Plantation - cess	16257.8	Station Plantation - cess
3rd	189.68	Killiecrankie	1485.0	Bowling Green	8239.8	Killiecrankie
4th	128.15	Bowling Green	228.0	Killiecrankie	6675.0	Bowling Green
5th	21.02	Cove LX	144.0	Cove LX	4500.0	Cove LX

Table 4.7 indicates that for all three rankings, Aldercar is in first place, Station Plantation lies in second, and Cove LX is in fifth. Killiecrankie lies in third place for transport mileage and functional unit and moves to fourth for staff hours, and Bowling Green sits at fourth ranking for transport mileage and functional unit, rising to third place for staff hours. Similar to refurbishment rankings, these results indicate a correlation between staff hours and staff transport mileage per volume and functional unit.

The cross reference exercise of case studies to the NR interventions (see Appendix D.5.9 -D.5.12), for these five renewals shows that Aldercar and Station Plantation are both implementing cess support works. The much longer length of time on site for Aldercar (85 shifts) is accounting for the increase in its metrics compared to Station Plantation (26 shifts), with additional staff member of between 12 and 19 on site per shift for Aldercar, compared to 6 to 10 for Station Plantation. When metrics for Aldercar are divided by its volume of 3 to enable comparison by volume with Station Plantation it is clear that the materials footprint (A1-3) for Aldercar is not equivalent to that of Station Plantation by volume (62,356 kgCO₂e versus 20,030 kgCO₂e). Aldercar has 38% of its A1-5 footprint by volume, attributable to steel products, compared to 56% for Station Plantation. Whereas Aldercar has 46% of its A5 by volume (piling rig 400 hours by volume, telescopic handler 233 hours by volume) carbon attributable to its total BAU A1-5 by volume, compared to 21% for Station Plantation (piling rig and telescopic handler, 48 and 15 hours respectively). This indicates that the fossil fuel use for this machinery in Aldercar is inflating this carbon footprint greatly, being around an order of magnitude greater in hours running of the machinery than that used for Station Plantation.

The low number of staff and short site time for Cove LX rank this case study at the bottom of the metrics tables. All the above indicate the close relationship between length of time on site, number of staff and staff mileage, with the functional unit rising as the mileage rises indicating a correlation.

A stacked percentage chart (see Figure 4.15) shows the contribution of each of the lifecycle stages for the renewal interventions.

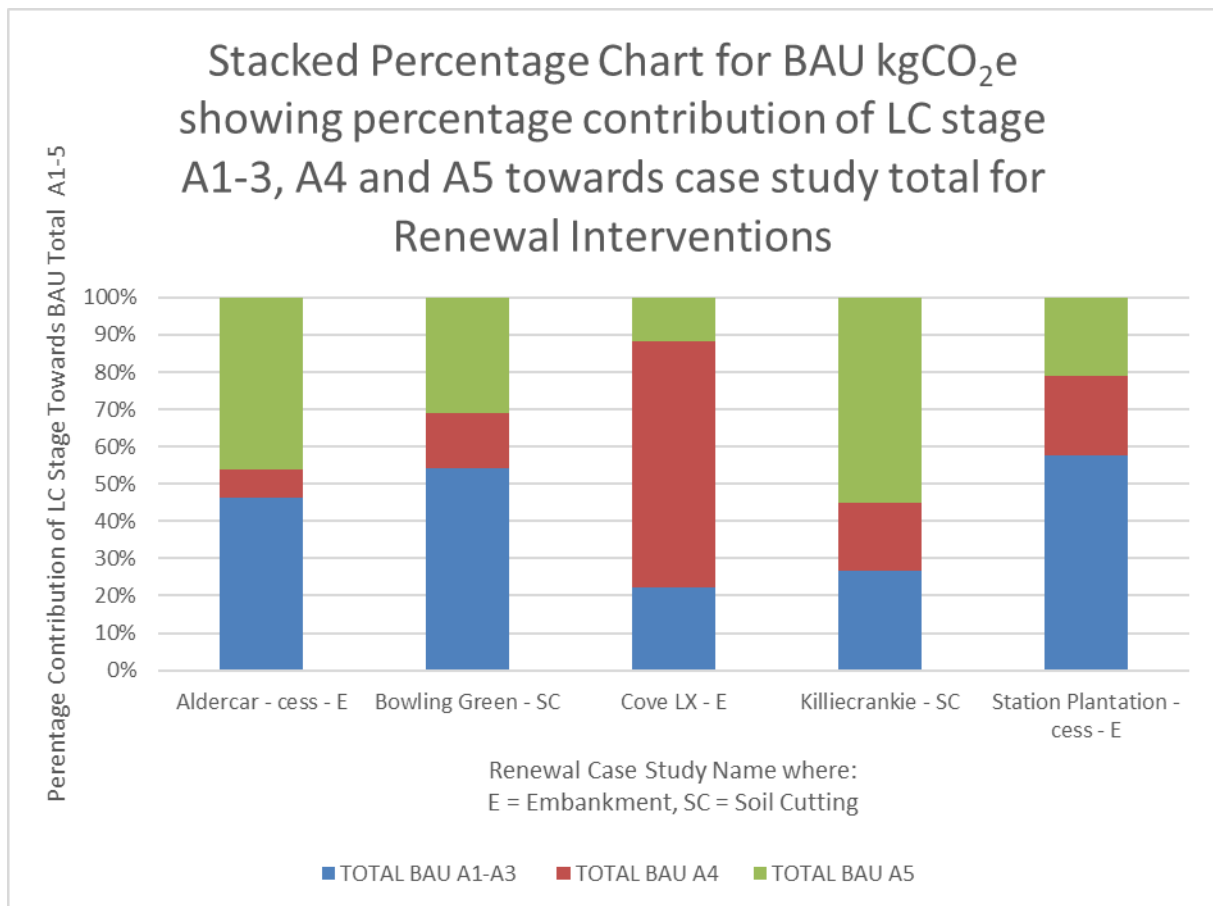


Figure 4.15 Renewals BAU kgCO₂e Showing Percentage Contribution of Each Stage

Figure 4.15 shows the percentage contribution of each lifecycle stage for renewal interventions. This illustrates that for renewals, 80% have half of total carbon from A1-3 and A4 sources, 20% have over half of total carbon from A5 sources, 20% have over half of total carbon from A4 sources and 40% have over half of total carbon from A1-3 sources. This indicates that decarbonisation efforts for renewals should focus on the “hot spots” of A1-3 and A4 sources.

Further analysis has been performed of this data in absolute terms to explore the relative amount of carbon in each lifecycle stage for interventions, including an “average” renewal value for comparison (see Figure 4.16).

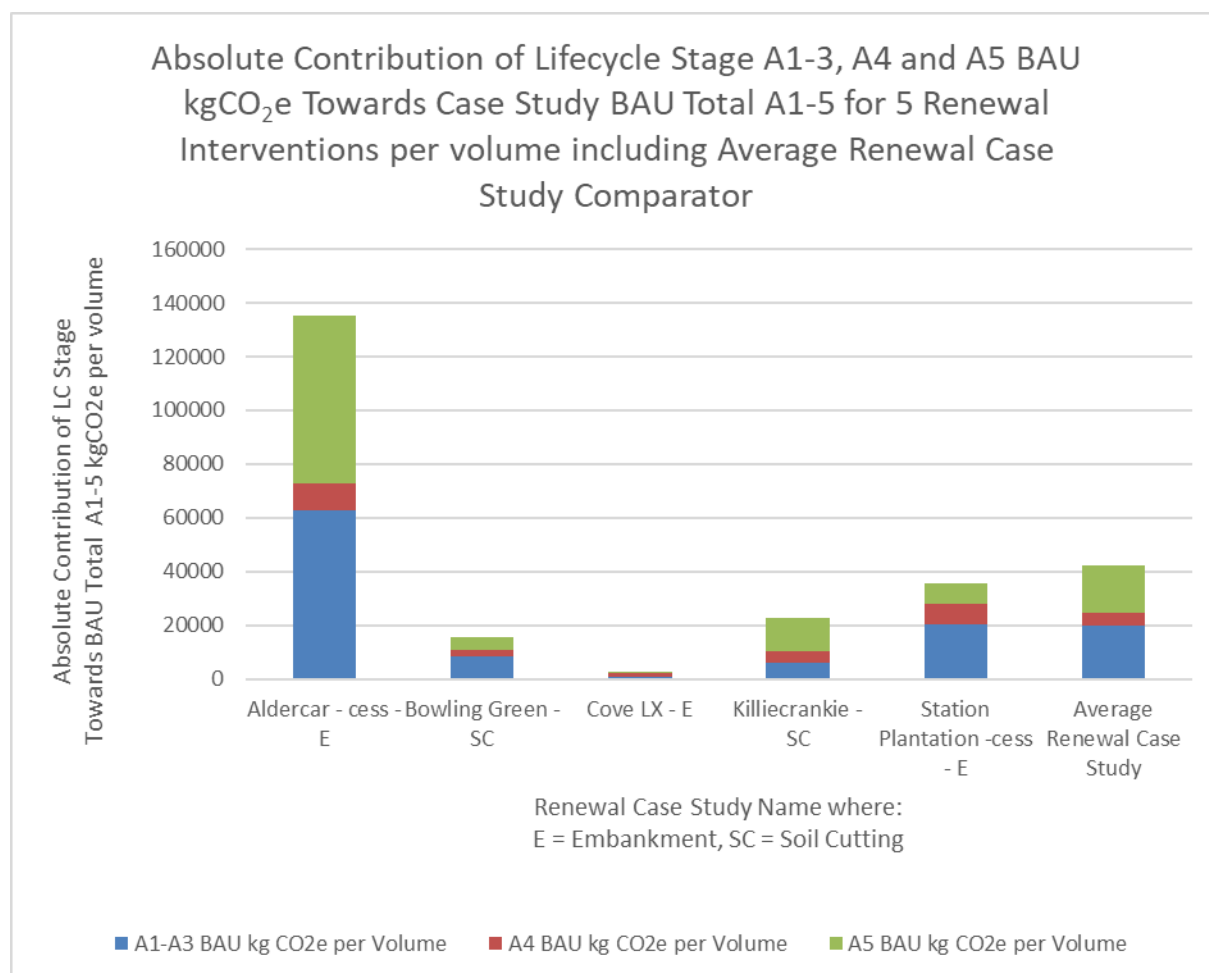


Figure 4.16 Renewals Absolute Contribution A1-3, A4 & A5 BAU kgCO₂e to BAU A1-5 per volume including “Average” Renewal Case Study Comparator

When the data is compared using absolute values per volume (see Figure 4.16), including “average” renewal values, the results show that for these 5 renewals the majority of the carbon, in absolute terms, lies in the A1-3 and A5 stages, with a smaller portion in the A4 stage, showing good alignment to the average renewal values. The A1-3 and A5 carbon in absolute terms are greater in Aldercar, which is potentially skewing the average figure and making it appear similar in terms of percentages in each lifecycle stage. However, examination of the absolute figures shows the absolute weighting of the A1-3 appearing to be approximately half of the total for Aldercar, Bowling Green and Station Plantation, indicating alignment with the percentage contributions graph as expected.

Investigating the comparator renewal case study, this is found to have around 19,658 and 17,503 kgCO₂e in stages A1-3 and A5 respectively, and 5,160 kgCO₂e in stage A4, equating to 46.5%, 12.2% and 41.4% respectively, giving a carbon “hotspot” of the A1-3 stage followed by A5.

This difference between percentage contribution of stages and absolute carbon contributions for these renewal case studies, mean that carbon reduction will need addressing on an individual project basis similar to that indicated for refurbishments, with an approximation of carbon at the planning

stage via use of the RSSB RCT and refinement on identification of hot spots for the particular renewal being undertaken to ensure that carbon reduction measures are implemented in the most appropriate stage in absolute terms. This analysis has indicated that broad assumptions are difficult to make with a small data set such as this, and that using percentages will not elicit the absolute carbon amounts. As such the use of the RSSB RCT is advocated to ensure those projects with items such as substantial use of stone or steel and excessive machine operating hours are addressed as a priority owing to their large absolute values of carbon contributing to each region and NR as a whole. The Mott MacDonald report commissioned by NW&C (Mott MacDonald, 2021) has analysed the carbon in the region in a similar way finding the “hot spots” in terms of projects which contribute the largest values in absolute terms. It is therefore imperative that such heavy carbon emitting projects are identified early on at design stage and appropriate carbon reduction measures (see Chapter 5) are applied.

This set of 5 renewals has been analysed here as a separate category and neither further disaggregated, to avoid using very small samples which may not be indicative of the full variability of real life interventions, nor has there been any correlation or regression analysis given the small sample size $n=5$ (Bevans, 2023), $n<20$ (Burmeister and Aitken, 2012). These renewals, as interventions suitable for expansion, with maintenance and refurbishment interventions being part of other renewal and new build interventions lifecycles, are expanded in later sections of this chapter and compared against the literature in Section 4.3.

4.1.7 Summary of all Case Studies

The expected life spans have been discussed separately, and are aggregated to provide a picture of overall trends. The findings of the stacked percentage charts for BAU kgCO₂e showing percentage contribution of A1-3, A4 and A5 towards the case study total was analysed against those which have a contribution of greater than half to the lifecycle stage in question and is presented in Table 4.8 and Figure 4.17. This is the basis for carbon “hotspot” identification, bearing in mind the proviso of absolute carbon on certain projects skewing the figures.

Table 4.8 Percentage of Case Studies that Contribute Greater Than Half of Each PAS2080 Lifecycle Stage to Total BAU

Expected lifespan of Intervention (in years)	A1-3	A4	A5	A1-3 + A4
Maintenance (2)	14%	60%	14%	87%
Refurbishment (20)	20%	30%	40%	60%
Renewal (120)	40%	20%	20%	80%

Table 4.8 shows a varied picture regarding where the carbon lies, in terms of lifecycle stages, for the three expected lifespans of intervention investigated. This data is illustrated in Figure 4.17

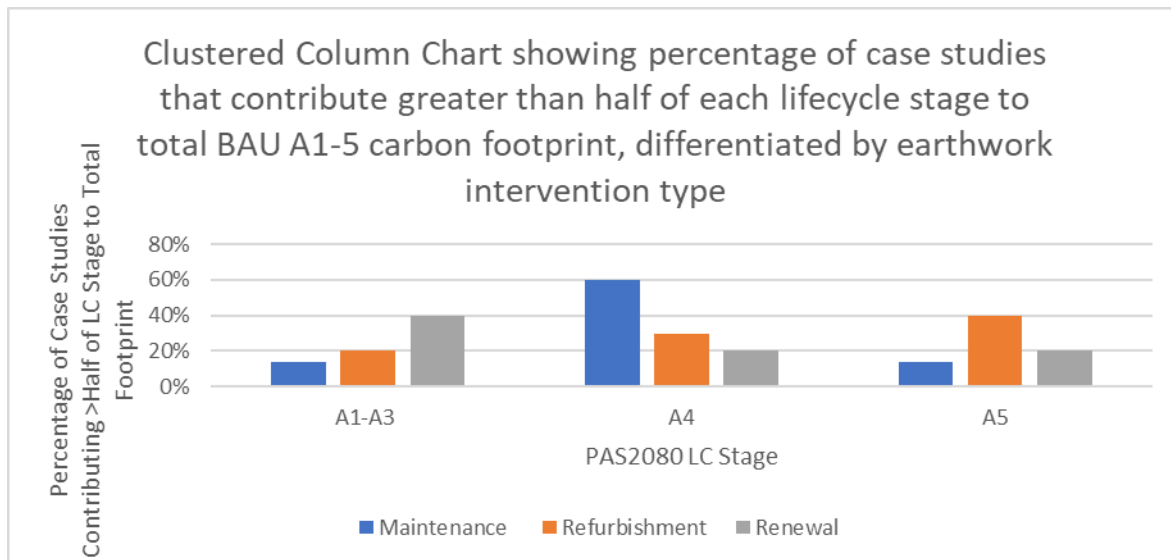


Figure 4.17 Percentage of case studies that contribute greater than Half of each lifecycle stage to total BAU A1-5 carbon footprint, differentiated by earthwork intervention type

Figure 4.17 indicates that for maintenance interventions the A4 stage dominates. For refurbishment interventions the A5 stage dominates and for renewal interventions the A1-3 stage dominates.

The data obtained from interrogation of the absolute carbon values is given below (see Table 4.9) from the average case study figures constructed for each expected lifetime for comparison with the “hot spots” found in Table 4.8 and illustrated in Figure 4.17.

Table 4.9 Contribution of “Average Case Studies” by Absolute Carbon per Volume for each PAS2080 Lifecycle Stage

Expected lifespan of Intervention (in years)	A1-A3	A4	A5	A1-A3 + A4
Maintenance (2)	35%	40%	25%	75%
Refurbishment (20)	44%	13%	43%	57%
Renewal (120)	47%	12%	41%	59%

Table 4.9 demonstrates similarities in the carbon hotspots found earlier using the frequency method of those with carbon greater than 50% in any stage. Table 4.9 is constructed using the data for an “average” case study, and follows the overall trend seen earlier of increasing carbon in the A1-3 and the A5 stage along with decreasing carbon in the A4 stage as the expected lifespan of interventions increases. An increase in A5 carbon contribution from maintenance to refurbishment interventions is seen compared to a decrease in A5 carbon contribution from refurbishment to renewal. The main

difference between data in Table 4.9 and Table 4.8 is the change of hot spot from A5 for renewals in the former, to A1-3 in the latter, although in the latter the A5 carbon is merely 1% away from the value of A1-3 so this relationship is less clearly defined in this graph of “average case studies,” as such primary and secondary “hot spots” are given in the summary table at the end of the section.

The A1-3 and A4 carbon values were aggregated to illustrate the large percentages these stages combined contribute to the whole, again showing a similar pattern with maintenance being accounted for to a greater extent than refurbishment or renewal by these two stages, and renewals contributing slightly more than refurbishments.

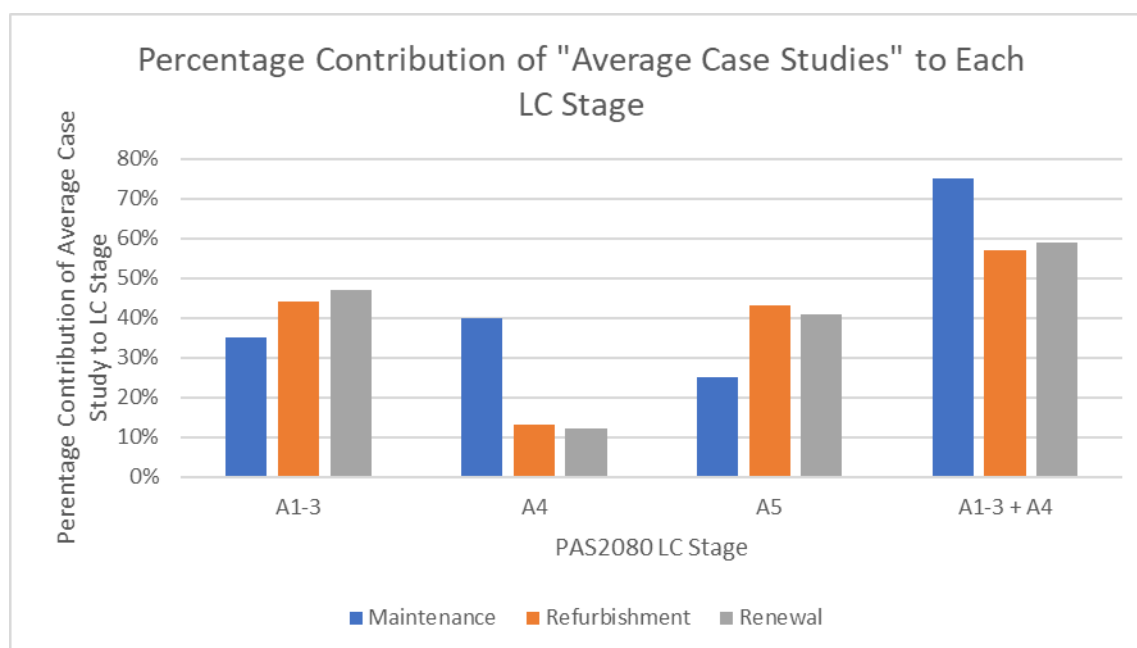


Figure 4.18 Percentage Contribution of "Average Case Studies" to Each Stage

This exercise serves as validation of the premise of the carbon “hot spots” as identified earlier of A4 for maintenance, A1-3 for renewal and A5 for refurbishment and gives additional detail with relation to the secondary “hot spots” for each intervention of A5 for renewals, and A1-3 for maintenance and renewals. The order for interventions to be implemented, to have the most ER impact, is presented in Table 4.10

Table 4.10 Primary and Secondary “Hot Spots” from “Average Case Studies” Data

Earthwork Intervention Type	Primary “Hotspot”	Secondary “Hotspot”
Maintenance	A4	A1-3
Refurbishment	A5	A1-3
Renewal	A1-3	A5

This data illustrates the need for targeted decarbonisation efforts for these “hot spots” depending on intervention type. Interventions should be targeted at reducing both staff, and plant and equipment

transport, such as lower carbon transportation options for staff for maintenance interventions, use of lower carbon machinery for refurbishment interventions and use of lower carbon materials for renewal interventions, see Chapter 5.

Implementation of the results from these small data sets must be used with caution as they may not be representative of larger data sets. Future research should focus on compiling larger data sets and comparing to these baselines providing validation of the conclusions found herein.

Next the cross-reference exercise of intervention types is explored further as the basis for an extrapolation exercise to identify the potential impact for NR of emissions reductions in these types of earthwork interventions across the whole of the network for a complete 5-year control period (CP).

4.1.8 NR Assets Compared to Case Studies & Extrapolation Exercise

A detailed cross-referencing exercise has been carried out, aligning the case studies interventions to those outlined in the NR Cost and Volume handbook, to build up a picture of the types of intervention commonly occurring for each earthwork and expected lifespan (see Appendix D.5).

Alignment with standard details is not given at this time, however this is an area for future exploration as a more targeted acquisition of case studies to meet these would be required. Use of intervention types aligns well with how the NR Cost and Volume handbook and assets are measured in each region, giving a basis for scaling up of average intervention type carbon to regions and all of NR to enable forecasting of carbon expenditure across a CP.

The summary of the findings of the cross-referencing exercise given in Appendix D.5, used as a basis for scaling up of interventions' impact across the whole of NR, are:

Maintenance n= 35, most commonly occurring interventions:

- vegetation management = 16
- debris and refuse clearance = 7
- survey only = 3

Refurbishment n =10, most commonly occurring interventions:

- Local regrade of slope = 3

Renewal n =5, most commonly occurring interventions:

- Cess support = 2

These figures, although for small size assets, due to their numerous numbers throughout NR (as indicated in the Cost and Volume handbook and in Table 4.11), give the potential for great carbon savings, see Chapter 5.

Table 4.11 shows the total number of earthwork assets held by NR. This illustrates the potential for carbon reduction over their entire asset base of these earthworks, and the dynamic nature of earthworks.

Table 4.11 NR Figures for Earthworks, amended from Network Rail (2021b) and (Rethish, 2023)

Area Covered	Geotechnical Asset Type	Quantity 2021 (volumes)	Quantity 2023/24 Period 01 (volumes)
National (ESW)	Embankment	102,347	102,448
	Soil Cutting	73,133	73,362
	Rock Cutting	16,543	15,826
	<i>Total</i>	<i>192,023</i>	<i>191,636</i>

Embankments are the most frequent earthwork asset and soil cuttings are more numerous than rock cuttings in the NR portfolio (see Table 4.11 with Period 01 being the first fiscal year in the CP). Table 4.11 indicates that the carbon emissions savings found in this thesis can potentially be multiplied across the whole network nearly 200,000 times giving a massive potential for carbon savings across NR.

Following this cross-reference exercise, further asset data was obtained from the Eastern region for the quantities of each intervention type currently in their “workbank” (data provided and subsequent calculations are presented in Appendix D.10). The types of maintenance interventions from the “workbank” were extrapolated up for a CP for all regions in NR, giving an anticipated 1,466 maintenance interventions. The percentage contributions to maintenance of specific interventions are outlined in Table 4.12 with an indication of the carbon, expended using BAU data.

Table 4.12 Eastern Region Assets Extrapolated to All NR for Whole of CP

Intervention	% Maintenance Contribution	Extrapolated No of Interventions	Average BAU Carbon A1-5 (kgCO ₂ e)	Total Carbon in CP (kgCO ₂ e)
Vegetation Management	36.2%	531	1,074.5	570,559.5
Vermin Eradication	23.4%	343	1,333.8	457,493.4
Surveys	21%	308	98.9	30,461.2
Drainage Maint.	23%	337	4,567.0	1,539,079
Total				2,597,593.1

Table 4.12 outlines the very large carbon in absolute terms involved in delivering these four maintenance interventions over the CP of 2,597,593.1 kgCO₂e (2,556 tCO₂e). To gauge the impact of application of the found ER measures on maintenance interventions over a control period the figures in Table 4.12 are discussed further with the ER percentage reduction applied in Section 5.8. The expansion of BAU to include for C4 and A0 lifecycle stages is given next.

4.2 Expanding Raw BAU A1-5 to Whole Lifecycle A1-C4 and A0 Carbon

Here the BAU baseline is expanded to A1-C4 and A0-C4 stages, and compared with the BAU A1-5, see Section 4.1. This is followed by a discussion around EOL pathways for materials left in situ and deconstructed. The section concludes with an overview of confidence in the results.

4.2.1 BAU A1-5 to A1-C4 Expansions for Renewal Interventions

Any new railway infrastructure should have a full LCA of its carbon encompassing, as a minimum, the A1-C stages and preferably the D stages too (Network Rail, 2022c, pp.14-16). However, the case studies for maintenance and refurbishment interventions would form part of the B stages of their respective lines' new construction design lifecycle, and, as such, are not suitable for expansion. Therefore, only the five renewal case studies, whose interventions are comparable to that of new infrastructure, have been expanded following the procedure outlined below (see Appendix D.11 for further details):

- BAU footprint used as a template.
- All materials assessed and assumptions made whether these would remain in situ or be deconstructed and removed from site at EOL.
- All travel distances assumed the same for deconstruction activities – Assumption based on disposal being considered the inverse of construction less material embodied carbon (Kaewunruen, Sresakoolchai and Peng, 2020, p.6) and staff transport distances are an often excluded item (Lokesh, Densley-Tingley and Marsden, 2022a, p.18).
- All machinery assumed the same for deconstruction activities - Assumption based on disposal being considered the inverse of construction less material embodied carbon (Kaewunruen, Sresakoolchai and Peng, 2020, p.6) although it is noted that construction emissions for deconstruction of 15% of construction are also found in the literature (Wei and Chen, 2020, p.4).
- All materials assumed requiring equivalent weight of disposal or recycling EFs if available in the RSSB RCT.

- B stage maintenance activities based on averages of suitable comparator from the maintenance case studies data set – Important to include for maintenance as accurately as possible as these activities are often excluded or only “roughly approximated” in LCA of transport (Saxe and Kasraian, 2020, p.1037).

See Appendix D.12 for details of the figures used to create the expansions and for estimation of B stages, and Appendix D.13 for further details of the calculations.

At EOL for these renewals, leaving materials in situ is deemed the suitable choice when the structure is considered part of the landscape and would not naturally degrade further in the time spans of centuries. As the EOL pathway for materials is not clear at time of construction for materials such as concrete, which could be reused as ballast following processing rather than being disposed of, it may be necessary to remove some materials but keep others in situ. Deconstruction has been applied where metal work is present and at EOL this would need to be removed if the line were to be closed and become a footpath or, replaced with new metalwork as part of a future renewal to extend the life for a further 120 years.

Following the bulleted procedure and the EOL choices outlined above, the carbon footprints were recalculated, see Table 4.13.

Table 4.13 Renewals BAU and Expansion (EXP) Scenario Footprints A1-C4

Case Study Name	Materials Left in Situ or De-constructed	Earthwork Type and Volume	Total Raw BAU A1-5 kgCO ₂ e	Total (EXP) Expanded A1-C4 kgCO ₂ e	Percentage Increase in Footprint BAU - EXP
Aldercar	Deconstructed	E, 3 volumes	406,121	755,299	86%
Bowling Green	Left in situ	SC, 1 volume	15,378	85,622	457%
Cove LX	Left in Situ	E, 1 volume	2,522	4,659	85%
Killiecrankie	Left in Situ	SC, 1 volume	22,761	93,005	309%
Station Plantation	Deconstructed	E, 1 volume	35,572	94,374	165%
Mean values (per volume)	Mixture of above	Per volume	42,321	105,885	150%

Table 4.13 illustrates that for the expanded LCA of A1-C4 stages an increase of 85-457% is seen in the carbon footprints for renewals compared to BAU A1-5. For the two sites which are deconstructed at EOL, an increase of 86% and 165% is seen respectively. For the three sites where the materials are left in situ, between 85% and 457% increases in the carbon footprints are seen. When an average is

taken of all the renewals' percentage increases, from A1-5 to A1-C4, a 150% increase in the carbon footprint is seen. The main contributory factors to this increase are activities that sit in the C (EOL) stages and are part of the deconstruction emissions, the emissions from disposal of deconstructed materials (see Appendix D.11) and addition of maintenance activities in the B stages (based on data from the maintenance interventions, see Appendix D.12). These figures highlight the need to perform expanded or full LCA, to avoid very large quantities of carbon being missed from accounting processes.

Reasons for this large disparity in the renewals' percentage increases when moving to expanded LCA cannot simply be attributed to whether the site is left in situ or deconstructed, as both the highest and lowest percentage can be found in those renewals where interventions are left in situ at EOL. These contributions are further analysed with the addition of the A0 LC stage in the next section.

4.2.2 Calculation of A0 Carbon Lifecycle Stage

Current guidance from NR for carbon footprinting, in the form of a chart demonstrating which lifecycle stages are required to be footprinted for each PACE stage (formally GRIP process stages) (Network Rail, 2022c, p.16) is illustrated in Table 3.1. This excludes the A0 lifecycle stage from future expansions of the PAS2080 lifecycle, which are either optional or not required (Network Rail, 2022c, pp. 14-16).

Use of the RCT is mandated notably at differing project stages which align with the carbon reduction curve, indicating the best time to make interventions, in terms of most carbon saved, as illustrated in Figure 2.3. This figure shows that the build less and build clever strategies (see Section 2.2.2 and advocated in industry (Halliwell, 2024)) can potentially make carbon savings of up to 80% and 50% respectively (HM Treasury, 2013). These figures demonstrate the enhanced decarbonisation benefit of early intervention strategies, lying in the A0 (design) stage.

In a full LCA the A0 stage is required (and forms part of the comprehensive expansion scenario, see Table 3.6). As such it has been investigated with project managers in NR Eastern Region to quantify the carbon emissions involved in pre-construction activities (see Figure 4.19).

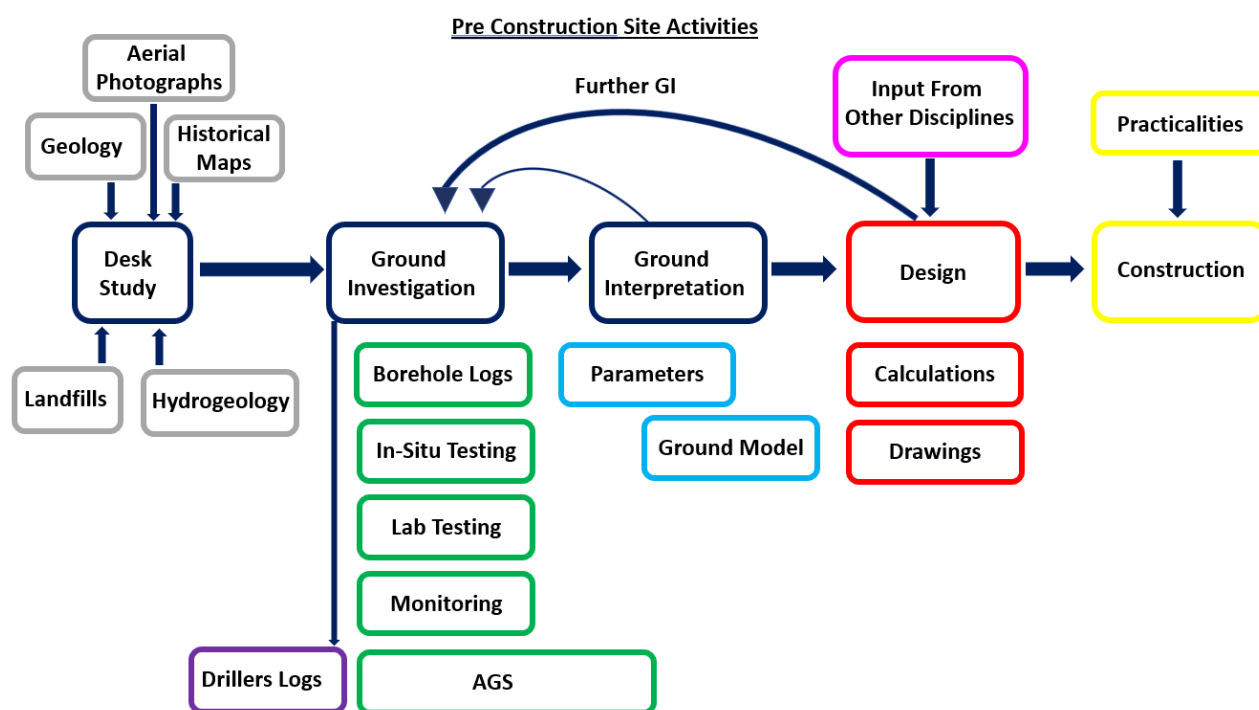


Figure 4.19 Pre-Construction Site Activities , amended from (Kennedy, 2019)

Figure 4.19 outlines differing stages that may be present in pre-construction site activities, covering the four broad areas of desk study, ground investigation, ground interpretation, and design. In this section estimates for A0 carbon for renewal type interventions are explored and applied. In Chapter 6 the ER scenario is applied to the expansions A1-C4, along with the A0 stage, to enable sequestration to be applied in the subsequent D lifecycle stages to offset the residual carbon. ER is a vital first step in balancing out carbon emissions (see Appendix A.5).

Estimated timings were added to the differing steps of the A0 stage of the PAS2080 lifecycle for renewal type activities (Najafpour Navaei, 2022), aligned to Figure 4.19. The timings and the methodology behind them are outlined in Table 4.14 and expanded in Appendix D.14.

Table 4.14 Renewal Type Interventions: A0 Stages' Estimated Carbon Allocation

Pre Site Stage	Pre Site Sub Stage	Estimated Timings	Methodology	Estimated Carbon Allocation
Desk Study Stage	Photos, geological survey data	2-3 weeks office based	Office and homeworking carbon values (Circular Ecology, 2023)	66 –100 kgCO ₂ e
	Meetings with consultants/ contractors	2-3 one-day meetings	Location of meetings unknown assumed office based and distance for average travel distance to site used as proxy	872 – 1,308 kgCO ₂ e

Pre Site Stage	Pre Site Sub Stage	Estimated Timings	Methodology	Estimated Carbon Allocation
	Walk over survey	1 day	Travel distance based on average daily distance from the 5 renewal case studies	28 kgCO ₂ e
Ground Investigation	Potentially further secondary ecological survey	2-3 weeks on site	Use average travel distance figure from all survey type case studies	2,961 – 4,443 kgCO ₂ e
	Sample transport to laboratories	1 one-way trip	Assumed included in above travel distances	Assumed included in above
Ground Interpretation	Read instrumentation	Monthly for at least 3 months	Use average travel distance figure from all survey type case studies	84 kgCO ₂ e
Design	Detailed scheme design	2-3 weeks office based	Office and homeworking carbon values (Circular Ecology, 2023)	66 – 100 kgCO ₂ e
Total Estimated Carbon in A0				4,077 – 6,063 kgCO ₂ e

The total figures for A0 activities in Table 4.14, highlight the estimated range of carbon expended in these activities. When compared to the BAU A1-5 mean figure for renewal case studies of 42,321 kgCO₂e, this figure equates to 10-14% of this total. This is in comparison to accounting for 3.9-5.7% when compared to the A1-C4 BAU lifecycle expansions' mean figure of 105,885 kgCO₂e for the five renewals, see Table 4.13. When the figures for A0 are given as a percentage of A0-C4 mean value (111,948 kgCO₂e) (see Appendix D.15, D.16, and D.17) these figures drop to 3.6% and 5.4% respectively for the lower and upper estimates. This illustrates the need for full LCA (see Table 3.6) as this percentage, demonstrated above, depends on which lifecycle it is assessed against.

A comparison to the literature is presented here providing insights into the conception (design) stage, aligning with PAS2080 A0, although it should be noted that this comparison is to elicit insights to the A0 stage only, and is not used further in this thesis as the data is from earthworks for HSR in China and therefore does not meet the parameters for further comparison with data from this thesis, see Section 4.3.2.

The A0 design stage figures found in the renewals expansion scenario A0-C4 are in contrast to the <1% figures for conception given in Kaewunruen, Sresakoolchai and Peng (2020), (which would align with the A0 design stage figures, where they comment that these emissions are “too small to be considered” (Kaewunruen, Sresakoolchai and Peng, 2020, p.1)), To clarify, these conception

emissions were based on electrical consumption per person for one year for 50 workers and no other emissions such as site visits or transportation were included). The figures found for this thesis indicate that carbon expended in the A0 stage of design should be considered as part of the LCA as it is potentially greater than the <1% figure from HSR design outlined above, depending on which of the design stage activities are required (see Figure 4.15), some of which involve travel to site alongside office working emissions as detailed in Table 4.14.

Inspecting the C stage of the expansion scenarios, with the addition of the A0 LC stages (see Appendix D.15, D.16, and D.17) align with “disposal”, it transpires that this stage contributes between 28.4% and 15.5% of the total A0-C4 footprint for Aldercar and Station Plantation respectively (the two renewals which were expanded based on deconstruction at EOL, whereas Bowling Green, Cove LX and Killiecrankie were assumed to be left in situ owing to the types of intervention involved not being readily deconstructed at EOL). Nonetheless Kaewunruen, Sresakoolchai and Peng (2020) found a figure of around 4% for earthworks “disposal” for the Beijing-Shanghai HSR. Reasons for this disparity are unclear as additional information regarding disposal, beyond the disassembly process being equivalent to the inverse of the construction stage, is not found in Kaewunruen, Sresakoolchai and Peng (2020). They also found that “building material play a more important role in carbon emissions than machineries” (Kaewunruen, Sresakoolchai and Peng, 2020, p.9). Comparative data as percentage contribution per lifecycle stage from Kaewunruen, Sresakoolchai and Peng (2020) for the Beijing-Shanghai HSR discussed above, is presented in

Table 4.15 with the full data being given in Appendix D.20.

Table 4.15 Contribution of Carbon Emissions from Earthworks Subdivided by Stage , amended from (Kaewunruen, Sresakoolchai and Peng, 2020, p.7), Compared to Renewal Examples – Aldercar and Station Plantation PAS2080 LC Stages

Four Stages of LC for HSR Earthworks for Beijing-Shanghai HSR	Earthwork % Contribution of each LC Stage for Beijing-Shanghai HSR	Equivalent PAS2080 LC Stage	Renewal % Contribution of each LC Stage for Aldercar	Renewal % Contribution of each LC Stage for Station Plantation
Conception	<1%	A0	2.4%	6.0%
Construction	71%	A1-5	52.5%	35.4%
Operation & Maintenance (O&M)	25%	B	16.8%	43.1%
Disposal	4%	C	28.4%	15.5%
Totals	100%		100%	100%

The findings of Kaewunruen, Sresakoolchai and Peng, 2020 counter the findings for embankments & cuttings for the case studies, however they do show tentative alignment with renewals when expanded, an example demonstrating this is provided in

Table 4.15 . Kaewunruen, Sresakoolchai and Peng, 2020 also present details of the carbon “hot spots” they identify, with the three materials of cement, gravel and steel contributing nearly 90% of carbon emissions during the construction stage.

Comparing the literature figures to the Aldercar example, both with and without the addition of the B stage maintenance, the A0 equivalent stage remains around 2.4%, the construction is with B stages 52.5%, O&M 16.8% and disposal 28.4%. The similarities between the Beijing-Shanghai HSR and Aldercar renewal example are that the construction stages take the majority of the footprint and the conception the least, whereas the O&M and disposal stages do not show good alignment in percentage terms. Some of the reasons behind this misalignment of lifecycle stages may be due to

the differences in constructing a new HSR in China compared to renewing an old railway in the UK, such as differences in the energy mix powering equipment (mainly coal powered in China (UK National Grid, 2020) and transport. Further comparison with data sets which meet defined parameters with the results of this thesis are presented in Section 4.3.

Given the complexity of the reason(s) for this misalignment, further analysis via percentage contributions of each lifecycle stage have been performed (see Figure 4.20).

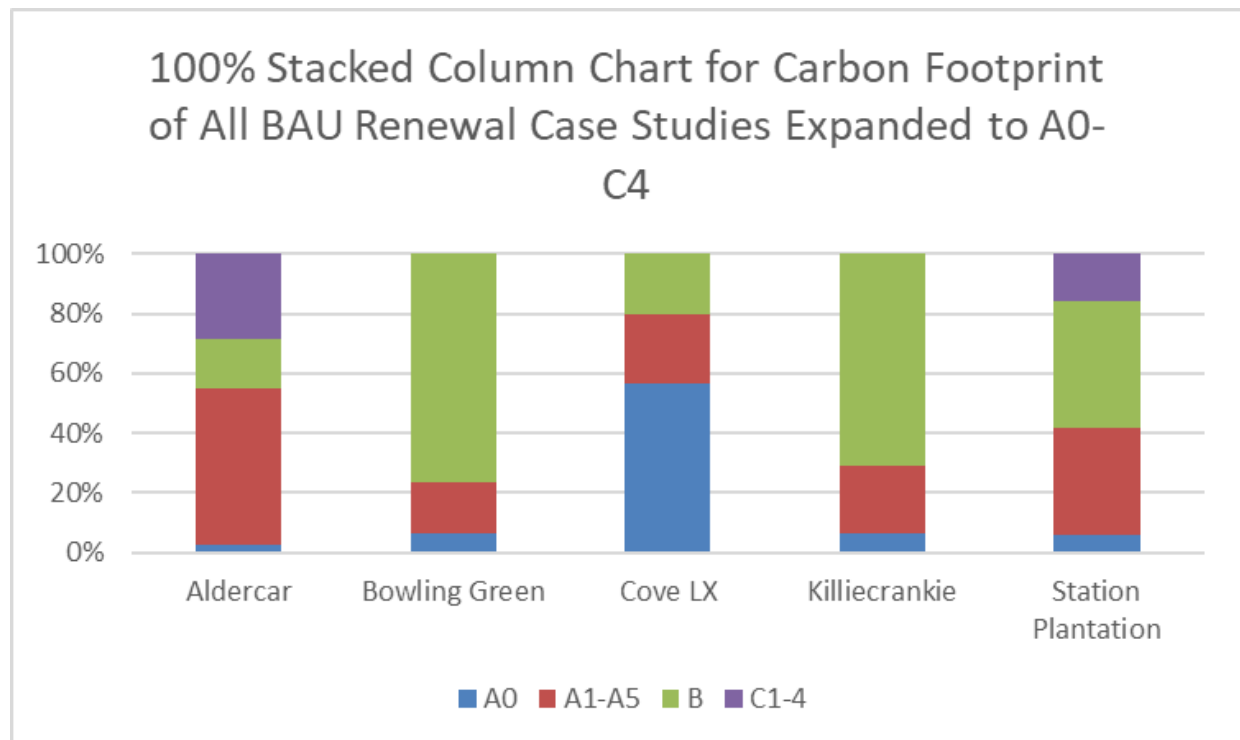


Figure 4.20 Renewals 100% Stacked Chart for Carbon Footprint Expanded to A0-C4

Figure 4.20 illustrates the contribution of the C1-4 LC stage to those renewals, in comparison to the HSR disposal stages, based on the deconstructed renewals case studies, Aldercar and Station Plantation. The A0 design stage, based as detailed in Appendix D.17 per volume, indicates the A0 LC contributing an increased percentage to Cove LX's A0-C4 lifecycle carbon, however in absolute terms this amount is appearing to account for a larger percentage of Cove LX owing to its smaller absolute size (A1-C4) compared to the other four case studies (see Table 4.13). The substantial contribution of the maintenance B stages to these renewals, particularly in Bowling Green and Killiecrankie (both soil cutting interventions), is highlighted here.

Aldercar, Cove and Station Plantation are all Embankments, however Aldercar is 3 volumes, this accounts for its B stages being relatively larger than that of the other two, see Appendix D.13. The B stages were calculated as described in Appendix D.12, with Cove LX being based on maintenance values found for a scour intervention, Claydon Embankment. For Aldercar and Station Plantation the maintenance value is based on the average of several similar maintenance interventions as

described, which may be skewing the figures. This is due to several large values found for Courteenhall (thousands of kgs), Stonebridge, and Dimbols (hundreds of kgs), compared to tens of kgs for the remaining five maintenance interventions.

Differences between the renewals in the expansion can also be partly attributed to EOL pathways as discussed in Appendix D.18, and also to the types of materials used, there is a large proportion of steel in Alder car, Bowling Green and Station Plantation. See Appendix D.18 for further discussion of EOL pathways and Appendix D for a brief discussion on confidence in results.

To conclude this expansion section a discussion on the uncertainties of the differing expansion assumptions is now provided.

4.2.3 Uncertainty in Expansion

In construction of the BAU A1-5 carbon footprints, uncertainty has been introduced via the methods used. In this section the general caveats applied to all case studies and the data used for the B and C lifecycle stage expansions will be detailed followed by a summary of the main areas of uncertainty in expansion. These descriptions of uncertainty will be provided by lifecycle stage alongside further details of the expansion methods used. This section will conclude with a discussion on the potential qualitative ranking of the lifecycle stages to highlight the greatest sources of uncertainty in the case studies' expansion.

The same set of assumptions are applied to each case study for consistency and to aid with comparability, however the effect of these assumptions has not been quantified here. The general exclusions applied are:

- Construction-phase consumable products (excluding fuel & water).
- Fossil fuel use for fixed/static plant & equipment for site operations and welfare.
- Grid electricity use by plant / equipment / services for site operations.
- Welfare and mains water use for site operations and welfare.
- Apportionment of carbon from overheads.

A summary table of the B and C stage approaches to expansion is provided here, along with key assumptions. See Table 4.16, Table 4.17 and Table 4.18 for B stage calculation approaches, and Table 4.19 for expansion scenario of A-5 to fulfil C stages based on the assumption that deconstruction is the inverse of construction (excluding materials).

In the calculations for the B2 maintenance lifecycle stage for the intervention of cess retention this would be zero, however as this sits adjacent to vegetation it was deemed necessary to recalculate

this taking into account biannual vegetation management. There are 8 vegetation management type interventions (standard details) in the data set for embankments and using this an average value for the functional unit was found. Using the figures found for such interventions an additional 360.38 kgCO₂e carbon would be allocated to maintenance (per volume).

Aldercar is 3 volumes in size, as such the average functional unit would need multiplying by 3 (volumes) and the 120 year lifespan of the renewal intervention, giving 129,735 kgCO₂e over the 120 anticipated life of the embankment based on BAU carbon allocated to the B2 Use stage of maintenance. The high and low boundaries from the data given are 33.48 and 1,333.07 kgCO₂e per volume/per year giving additional carbon per volume of 12,052.80 and 479,905.20 kgCO₂e respectively. Use of these upper and lower bounds, and the resulting impact on the expansion exercise is addressed later in this section for the B stages, A0 stages and C stages. Below are the data from the maintenance case studies used for the expansion scenarios.

Table 4.16 Average Functional Unit for Maintenance of Embankment

Maintenance Embankment Case Study Name	Functional Unit BAU kgCO ₂ e per Volume/Per Year
Appley Locks	33.48
Bathpool Reservoir	52.98
Courteenhall	1333.07
Dimbols farm foot crossing	491.30
Lime Chalk Embankment	43.42
NAJ2 South Ruislip	43.87
Old Hill	39.45
Stonebridge	845.43
Average	360.38

In calculating the B2 maintenance stage for the soil cutting renewals four maintenance case studies were identified as being maintenance de vegetation as such their average functional unit was used to calculate the B2 lifecycle maintenance stages for the expansion scenario. The high and low boundaries from the data given are 2,169.24 and 34.14 kgCO₂e respectively.

Table 4.17 Average Functional Unit for Maintenance of Soil Cutting

Soil Cutting Case Study Name	Functional Unit BAU kg CO ₂ e per Volume/Per Year
Dalton Junction Overhang	2,169.24
Hattersley No. 2	98.98
Postwick interchange	39.12
Ipswich southern tunnel portal	34.14
Average	585.37

In calculating the B2 maintenance lifecycle stage for the scour protection renewal, Cove LX, only one case study pertained to scour maintenance, Claydon, as such the functional unit for this maintenance intervention was used to calculate the B2 stage.

Table 4.18 Functional Unit for Scour Maintenance of Soil Cutting

Soil Cutting Case Study Name	Functional Unit BAU kg CO ₂ e per Volume/Per Year
Claydon Embankment	17.81

In conducting the expansion scenario, based on the data collected and previously manipulated in the BAU A1-A5 carbon footprints, the uncertainty that has been introduced is summarised in Figure 4.21 against each lifecycle stage.

Expansion A1-C4	Alder car E120	Action to Expanded	Bowling Green SC120	Action to Expanded	Cove LX E120	Action to Expanded	Killiecrankie SC120	Action to Expanded	Station Plantation E120	Action to Expanded
Brief Description of Works	Embankment Cess Renewal - retention added via h section pile, armco barrier and kee clamp		Install 6G Drainage Blanket, regularise slope profile		Scour protection		Removal of debris following landslip and installation of gabion baskets at toe of soil cutting, along with new catch fence netting, cables and erosion matting.		Embankment cess renewal. Cess retention using universal columns, armco barrier and kee klamp barrier.	

Expansion A1-C4	Alder car E120	Action to Expansion	Bowling Green SC120	Action to Expansion	Cove LX E120	Action to Expansion	Killiecrankie SC120	Action to Expansion	Station Plantation E120	Action to Expansion
A1-A3	H section piles	Dispose/ Recycle same weights of materials in C4	Pallisade fencing	Leave in situ	Coir matting	N/A as materials left in situ	Gabion Basket	N/A as materials left in situ	H section piles	Dispose/ Recycle same weights of materials in C4
A1-A3	Armco barrier 3mm	Dispose/ Recycle same weights of materials in C4	Post mix	Leave in situ	fence posts wooden	N/A as materials left in situ	Erosion Matting	N/A as materials left in situ	Armco barrier 3mm	Dispose/ Recycle same weights of materials in C4
A1-A3	Kee klamps various sizes	Dispose/ Recycle same weights of materials in C4	Terram	Leave in situ	Metal posts	N/A as materials left in situ	Galvanised wire rope	N/A as materials left in situ	Kee klamps various sizes	Dispose/ Recycle same weights of materials in C4
A1-A3			6G Stone	Leave in situ	Timber pegs	N/A as materials left in situ	Bulldog wire rope	N/A as materials left in situ		
A1-A3			Ballast	Leave in situ	Jay pegs for coir matting	N/A as materials left in situ	Macferrimesh	N/A as materials left in situ		
A1-A3					Type 1 aggregates	N/A as materials left in situ	Steel dowel	N/A as materials left in situ		

Expansion A1-C4	Alder car E120	Action to Expand	Bowling Green SC120	Action to Expand	Cove LX E120	Action to Expand	Killiecrankie SC120	Action to Expand	Station Plantation E120	Action to Expand
A1-A3					Postcrete	N/A as materials left in situ	Cement	N/A as materials left in situ		
A1-A3	Embodied carbon in plant and equipment	Same figure in C1 - deconstruction site activities	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	Same figure in C1 - deconstruction site activities
A4	Product and material transport	Same figure in C2 - transportation of deconstructed materials	Product and material transport	N/A as materials left in situ	Product and material transport	N/A as materials left in situ	Product and material transport	N/A as materials left in situ	Product and material transport	Same figure in C2 - transportation of deconstructed materials
A4	Worker travel	Same figure in C1 - Deconstruction site activities	Worker travel	N/A as materials left in situ	Worker travel	N/A as materials left in situ	Worker travel	N/A as materials left in situ	Worker travel	Same figure in C1 - Deconstruction site activities
A4	Plant and equipment transport	Same figure in C1 - Deconstruction site activities	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	Same figure in C1 - Deconstruction site activities

Expansion A1-C4	Alder car E120	Action to Expansion	Bowling Green SC120	Action to Expansion	Cove LX E120	Action to Expansion	Killiecrankie SC120	Action to Expansion	Station Plant E120	Action to Expansion
A5	Fossil fuel for mobile plant and equipment	Same figure in C1 - Deconstruction site activities	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	Same figure in C1 - Deconstruction site activities

Table 4.20 details the actions taken in expanding the renewals case studies from A1-5 to A1-C4 and the uncertainties detailed in Figure 4.21 are expanded on in Table 4.20 by lifecycle stage alongside a summary of the calculation method/data used for calculation.

The main caveats highlighted in

Expansion A1-C4	Alder car E120	Action to Expanded	Bowling Green SC120	Action to Expanded	Cove LX E120	Action to Expanded	Killiecrankie SC120	Action to Expanded	Station Plantation E120	Action to Expanded
Brief Description of Works	Embankment Cess Renewal - retention added via h section pile, armco barrier and kee clamp		Install 6G Drainage Blanket, regularise slope profile		Scour protection		Removal of debris following landslip and installation of gabion baskets at toe of soil cutting, along with new catch fence netting, cables and erosion matting .		Embankment cess renewal. Cess retention using universal columns, armco barrier and kee klamp barrier .	
A1-A3	H section piles	Dispose/ Recycle same weights of materials in C4	Pallisade fencing	Leave in situ	Coir matting	N/A as materials left in situ	Gabion Basket	N/A as materials left in situ	H section piles	Dispose/ Recycle same weights of materials in C4
A1-A3	Armco barrier 3mm	Dispose/ Recycle same weights of materials in C4	Post mix	Leave in situ	fence posts wooden	N/A as materials left in situ	Erosion Matting	N/A as materials left in situ	Armco barrier 3mm	Dispose/ Recycle same weights of materials in C4
A1-A3	Kee klamps various sizes	Dispose/ Recycle same weights of materials in C4	Terram	Leave in situ	Metal posts	N/A as materials left in situ	Galvanised wire rope	N/A as materials left in situ	Kee klamps various sizes	Dispose/ Recycle same weights of materials in C4

Expansion A1-C4	Alder car E120	Action to Expansion	Bowling Green SC120	Action to Expansion	Cove LX E120	Action to Expansion	Killiecrankie SC120	Action to Expansion	Station Plantation E120	Action to Expansion
A1-A3			6G Stone	Leave in situ	Timber pegs	N/A as materials left in situ	Bulldog wire rope	N/A as materials left in situ		
A1-A3			Ballast	Leave in situ	Jay pegs for coir matting	N/A as materials left in situ	Macferrimesh	N/A as materials left in situ		
A1-A3					Type 1 aggregates	N/A as materials left in situ	Steel dowel	N/A as materials left in situ		
A1-A3					Postcrete	N/A as materials left in situ	Cement	N/A as materials left in situ		
A1-A3	Embodied carbon in plant and equipment	Same figure in C1 - deconstruction site activities	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	Same figure in C1 - deconstruction site activities
A4	Product and material transport	Same figure in C2 - transportation of deconstructed materials	Product and material transport	N/A as materials left in situ	Product and material transport	N/A as materials left in situ	Product and material transport	N/A as materials left in situ	Product and material transport	Same figure in C2 - transportation of deconstructed materials

Expansion A1-C4	Alder car E120	Action to Expand	Bowling Green SC120	Action to Expand	Cove LX E120	Action to Expand	Killiecrankie SC120	Action to Expand	Station Plantation E120	Action to Expand
A4	Worker travel	Same figure in C1 - Deconstruction site activities	Worker travel	N/A as materials left in situ	Worker travel	N/A as materials left in situ	Worker travel	N/A as materials left in situ	Worker travel	Same figure in C1 - Deconstruction site activities
A4	Plant and equipment transport	Same figure in C1 - Deconstruction site activities	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	Same figure in C1 - Deconstruction site activities
A5	Fossil fuel for mobile plant and equipment	Same figure in C1 - Deconstruction site activities	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	Same figure in C1 - Deconstruction site activities

Table 4.20 are that travel distances, machinery running times and transport distances of machinery and staff are all assumed to be the same as for construction (deconstruction emissions inverse of construction (Kaewunruen, Sresakoolchai and Peng, 2020, p.6)). This helps to fill the gap that staff transport distances are an often excluded item (Lokesh, Densley-Tingley and Marsden, 2022a, p.18). All materials assumed requiring equivalent weight of disposal or recycling EFs if available in the RSSB RCT. It is important to include for maintenance as accurately as possible as these activities are often excluded or only “roughly approximated” in LCA of transport (Saxe and Kasraian, 2020, p.1037) as such B stage maintenance activities based on averages of suitable comparator from the maintenance case studies data set.

PAS 2080 Lifecycle Stage	Method	Sources of Uncertainty
A0	Calculated: Literature & NR Discussions	Four pre-construction stages identified: Desk Study, Ground Investigation, Ground Interpretation, Design. Upper and lower values given using the range data from NR and sources in the literature were calculated giving 4,077 – 6,063 kgCO ₂ e.
A1-5	Calculated: Bath ICE & DfT Data	For A1-3 materials RSSB RCT values used. For A4 transport HGV unknown type, unknown size average load used for all HGV movements, for car transport assumed average car fuel unknown. For A5 construction closest match machinery and engine size used. Mileage and no. of journeys data based on NR provided data.
B1-9	Estimated based on A1-5 Figures	Maintenance figures based on mean figures from similar case studies; embankments (8 no.) and soil cuttings (4 no.). Only one scour maintenance figure was available to use for the scour intervention. Type of maintenance actually required may not be vegetation management.
C1-4	Estimated based on A1-5 Figures	In-situ (concrete) vs deconstruction (metals) scenarios based on materials utilised in construction. Deconstruction based on inverse of construction less materials. Other (lower) percentage figures are found in the literature.
D	Calculated: EW & WCC Lit. Figures	EW, three rates used from literature, 10 differing percentage scenarios of line side track usage from 10-100%. WCC figures based on grassland to woodland and arable to woodland with corresponding 10-100% figures.

Figure 4.21 Uncertainty in Expansion

Table 4.19 Renewals BAU A1-5 to EXP Scenario A1-C4 Actions Per Stage

Expansion A1-C4	Aldercar E120	Action to Expand	Bowling Green SC120	Action to Expand	Cove LX E120	Action to Expand	Killiecrankie SC120	Action to Expand	Station Plantation E120	Action to Expand
Brief Description of Works	Embankment Cess Renewal - retention added via h section pile, armco barrier and kee clamp		Install 6G Drainage Blanket, regularise slope profile		Scour protection		Removal of debris following landslip and installation of gabion baskets at toe of soil cutting, along with new catch fence netting, cables and erosion matting.		Embankment cess renewal. Cess retention using universal columns, armco barrier and kee klamp barrier.	
A1-A3	H section piles	Dispose/Recycle same weights of materials in C4	Pallisade fencing	Leave in situ	Coir matting	N/A as materials left in situ	Gabion Basket	N/A as materials left in situ	H section piles	Dispose/Recycle same weights of materials in C4
A1-A3	Armco barrier 3mm	Dispose/Recycle same weights of materials in C4	Postmix	Leave in situ	fence posts wooden	N/A as materials left in situ	Erosion Matting	N/A as materials left in situ	Armco barrier 3mm	Dispose/Recycle same weights of materials in C4
A1-A3	Kee klamps various sizes	Dispose/Recycle same weights of materials in C4	Terram	Leave in situ	Metal posts	N/A as materials left in situ	Galvanised wire rope	N/A as materials left in situ	Kee klamps various sizes	Dispose/Recycle same weights of materials in C4

Expansion A1-C4	Aldercar E120	Action to Expand	Bowling Green SC120	Action to Expand	Cove LX E120	Action to Expand	Killiecrankie SC120	Action to Expand	Station Plantation E120	Action to Expand
A1-A3			6G Stone	Leave in situ	Timber pegs	N/A as materials left in situ	Bulldog wire rope	N/A as materials left in situ		
A1-A3			Ballast	Leave in situ	Jay pegs for coir matting	N/A as materials left in situ	Macferri mesh	N/A as materials left in situ		
A1-A3					Type 1 aggregates	N/A as materials left in situ	Steel dowel	N/A as materials left in situ		
A1-A3					Postcrete	N/A as materials left in situ	Cement	N/A as materials left in situ		
A1-A3	Embodied carbon in plant and equipment	Same figure in C1 - deconstruction site activities	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	Same figure in C1 - deconstruction site activities
A4	Product and material transport	Same figure in C2 - transportation of deconstructed materials	Product and material transport	N/A as materials left in situ	Product and material transport	N/A as materials left in situ	Product and material transport	N/A as materials left in situ	Product and material transport	Same figure in C2 - transportation of deconstructed materials

Expansion A1-C4	Aldercar E120	Action to Expand	Bowling Green SC120	Action to Expand	Cove LX E120	Action to Expand	Killiecrankie SC120	Action to Expand	Station Plantation E120	Action to Expand
A4	Worker travel	Same figure in C1 - Deconstruction site activities	Worker travel	N/A as materials left in situ	Worker travel	N/A as materials left in situ	Worker travel	N/A as materials left in situ	Worker travel	Same figure in C1 - Deconstruction site activities
A4	Plant and equipment transport	Same figure in C1 - Deconstruction site activities	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	Same figure in C1 - Deconstruction site activities
A5	Fossil fuel for mobile plant and equipment	Same figure in C1 - Deconstruction site activities	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	Same figure in C1 - Deconstruction site activities

Table 4.20 Calculation Approach and Sources of Uncertainty in Expansion

PAS2080 Stages			Calculation Approach	
A0	Pre-Construction	Preliminary Studies, Consultations	Desk Study Office and homeworking carbon values used. Numbers of days is based on conversation with NR, however actual quantity may vary. Ground Investigation Average travel distance figure from all survey type case studies used. Ground Interpretation Average travel distance figure from all survey type case studies used. Design	Desk Study Further data collection in this area would bring more certainty to the accuracy of this data. Ground Investigation Due to small sample size, these may not be representative of actual travel distances. Larger sample sizes would refine this figure. Ground Interpretation Due to small sample size, these may not be representative of actual travel distances. Larger sample sizes would refine this figure.

			Office and homeworking carbon values used. Numbers of days is based on conversation with NR, however actual quantity may vary.	Design Further data collection in this area would bring more certainty to the accuracy of this data. Upper and lower values given the range data from NR were calculated giving a range of 4,077 – 6,063 kgCO ₂ e, see Table 4.14.
A1	Product Stage	Raw Material Supply	Data provided on carbon data collection form by subcontractor.	Uncertainty is added however in choice of material factor to use in RSSB RCT and age of data in tool (version of Bath ICE database used)
A2	Product Stage	Transport	A2 data is included within A1-A3 emissions factors in the database used.	Therefore there is uncertainty regarding this choice as it is embedded into the emissions factor chosen.
A3	Product Stage	Manufacture	A3 data is included within A1-A3 emissions factors in the database used.	Therefore there is uncertainty regarding this choice as it is embedded into the emissions factor chosen.
A4	Construction Stage	Transport to Works Site	Data provided on carbon data collection form by subcontractor.	Uncertainty is added however in choice vehicle used in case studies to allow for comparison between staff transport which was average car. Also, limited data on engine sizes was provided. Transport of materials to site was from stockist or contractor location, not from manufacturing gate.
A5	Construction Stage	Construction/Installation Process	Data provided on carbon data collection form by subcontractor.	Uncertainty is added however in choice of engine based on data supplied for plant used on site.
B1	Use Stage	Use	Assumed no carbon expenditure in this stage for earthworks	Assumed no carbon expenditure in this stage for earthworks.
B2	Use Stage	Maintenance	Averages from Maintenance BAU functional unit for case studies used. For maintenance of embankments: Mean value is 360.38kgCO ₂ e/per vol/per year based on 8 values and range of 33.48 to 13,333.07 kgCO ₂ e/per vol/per year see Appendix D.12.1. For maintenance of soil cutting vegetation: Mean value is 585.37 kgCO ₂ e/per vol/per year based on	These may not be representative of actual maintenance requirements. These maintenance interventions are based on mowing/cutting/vegetation regimes of the embankment or soil cutting. Any errors in the maintenance of embankments and soil cutting vegetation will be multiplied here as these values are multiplied by the expected lifespan of the intervention 120 years.

			4 values and range of 43.14 to 2,169.24 kgCO ₂ e/per vol/per year see Appendix D.12.2.	
B3	Use Stage	Repair	Excluded– lack of data to allow for estimation	
B4	Use Stage	Replacement	Excluded – lack of data to allow for estimation	
B5	Use Stage	Refurbishment	Excluded – lack of data to allow for estimation	
B6	Use Stage	Operational energy use	N/A	Excluded - assumed not applicable to earthworks
B7	Use Stage	Operational water use	N/A	Excluded - assumed not applicable to earthworks
B8	Use Stage	Other operational processes	N/A	Excluded - assumed not applicable to earthworks
B9	Use Stage	Users' utilisation of infrastructure	N/A	Excluded - assumed not applicable to earthworks
C1	End of Life Stage	Deconstruction	Based on disposal being the inverse of construction, excluding embodied material emission factors, as per the literature as detailed in the thesis.	These may be an over-estimation as figures as low as 15% have been found in the literature. Construction emissions for deconstruction of 15% of construction are found in the literature (Wei and Chen, 2020, p.4).
C2	End of Life Stage	Transport	Based on disposal being the inverse of construction as per the literature as detailed in the thesis.	Based on inverse of construction as per the literature as detailed in the thesis.
C3	End of Life Stage	Waste Processing for Recovery	Assumed metal work can be recycled where deconstructed. Assumed concrete is left in-situ.	Assumed metal work can be recycled where deconstructed. Assumed concrete is left in-situ.
C4	End of Life Stage	Disposal	Disposal figures from RSSB RCT used for metal work. In the renewal examples steel has been assumed to be deconstructed and removed from site, resulting in additional carbon from machinery, staff transport and waste disposal, concrete has been assumed to be left in-situ.	Kaewunruen, Sresakoolchai and Peng (2020) found a figure of around 4% for earthworks “disposal” for the Beijing-Shanghai HSR.

The values used for the B stages (detailed in Table 4.16, Table 4.17 and Table 4.18) are averages and these are used in the original set of expansion further detailed in Table 4.21. To demonstrate the extent to which the expansion figures used in this thesis are sensitive to uncertainty, these expansion scenarios have been recalculated using higher and lower values for A0, B and C lifecycle stages. Using the higher value of these figures along with the higher A0 and C values (inverse of construction) the resultant final expansion figures are as indicated in Table 4.22 and using the lower bound for A0, B and C stages as indicated in Table 4.23 the resultant final figures are shown.

The results show that the average A0-C4 expansion carbon figure of 153,628.51 kgCO₂e/Volume can rise to as much as 274,642.29 kgCO₂e/Volume using the higher values mean figure and can fall as low as 81,195.21 kgCO₂e/Volume using the lower values mean figure.

These mean values of these expansion figures are then plotted as bar graphs showing absolute contribution of carbon to each life cycle stage in the expansion scenario to illustrate the effects of using higher and lower boundary figures in expansion. These indicate that the greatest uncertainty lies in the B lifecycle stages, see Figure 4.22.

Table 4.21 Details of Carbon Per Lifecycle Stage for Expansions – as used for in this thesis

Renewal Case Study Name	Materials Left in Situ or Deconstructed	Earthwork Type and Volume	A0	A1-A5	B	C1-4	A0-C4 total
Aldercar	Deconstructed	E, 3 volumes	18,189.00	406,121.00	129,736.80	219,441.00	773,487.80
Percentage Values			2.35	52.51	16.77	28.37	100.00
Bowling Green	Left in situ	SC, 1 volume	6,063.00	15,378.00	70,244.00	0	91,685.00
Percentage Values			6.61	16.77	76.61	0.00	100.00
Cove LX	Left in Situ	E, 1 volume	6,063.00	2,522.00	2,137.20	0	10,722.20
Percentage Values			56.55	23.52	19.93	0.00	100.00
Killiecrankie	Left in Situ	SC, 1 volume	6,063.00	22,761.00	70,244.00	0	99,068.00
Percentage Values			6.12	22.98	70.90	0.00	100.00
Station Plantation	Deconstructed	E, 1 volume	6,063.00	35,572.00	43,245.60	15,556.00	100,436.60
Percentage Values			6.04	35.42	43.06	15.49	100.00
Average Carbon Values per Volume			6,063.00	68,907.71	45,086.80	33,571.00	153,628.51
Average Percentage Values per case study			15.53	30.24	45.46	8.77	100.00

Table 4.22 Details of Carbon Per Lifecycle Stage for Expansions Using Highest Boundary Figures for A0, B and C

Renewal Case Study Name	Materials Left in Situ or Deconstructed	Earthwork Type and Volume	A0 - Highest value per volume	A1-A5 - Kept as BAU	B - Highest value per volume	C1-4 - Highest value used, inverse of construction	A0-C4 total
Aldercar	Deconstructed	E, 3 volumes	18,189.00	406,121.00	479,905.20	219,441.00	1,123,656.20
Percentage Values			1.62	36.14	42.71	19.53	100.00
Bowling Green	Left in situ	SC, 1 volume	6,063.00	15,378.00	260,308.80	0	281,749.80
Percentage Values			2.15	5.46	92.39	0.00	100.00
Cove LX	Left in Situ	E, 1 volume	6,063.00	2,522.00	2,137.20	0	10,722.20
Percentage Values			56.55	23.52	19.93	0.00	100.00
Killiecrankie	Left in Situ	SC, 1 volume	6,063.00	22,761.00	260,308.80	0	289,132.80
Percentage Values			2.10	7.87	90.03	0.00	100.00
Station Plantation	Deconstructed	E, 1 volume	6,063.00	35,572.00	160,044.00	15,556.00	217,235.00
Percentage Values			2.79	16.37	73.67	7.16	100.00
Average Carbon Values per Volume			6,063.00	68,907.71	166,100.57	33,571.00	274,642.29
Average Percentage Values per case study			13.04	17.87	63.75	5.34	100.00

Table 4.23 Details of Carbon Per Lifecycle Stage for Expansions Using Lowest Boundary Figures for A0, B and C

Renewal Case Study Name	Materials Left in Situ or Deconstructed	Earthwork Type and Volume	A0 - Lowest value per volume	A1-A5 - Kept as BAU	B - Lowest value per volume	C1-4 - Lowest values of 15% for C1 and 4% for C4.	A0-C4 total
Aldercar	Deconstructed	E, 3 volumes	12,231.00	406,121.00	12,052.80	29,577.50	459,982.30
Percentage Values			2.66	88.29	2.62	6.43	100.00
Bowling Green	Left in situ	SC, 1 volume	4,077.00	15,378.00	4,096.80	0	23,551.80
Percentage Values			17.31	65.29	17.39	0.00	100.00
Cove LX	Left in Situ	E, 1 volume	4,077.00	2,522.00	2,137.20	0	8,736.20
Percentage Values			46.67	28.87	24.46	0.00	100.00
Killiecrankie	Left in Situ	SC, 1 volume	4,077.00	22,761.00	4,096.80	0	30,934.80
Percentage Values			13.18	73.58	13.24	0.00	100.00
Station Plantation	Deconstructed	E, 1 volume	4,077.00	35,572.00	4,017.60	1,494.80	45,161.40
Percentage Values			9.03	78.77	8.90	3.31	100.00
Average Carbon Values per Volume			4,077.00	68,907.71	3,771.60	4,438.90	81,195.21
Average Percentage Values per case study			17.77	66.96	13.32	1.95	100.00

Using the data from Table 4.21, Table 4.22, and Table 4.23, a graph has been constructed illustrating the differences in lifecycle stages using these three approaches; 1) as used in this thesis, 2) using highest figures, and 3) using lowest figures.

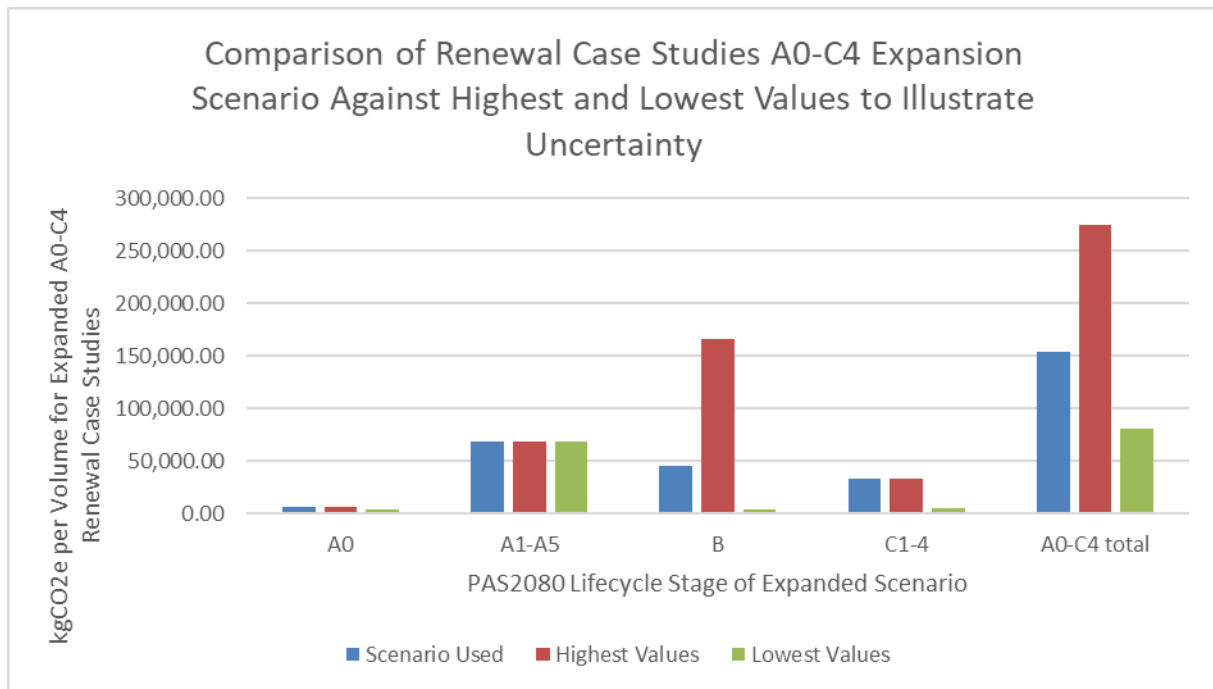


Figure 4.22 Comparison of Scenario Used for Expansion Against Highest and Lowest Values

Figure 4.22 illustrates that the A0 along with the A1-5 (the latter remaining the same as the BAU scenario for this exercise) did not vary greatly using the highest and lowest values. The B stages had the greatest difference between the scenario used with the highest and lowest values, indicating that it is in this lifecycle stage that the greatest uncertainty lies. The C stages used in the original scenario for expansion were the highest values, therefore there was no change when the highest values were used, however when using the lowest values, these show a significant decrease compared to the highest values. Overall, the A0-C4 totals showed an increase of nearly 100% from the original scenario used compared to the highest values, and a decrease of nearly 50% compared to the lowest values used. It should however be borne in mind that these figures have been obtained from a very small data set (renewals = 5) and may not be reflective once a larger data set is interrogated. It is recommended that these processes for expansion are applied to a larger data set to validate the assertion that the B stage has the greatest uncertainty in expansion scenarios from A1-5 to A0-C4.

The next section will focus on comparisons of the BAU and expanded data renewal scenarios with the literature.

4.3 Comparison with the Literature

4.3.1 Introduction

Several previous studies have been highlighted as potentially suitable for comparison with the case studies. Prior to using these, several parameters have been assessed to justify their inclusion, see Section 4.3.2. Following this assessment comparisons are provided for the literature deemed to meet these parameters which are HS2 Phase 1 works (earthworks of selected interventions between Euston Station to Old Oak Common Station) (HS2 Limited, 2022i;c;b;a;g), NR NW&C Carbon Footprints (Mott MacDonald, 2021, p.12), railway track system interventions (switches and crossings footprints) whole life carbon model including detailed construction carbon data (Rempelos, 2023), and finally data on ballasted or ballastless track (Lokesh, Densley-Tingley and Marsden, 2022a).

A correlation comparison against construction GHGs (Ozcan-Deniz and Zhu, 2017) using the correlations calculated in Section 4.1.4, 4.1.5, and 4.1.6 are presented, and this chapter ends with conclusions.

4.3.2 Parameters for Comparative Literature Selection

In choosing suitable literature for comparison several factors were assessed to ensure that the comparisons are meaningful. These are fundamental factors that need to be assessed to determine whether earthworks are suitable for comparison, between conventional rail, HSR and highways infrastructure. The factors assessed are:

- Temporal – Completed post 2017
- Spatial – UK required for comparable energy mix
- Asset Type – Embankment or Cutting
- Asset Size – Known and Adjusted to Functional Unit, 100m
- Climate Change Factor – CO₂e not CO₂ or carbon

Literature used for comparison has been assessed against the factors listed above, see Appendix D.21. Those literature meeting the parameters are compared below.

4.3.3 Comparison with HS2 Earthworks (A1-5)

HS2, as a newly built HSR, is an appropriate comparator for renewals with equivalent lifespan of 120 years. Data for selected earthworks of embankments and cuttings between Euston Station and Old Oak Common has been provided from HS2 Limited (HS2 Limited, 2022i;c;b;a;g), following a request for additional details of whole life carbon baselines found for embankments and cutting in phase one

of HS2 (HS2 Limited, 2020, p.9), in a PAS2080 format congruent for manipulation to align with volumes per year to allow for comparison to the A1-5 BAU renewals case study scenario data described in Section 4.1. See Appendices D.22, D.23, and D.24.

A stacked percentage chart, see Figure 4.23, compares renewals BAU A1-5 data and HS2 data.

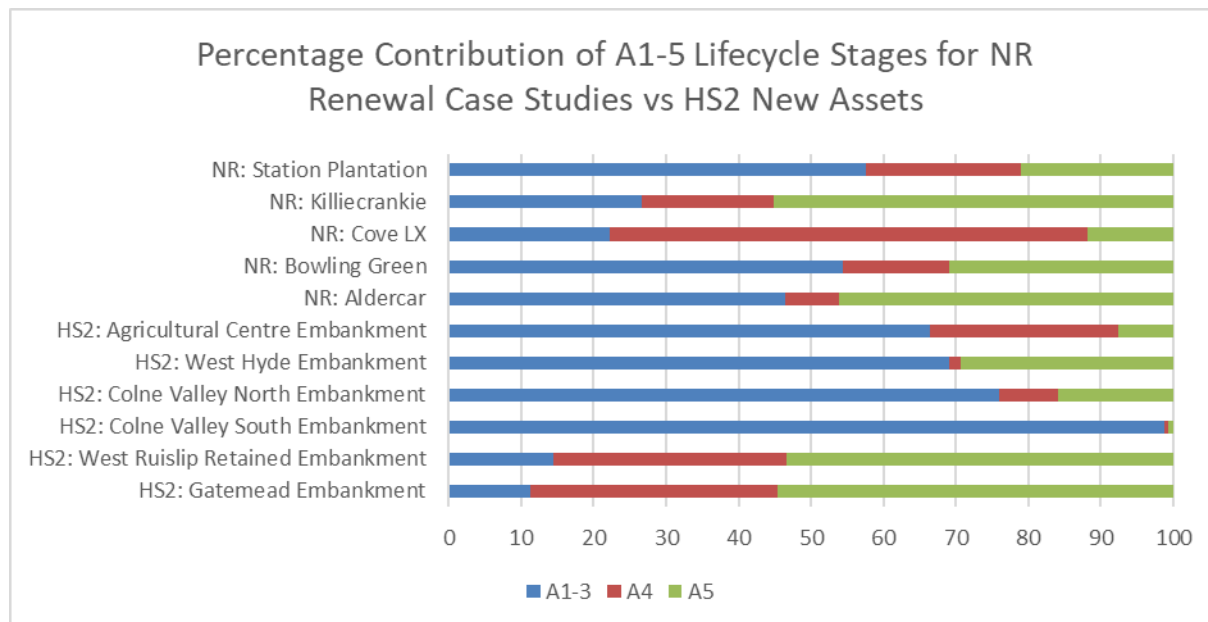


Figure 4.23 Contribution of Stages for Renewal Case Studies & HS2 Interventions

Figure 4.23 shows that A1-3 contributions vary from 11 to 99% for HS2 and 22 to 58% for NR, A4 contributions vary from 0% to 34% for HS2 and 7% to 66% for NR, and A5 contributions vary from 1% to 55% for HS2 and 12% to 55% for NR. Figure 4.23 also illustrates the similarities between NR Killiecrankie and HS2 West Ruislip and Gatemead embankments, in terms of proportions of carbon in the lifecycle stages.

Figure 4.24 demonstrates the percentage of interventions which have over half of their total carbon from that stage.

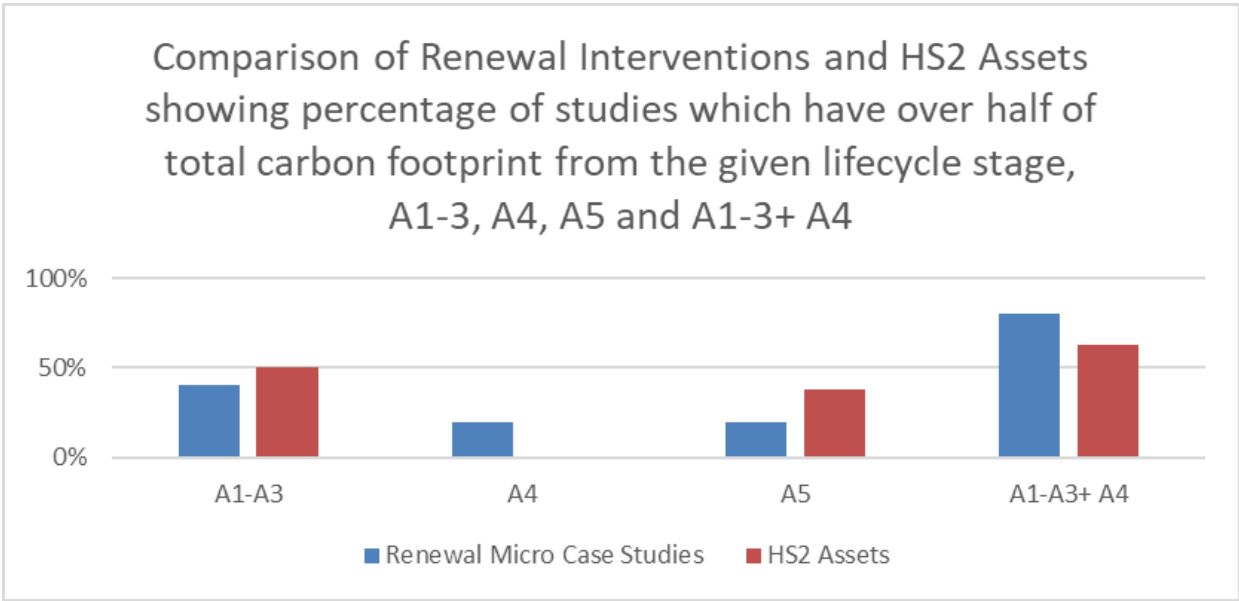


Figure 4.24 Comparison of Renewal Interventions and HS2 Assets

Figure 4.24 highlights the small percentage share of the total footprint provided by the A4 stage for HS2 assets. Comparative analysis has been made using descriptive statistics for the two data sets, see Appendix D.24, calculated for the functional unit of the HS2 data set with the previously presented descriptive statistics for the renewals data set, see Section 4.1.3. This analysis shows that both data sets have similar Kurtosis with peaked distributions and skewness values indicating highly skewed data distribution. Accordingly, the data has more outliers as indicated in Appendix D.24. The spread of data for A1-3, A4 and A5 ranges respectively, from 11 to 99%, 0 to 34%, and 1 to 55% for HS2 and for NR 22 to 58%, 7 to 66%, 12 to 55%.

4.3.4 Comparison with Mott Macdonald NW&C Carbon Assessment (A1-3, A4)

The assessment of carbon in delivery works in NR NW&C report found that construction emissions accounted for 61% of the total emissions, the CAM portfolio 35% and operations 4% (Mott MacDonald, 2021, p.12). The 61 projects assessed in this carbon report, when plotted on a pareto, show a trend similar to the whole data set for the 50 case studies. They have several projects which account for the majority of the carbon, 65% of carbon accounted for by the top three projects in the Mott MacDonald report compared to the top two in the case studies accounting for 60% (see Section 4.1.1). The largest project in the NW&C report represents over 45% of the capital projects emissions of which the greatest proportion of carbon in this top project is found in construction materials and their associated transport (Mott MacDonald, 2021, p.15).

For the three highest emissions projects construction materials dominate the carbon emissions. Construction transport and construction plant account for a much smaller proportion. The emissions from stone and its transport make a considerable contribution to the carbon footprints (Mott

MacDonald, 2021, p.15). This large contribution of stone to emissions is found in the Killiecrankie renewal case study which included 27.2t of gabion stones, accounting for 47% of A1-3 carbon and 7% of A4 transport, and Braystone refurbishment which included 10t of stone accounting for 88% of A1-3 carbon and 12% of A4 transport carbon.

Operational emissions, while the smaller of the three main areas, had a significant portion, 63%, from plant and 23% from transport (Mott MacDonald, 2021, p.18) indicating that changes to lower emissions equipment and transportation modes would be beneficial here, similar to that found for the case studies, explored further in Chapter 5.

4.3.5 Comparison with NR Switches & Crossings: Rempelos (2023)

The percentage breakdowns for materials, plant and labour data analysed by Rempelos (2023) for S&C, have been aligned with PAS2080 stage A4 (for material, plant and staff transport respectively) to enable comparison with the data from the case studies averaged for the differing intervention types of maintenance, refurbishment and renewals.

The percentage contributions to track construction found by Rempelos (2023) have been compared to those of the case studies, split by intervention type as presented in Table 4.24.

Table 4.24 Comparison of Renewals with Rempelos (2023) A4 Data Split to Case Studies A4 Data Split by Each Temporal Intervention Type

Percentage Contribution to Total A4 LC stages	Rempelos Transport Emissions First Set of Scenarios (second set in brackets)	Maintenance Case Studies Average	Refurbishment Case Studies Average	Renewal Case Studies Average
Material Transport	3.5% (3%)	2%	9%	6%
Plant Transport	78.9% (67.8%)	20%	32%	31%
Staff Transport	17.7% (29.2%)	78%	58%	62%
Waste	No data provided	0%	0%	1%

Table 4.24 indicates for the case studies, most emissions were attributable to staff transport, with the second largest being plant and the least, being materials, showing similarities to the Rempelos (2023) data set. The maintenance case studies show quite striking opposite results to those of Rempelos in that the staff transport percentage for Rempelos (2023) is approximately the same percentage as that for plant transport for maintenance case studies, and that the staff transport

percentage for maintenance is almost exactly the same as plant transport for Rempelos, track construction (Rempelos, 2023, p.113).

Rempelos presents a percentage breakdown by lifecycle stage, however these do not align with the PAS2080 A1-5, B, and C stages that this thesis was split by and are therefore unsuitable for direct comparison. Rempelos (2023) concludes that in the breakdown by LCA phase, construction accounts for between 23.6%-29.1%, maintenance 10.4% to 13.6% and EOL a figure of below 2% irrespective of scenario (Rempelos, 2023, p.135). This data has been compared to the case studies split by temporal intervention in Table 4.25.

Table 4.25 Comparison Table of Rempelos and Renewal Case Studies

Percentage Contribution to Total LC	Rempelos Transport Emissions First Set of Scenarios	Renewal Case Studies Expansion A1-C4 Average
Construction	23.6% - 29.1%	18%-54%
Maintenance	10.4% - 13.6%	17-82%
EOL	<2%	0%-29%

Rempelos (2023) analysed changes to footprints from modal shift of a movement from road to rail for transporting materials, labour and plant which surprisingly only gives a reduction to the footprint of between 3.6% to 5.0% (Rempelos, 2023, p.128). It is expected for rail freight to give greater reductions in the carbon footprint compared to HGV transport as the EF for rail freight is 64% less than that of road freight (rail freight 0.04107 kgCO₂e/tkm compared to HGV freight 0.1136 kgCO₂e/tkm in the RSSB RCT).

4.3.6 Comparison with Measuring Railway Infrastructure: Lokesh, Densley-Tingley and Marsden (2022a)

Lokesh provides an up to date review measuring railway infrastructure carbon specifically, and also addressing a whole-life approach to carbon in new infrastructure to enable assessment of the carbon implications of decisions made by bodies such as NR or TfN, (Lokesh, Densley-Tingley and Marsden, 2022a). Lokesh, Densley-Tingley and Marsden (2022a) has system boundaries which align well with those of the A1-C4 BAU expansion scenarios, and is illustrated in Figure 4.25.

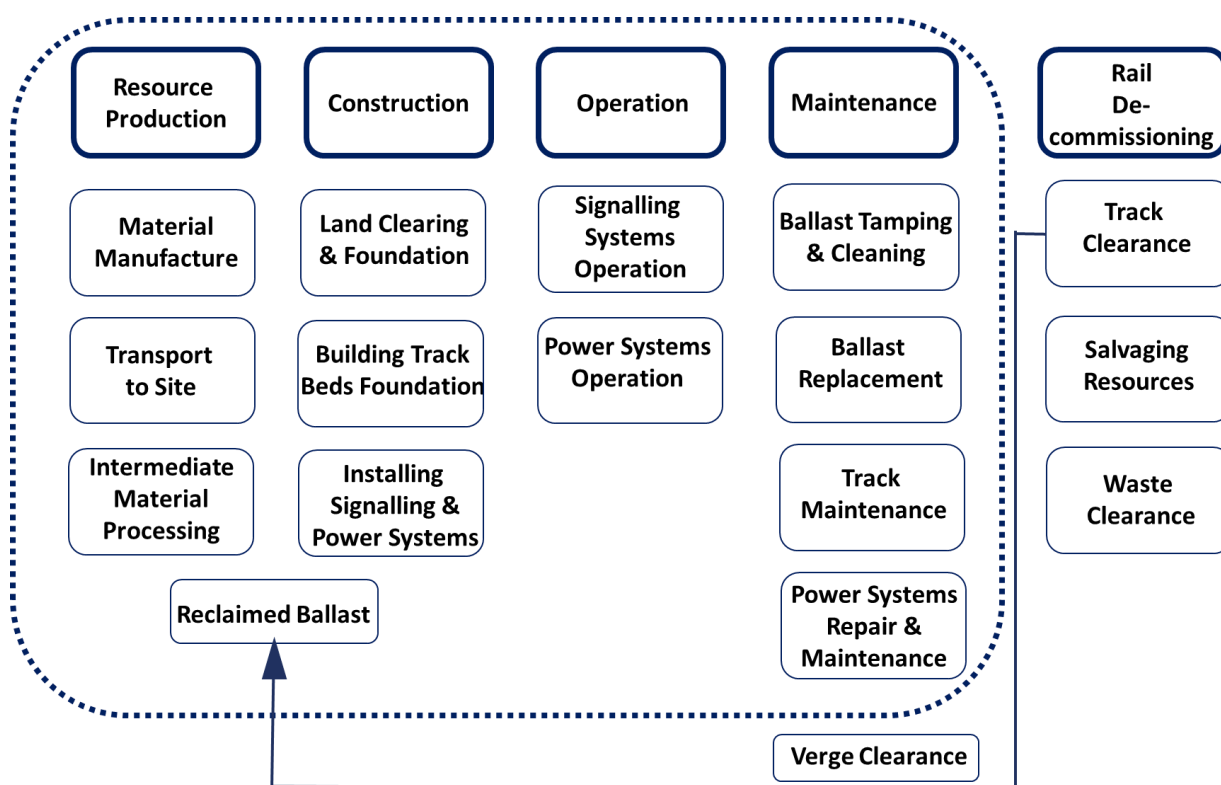


Figure 4.25 System Boundary amended from (Lokesh, Densley-Tingley and Marsden, 2022a)

The boundaries in Lokesh, Densley-Tingley and Marsden (2022a) align with the PAS2080 stages: Resource production – A1-3, construction – A4/5, operation/maintenance – B stages. Although the Lokesh, Densley-Tingley and Marsden (2022a) review does not specifically address earthworks, the inventory analysis includes for stations, train construction, rail track foundation, track construction OLE, and tunnels and bridge construction. It is assumed that earthworks would lie within the rail track foundation part of the inventory. The review concludes that the carbon associated with construction and maintenance machinery, is “mainly fuel consumption” (Lokesh, Densley-Tingley and Marsden, 2022a, p.14) which aligns with the results for the NR case studies whereby fuel from engine hours running activities accounts for 99.6-100% of A5 construction carbon for the BAU A1-5 renewals case studies.

4.3.7 Correlation Comparison: Ozcan-Deniz and Zhu (2017)

A suitable comparator for the correlations found for the whole data set in Section 4.1.2 is found in the literature in a multi objective optimisation of GHG emissions in highway construction projects, a comparable linear infrastructure to railway infrastructure, carried out by Ozcan-Deniz and Zhu (2017). Their analysis shows that time and cost have a strong correlation, cost and GHG emissions having a moderate correlation and, their weakest correlation, between time and GHG emissions. Table 4.26 presents the correlations for the whole data set, and disaggregated by temporal type, compared to Ozcan-Deniz and Zhu (2017).

Table 4.26 Comparison Table of Selected Correlations Between Research and Literature

Correlation	Intervention Type	Correlation Results from this Thesis	Correlation Results from Ozcan-Deniz and Zhu (2017)
Time and cost	Maintenance	No Data	Strong Correlation
	Refurbishment		
	Renewal		
Cost and GHG emissions	Maintenance	Positive 0.92 correlation coefficient	Moderate Correlation
	Refurbishment		
	Renewal		
Time and GHG emissions	Maintenance	Positive 0.93 correlation coefficient	Weak Correlation
	Refurbishment	Positive	
	Renewal	Positive	
Transport Distance and GHG emissions	Maintenance, Refurbishment & Renewal	Positive 0.97 correlation coefficient	No data

4.4 Conclusion

This chapter has presented the results of all the case studies in a BAU A1-5 format, and the renewals in an expanded format A1-C4 and A0-C4. The results have been presented disaggregated by earthwork types and temporal type further subdivided by earthwork type where appropriate. The main trends highlighted are listed below:

A good mixture of case studies covering all three earthwork types and all three temporal interventions, bar renewals rock cuttings, was collated as illustrated in Table 3.5 with the maintenance data set being of sufficient size (n=35) for further correlations to be performed.

The 50 Case Studies raw BAU Data range is 15.39 to 406,120.59 kgCO₂e. The means for functional unit vary from 577.08 kgCO₂e/volume/year for maintenance, 556.54 kgCO₂e/volume/year for refurbishment and 352.68 kgCO₂e/volume/year renewal which is not as expected as the smallest temporal scale has the highest amount of carbon per functional unit. The whole data set mean of 550.53 kgCO₂e/volume/year lies between the mean for renewals and refurbishments in ascending order.

Positive relationships have been illustrated between time on site, staff transport mileage and cost against carbon.

Renewal type case studies do not necessarily have the highest (or maintenance the lowest) of A4 transport as a percentage of total BAU footprint. The greatest potential for emissions reduction for

maintenance earthwork interventions lies in the A4 transport stage, for refurbishment of embankments in the embodied carbon A1-3, and in the A5 construction process for rock and soil cutting refurbishments. For all renewals earthwork interventions, both A1-3 embodied carbon and A4 transport should be focused on for reduction.

Use of rented equipment with longer lifespans could reduce overall lifetime embodied carbon in this machinery. This amounts to up to 2% of BAU A1-5 and up to 100% of A1-3 CO₂e across the 50 case studies.

There is not an order of magnitude difference between the differing expected lifespans of interventions, but a multiple difference of the mean values of 2.8 between maintenance and refurbishment and 4.1 between maintenance and renewal.

Tentative alignment between renewals BAU EXP scenario A0-C4 and the findings of Kaewunruen, Sresakoolchai and Peng, 2020 in terms of proportions of carbon in each lifecycle stage are found in

Table 4.15.

There is a clear need and drive towards creating baseline carbon accounts in NR (Network Rail, 2020e). This research has addressed the issue of how much carbon is currently being emitted from earthworks projects and provided a framework for ongoing consistent and comparable collection of data for footprinting of earthworks.

When expanded to A1-C4 the five renewals showed a percentage increase on the BAU A1-5 ranging from 85% to 457%, with left in situ or deconstructed showing no alignment with higher or lower percentages. A0 carbon expressed as a percentage of A0-C4 mean value gives 3.6-5.4% of total carbon using the lower and upper estimates respectively, indicating that this “design” stage carbon should be considered as part of an LCA. When expanded to A0-C4, A0 stages contributed 1%, A1-5 53%, B stages 17%, and C stages 29% of the whole lifecycle footprint. When conducting expansions, uncertainty surrounds differing expansion stages, as described and detailed in the summary table provided.

From the comparisons with the literature the HS2 data sets (HS2 Limited, 2022i;c;b;a;g), split by lifecycle stage, showed reasonable alignment with the renewal case studies. The Mott MacDonald data set showed several similarities with the full data set in that this also had several case studies dominating the results and accounting for greater than half of all the total carbon in the data set.

The Rempelos (2023) data set for S&C showed some alignment with the renewal in terms of proportions of carbon being least in material transport, however showed contradictory figures for the percentages of plant transport versus staff transport.

The case studies illustrate the importance of accurate transport distances, due to their potential for the greatest contribution to variability in material transport (A4 section of LCA) (Lokesh, Densley-Tingley and Marsden, 2022a, p.23). A great spread is found (5km Lime Chalk for paint, to 414km for Aldercar for Kee Klamps) and the use of an average would potentially skew final figures, although this practice was identified in LCAs by others in transport infrastructures. For example HS2 assume 55km dry material transport distance and 100km wet (HS2 Limited, 2013b, p.19) with the use of the closest depot for materials and equipment not always being the case when using subcontractors.

Use of the novel Carbon Calculation Data form will aid in collating data in a format congruent with PAS2080 stages and hence aid in future comparisons by lifecycle stage between carbon footprints of projects created using the RSSB RCT.

Chapter 5 Assessing Potential for Emissions Reduction

5.1 Introduction to Assessing Emissions Reduction

Following the carbon “hot spot” identification by intervention type in Chapter 4, the potential for emissions reduction (ER) will now be assessed in the following areas, to meet Objective 3:

- transport carbon, via:
 - greener vehicles for staff transport and
 - greener fuels for Heavy Goods Vehicles (HGVs)
- construction carbon of hand-held tools and Non-Road Mobile Machinery (NRMM)
- lower carbon alternative construction materials
- identifying areas that are hard to decarbonise

As emissions are a function of the emissions factor (EF), see Equation 1, the literature reviews of transport (Section 5.2), construction (Section 5.3) and materials (Section 5.4) demonstrate where the lowest carbon EFs are currently found. In the BAU the EFs chosen were the closest match to the material given in the Carbon Calculation Data form that were available in the RSSB RCT. In the ER scenario, where a lower value EF cannot be found in the RSSB RCT, a HM Government figure is used. Subsequently, in cases where this EF is not found in these databases, trade body figures from the UK and then the world, followed by EFs found in the literature, are used.

The remainder of this chapter focuses on the application of the reduced EFs to the case studies, presentation of the ER scenario case studies, and comparison with the BAU, as well as expanding the ER scenario to include A0-C4 stages. In the end, a taxonomy of interventions for decarbonisation of earthworks differentiated by temporal intervention type is presented. The taxonomy provides the tools to enable evaluation of the optimum order to implement reduction measures to gain the greatest reduction in carbon emissions for earthworks interventions found in the case studies, aligning to those in CE Thinking, the Carbon Reduction Curve and the BVRT, see Table 2.4. This chapter concludes with a discussion of the results along with other decarbonisation strategies.

In conducting this emissions reduction exercise it needs to be acknowledged that there are limitations to this exercise, namely that it has been assumed that lower carbon alternatives used in this exercise for transport, construction and materials emissions are assumed to have the same performance and lifespan to the originals specified. The impacts of different sourcing locations for materials and plant are also not considered in this analysis.

5.2 Reducing Transport Carbon: Assessing the Options

This section provides an overview of the carbon from transport to/from sites (A4 stage) and points to two specific areas highlighted in the case studies for further ER exploration. First, a change to EVs for staff transport in cars and vans, and second use of greener power generation in HGVs for transport of materials and plant.

5.2.1 Staff Transport – A Change to EVs?

From among the obvious carbon reduction options for staff transport, increased uptake of car sharing among staff members and use of public transport to site have been discounted in this thesis, as these requires behavioural change as well as changes to working practices which fall outside the scope of this research, see Section 1.4. This thesis focuses on use of lower emission vehicles such as EVs or vehicles powered by biofuels to deliver ER. The UK's Sixth Carbon Budget identified movement to EVs during the 2020s as a suitable path to advance net zero goals (Climate Change Committee, 2020b). Additionally, ER has been legislated by the UK Government, with a ban on the sale of new fossil fuel vehicles from 2035 (Sunak, 2023). This aligns with NR's own policy to shift to use of EVs for 100% of its own fleet by 2027 (DfT, 2021d, p.19), implying that the movement of the NR fleet will be to BEVs. These BEVs are the only zero emission (at point of use) type of EV currently available. Three other types of EV, hybrid, plug-in hybrid and fuel cell are considered interim provisions due to not being fully electric or at a viable roll out stage for general consumption in the market (Fernandez-Dacosta *et al.*, 2019). Given that NR's fleet comprises around 9,550 road vehicles, an estimated 48,600 tonnes of CO₂ could be saved each year via this change (DfT, 2021d, p.19). Use of BEVs aligns with the literature, where use of environmentally friendly vehicles is also advocated (Kolosz *et al.*, 2017, p.79).

Validation of BEVs being the lower carbon option compared to PHEVs, as assumed, is given in Appendix E.1.

Although BEVs are zero emission at point of use, the caveat is that they are much less energy efficient than other forms of mass public transport, notably rail, and they could create the adverse consequence of increased road congestion as the public and business move en masse from fossil fuel vehicles to EVs (European Union Agency for Railways, 2020, p.10) under the (mistaken) belief that these are the lowest form of carbon transport. Given the projections for road vehicles (worldwide) are 2 billion by 2050 (Ghosh, 2020, p.1), this is an issue that should not be ignored.

When advocating a change to EVs there is a need to ensure that the electricity mix supplying these will not adversely affect their carbon footprint. EVs will have lower carbon footprints in countries

where renewable energy production is advanced, and vice versa in countries where the production is less advanced (Muha and Perosa, 2018, p.50). Some EV carbon footprints (given the German electricity mix in 2014) can even be as high as that of an efficient diesel engine vehicle (Johrens and Helms, 2014, p.5), although these footprints will be reducing over time as these grids decarbonise, (illustrated by a Czech Republic example (Jursova, Burchart-Korol and Pustejovska, 2019, p.1)). Of the estimated 2 billion cars worldwide by 2050 (Ghosh, 2020, p.1), around 150 million are projected to be EVs (Vitta, 2021, p.2), meaning the overall impact of the energy mix will be thus multiplied. As the power generation element can account for between 44-80% of BEV lifecycle GHG emissions (Ambrose *et al.*, 2020, p.2) this could negate the potential for up to 71% saving of GHG emissions via use of EVs compared to fossil fuel vehicles (Onat *et al.*, 2019, p.780) in those countries with higher emission energy mixes. There is an increased need for LCA, particularly to ensure circularity is built into the battery recycling process due to the inclusion of valuable rare earth metals in EV batteries (Ghosh, 2020, p.10) with such large quantities of EVs projected. Technical readiness levels of fuels must also be evaluated alongside fiscal and environmental factors to ensure deployment is optimised given the large quantities of vehicles forecast to be on the road in 2050 (Fernandez-Dacosta *et al.*, 2019, p.591).

The two options for BEVs provided in the RCT, “All Scope” and “scope 1 or 3” were explored alongside the GHG Conversion Factors for 2018 and 2023, see Appendix E.2. The “All Scope” option was found to be a suitable choice for BEVs as the HM Government Conversion Factors for “All Scope” for 2018 align with the values presented in the RSSB RCT.

The “All Scope” BEV option was also compared to the literature (for both cars and vans), see Appendix E.3. This comparison finds that the car and van BEV figures in the RSSB RCT align to some extent with results found in the literature from Moro and Helmers (2017), Peng *et al.* (2017), and Pipitone, Caltabellotta and Occhipinti (2021), and, as such, will be used in the ER scenarios.

The figures in the RSSB RCT have also been subject to validation by the tool owners (Atkins) and their respective databases are detailed in the footprints created, providing some background to the data used. Additional validation for use of the RSSB RCT databases’ Bath ICE figure is found in the literature, where it is regarded as one of the “premium carbon factor libraries” in the infrastructure industry (Rothwell, 2022, p.33).

5.2.2 HGVs – A Move Towards Greener Biofuel?

In this section a range of greener power modes for HGVs are reviewed, see Appendix E.4, demonstrating that biofuels are the most viable to use in this thesis.

A GHG reduction of between 60-86% by carbon intensity (DfT, 2023) is possible, with differing percentage ranges for differing generation feedstocks, 72-97% on gasoline and 65-93% on diesel for generation II biofuel vehicles, (Peng *et al.*, 2017, p.14). These fuels, alongside biofuels, form part of an interim solution on the path to net zero (Zemo Partnership, 2024, p.6). The use of biofuels in HGVs is considered the most viable option for implementation today with their availability in increasing percentages in the fuel mix, right up to B100 (100% biodiesel), have been found to have Scope 1&3 WTW EFs of around one third of B65 diesel (Velazquez Abad, 2016, p.197). Further reductions on whole lifecycle carbon from B7 to B100 of 78% for rigid HGVs 12-32t, and 79% reduction for articulated HGVs 30-44t have been found (Zemo Partnership, 2024, p.24). All HGVs in the UK can use biodiesel B7, with up to 7% biofuel content, and many of the main vehicle manufacturers do not guarantee their power train with more than 7% FAME biodiesel (first generation biofuel) content or 30% HVO (second generation biofuel). Some Euro V vehicles can be used with up to B100 FAME with minor changes such as unit injectors (Velazquez Abad, 2016, p.78).

The above highlights the use of biofuels as particularly suitable for the NR applications of HGVs and LGVs (for use in NRMM see Section 5.3.3), given that in many cases for Light Duty Vehicles (cars and vans) biofuels are suitable “for being used in current powertrains” (caveated by the percentage of biofuel content and addition of unit injectors detailed above) and using the current fuel infrastructure (Puricelli *et al.*, 2021, p.1).

A mixed approach involving lower emissions fuels and electrification of powertrains may offer the best potential for overall ER in HGVs (and NRMMS), and this mixed approach may aid in implementing emissions savings in the short term, rather than waiting for a technological advance, owing to their cumulative effect (Zemo Partnership, 2024, p.6). However, considering the limited data availability on electrification and hydrogen, and the greater emissions potential highlighted above in retrofitting and reuse of existing machinery adapted for biofuel use, in HGVs (and NRMMS), biofuels have been applied to the HGVs case studies in the ER scenarios.

Other low carbon technologies, such as spray reduction mudflaps, low rolling resistance tyres, and automatic tyre pressure monitoring systems for HGVs have demonstrated potentials of between 7 and 17% for reduction of carbon emissions (across differing transport distances from urban to long haul) compared to a do nothing scenario (Velazquez Abad, 2016, p.273). Use of used cooking oil has also found to reduce GHG emissions by 85% (Velazquez Abad, 2016, p.274), aligning with the reduction range found in this thesis (although this is not a scalable solution given the total volumes of used cooking oil in the UK are a small fraction of the fuel required to power the HGV/LGV fleet).

A limitation on using hydrogen in the HGV sector is that the costs of producing and distributing hydrogen are currently prohibitive, and there is no clear path to increased hydrogen use with the

current technology, as the electrolysis of water does not benefit from economies of scale (Fernandez-Dacosta *et al.*, 2019). Both hydrogen and EVs in the HGV sector are relatively immature, with electrification only currently technically feasible for vans and light HGVs (DfT, 2017, p.12), and non-fossil based hydrogen accounting for only a single digit percentage of total hydrogen produced (Fernandez-Dacosta *et al.*, 2019). Electrification of HGVs is burgeoning but is not at a viable roll out stage (interchange25, 2024). Given this relative immaturity in both hydrogen and EVs in the HGV sector, emissions reduction for HGVs, is assessed via a change to lower carbon fuels, namely biofuels, with compressed natural gas (CNG) and liquified natural gas (LNG) are not considered here due to their fossil fuel derivation. See Appendix E.5 for a summary table of biofuel carbon emissions factors/percentage reductions from fossil fuels.

Using the mileage of the case studies and an equivalent mileage per litre figure found by using an equivalency exercise for the carbon emitted from one km of diesel and one litre of diesel, a percentage reduction figure for using biofuel has been established (-74% diesel to biodiesel, -63% petrol to bioethanol based on Scope 1&3), see Appendix E.6.

In line with other EFs used in the RSSB RCT and that these figures have also been the basis of the carbon footprint for HS2 (HS2 Limited, 2023), the government figures presented in HM Government (2023c) will be used here to calculate an emissions reduction factor to apply to HGVs in the RSSB RCT, see Appendix E.7.

Table 5.1 Total Carbon All 50 Case Studies: Fossil Fuels and Biofuels for Scope 1&3

Metric/ Fuel	Diesel	Biodiesel	Petrol	(Bio)ethanol
Total Mileage (all 50 Case studies)	201,211	201,211	201,211	201,211
Mileage per litre of fuel	14.77		12.80	
Conversion to Litres	Total Mileage/ Mileage per litre of fuel	Litres Diesel x 1.3*	Total Mileage/ Mileage per litre of fuel	Litres Petrol x 1.7*
Litres of fuel	13,623	17,710	15,720	26,724
Carbon Emissions kgCO ₂ e/l (Scope 1 & 3)	3.12101	0.6151	2.68094	0.58403
Calculation	Total L x Carbon Emissions	Total L x Carbon Emissions	Total L x Carbon Emissions	Total L x Carbon Emissions
kgCO ₂ e Based on CO ₂ e per litre Scope 1 & 3	42,518	10,893	42,144	15,608
% emissions saving biofuel to fossil fuel using CO ₂ e/l	N/A	-74%	N/A	-63%

NB: Carbon emissions kgCO₂e/l for fossil fuels Scope 3 and Out of Scope factors from (HM Government, 2023c) and Biofuels conversion from Renewables 2018 Global Status Report (REN21, 2018)

The calculated reduction percentages from Table 5.1, are applied to the EFs used in the BAU scenarios for Vans (used for freight not staff transport) and HGVs in the RSSB RCT, see Section 5.2.3.

5.2.3 Concluding Table of Emissions Factors to Use in Transport

Table 5.2 is a summary table of all EFs and percentage reductions regarding transport used in the ER EF scenarios.

Table 5.2 Concluding Table of EFs to Use in Transport ER Scenario

RSSB RCT Library Name	BAU Carbon Factor Value kgCO ₂ e/vkm	ER Carbon Factor Value kgCO ₂ e/vkm	% Emissions Reduction on BAU Value	Source of ER Value
Car Avg. /EV Car	0.22658	<u>0.07469</u>	67.04%	RSSB RCT Defra Cars All Scope (2018)
Van Avg. (Scope 1 or 3)/EV Van	0.25654	<u>0.07951</u>	69.01%	RSSB RCT Defra Vans All Scope (2018)
Freight Van Diesel/ Freight Van Biofuel (Biodiesel)	0.26866 (vkm)	<u>0.069852 (vkm)</u>	74.00%	Equivalency Exercise and Conversion to Biofuel Above
Freight HGV Diesel/ Freight HGV Biofuel (Biodiesel)	0.1136 (tkm)	<u>0.029536 (tkm)</u>	74.00%	Equivalency Exercise and Conversion to Biofuel Above

5.3 Construction Industry Emissions including Hand-Held Tools & NRMMs

Use of electric plant and equipment, and battery powered hand tools, will aid the decarbonisation of earthworks' construction sites. For the plant and equipment used on site there are several pathways to reduce emissions, one being direct electrification of plant and machinery via power from the grid, the second is battery powered electric equipment – which is generally only feasible for hand powered tools, the third is via hydrogen or biofuels, similar to HGVs. Following an overview of carbon in construction more generally, all three will be explored.

In the construction stage of projects, machinery operations can contribute between “72-87%” of the energy consumption of urban transportation infrastructure including roads, subway and railway, indicating that choice of machinery and construction techniques employed affects the energy use on site and hence carbon emissions (Wei and Chen, 2020, p.6). This contribution is comparable to the renewal case study for Killiecrankie where a significant part of the embodied carbon is in the construction (A5) stages in construction machinery operations, see Figure 4.15. This also aligns with LCCAs of rail projects showing the greatest quantity of GHGs being associated with embodied carbon in materials plus those of construction emissions (Saxe *et al.*, 2015). Construction activities in the UK emit around 3% of territorial GHG emissions, meaning that this is an area that has great potential for emissions reduction (Allwood *et al.*, 2022, p.11).

There is a need to reduce diesel use on construction sites to aid in the path to net zero. This ambition to reduce diesel on UK construction sites is practically addressed by the Construction Leadership Council who have outlined their strategy for 78% reduction of diesel on sites by 2035 (Construction Leadership Council, 2023, p.17). This reduction is achieved via a variety of measures across four broad themes of improving efficiency, transition to cleaner fuels, transition to electric, and wider industry support (Construction Leadership Council, 2023, p.7). Other measures include actions such as the launch of an anti-idling toolbox talk video, NRMM management plan to choose the right plant for the job and explore viable alternatives (Construction Leadership Council, 2023, p.16), and targets including 100% use of biofuels used by construction certified as sustainably sourced by 2025.

An 85% reduction in carbon emissions is given in the literature from a change to biofuels from fossil fuel diesel (Velazquez Abad, 2016, p.274), aligning reasonably to the 74% reduction found in the calculation exercise for HGVs see Section 5.2.2. This is noted in the literature as an action that can be taken currently (Karlsson, Rootzén and Johnsson, 2020, p.9).

HS2 is showing a promising path for removal of diesel from its sites and its replacement with a mixture of electric powered (via renewable tariffs), hydrogen and biodiesel. HS2 has set itself more ambitious targets than the UK government, with a target for overall operations to be net zero by 2035, with interim targets of diesel-free sites by 2029 (the first being achieved in 2022) (HS2 Limited, 2022h). HS2 has successfully trialled a hydrogen fuel cell electricity generator in London in 2022 (RailBusinessDaily, 2022) and a FOI has been made to establish the whole lifecycle emissions (HS2 Limited, 2023), as HS2 advocate its use based on zero emissions at point of use, although at thesis submission they have not provided this information.

Alternative decarbonisation strategies for construction include marginal gains, low carbon technologies, task optimisation and hiring of vehicles, implemented alongside industry strategies and

via on site trials, see Section 5.3.4. What follows is the overview of the three pathways of electric, battery, and hydrogen and biodiesel powered tools and equipment.

5.3.1 Electric Powered Tools and Equipment

A switch away from diesel powered equipment in construction and maintenance to electric drives could significantly reduce the GHG emissions of railway track construction and maintenance (depending on the particular country's electricity mix), as this type of work contributes to around 12% of railway track GHG emissions (Landgraf and Horvath, 2021, p.12).

The first electric powered machinery is being trialled in the UK on HS2 (Davidson *et al.*, 2023b, p.229) and on NR sites (Johnson, 2023), with the use of electric NRMMS powered via cables in a cable drum from a 400Vac supply and mobile transformer station also being trialled in Norway (Wiik *et al.*, 2023). A pilot study in Sweden ("Electric Site") found that that a 98% reduction in carbon emissions and up to a 25% reduction in operational cost were possible following replacement of all fossil fuel powered plant on a site with electrically powered alternatives (McCann *et al.*, 2021, p.78), illustrating the additional cost savings possible via a switch to electric machinery.

Although the carbon benefits at point of use are well evidenced, carbon savings from embodied carbon in machinery need further analysis, due to the steel intensive nature of this heavy machinery having considerable embodied carbon. It is also vital that repair and refurbishment of existing machinery is undertaken due to "resource constraints" and the embodied carbon locked in these heavily embodied carbon items of machinery (Allwood *et al.*, 2022, p.11). The embodied carbon in machinery has been discussed in Appendix C.12 and found to account for 100% of the A1-3 BAU carbon (which includes embodied carbon in materials and machinery used on site) in case studies where there are no materials and only equipment is used, and for up to 28% of A1-3 BAU carbon where materials are also included. When measured as a percentage of A1-5 BAU this embodied percentage falls to between 0.01 and 2%.

The carbon embodied in power from the UK grid, owing to the mix of technologies used to create this, is a further area for future analysis, however the UK power mix has not been analysed in depth in this thesis. Details of the potential scenarios for decarbonisation can be found in FES2020 (UK National Grid, 2020), and values for power generation and Transmission & Distribution (T&D) losses have been found to be 0.01792 kgCO₂e per kWh (HM Government, 2023c).

Direct electrification, owing to the need to tap into the mains power grid in sometimes very rural locations (see Appendix C.11), is not a pathway that is advocated at this time. Directly utilizing mains electric power, which is running to power electrification of cables adjacent to some 38% of the

15,846km of GB track infrastructure (ORR, 2023) of which a NR maintains a good proportion, could be one potential source of electrification for machinery in remote sites, which is an area for future research. As electrification is rolled out in the construction sector this will lead to investment in electrified plant and equipment, however this will require “transformative change” and new ways of thinking to be embraced (Allwood *et al.*, 2022, p.1). In summary, decarbonising of on-site activities should be seen as an opportunity, rather than a hurdle for the construction industry to embrace (Allwood *et al.*, 2022, p.7).

5.3.2 Battery Power for Hand Tools and NRMMS

Battery powered tools and NRMMS are zero emissions at point of use. Here, a change to battery power for tools and NRMMS is discussed using EFs based on kWhs. An overview of the potential ER achievable using this strategy compared to the BAU is now given.

Whole lifecycle CO₂e emissions need to be considered when deciding which current fossil fuel powered hand-held tools to change to electric powered (Vogiatzis *et al.*, 2023, p.1). Carbon from the battery’s materials dominates the embodied emissions of the battery electric tool (at 82%) (Vogiatzis *et al.*, 2023, p.9) and the total materials embodied carbon was found to be 91% versus 9% for manufacturing processes of electric tools (Vogiatzis *et al.*, 2023, p.10). When a reference fossil fuel power train is compared to a hybrid fossil fuel with electric power train, and battery electric power train, higher carbon emissions for production stages, lower in use emissions, and higher EOL emissions are seen for the battery electric tool compared to the reference and hybrid versions with overall whole life being lowest for the battery electric tool, see Figure 5.1.

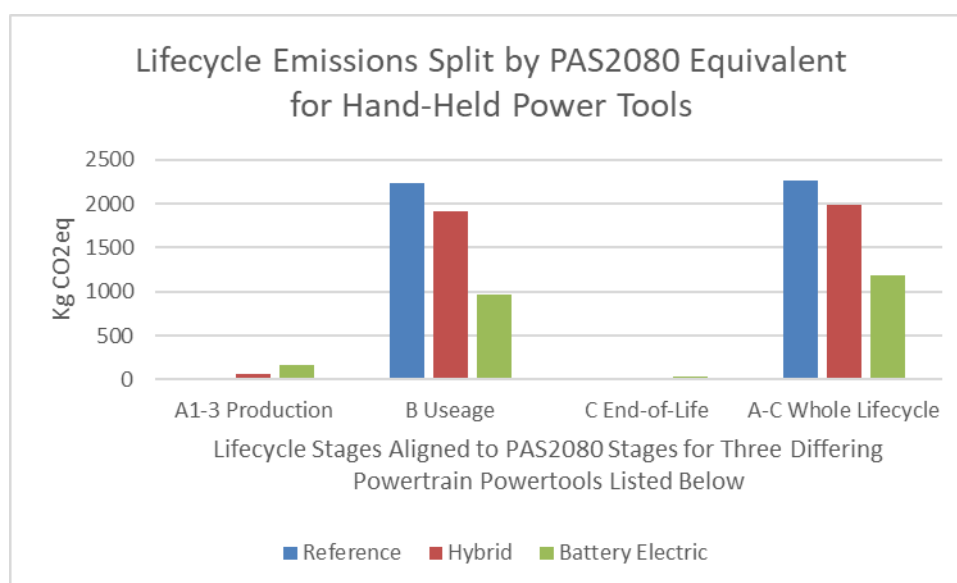


Figure 5.1 Lifecycle Emissions Attributed to Each Phase for Hand-Held Power Tools , amended from (Vogiatzis *et al.*, 2023, p.11)

Figure 5.1 presents a fuller picture of the move to battery electric as fossil fuels are phased off site, indicating that use of battery electric tools will have lower whole lifecycle emissions (by around half) compared to fossil fuel powertrains or fossil fuel with electric powertrain tools.

The running hours are known for plant and equipment in the case studies, however, equating these running hours with a battery charge time is challenging. Several differing emissions factors have been found based on kWh. From a larger battery study a range of 58.0-77.9 kgCO₂e/kWh is found (Pell and Lindsay, 2022, p.4) and an average of 73 kgCO₂e/kWh for lithium-ion batteries, which sits within the aforementioned range is also found (Melin, 2019, p.8). This average figure is a cradle-to-gate figure exclusive of charging emissions (with a range of 39-196 kgCO₂e/kWh (Melin, 2019, p.2)). Limited data is available on how many recharges this figure includes during the lifetime, while the effects of using differing energy mixes, while addressed in Melin (2019), are unclear as to their effect on UK battery recharges.

Due to the potential ambiguities introduced with limited recharge data, this scenario was explored further with equivalent kWh battery used for NRMMS and handheld tools as a conceptual exercise. When applied to all of the case studies, details of ER percentages were found to vary between 23-84% against the BAU compared to 23-94% for the biofuel scenarios used in the ER. The battery scenario increases the reduction percentages found in the ER biofuel scenario by between 1 and 11% further for some studies. For some studies there was a decrease in the ER potential, largely due to embodied carbon and carbon expended in charging adding to the overall footprints.

Due to the ambiguities of recharge data and potential large size of batteries required for NRMMS (which may, as explored at the beginning of this section, result in larger lifetime carbon costs), battery electrification is a pathway that cannot be advocated at this time. However, as battery technologies mature and circularity principles are embedded in their production and disposal stages, this may become a more viable option should the lifetime carbon of these items lower considerably.

As such, the biofuels savings will be applied to these items, with the note that use of electric/battery equipment may provide further savings and is an area for future research. Encouraging a move towards biofuels now will ensure these large items of plant currently in use with protracted lifetimes (20-30 years in some cases) are not prematurely scrapped, thus saving on their embodied carbon being wasted and additional carbon being used for new machines. As machines reach their EOL they could then be replaced with battery/electric models as appropriate for the sites they will be used on.

5.3.3 Hydrogen & Biodiesel Powered Tools & Equipment Including NRMMS

Due to the relative infancy of hydrogen use in NRMMS and lack of data in the literature (HS2 declined the FOI request to provide full LCA at this time (HS2 Limited, 2023)) biofuels will be used as the ER strategy for plant and equipment currently powered by diesel or petrol on site, and the biofuels conversion factors to fossil fuels discussed in Section 5.2.2 will be used here. This section begins with an overview of strategies to reduce carbon in railway infrastructure construction, followed by an overview of the calculations performed for both diesel and petrol engine to arrive at a reduction percentage to be applied to the EF used in the BAU scenarios for engines based on kWh.

HS2, in their bid to lower emissions and pollutants, have required all NRMMS to meet stage V certification for emissions via retrofitting of these extended lifespan plant items (Davidson *et al.*, 2023a, p.217) and increasing the life of these heavy assets on site thereby avoiding earlier scrapping and increase lifetime embodied carbon costs for this machinery (Davidson *et al.*, 2023a, p.226). A trial of HVO and its performance vs red diesel was carried out by HS2 in 2021, finding that although air pollution benefits were found, carbon reduction benefits could also be realised by such a change (Davidson *et al.*, 2023c, p.255). The trial further highlighted the differing “bridging” fuels, aside from biofuels, that could be utilised to give some form of carbon saving, including low carbon fuels: defined as “fuels that can provide GHG savings compared to fossil fuels on a life-cycle basis,” renewable fuels, which are defined as “fuels made from biomass and renewable electricity” (Davidson *et al.*, 2023c, p.257). The trial also highlighted that the biggest savings could be made by retrofitting older machinery to accept such fuels (Davidson *et al.*, 2023c, p.259).

HS2 has successfully engaged with three UK technology companies to trial, at the HS2 construction site near Euston station in 2020, a hybrid Clean Air Gas Engine (CAGE) to reduce emissions by replacing diesel power in construction (Davidson *et al.*, 2023b, p.229). This CAGE uses clean gas and biogas fuels to replace diesel with the dual purpose of CO₂ reduction and reduced exhaust emissions. The new gas engine technology developed as part of this project is “incorporated into gas-solar battery hybrid power systems for off grid buildings and welfare units” (Davidson *et al.*, 2023b, p.230). This system reduces the 24/7 use to between one and three hours per day to charge the batteries when low. This technology was proven in this trial as viable, though not yet fully scalable.

Use of alternative fuels has been explored by HS2 as part of their drive to net zero via a trial of HVO and enhanced HVO at a HS2 construction site near Coventry in 2021 (Davidson *et al.*, 2023c). The test focused on tailpipe emissions in NRMMS, however it acknowledged that use of bio diesel compared to red diesel would give carbon savings. Most notable in this study is that new machines required only a change of fuel filter to run with the biofuels, although no percentage of biofuels in the mix is given, it is assumed therefore that these were 100% HVO and enhanced HVO.

Fuel substitution to 100% HVO100 for all of the construction machinery and heavy transportation in a Swedish study was found to contribute around “half of the abatement from the benchmark to BAT” (Best Available Technology) (Karlsson, Rootzén and Johnsson, 2020, p.9).

The EFs used for biofuels required calculation as a percentage decrease from diesel or petrol equivalent as these biofuels were not available in the RSSB RCT. An equivalency exercise was carried out and the calculations for determination of EF to use for biofuels in diesel and petrol machinery based on Government Databases, see Appendix E.8 and E.9

Appendix E.8 outlines the calculations performed to determine L of biodiesel for diesel machinery based on kWh to then be converted to L of Biodiesel. Following on from this exercise the reduction values used for scope 1 and scope 1&3 were compared to the values to validate which percentage to use and apply to the kWh which was found to be an 74% reduction for diesel powered plant using biofuel.

Appendix E.9 outlines the calculations performed to determine L of bioethanol for petrol machinery based on kWh to then be converted to L of Bioethanol. Following on from this exercise the reduction values used for scope 1 and scope 1&3 were compared to the values to validate which percentage to use and apply to the kWh which was found to be an 80% reduction for petrol powered plant using biofuel.

5.3.4 Alternative Decarbonisation Strategies

There are a variety of alternative decarbonisation strategies for NRMMS outside of changing the power source. Potential marginal gains in carbon reduction can also be found via design of a reverse logistics network to minimise carbon emissions and transportation distances (Aljuneidi and Bulgak, 2020, p.107), with speed and load playing a role in determining carbon emissions (Akan, Dhavale and Sarkis, 2017, p.1202).

Halving emissions over the lifetime of a construction is one of the challenges being worked towards by the UKRI and industry via increasing R&D, investment, establishing new models for doing business, and speeding up new technology adoption, moving away from lowest cost towards whole life costing and increasing knowledge sharing and dissemination. Nearly half of those employing such strategies respond that these are having a large positive impact on CO₂ emissions produced on site and waste produced on site (Frontier Economics and BMG Research, 2022, p.110). Designing out carbon, task optimisation, hiring of vehicles and increased carbon literacy as strategies to reduce carbon are now explored.

5.3.4.1 Designing Out Carbon

Designing out carbon at the earliest possible stage links to the carbon reduction curve presented in Figure 2.3, where this will realise the greatest carbon savings. For NR earthworks designing out carbon could be via size of the earthwork required, use (or not) of piles on engineered embankments (Powrie, 2024) or for maintenance interventions, use of low nutrient soil and plantings to reduce future mowings (Sterling *et al.*, 2023). Use of BIM advocated by UK government as a key strategy to bring about sustainable, low-carbon, green construction in the UK (HM Government, 2013) and inroads are being made as shown by the results being seen in the industry of lower carbon and less waste on construction sites (Frontier Economics and BMG Research, 2022). Efforts need to increase in the transport sector as current evidence shows that the sector is lagging behind the energy and waste sectors in emissions reductions (DfT, 2020, p.10).

In addition to the large-scale NR internal decarbonisation programme, with activities planned across the entire estate and operations, the riding sunbeams project is advocated by NR. In this project solar PVs directly powering trains, (DfT, 2020, pp.27-29) could be installed on rail corridors and south facing embankments. This could aid in turning unproductive land, such as land not suitable for biodiversity increase or future vegetation maintenance into an energy producing asset and, jointly with other offsetting measures such as sequestration via plantings, add to the decarbonisation of NR projects.

5.3.4.2 Task Optimisation

Carbon savings can be realised on site from task optimisation. As heavy NRMMs perform multiple repetitive actions that produce large quantities of carbon emissions (Parente, Correia and Cortez, 2016, p.3601), actions to optimise tasks on site, such as minimising idling could bring about additional carbon savings. The over specification of this type of equipment could also be addressed to reduce both the in use carbon and the embodied carbon locked into such equipment (Parente, Correia and Cortez, 2016, p.3602). Task optimisation such as planning out tasks is less relevant for the majority of the case studies, due to the small nature of the machinery used, although for some of the renewals, with longer project times, up to 17 weeks, this could prove beneficial.

A report by ICE on environmental LCA of railway track beds finds that sensitivity of external factors, such as ballast, cement and steel, “alternative construction and maintenance machinery use and fuel consumption”, can have a great effect on the overall footprint (Kiani, Parry and Ceney, 2008). This further points towards reduction in fuel consumption which could be achieved via task optimisation and improved selection of machinery sizes, as a valid method for reducing carbon in railway infrastructure.

5.3.4.3 Hiring of Vehicles

Reducing emissions resulting from fossil fuel use, particularly of NRMMs, can make a significant impact on individual project's carbon footprint, as this accounts for between 99.6% and 100% of the A5 stage of the renewal carbon footprints.

The change to hiring from ownership could form part of an in depth supply chain analysis, the starting point highlighted by Onat and Kucukvar (2020). This could enable a move towards a carbon neutral construction industry in countries by identifying the role of larger more complex supply chains in their procurement of construction machinery for example, rather than just focusing on regional impacts (Onat and Kucukvar, 2020, p.1).

Hiring of vehicles may reduce some of the embodied emissions as only the emissions from use of the equipment on any particular site will need accounting for, similar to that used for this thesis. This may incentivise the manufacturers to provide longer lifespan equipment to the rental companies (UIC, 2021, p.22) and allow access to newer machinery on site meeting higher emissions standards. This newer standard construction machinery is engineered to meet differing standards having reduced CO₂ emissions Stage III-B machines average 525g/kWh, Stage III-A machines average 875g/kWh, Stage IV machines average 575g/kWh (Desouza *et al.*, 2020, p.1). The factors for stage IV and III-B machines are significantly lower than some of the factors found in the case studies where a 14t excavator 70kW with BAU EF of 57.52kgCO₂e per hour equating to 821gCO₂e/kWh and Colmar T10000F 150kW with BAU EF of 118.5kgCO₂e per hour equating to 790gCO₂e/kWh. The stage of machinery was not captured by the subcontractors; this is an area where significant carbon savings could potentially be made via specification of the lowest emission construction machinery.

For large infrastructure owners this may provide a useful carbon reduction over their fleet and reduce lost carbon from scrappage as machines are hired and not owned. It is noteworthy that the carbon should not just be "outsourced" to the rental company to avoid the perception of greenwashing.

An example of sharing plant and equipment between sites located close together was found in the case studies analysis for Ox Hey whereby the machinery used previously in Fields Bridge (13t longreach, telehandler, tower lights and RRV) was also used here resulting in 0 km transport distance for Ox Hey. Thereby reducing the transport of plant and machinery carbon footprint for Ox Hey. A second example of equipment reuse is found in WHL whereby the stainless-steel anchors were removed from site following use for re-use at other sites. Advocating sharing of resources between geographically proximate sites is therefore potentially advantageous for NR in terms of reducing CO₂e in plant transport.

5.3.4.4 Carbon Literacy

Behaviour, communication and skills are the three key requirements for collaboration and culture change required to achieve carbon reduction. These three requirements can be met via improved carbon literacy which, when improved throughout the supply chain, has the potential to impact carbon reduction positively and has been publicised by HS2 with their involvement with the Supply Chain Sustainability School (Ellis, Manidaki and Pantelidou, 2020, p.7). Carbon literacy is further described as “a crucial skillset” (Institution of Civil Engineers, 2021, p.20) and noted by the ICWG (ICWG, 2021) as requiring promotion in terms of knowledge and tools, highlighting the critical importance for all engineers to attain this vital skillset.

Use of PAS2080 is seen as key to enabling collaboration in the industry but its uptake has been “cautious” (Ellis, Manidaki and Pantelidou, 2020, p.7). Those who are aligned with the standard have found that the relationship between carbon reduction and cost reduction is clear, owing to carbon being a suitable proxy for materials and energy used in building infrastructure (Ellis, Manidaki and Pantelidou, 2020, p.7).

5.3.5 Concluding Table of EFs for Plant and Equipment

ER carbon factors have been calculated based on the percentage reductions outlined in Table 5.3, see Accompanying Materials for full details of reductions, found in the RSSB RCT.csv downloads for ER Scenarios.

Table 5.3 Concluding Table of NRMM Emissions Factors with Examples

RSSB RCT Library Name	BAU Carbon Factor Value kgCO ₂ e/hr	ER Carbon Factor Value kgCO ₂ e/hr	% Emissions Reduction on BAU Value	Source of ER Value
155kW Plant	118.5	<u>31.33</u>	74% (73.56%)	2023 GHG Emissions Factors Scope 1+3 for Biodiesel
Drilling Rig 200kW	319.7	<u>63.25</u>	80% (80.22%)	2023 GHG Emissions Factors Scope 1+3 for Bioethanol

5.4 Assessing Emissions Reduction from Materials

5.4.1 Introduction to Materials Used in the Case Studies

In this section the materials found in the case studies are detailed and lower carbon alternatives outlined, with the lower value EFs then applied to the ER scenario. The materials used in the case studies are detailed material by material, with additional explanation of the process provided in Appendix E.10. For each material an overview of the material percentages used in the case studies and an assessment of greener materials has been conducted and a suitable emissions factor to apply to the ER scenario detailed. When choosing a suitable ER EF the order of precedence outlined in Section 5.1 has been used. The final EFs chosen for each material are presented in the concluding materials' summary table in Appendix E.11. The material "hotspots" found here align well with those found on analysis of RSSB RCT footprints in RSSB DECARB report T1228 whereby granite, soil and concrete all contributed large percentages to the overall footprints, around 88%, 7%, 6% respectively (RSSB, 2024b, p.16).

5.4.2 EF Review of Aggregates, Granite, Limestone, Sand, Slate, Stone & Gravel

Aggregates, granite, limestone, sand, slate, stone and gravel are used in case studies in quantities from several kilograms to tens of tonnes. Percentage contributions of these materials to the case studies' A1-3 stage for the BAU scenarios are presented in Appendix E.10.1. The percentage contribution illustrates the range of percentage contribution values of the differing materials, from less than 1% to 100% for the case studies. The EFs of the materials presented in Appendix E.10.2 will now be reviewed and justification for the ER EF chosen presented in Appendix E.10.3 after a summary of the influence of transport mode and distance on these embodied carbon factors.

Circularity and transport play a large part in the footprint of these materials. Using natural gravel as concrete aggregates uses less fossil fuel and emits less CO₂ than crushed gravel. This may not always be possible to implement at a site due to natural gravel not being available or environmental impacts of gravel extraction (Gustavsson and Sathre, 2006). Transport by rail compared to road will also have emissions savings for these materials when looking at the operating carbon, however if future road haulage is used with a modernised and therefore an assumed more fuel efficient vehicle fleet this will be the more realistic and economically viable solution to aggregate transportation (Zuo *et al.*, 2018). Data from Rempelos (2023) does not indicate large percentage reductions in footprints using rail transport, see Section 4.3.5. The use of rail to transport bulk materials may be more feasible for NR given their links to Freight Operating Companies (FOCs) and the location of their work sites (on or adjacent to the existing railway infrastructure network). Transport by rail will require future in depth

LCA analysis before being advocated as it may be found to have a limiting distance factor for a given weight of material (Lefebvre *et al.*, 2019). This is due to the potential for rail freight to include extended distances to quarries offering “lower emission products.” The geographical distance to the quarry from site, may be negated when investigated further and a local quarry (with potentially higher emission products), using HGV transport may be the lower emission solution overall. For example, using RSSB RCT EFs for transport load for 1 t 50 km via HGV gives 5.7 kgCO₂e compared to rail freight for 600 km giving 25kgCO₂e, the rail freight figure would need to reduce to less than 140 km to match the emissions figure for HGV freight.

5.4.3 Emission Factor Review of Bricks

Bricks play a minor part in the case studies, accounting for between 1 and 13% of the A1-3 stage for Fearn Station and Wellington St respectively. Bricks with a lower EF could not be found in the RSSB RCT, and figures for bricks via the primary material production route are available in the 2023 GHG conversion Factors (HM Government, 2023c). A figure of 0.24175 kgCO₂e/kg for primary production, is found but no further figures are provided for re-use, open loop or closed loop source production. This figure does not represent a reduction in emissions, as such EPDs were sourced from the case studies to see if these had a lower EF. It is known from the literature that bricks can be made more sustainable via use of waste incorporated into bricks such as waste sludge, agro waste (agricultural waste), plastic waste, industrial wastes, Construction & Demolition (C&D) wastes (Saravanan, 2023). A real life example of this concept is the K-BRIQ (solid/perforated brick weight of 2.4/2.2 kg) and with EF of 16.67 gCO₂e per unit made from 90% C&D waste (KENOTEQ, 2024). The figures outlined above are presented in Appendix E.10.4.

From the EPD sheet for an engineering brick as used in the case studies several differing EFs are given, the lowest available is detailed in Appendix E.10.4, and used for the ER scenario. The EPD is considered to be the most accurate data as it is based on actual production data. EPDs are created according to ISO 14025 & EN 15804.

5.4.4 Emission Factors Review of Concrete & Cement

Concrete and cement use occurs in several of the case studies and accounts for between less than 1%, and up to 100% of the A1-3 stage. The contributions of this material to the case studies are detailed in Appendix E.10.5.

This section explores concrete use in infrastructure, railways especially. A detailed exploration of specific green concretes and cements currently available is provided in Appendix E.10.5. It concludes with justification for the ER EF chosen for both cement and concrete.

The LCA of transportation infrastructure including railway infrastructure is highly dependent on a small number of materials including cement and concrete (Grossrieder, 2011; Kjerkol and Kalager, 2011; Wei and Chen, 2020). Cement is found to account for 32% of LCA in a Swedish Study (Stripple and Uppenberg, 2010, p.13) and cement and concrete accounted for 30.53% of emissions in a LCA of energy use and CO₂ of passenger rail systems in the Rio de Janeiro Metro (de Andrade and D'Agosto, 2016, p.526). Optimising design to reduce volumes of construction materials which have the greatest impact such as cement and steel is highlighted by Kadehors *et al.* (2021) who note energy use over the lifecycle and minimizing emissions from transport and site operations as notable measures to achieve carbon reduction in infrastructure construction.

Carbon additions and subtractions in the manufacture, transport and use of cement and concrete are detailed in the industry's roadmap to Net Zero (MPA, 2020). Additions to CO₂ include quarrying raw materials, raw material preparation, preheating and calcination, clinker formation in the kiln, milling and blending, cement despatch, concrete production and delivery. Clinker cooling and storage provide circularity of CO₂ in the economy, whereas concrete use, EOL and recyclability, along with the built environment, give (future) negative CO₂ emissions. UK Cement manufacturers have started on the path to net zero by investing in the latest technology, switching from fossil fuel to greater use of renewable energy. They have also developed lower carbon cements and concretes via use of waste products (MPA, 2020) and industrial by-products as partial cement replacements to lower carbon content (Hamad, 2019, p.1). Research is also ongoing into concrete that can sequester carbon as calcite, up to 22g per 1kg in the latest formulations compared to 13g per 1kg in traditional concrete (Hamad, 2019, p.37).

LCA has been applied to the manufacturing of common and ecological concrete, using the most commonly used boundary in such studies of cradle-to-gate in work by Vieira, Calmon and Coelho (2016), aligned to A1-5 of PAS2080 (BSI, 2016). In a review of 12 studies published between 2010 and 2015 in various countries around the world including France, the US, Iran, and Denmark, it is cited that products should be designed such that they contain recycled waste as their raw material, and that at EOL they can be recycled and used again, becoming the raw materials in yet another product, and so on and so forth (Vieira, Calmon and Coelho, 2016). This reuse of materials at EOL is essential if embodied carbon emissions are to be reduced and will be possible given that concrete gravel recycling recovery rates are considered to be 50% (Wei and Chen, 2020). One example of waste being used as a Supplementary Cementitious Material (SCM) is steel making waste which has a further use in mineral carbonisation. This would work as both a capture and storage technology increasing sequestration of carbon (Ibrahim *et al.*, 2019). This topic will be explored further in Chapter 6 when offsetting and sequestration is discussed in depth.

A diagram of replacement materials currently available is presented in Figure 5.2. This diagram is constructed using data from various sources as cited. This diagram outlines several methods for emissions reduction including use of SCMs, transport distances and differing aggregates. A more in-depth review of concrete and cement EFs, forming the basis of the ER EFs used is presented in Appendix E.10.5.

Based on *Al-Hamrani, A. et al (2021)*, *Mostert et al. (2021)*, *Roychand et al. (2020)*, *Deschamps et al. (2018)*, *Scrivener, K.L et al (2018)*, *Miller (2018)*, *The Concrete Centre (2020)*

Globally abundant ultramafic rocks – could be truly carbon negative
Scrivener, K.L et al (2018)

Calcareous Material
eg Limestone

⊕ Melted at 1400 to 1650°C = Cement Clinker

Argillaceous Material
eg Clay

Round gravel

NCA

Natural Coarse Aggregates
CO₂ footprint two orders of magnitude lower than cement, typically 10% of CO₂ footprint (Scrivener, K.L et al 2018)

OPC
Ordinary Portland Cement

PCC

Portland Cement Concrete



Recycling Solutions include Aggregates production, recycled sand. High amount of CaO rich fines produced – can be used a raw materials for clinker. Scrivener, K.L et al. (2018)

Admixtures
>5% of mix Carbon itself therefore negligible, but gives carbon reduction benefits in terms of reduced water use etc
The concrete Centre (2020)

WRA/HRWRA
“In terms of current usage two main types are dominant: water-reducing admixtures (WRA) and high range water-reducing admixtures (HRWRA) also referred to as super-plasticising admixtures”
The concrete Centre (2020)

Reduced Carbon footprint Compared to OPC

- GGBFS + FA = “Superior to PCC in terms of long-term resistance to sulfate attack” (Al-Hamrani, A. et al, 2021)
- “High levels of SCM replacement do not consistently result in lower GHG emissions for the production of concrete per unit strength (Miller, 2018)
- GGBFS + Red Gypsum as binder (see production of green concrete using red gypsum and waste – Hughes et al (2009) ref to be added above)

GGBFS: Ground Granulated Blast Furnace Slag
[Steel slag from waste water plants Roychand, et al. (2020)]



MK
Metakaolin

NCA Vs RCA

- RCA Concrete transport distance should not be more than 2 X NCA (Mostert et al. 2021)
- Energy demand for stone crushing higher than for extraction of gravel, RCA may be less favourable to gravel based concrete, NCA (Mostert et al. 2021)
- For the use of truck transport instead of rail, there is an increase of 7-100% [of GHG/Mpa] for these mixtures (Miller, 2018)

SCMs
Supplementary Cementitious Materials

Cellulose Nanocrystals extracted from plants and trees

Group 1: Industrial Waste

FA
Fly Ash

SF
Silica Fume

SCMs “not recommended in concrete exposed to a higher temperature than 400°C”
(Al-Hamrani, A. et al, 2021)

Group 2: Agricultural Waste

RHA
CA, Corn-cob ash
SA, Sawdusts ash

Group 3: Municipal Waste

Glass & Plastics
[GP = glass powder Deschamps et al., (2018)]

RCA
Recycled Coarse Aggregates

Lower Carbon Footprint than NCA, Lower Cost (using local material), Plus avoided landfill

C&D
Construction and Demolition Waste

Green Concrete

- Increased use of low-CO₂ supplements (SCMs) and more efficient use of PC clinker (Scrivener, K.L et al 2018)
- Contributes toward better exploitation of waste materials, Less consumption of natural resource and Less carbon footprint (Al-Hamrani, A. et al, 2021)

CCS & CCU

Scrivener, K.L et al (2018)

Figure 5.2 Diagram of Replacement Materials Available for Green Concrete

5.4.4.1 Green Concrete

To arrive at the final concrete factor for the reinforced and precast concrete, the concrete type itself plus the modification factors as listed must be used. As such the concrete with 70% Blast Furnace Slag is used coming from the most recent Bath ICE in the RSSB RCT plus the original modification factors which are from Bath ICE 2.0 and for which no lower values could be found in the RCT or in the GHG conversion factors or literature. The concluding table of concrete ER EFs to be used in the case studies is illustrated in Appendix E.10.9.

5.4.4.2 Green Cement

Details of UK EFs to use for differing cement mixes are given in Appendix E.10.10, indicating the higher and lower EFs of the two differing cement mixes used in the case studies. The lower value where given has been used and added to the comparison table of emissions factors, see Appendix E.10.11.

For Portland Cement, no lower value is available in the RSSB RCT or in the GHG conversion tables, therefore, the trade body figure has been taken as the ER EF. For CEM II/A-L cement, the RSSB RCT figure for 28% cement replacement is used. Cement with 80% GGBS is not used as this is not considered comparable as it is specified CEM II/B only and does not cover a range of cement as the CEM II/A-M does.

5.4.5 Emission Factor Review of Geotextiles

Geotextiles are utilised in geogrids in the case studies. Terram (geotextile trade name) T10000 is the geogrid used in several of the case studies and as per its data sheet consists of 70% PP and 30% PE (Groundtrax, 2022). EFs are available in the RSSB RCT (from Plastics Europe EPD 2008 and the Bath ICE database v2.0) for Polypropylene and Polyethylene materials as detailed in Appendix E.10.12. The ICE values have been examined by Raja *et al.* (2015) and compared to primary manufacturing data. The ICE values were found to have an EF 46% higher indicating that the ICE values overstate the embodied carbon in geotextiles. Reduced values (against ICE database) for woven geogrids calculated in Raja *et al.* (2015) are 2.35 kgCO₂/kg nonwoven average, extruded geogrids 2.97 kgCO₂/kg, 2.36 kgCO₂/kg woven geogrid (Raja *et al.*, 2015, p.398). These figures are used for the ER scenarios as these have been assembled using primary manufacturing process data. Use of the 2.36 kgCO₂/kg woven geogrid EF however has resulted in a 9% gain in emissions compared to the BAU EF values when apportioned 70% PP/30% PE.

In the BAU scenario the figures for Geogrid were not available in the RCT database, therefore the material was input as two constituent materials of PP and PE. Following the ER exercise the Raja *et al.* (2015) figures were considered to be the most accurate as they were for the actual product being used. Use of these figures highlights that when actual materials values are used, such as those from EPDs, these do not necessarily lead to an emissions reduction. A summary of the figures used in the BAU and found in the literature are presented in Appendix E.10.12.

Further carbon savings can be attributed to geosynthetic based solutions due to their use allowing 'marginal' soils that are site derived to be reused, and as such reducing the amount of imported fill material and its associated transport related emissions. From the case studies fill materials can account for considerable quantities of carbon, outlined in Section 5.4.4, and in Appendix E.10.7 and E.10.8 which illustrates the percentage contributions of transport distances of these fill materials (Dixon, Fowmes and Frost, 2017, p.463). These further reductions cannot be quantified without additional data, so further reductions in EF for use of geosynthetic materials is therefore not included, and the figure used from Raja *et al.* (2015) is used with a ER of -9%. In the future, following identification of suitable case studies involving fill materials and geosynthetic solutions a comparison carbon footprint could be created using the Carbon Calculation Data form capturing weights and emissions factors of fill and geosynthetic material emissions factors, to compare to use of imported fill (without use of geosynthetic materials) but including transport emissions of the fill to enable such comparisons to be conducted. A comparison such as this is what the RSSB RCT is intended to be used for, and incorporating use of the novel data capture form would ensure all relevant PAS2080 lifecycle emissions are captured and compared (as required by NR guidance, see Table 3.1).

5.4.6 Emissions Factors Review of Paint

Paint is used in one case study, Lime Chalk Embankment, and accounts for 16.76% % of the A1-3 stage in this case study. The paint used in the BAU is general paint with an EF of 2.91 kgCO₂e/kg, however when water borne paint is chosen, a lower EF of 2.54 kgCO₂e/kg is used in the ER scenario.

5.4.7 Emissions Factors Review of Steel

The impact of the energy to produce primary steel is "unquestionably the most important process on all the impact categories on the entire lifecycle" of HSR and standard railway (de Bortoli, Bouhaya and Feraille, 2020, p.814). A further route to lower steel embodied carbon in projects is to substitute steel with low carbon alternatives such as plastic (Mi-ROG, 2020, p.10).

The quantity of steel varies in earthworks, with the amount being dependent on the intervention type. For three of the renewals, the embankments of Station Plantation and Aldercar, and the soil

cutting at Bowling Green, cess support works were carried out on the embankments and the soil cutting has a regrade slope type intervention carried out (see Appendix A.1). For all three interventions the steel in these works accounted for 56%, 46% and 42% respectively of their A1-5 BAU CO₂e.

Steel tends to represent a significant proportion of the A1-3 material embodied carbon stage across the case studies, ranging from just under 10% to close to 100% with further details of the percentage contributions to embodied carbon presented in Appendix E.10.13. When calculated as a percentage of the A1-5 BAU they can account for around half of the footprint values of renewals (detailed above). Additionally Appendix E.10.13 outlines further issues with regards to scrap and virgin steel routes. The concluding table of steel factors ER EFs can be found in Appendix E.10.14.

In conclusion NR needs to increase its steel recycling rates and ensure all EOL steel is processed appropriately to increase the stocks of recycled steel available in the market and to them. This will enable NR to take advantage of the reduced carbon emissions from steel production via this route and to be able to move closer towards achieving full circularity of its steel.

5.4.8 Emission Factor Review of Timber

The case studies reveal that the wood utilised in earthworks is in above ground features such as fencing, and its substitution benefits are unknown in this context. The bulk of the literature focuses on wood substitution in buildings with few references for railways, apart from use in sleepers being found in Rempelos, Preston and Blainey (2020). Wood use in construction has both substitution and sequestration benefits, the latter is explored further in Chapter 6. Regarding substitution benefits, wood products show notable emissions savings when compared to non-wood alternatives (Bergman *et al.*, 2014). A concluding table of ER EFs for wood is presented in Appendix E.10.15.

5.4.9 Concluding Table of Material ER EFs

A concluding table of the BAU and ER EFs for all materials indicating the percentage reduction potential from BAU for each material chosen can be found in Appendix E.11 and copied below for ease of reference, see Table 5.4 .

Table 5.4 Concluding Table of Material Factors Used in Case Studies , with BAU EF from RSSB RCT and ER EF Value from Cited Source with ER Figure Bold and Underlined

RSSB RCT Library Name (A-Z)	BAU Carbon Factor Value kgCO ₂ e/kg	ER Carbon Factor Value kgCO ₂ e/kg	% Emissions Reduction on BAU Value	Source of ER Value
Aggregates and Sand - Expanded Clay	0.39321	<u>0.06332</u>	83.90%	RSSB RCT Bath ICE 3.0
Bricks - General	0.213	<u>0.1309</u>	38.54%	EPD from (Almeida <i>et al.</i> , 2010); Marshalls Bricks & Masonry (2021)
Cement - CEM I - Portland Cement	0.912	<u>0.860</u>	5.70%	The Concrete Centre (2020)
Cement - CEM II/A-L - Portland-Limestone - 13% Limestone	0.799	<u>0.666</u>	16.65%	RSSB RCT Bath ICE 3.0
Concrete - RC40/50 - C40/50 MPa - Cement Replacement - 0%	0.169	<u>0.072</u>	57.40%	RSSB RCT Bath ICE 3.0
Concrete - Reinforced - modification factors	0.077	0.077	0%	RSSB RCT Bath ICE 2.0
Concrete - Precast (prefabricated) concrete - modification factors	0.029	0.029	0%	RSSB RCT Bath ICE 2.0
Granite	0.7	<u>0.0030</u>	99.57%	Trade Body (MPA, 2022)
Limestone - General	0.09	<u>0.034</u>	62.22%	RSSB RCT Bath ICE 2.0
Paint - General	2.91	<u>2.54</u>	12.71%	RSSB RCT Bath ICE 2.0
Geogrid (Terram) PE 30% of 2.54 PP 70% of 2	0.762+1.4=2.162	2.97(extruded geogrids) <u>2.36</u> (woven geogrid)	-9.16%	Raja <i>et al.</i> (2015)
Sand - General	0.0051	<u>0.0027</u>	47.06%	MPA (2022)
Stainless Steel – General	6.52	<u>2.08</u>	68.10%	(Worldstainless, 2023, p.8)
Slate - General – Mid	0.035	<u>0.007</u>	80.00%	RSSB RCT Bath ICE 2.0
Steel - Coil - Galvanised -	2.03	<u>1.54</u>	24.14%	RSSB RCT Bath ICE 2.0

World Average Recycled Content				
Steel - Sheet - Galvanised – Virgin	3.01	<u>1.54</u>	48.84%	RSSB RCT Bath ICE 2.0
Steel - Wire – Virgin	3.02	<u>0.47</u>	84.44%	RSSB RCT Bath ICE 2.0
Stone - Gravel/Chippings	0.017	<u>0.0027</u>	84.12%	(MPA, 2022)
Timber - Softwood - Exc. CS	0.263	<u>-1.29</u>	590.49%	RSSB RCT Bath ICE 3.0

The ER EFs in Appendix E.11 have been applied to the BAU scenarios to create the ER scenarios, see Section 5.5.

5.5 Applying Emission Reduction to Case Studies

The ER scenario case studies were constructed using the same process as that outlined for the BAU in the User Manual (see Accompanying Materials), but using the values for ER EFs for transport outlined in Section 5.2.3, plant and equipment outlined in Section 5.3.5, and materials outlined in Section 5.4.9. The ER case studies include the same set of assumptions and exclusions from Section 3.4.5 and the same embodied carbon values as the BAU, outlined in Appendix C.12.

In summary the major reductions are use of biodiesel as a 100% replacement for fossil fuel for road freight, staff transport changed to BEVs, and all fossil fuel powered hand-held equipment and NRMMS replaced with 100% biofuel, These are detailed against each case study in Appendix E.12.

5.6 Results of Applying Emissions Reduction to Case Studies

Following application of the ER EFs to the BAU case studies the ER scenarios were created as described in the section above. The ER scenario carbon amounts, see Appendix E.13, were found, with a highest ER reduction potential percentage of 94% and a lowest value of 23%. The mean values for all case studies, differentiated by temporal intervention type and earthwork intervention type are presented in Table 5.5.

Table 5.5 Mean ER Scenario Carbon Reduction Percentage from BAU kgCO₂e

	Mean ER Carbon Reduction Percentage			
<i>Intervention Type</i>	<i>All</i>	<i>Embankment</i>	<i>Rock Cutting</i>	<i>Soil Cutting</i>
Maintenance	68%	65%	70%	68%
Refurbishment	74%	79%	74%	72%
Renewal	65%	68%	N/A	61%

Table 5.5 demonstrates the differences in the mean ER carbon reduction percentages. The percentages given are the percentage reduction of the ER scenario from the BAU scenario, meaning that for example for “Maintenance All” the ER scenario CO_{2e} is around one third of the BAU value. There are differences between both temporal intervention types, with refurbishment having the greatest and renewals the least impact between earthwork intervention types. When differentiated by the temporal and intervention type, embankment refurbishments have the greatest potential for reduction and soil cutting renewals the least potential for reduction using these ER measures.

Descriptive statistical analysis (see Appendix E.15, E.16, E.17, E.18, E.19, E.20) finds the average reduction percentage of all 50 case studies by differing lifecycle stage, see Appendix E.18. The mean ER percentage by lifecycle stage between ER and BAU scenario is presented in Figure 5.3.

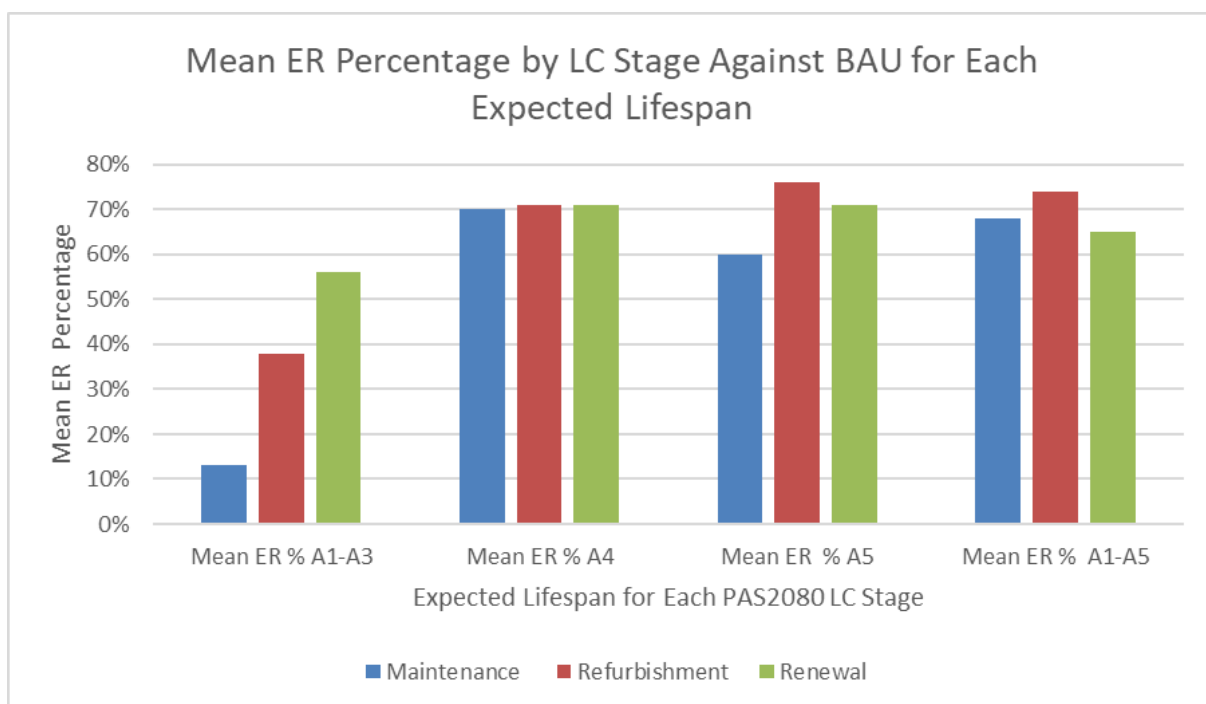


Figure 5.3 Mean ER Percentage Reduction by Stage Against BAU for Each Lifespan

Figure 5.3 illustrates that for interventions on the maintenance temporal scale, the focus should be in the A4 stage of the lifecycle where staff transport and transport of materials and/or plant to site is situated. For interventions on both the refurbishment and renewal timescale, the largest emission reductions can be made in both A1-3 and A5 lifecycle stages. These large emissions reduction potentials, align with renewal hotspots of A1-3 and A5 (Najafpour Navaei et al., 2022). There are differences in the emissions savings that can be made, over 50% emissions savings from materials in the A1-3 lifecycle stage for renewals, and nearly 40% for refurbishment. These figures reflecting that maintenance interventions do not contain the same amounts of A1-3 carbon owing to their limited use of materials due to the types of intervention carried out under this temporal scale (such as surveys). A 60% reduction in the A5 lifecycle stage for maintenance type interventions can be

attributed primarily to use of handheld fossil fuel powered machinery and/or NRMMS here. These results indicate that the biggest savings in carbon can be made by a rapid change from fossil fuel powered vehicles for staff transport to BEV models. It is found from closer inspection of these items in the RCT that savings of around 2/3 compared to fossil fuel vehicles were found, and a carbon saving of over 60% can be made across all temporal interventions for the A4 lifecycle stage, illustrated in Figure 5.3.

Variations found in the ER can be aligned with the carbon hotspots found in the BAU scenarios of A4 for maintenance, A5 for refurbishment and A1-3 for renewal, where 60%, 40% and 40% respectively of the relevant case studies had more than half of their respective A1-5 carbon in that lifecycle stage.

Fuel consumption in the A5 stage used in construction and maintenance activities dominates that stage in all case studies, particularly the refurbishment case studies, which corresponds with the literature (Lokesh, Densley-Tingley and Marsden, 2022a, p.14). The next steps following ER, align to the carbon reduction hierarchy from HS2 (HS2 Limited, 2017b), with carbon sequestration being the next step to apply to the residual carbon to achieve net zero, discussed further in Chapter 6.

Application of a range of interventions simultaneously as outlined above in the ER scenarios demonstrates that the carbon footprint of the earthworks' studies in stage A1-3 could be reduced by around 60%, 40% and 30% via a change to lower carbon materials for renewals, refurbishment, and maintenance type interventions respectively. In the A4 stage all earthwork types can have their carbon emissions reduced by over 60% via a switch to BEVs for staff transport. Fossil fuel carbon emissions dominate in the A5 stage for all earthwork types, and it is in this stage that around 60-80% carbon reductions can be made. From the taxonomy of interventions several can be utilised in the short term, such as use of BEVs, with additional carbon savings accumulating via continued and increased use of these as the UK power grid itself further decarbonises in parallel (UK National Grid, 2020). As the UK National Grid decarbonises to net zero by 2050, a number of scenarios are being considered. The fastest to slowest trajectories being respectively, "leading the way" (achieved via the fastest decarbonisation route, significant changes to lifestyle and use of hydrogen and electrification for heating) also giving a small negative carbon emission balance of around 10 MtCO₂e by 2050 (for the UK), followed by "system transformation" and "consumer transformation." The "steady progression" scenario is the slowest decarbonisation route, with minimal behaviour change and no decarbonisation of heat, leaving a considerable gap to achievement of net zero in 2050 of 258 MtCO₂e (for the UK) (UK National Grid, 2020, pp.6,12).

Further innovations ready for immediate deployment, for specific interventions for both earthworks and NR in general, include low carbon plant and lower carbon standard high volume elements (McCann *et al.*, 2021). In the long term, technological advances in electrification of both large

NRMMs and handheld power tools could bring about even greater decarbonisation benefits in construction. Emerging technologies in this arena, in the form of battery and direct powering of large NRMMs (via cables from a cable drum for a 400Vac power supply and mobile transformer station) (Wiik *et al.*, 2023) are evolving at pace. In the long-term modification and procurement of new build NRMMs using this zero emissions at point of use technology may be able to bring about substantial additional decarbonisation benefits in the A5 stage to those projects where they are suitable and viable to be used.

The mean figures for the ER scenarios compared to the BAU for all 50 case studies have been translated into a hierarchy of interventions by lifecycle stage to show the optimum implementation order by temporal intervention type and lifecycle stage, to bring about the greatest decarbonisation benefits for NR see Table 5.6.

Table 5.6 Hierarchy of Interventions by Stage for Differing Expected Lifespans

Intervention Type	1 st Intervention	2 nd Intervention	3 rd Intervention
Maintenance	A4	A5	A1-3
Refurbishment	A5	A4	A1-3
Renewal	A4, A5	A1-3	-

For refurbishment and renewal type interventions, the additional savings to currently used fossil fuel powered equipment and NRMMs, via a switch to electrification, will be of greatest benefit in their A5 stages which are the primary intervention for both.

5.7 Applying ER to Expansion A0-C4

The ER principles have been applied to the expansion scenario A0-C4, created for the BAU scenario, creating a new scenario of ER EXP for the five renewals. Further details pertaining to expansion of the five renewals is found in Appendix E.21, E.22, and E.23 with A0 values as detailed in Appendix E.14.

The BAU and ER Expansion percentage contribution graphs are presented in Figure 5.4 and Figure 5.5. Note the similarities between the two in terms of percentage distributions. See Appendix E.24 and E.25 for the tables used to create this data.

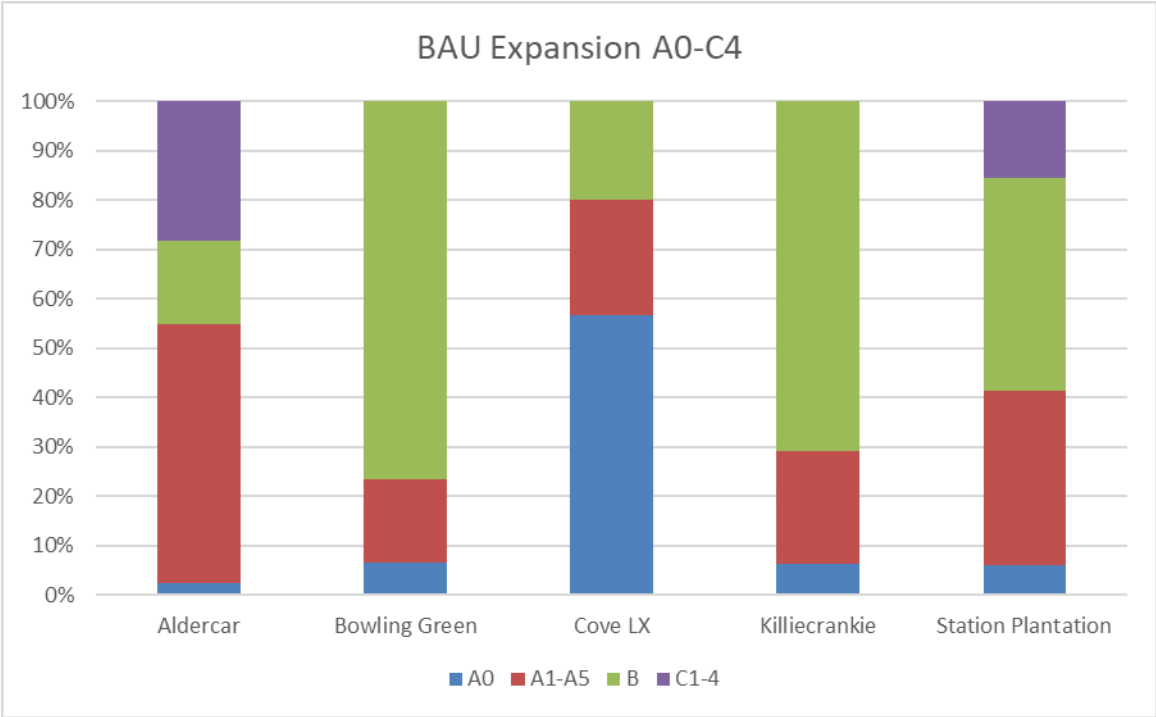


Figure 5.4 Percentage Contribution of Each Lifecycle Stage for BAU Expansion A0-C4

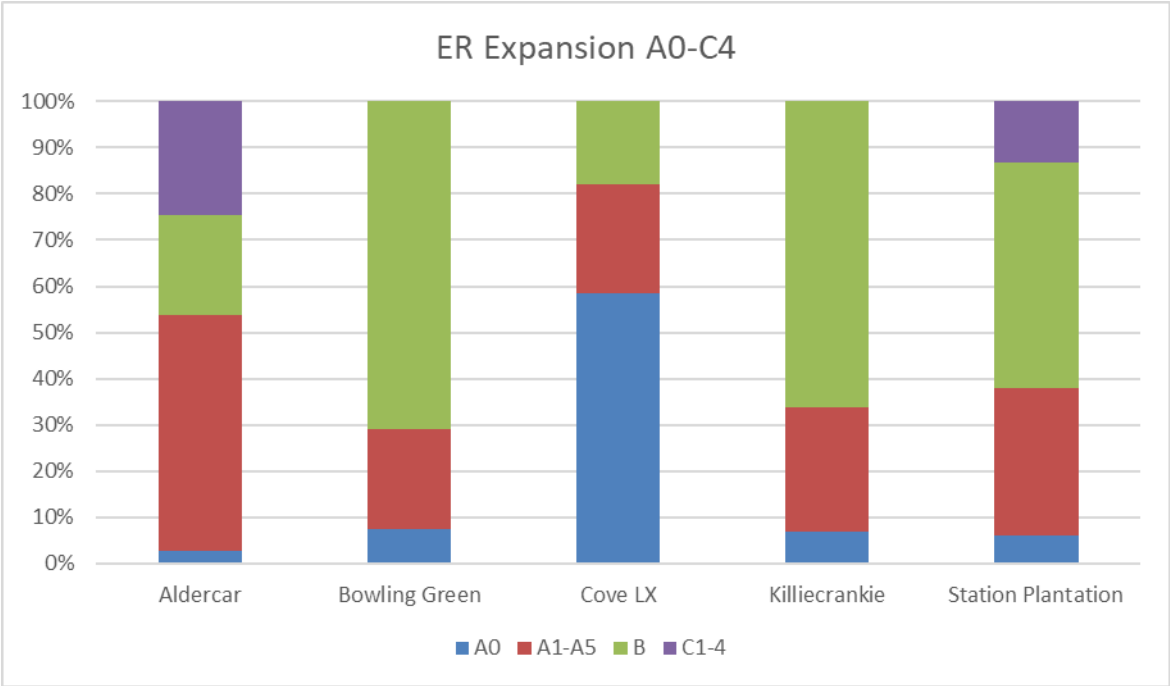


Figure 5.5 Percentage Contribution of Each Lifecycle Stage for ER Expansion A0-C4

Further analysis in the form of percentage differences between the total A0-C4 between BAU and ER expansion scenarios are given in Appendix E.26. The percentage difference between BAU EXP and ER EXP ranged from 64% to 69% reduction across the five renewals. The residual values found after applying ER, ranging from 3,699 kgCO₂e in Cove LX to 241,707 kgCO₂e in Aldercar, are offset as part of the D stage, see Chapter 6.

5.8 Discussion of Results of Applying Emissions Reduction

Here the impact of ER across assets in the NR portfolio is addressed. The impact of the transport changes with a move to BEVs for staff transport and biofuels for HGVs, along with a change to biofuels for NRMMS and plant and equipment on site, and the implications of use of lower carbon versions of materials, are given in relation to how this mitigation aids NR in its journey towards net zero by 2050.

As emissions from “maintenance of the existing network” (Marsden, Lokesh and Densley-Tingley, 2022, p.2) are at least as significant as any new infrastructure emissions, there is a need to address these emissions. The extrapolation below illustrates their size in relation to the NR portfolio.

The impact of ER on NR assets extends beyond the 50 case studies found in this research. Using the NR Asset Count (as per NR data (Rethish, 2023)) gives an indication of the impact of carbon reduction of applying ER measures. Figures from NR for 2023/4 Period 01, aligning with April 2023, show the total number of embankments are 102,448, rock cuttings 15,826 and soil cuttings 73,362, giving a total of 191,636 earthworks assets that the findings of this research can potentially impact.

Using the “workbank” data from the Eastern Region, extrapolated for the whole of NR and a whole CP, along with the average BAU carbon amounts from the case studies, the carbon implications for the top four maintenance interventions, accounting for ¾ of all anticipated maintenance interventions have been found. The extrapolated data for the whole of NR over the CP suggests around 1,466 maintenance interventions are anticipated. The four main intervention types, accounting for 75.1% of maintenance interventions, were found to be vegetation management, vermin eradication, surveys and drainage maintenance. When these four intervention types are aligned with their BAU averages, from the case study data, it is found that these account for around 2.6 million kgCO₂e over the CP, see Table 4.12. Application of the ER measures could make savings of around 68% to these maintenance interventions, or around 1.8 million kgCO₂e could be saved. The quantities of carbon, percentage contributions, and extrapolation details are presented in Appendix E.27.

5.8.1 Transport

The impact of the transport changes with a move to BEVs for staff transport and biofuels for HGVs has been illustrated in the ER scenario with percentage reductions from BAU of 67-69% for BEVs for cars and vans respectively, and 74% for HGVs being possible via a move to B100 biofuels. Any movement to EVs should be made in such a way that there is no premature scrappage of ICEVs and that these are only replaced at EOL.

5.8.2 Construction

It is clear that decarbonisation of machinery supporting maintenance and construction activities on the rail network is required to enable NR to move towards their goal of net zero by 2050 (DfT, 2021d, p.20). From the overview of differing technologies to reduce emissions from NRMMS a movement to use of 100% biofuels has been advocated as the preferred technological solution for implementation at the current time, with use of electrification being possible once this reaches greater technological maturity.

The recent announcement of the first HS2 diesel free site where a range of diesel-free new technologies and greener equipment have been deployed demonstrates that implementation of diesel-free sites to all in infrastructure construction is a viable option (HS2 Limited, 2022f). HS2 is leading the way in innovative solutions to both net zero carbon trajectories and air pollution with the CAGE (Davidson *et al.*, 2023b, p.229) and NRMMS retrofit solutions (Davidson *et al.*, 2023a) discussed earlier, alongside other novel solutions such as fully electric renewable energy on site via solar pods (HS2 Limited, 2022f).

B20 and B30 are the current biofuel used for NRMMS (British Ports Association, 2021) with use of B100 a potential future choice of biofuel with modifications, despite it being in the research stage (Suthisripok and Semsamran, 2018). The use of biofuels for HGVs and NRMMS is made alongside the need for NR to meet net zero emissions in its own fleet being reflected in its sub-contractors choices as they also have their own Science Based Targets to meet as NR contractors (Network Rail, 2020b). New cars and vans are to be zero emission via EV implementation from 2035, new HGVs weighing under 26 tonnes to be zero emission by 2035, and all HGVs by 2040 changing to biofuels as an interim solution to plug this gap (HM Government, 2022a, p.167).

Alongside changes to the energy source for NRMMS there is a need to make a more rational choice of, and efficient use of, construction machinery on site via optimisation of the management of construction processes (Cheng *et al.*, 2020, p.1). This could be achieved via greater use of those with relatively low energy consumption, which will reduce both fuel and electric power consumption on HSR construction sites (Kaewunruen, Sresakoolchai and Peng, 2020, p.13). A similar saving could be realised for the case studies using significant amounts of machinery on site.

5.8.3 Materials

Minimising use of high carbon construction materials as a piece of the carbon reduction puzzle alongside recycled material and construction waste management are advocated to reduce emissions from HSR construction (Kaewunruen, Sresakoolchai and Peng, 2020, p.13). Acknowledgement that

use of greener materials use is beneficial to carbon reduction is given by DfT (DfT, 2021d, p.20). Furthermore, the need for whole life carbon to be factored into all infrastructure projects by 2027 is explicitly stated in DfT (2021d, p.21).

The main area investigated in the ER scenario in relation to reduction of embodied carbon is via the use of greener, lower carbon products. Other strategies could include using less material, but as this decision would form part of the design of an earthwork, this is outside the scope of this thesis.

Differing outcomes of interventions to reduce carbon at differing stages of building projects have been illustrated previously in the carbon reduction curve in Figure 2.3 where the greatest impacts on carbon emissions from a project being implementable at the earliest intervention stage of “build nothing.” As the case studies concern earthworks that need interventions, it is in the “build clever” and “build efficiently” realm that materials, transport and construction activities can be levered to realise carbon savings. Utilising these two aforementioned principles, cost savings can also be made, delivering a cost savings of around 5% directly from carbon reductions in a linear infrastructure scheme to widen the M25, and further carbon savings have also been achieved in the same scheme via use of recycled aggregates (HM Treasury, 2013, p.14).

Barriers to implementation of lower carbon alternatives must be removed. Suppliers and manufacturers comment that a great many low carbon innovations are being produced, however designers need to specify their use and contractors need to buy them (HM Treasury, 2013, p.16). This requirement is alongside the need for the regulatory environment to support use of these low carbon innovations (HM Treasury, 2013, p.16). This disconnect between innovation and industry needs further investigation to ensure all relevant innovations are applied in an expedient manner. This expedient application is required to ensure that the greatest possible carbon savings can be applied to NR infrastructure in the fastest possible time.

Although transport emissions for materials can be significant, as highlighted in the concrete and cement section, alternative materials and technologies utilized in the concrete and cement industry provide the greatest potential opportunities for emissions reduction (Akan, Dhavale and Sarkis, 2017, p.1206) and it is here that efforts should be made to mitigate carbon emissions. Incentivisation of contractors to use local suppliers to reduce the transport emissions of using these materials should not be discounted, as these can account for relatively large percentages of the materials’ transport emissions (Akan, Dhavale and Sarkis, 2017) and (MPA, 2021, p.9). The speed and load of the transport choice must also be taken into account as additional mitigation can be found here. For a fuller exploration of this mitigation with respect to HGVs see Velazquez Abad (2016).

5.8.4 Databases

Use of databases and data in literature rather than primary data represents a weak point in LCA analysis (Colangelo *et al.*, 2020, p.1803). Use of such data could potentially skew results depending on what assumptions are made, such as size of HGV, which may be standardized across a particular study for all materials (Colangelo *et al.*, 2020, p.1796) such as that used for this study whereby all HGVs have been classified as HGV average. This is an area where in future more detailed data may garner more detailed carbon footprints.

5.8.5 Summary

In summary, construction remains an area where there is a “core of emissions” which are hard to decarbonise, despite the application of potential new innovations. (Marsden, Lokesh and Densley-Tingley, 2022). Regarding implementation of differing ER strategies outlined in this chapter, industry evidence shows that a significant portion of the reduction in emissions is achievable with scaling up and deploying of existing technologies/processes (McCann *et al.*, 2021, p.10) and (Mott MacDonald, 2019, p.5).

From 2017 data, the UK infrastructure industry has control over 13% of these emissions in terms of capital and operation carbon, and influences a further 41% via end users in conjunction with actions made by others (McCann *et al.*, 2021, p.10). All carbon reduction strategies deployed in the race to net zero must align with the ambitions of the UK see Appendix B.7.1 and NR, see Figure 2.13. This is to ensure SBTs are deployed in line with the rapid levels of decarbonisation required in the 2020s CP6 and 7 for NR, giving a 65% reduction in embodied carbon versus 2020 levels. The normalising of decarbonisation in the 2030s aligns with CP8 and 9 for NR, giving an 85% reduction by 2040 on 2020 levels, and then during the 2040s, CP10 and 11, the final push to net zero must be made (Expedition, 2020, p.15).

It is clear that PAS2080 is beginning to be adopted in the linear transport infrastructure industry (see Table 3.1 and HS2 Limited (2021)), however it has yet to be fully adopted which could potentially stifle collaboration between infrastructure owners and contractors and slow down adoption of novel innovations to the carbon mitigation problem (McCann *et al.*, 2021, p.31). The need for more granularity in data collection is addressed in this thesis via use of the PAS2080 template in the RSSB RCT and use of the novel carbon calculation data form to allow for detailed, consistent and complete data collection and carbon footprint creation to allow for useful benchmarks in earthworks interventions to be set by NR (McCann *et al.*, 2021, p.32). A specific earthworks strategy for carbon reduction is proposed in this thesis with differing solutions based on intervention type and temporal intervention lifetime, with a specific focus on the PAS2080 stage that will realise the greatest

mitigation potential for that particular intervention based on the case study data. As the reduction strategy is focused on lifecycle stages, it is not overly prescriptive on how it is to be achieved. This will provide NR project managers with freedom in how they apply reduction in a given PAS2080 stage and open up use of novel and emerging strategies for carbon mitigation.

Implementation of the measures outlined in the ER scenarios will aid in bringing NR emissions down in line with the NDC 2030 target of 68% reduction compared to 1990 levels, in line with the UK's net zero goals (HM Government, 2022b, p.1) as well as their own targets of 46% by 2029 and 65% by 2034 as per their SBTi trajectory outlined earlier in Figure 2.13. Implementation of the ER EXP scenario as applied to the renewal case studies shows that reductions of between 64 and 69% between the BAU EXP and the ER EXP A0-C4 scenarios can be achieved via use of the identified emissions reductions outlined in detail in Chapter 5. This means that in line with the NR SBTs these would be in line with the reductions expected by 2034 and as such their implementation needs to be by this date. The emissions reductions targets discussed above are not static. It is reported by the BBC that the CCC indicate a more ambitious target of 81% reduction by 2035 (on 1990 emissions) is required for the UK to make a "credible contribution" towards the 1.5°C Paris target (BBC News, 2024; Climate Change Committee, 2024).

A minimum cost route to net zero has emerged from the zero carbon world project (McCann *et al.*, 2021, p.11) and is interpreted in Figure 5.6 alongside strategies applied in the two scenarios of ER and ER EXP and the projected net zero. A multi-pronged approach is required to carbon reduction, with these solutions being additive for carbon reduction, similar to the strategy outlined from responses to the MaGIC survey (Wise and Winslow, 2019), and that found in the SNCF REUSE project (UIC, 2021) discussed in Chapter 2. This figure has a focus on technological substitution instead of process improvement which for construction and maintenance are known to have high levels of error and waste (McCann *et al.*, 2021, p.12).

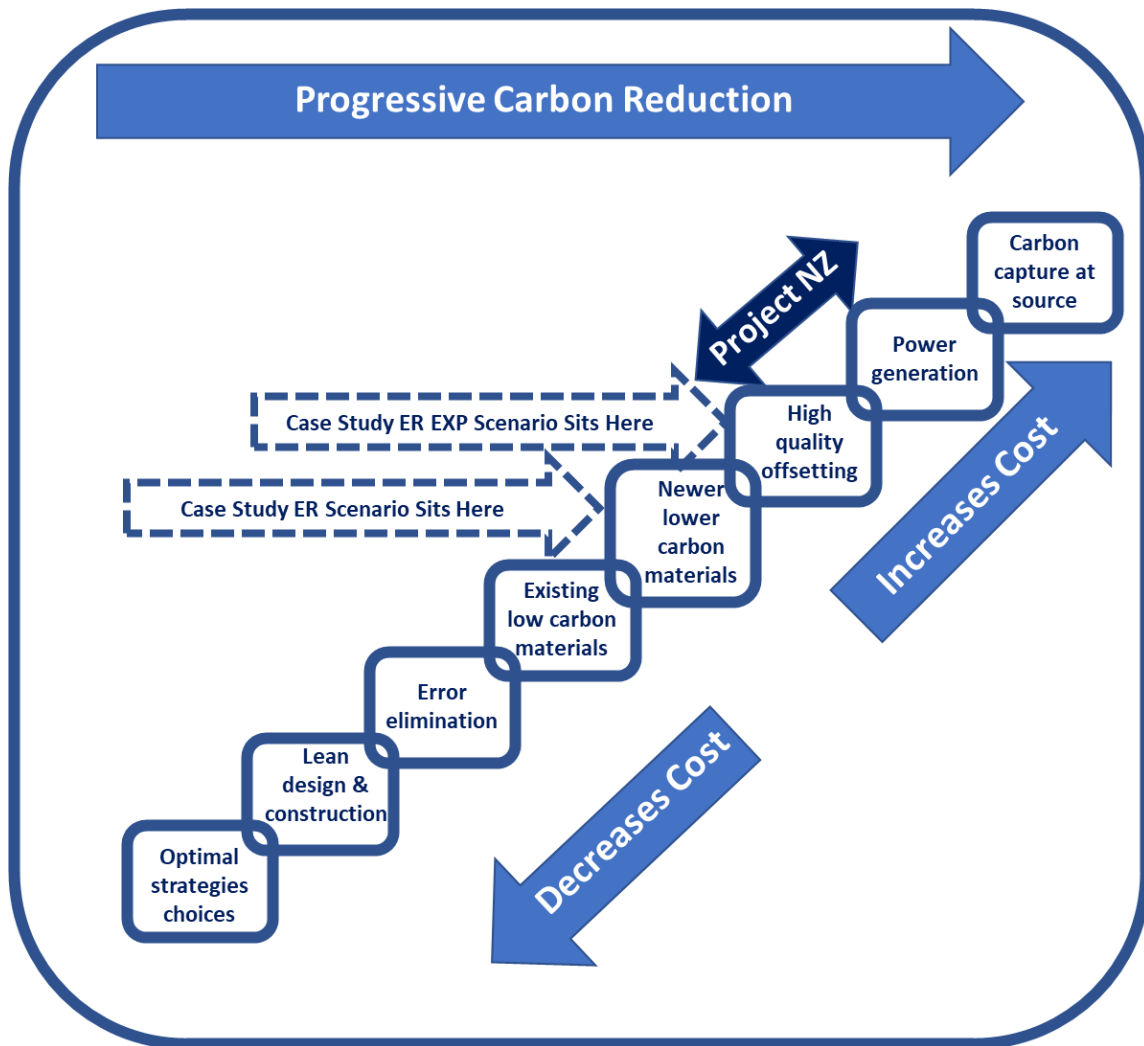


Figure 5.6 Minimum Cost Route to Net Zero Carbon, amended from (McCann *et al.*, 2021, p.11)

Use of the RSSB RCT and PAS2080 template are advocated in this thesis along with implementation of carbon reduction measures in the PAS2080 lifecycle stages as indicated for specific earthworks, see Table 5.6. Aligned to these recommendations, there are initiatives in low carbon that have the potential for progression in the future for NR and include standardisation and adoption of carbon accounting tools, (McCann and Behar, 2021, p.11)..

Chapter 6 Assessing Potential for Emission Offsets

6.1 Introduction to Offsetting

Following carbon mitigation measures outlined in Chapter 5 the potential for carbon offsetting for the residual carbon is now assessed, the differing methods compared, and the CDR methods chosen justified, and then applied to the ER EXP scenario renewal case studies. This is followed by quantification of the offset required to balance the residual carbon in the case studies to reach net zero, meeting Objectives 4 and 5. This section provides an introduction to offsetting followed by an overview of the variety of terminology used in offsetting, including NETs, CDR, NbS for carbon sequestration, see Section 6.2.

The remainder of this chapter focuses on a review of rail corridor vegetation, linear forests and hedgerows, as habitats aligned to railways, see Section 6.3. Details of the differing methods available for calculation of the chosen CDR for the five renewal case studies are then given. This is followed by application of the chosen methods to the case studies, as well as the application to the whole NR estate, see Section 6.4.

The outcome of the above, a taxonomy of interventions, provides results to enable evaluation of the best order of intervention to gain the largest offsets in carbon emissions for a variety of earthwork interventions typically used throughout the railway. The chapter ends with two substantive discussions on assessing the potential of combined CO₂e reduction and offsetting to reach net zero, see Section 6.5, and the potential sustainability co-benefits of CO₂e offsetting, see Section 6.6.

Use of Carbon Dioxide Removal (CDR) is “unavoidable” in meeting the path to 1.5°C and remaining within the remaining carbon budget (IPCC, 2022, p.4). Without CDR, traditional mitigation technologies will not be sufficient to meet net zero by 2050 (Beuttler, Charles and Wurzbacher, 2019 p.2).

A crucial assertion of offsetting, as a method of CDR, is that an amount of carbon sequestered is interchangeable with an equivalent amount of carbon emissions reduction on a global scale (Conant, 2011, p.238). It is on this premise that carbon offsetting is applied following emissions reduction to illustrate the potential for the renewal case studies to reach net zero. This premise is not the contention of all, some indicate that the value of carbon sequestered is not the same as that mitigated (Arias *et al.*, 2021, p.TS64; Patrizio *et al.*, 2021, p.2), and that this asymmetrical relationship implies additional CDR is required as compensation for emissions to claim the same change in atmospheric CO₂ (IPCC, 2021, p.99). Others argue there is not an exact relationship between the effect of emissions and the sequestration capacity of nature (Fang, Heijungs and de Snoo, 2013,

p.81), and also that “afforestation is not a substitute for reduced GHG emissions” (Arora and Montenegro, 2011, p.514), with the carbon cost of increased afforestation needing to also be accounted for (Plantinga, Mauldin and Miller, 1999, p.823). The literature is inconclusive on whether these offsets should be counted against infrastructure carbon (Marsden, Lokesh and Densley-Tingley, 2022, p.2), and use of Nature-based Solutions (NbS) and Negative Emissions Technologies (NETs) is advocated to tackle stubborn emissions (Marsden, Lokesh and Densley-Tingley, 2022, p.7).

A distinction between mitigation and offsets is provided in the Oxford Principles of Offsetting (Axelsson *et al.*, 2024) with three gradients of reduction and two of removal. The three reduction principles are avoided emissions from the geosphere (without storage), from the biosphere, and then from the geosphere with storage. The two removal principles are to the biosphere, and then to the geosphere, aligning to a higher risk of reversal followed by lower risk (Axelsson *et al.*, 2024, p.12). The higher risk meaning that this sequestered carbon in the biosphere, in forests for example, could be rereleased due to forest fire. The lower risk in the geosphere as this carbon is effectively ‘locked away’ in geological storage, see Section 6.5.4 and Figure 6.12.

A risk for all organisations is that *ALL* will be able to access the “net” in net zero, thus reducing the necessity for *ALL* to act now and begin mitigation efforts (Marsden, Lokesh and Densley-Tingley, 2022, p.12). This illustrates mitigation as the primary step followed by offsets for “stubborn carbon,” a main contributor of which is embodied carbon in materials (Lokesh, Densley-Tingley and Marsden, 2022a, p.7). This hard to decarbonise gap is around 22-48% of the whole life carbon for 1 km of new electrified single track (Lokesh, Densley-Tingley and Marsden, 2022a, p.7), which is similar to that found after application of the ER scenario to the case studies, leaving a gap of 31-36% (BAU EXP A0-C4 to A0-C4 ER EXP) across the 5 renewals to be offset.

6.2 Overview of NETs, CDR and NbS

Six major NETs or CDR (including NbS) are afforestation reforestation (AR), biochar and soil carbon sequestration (SCS), ocean fertilisation (OF) or blue carbon, bioenergy with carbon capture and sequestration (BECCS), enhanced weathering (EW), and direct air capture (DAC), and are briefly overviewed in Figure 6.1 (Minx *et al.*, 2017, p.2). Further exploration of these topics can be found in Appendix F.15.

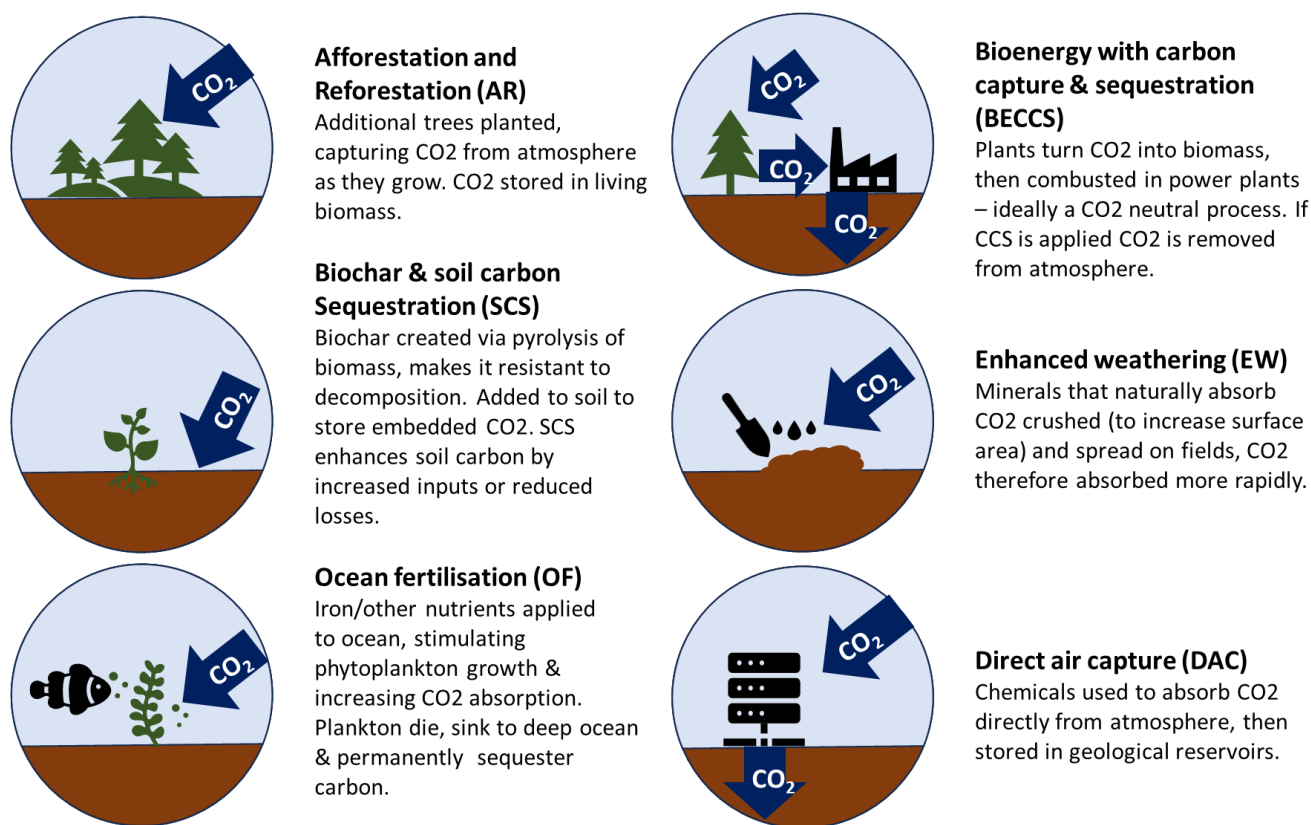


Figure 6.1 Six Major Offsets, amended from (Minx *et al.*, 2017, p.2)

The strands of CDR used for offsetting in this thesis are explored further and detailed fully in the appendices, see Appendix F.15.1. A brief summary of AR including SCS and LULUC and trees followed by EW, permanence of storage, saturation, and leakage, and sequestration rates for AR and EW from the literature only is provided here.

6.2.1 Afforestation and Reforestation (AR)

Here forest area and diversity of planting are discussed, followed by LULUC. See Appendix F.3 for further details of peatlands and grasslands.

With regards to forest area, the UK has great potential to adopt AR and utilise carbon sequestration to offset residual carbon emissions owing to its relatively low percentage of forest area as a total of land area, 13% compared to the European and world percentages of 46% and 31% respectively (Forestry Research, 2020, p.206).

Ancient and long established woodlands make a greater percentage contribution to the carbon stocks in GB, 36% versus 25% (Reid *et al.*, 2021, p.13). Older trees, of larger diameter, store and sequester more carbon than smaller diameter trees (Chaparro and Terradas, 2009, p.46) highlighting the link between tree age and sequestration rates. Speed of growth also affects sequestration rate,

with fast growing species sequestering carbon at a greater rate than slow growing species (Hirons and Sjöman, 2019, p.39).

A clear understanding of sequestration rate versus storage potential is needed, (see Figure 6.2 (Gregg *et al.*, 2021)). The early peak in carbon sequestration rate can be seen in this figure along with the increasing cumulative carbon storage amount at a decreasing sequestration rate.

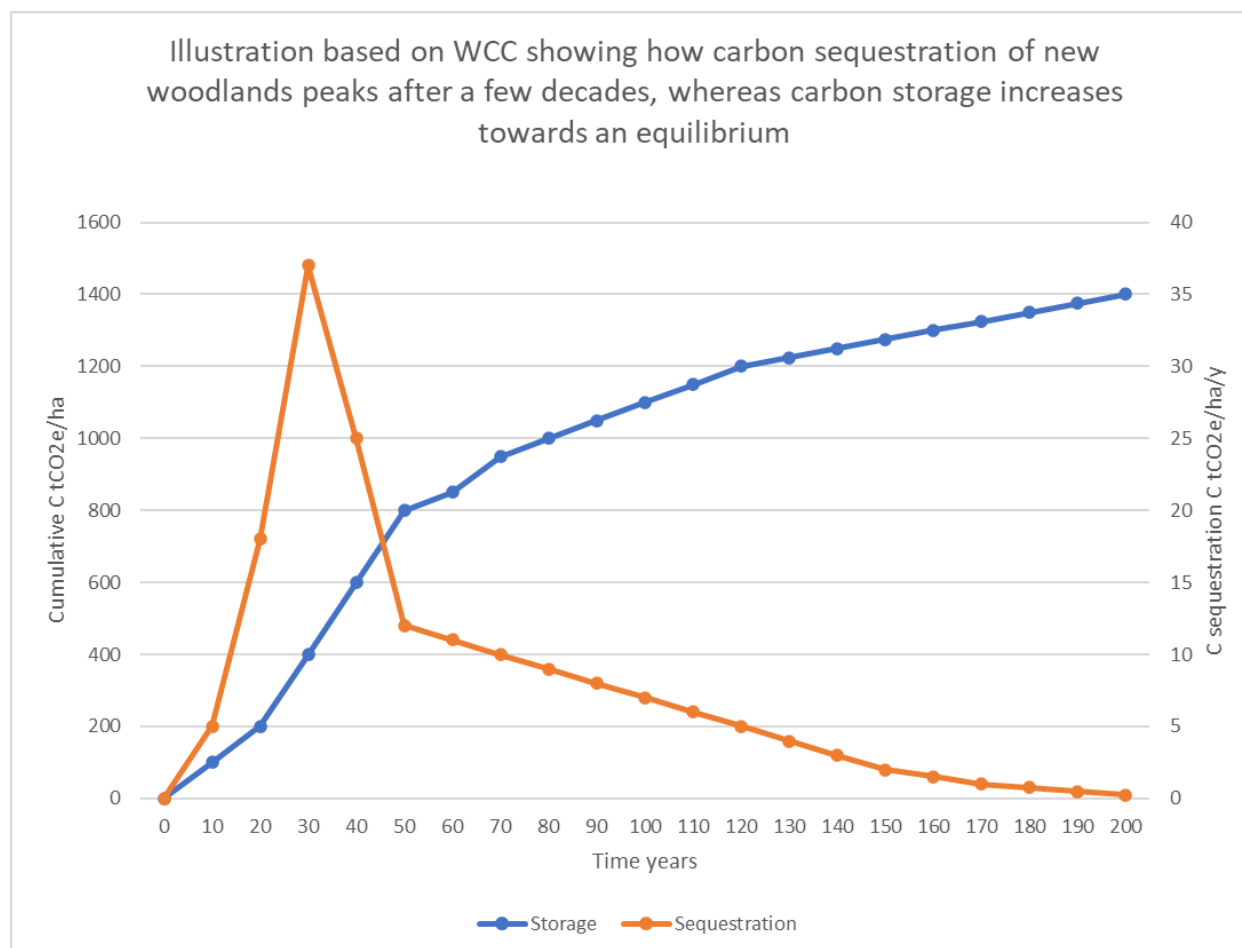


Figure 6.2 Carbon Sequestration Rate vs Cumulative Storage amended from (Gregg *et al.*, 2021)

Regarding diversity of planting, current research shows uncertainty as to which planting regime will sequester the greatest levels of carbon (Hulvey *et al.*, 2013, p.869). Specific research on diversity of planting, and effect on carbon storage potential find that adding diversity in specific carbon plantings “may maximize aboveground C storage in planted forests when compared with the average productivity of monocultures” (Hulvey *et al.*, 2013, p.871), this is alongside theoretically contributing to other ecosystem service goals (Hulvey *et al.*, 2013, p.869), including ecological resilience (Standish and Prober, 2020, p.165). Increased diversity therefore increases the total carbon sequestration rate and the carbon storage pool (Hulvey *et al.*, 2013, p.873).

AR is therefore an area that NR can potentially add to via its land assets, fulfilling the temperate region criteria to harness improved forest management. As this technology is at a suitable stage of technological readiness for deployment, it could be implemented in the short term.

Changes in LULUC can affect SOC stocks and should be included in carbon footprints (Williams *et al.*, 2012, p.65). The relative proportion of carbon stored in soil accounts for around $\frac{3}{4}$ of all carbon in UK forests, compared to less than a quarter in above ground biomass. The remainder being attributed in below ground biomass (BGB), dead wood and litter. As such, changes in the soil carbon stocks will have greater impact to carbon storage than that of above ground biomass (Gregg *et al.*, 2021, p.17).

Use of the UK Woodland Carbon Code (WCC) tool (UK Woodland Carbon Code, 2021b) will include for soil conditions and land use changes. It is therefore considered a more comprehensive tool than simply utilising differing tree sequestration rates which may not take account of the soil and LUC.

Land will always have competing uses including abatement, agriculture, water and biodiversity and leisure spaces (such as golf courses (Fitzpatrick, White and Matthews, 2021), and this will affect its value in both monetary and carbon terms (Bryan *et al.*, 2015, p.4112). NR needs to view its land assets differently, see Section 6.5.1, and explore ways of improving and expanding existing assets, to improve not only biodiversity but also the dual benefit of additional sequestration.

The simplicity and scalability of EW (with 10,000-10,000,000 Gt CO₂ sequestration potential) make it a serious contender for implementation in the race to net zero (Tan and Aviso, 2021, p.1).

EW is concerned with speeding up an otherwise natural geological process of storing CO₂ in minerals. This mineral situation can be divided into two discrete methods of in situ or ex situ. In situ sequestration is the injecting of CO₂ into underground geological storage chambers where it will react with existing minerals to form carbonates. Ex situ sequestration is concerned with the carbonation process taking place above ground. Here the minerals used for carbonation require mining and grinding, and then spreading before the carbonation process takes place (Ibrahim *et al.*, 2019, p.4). In EW the minerals (silicate or carbonate) react with atmospheric CO₂ in the presence of water and form soluble bicarbonates which are transported to the ocean deep carbon store via run-off water (European Academies Science Advisory Council, 2018). Storage times here can be considered permanent as carbon can be sequestered indefinitely in the ocean. Via carbonation the EW reaction may also form solid carbonates, also considered a permanent sequestration of the carbon in the form of CaCO₃ for example (Tan and Aviso, 2021).

Particle size is crucial for all types of minerals utilised for EW, owing to the high energy requirements, and hence additional carbon for grinding the materials to sufficiently small size (Fuss *et al.*, 2018, p.33). Two main classes of feedstocks are available for ex situ carbonation, natural minerals

(including Basalt, Brines, Brucite, Olivine, Serpentine and Wollastonite) and industrial by products (including cement wastes, fuel combustion ashes, iron and steel slags, and mine tailings), with the latter having potential circularity co benefits of re use of these waste materials for sequestration purposes (Yadav and Mehra, 2021).

For a summary of side effects of EW see Table 6.1.

Table 6.1 Positive and Negative Side Effects of EW, amended from (Hartmann *et al.*, 2013, p.136) and (Fuss *et al.*, 2018)* and (Birkinshaw and Jarvis, 2021)** and (Garcia *et al.*, 2020)***.

Positive Side Effects of EW	Negative Side Effects of EW
Increasing pH of ocean water, counteracting CO ₂ induced acidification.	Change in pH of soils and surface waters, affecting terrestrial and aquatic ecosystems.
Supply of Si to coastal oceans: Ocean fertilization to enhance sequestration of atmospheric CO ₂ via the organic carbon biological pump.	Change in Si concentration of surface waters, altered nutrient ratios affecting ecosystems.
Supply of Si and other nutrients to terrestrial ecosystem: Increase in terrestrial productivity and lead to greater sequestration of CO ₂ in terrestrial biomass; increase in crop production; additional income for farmers via CO ₂ certificate trading.	Release of trace metals associated with target minerals.
Increased phosphorus. ***	Generation of dust.
Making forests healthier. ***	Socioeconomic and sociopolitical consequences for agricultural communities.
Recycling of quarry waste to recycle CO ₂ and put it back into the circular economy. **	Environmental costs of increased magnitude in olivine mining.
	Local air pollution. *
	Heavy metal pollution in soils. *

Table 6.1 illustrates that EW could be a cost-effective solution for use on land unsuited to plantings. It could also be used along with those parts of the NR estate which do not have engineering constraints on them, such as non-load bearing access footpaths and be used to increase sequestration for the estate as a whole (see Figure 6.3), as long as the transport carbon costs can be kept to a minimum.

6.2.2 Permanence of Storage, Saturation & Leakage

Permanence of carbon storage, saturation, and leakage using AR and EW, cannot be ignored. The carbon stored in trees is not a permanent carbon sink in geological timescales. The carbon will be released when the tree dies or is destroyed (Davies *et al.*, 2011, p.1131). This indicates that AR activities will always be inherently at risk of leakage, and the implementation of robust forestry management practices is required to reduce this risk from forests that can occur due to natural or

human disturbance from drought, forest fires and pests, or reversals in land use (Fuss *et al.*, 2018, p.16).

There is a point where natural carbon sinks including trees, land, and oceans will reach saturation level. This is usually within decades to centuries for forests, compared to geological underground storage which reaches maximum capacity within centuries (but up to thousands of years in some instances (Fuss *et al.*, 2018)). Trees reach maturity at the point where net removal of GHGs reverts to zero (Fajardy *et al.*, 2019, p.52). Further discussion of this topic can be found in Appendix F.15.2.

6.2.3 Sequestration Rates

For AR a variety of carbon sequestration rates can be found by extensive research reports published in the literature by tree species (Mutch *et al.*, 2017, pp.39-41) and by habitat (Gregg *et al.*, 2021, p.12) (McGeever *et al.*, 2019, p.7).

A comprehensive overview of sequestration rates has been found in the literature, covering the range of vegetation overviewed in Appendix F.15.3, see Table 6.2.

Table 6.2 Habitat Sequestration Rates, amended from (Trewick and Anderson, 2023) and (Qubaja, Moinester and Kronfeld, 2022)

Habitat	Carbon Sequestration Rate (tCO ₂ eha ⁻¹ yr ⁻¹)	Cited Author's Reference
Mixed broadleaved woodland	7-14.5	Gregg et al. 2021
Natural woodland generation on former arable soils	7.3-14.3	Poulton et al. 2003; Anderson 2021
Conifer plantation (Sitka spruce)	11-20.5	Dewar and Cannell 1992; Anderson 2021
Old growth forest and ancient broadleaved woodland	4.77-17-97	Anderson, 2021
Hedgerows	0.47-23.36	Gregg et al. 2021
Heathlands	3.34-12.65	Alonso et al. 2012; Quin et al. 2015; Anderson 2021
Improved grassland	0.18-1.78	Janssens et al. 2005
Reversion of arable land to low input grassland	1.59	Warner et al. 2020; Gregg et al. 2021
Peatlands	0.18-3.70	Artz et al. 2013; Anderson 2021
Restored peatlands	3.23-25.41* *mostly reduction in carbon lost rather than sequestration	Artz et al. 2013; Anderson 2021
Planted Pine forest growing at semi-arid timberline	550g CO ₂ m ⁻² yr ⁻¹ converted to tonne.ha = 5.5tCO ₂ haYr ⁻¹	Qubaja, Moinester and Kronfeld (2022)

Owing to the wide range of sequestration rates in the literature for differing habitats, the rates given in the WCC (used extensively in the Nature England Report (Gregg *et al.*, 2021)), which also includes for initial soil conditions, have been used to calculate this value for case studies offsets, see Section 6.4.

For EW, several values have been found in the literature, fully detailed in the Appendix F.15.3.

The values used in the thesis are:

- Lower Bound demonstrated value for Dolerite $18 \text{ tCO}_2\text{ha}^{-1}\text{yr}^{-1}$
- Mid Bound predicted value using Crushed Concrete $85 \text{ tCO}_2\text{ha}^{-1}\text{yr}^{-1}$
- Upper Bound theoretical value using Dunite $120 \text{ tCO}_2\text{ha}^{-1}\text{yr}^{-1}$

Using these values, the area of land in hectares that would be required to have minerals applied to it to sequester the lifetime carbon A0-C4 for each renewal ER scenarios over the 25 year time period from a 2025 application year, to enable net zero by 2050, are calculated, see Section 6.4.2.

In addition to the above values from the literature, application of dunite consisting of approximately 90% olivine has been found in Delatares (2021) giving a value of 40kg carbon capture over 20-30 years per 1,000kg of olivine used as ballast. Therefore, use of olivine as ballast, could have additional sequestration potential for NR in the future.

In this thesis the focus has been offset via AR owing to the potential co benefits for biodiversity. EW has been overviewed in depth as an alternative strategy to sequestration in those areas of trackside where plantings are not feasible. The amount of trackside available to NR (15,846 km (ORR, 2023)) which has the potential to be utilised as a carbon offset “zone”, see Figure 6.3, is a unique beneficial asset for NR to galvanise and utilise in its trajectory to net zero, discussed further in the next section.

6.3 Rail Corridor Vegetation, Hedgerows and Other Linear Forest Formations

In this section specific literature on rail corridor vegetation, hedgerows and linear forest formation is reviewed. This is followed by a discussion on line-side vegetation and its management along with the potential for EW zones trackside.

Further exploration of these topics can be found in Appendix F.16.

NR is caretaker to over 16,000 miles of lineside vegetation, as such, changes here could have great potential (Varley, 2018, p.7). However, few long-term carbon studies have been found investigating carbon sequestration in rail corridors. One example found looked at measures to bind sand dunes along railway on the edge of the desert in China (Li *et al.*, 2016) finding that over around 60 years an increase of total SOC from 14.9 to 58.5% was found and concluding that afforestation produced a “substantial and steady gain” in the SOC content (Li *et al.*, 2016, p.191). There are constraints to plantings along with other interventions trackside, due to the need to keep the lines clear of leaf debris and not impinge on the soil area taking the overburden pressure from the track construction. Suitable areas for potential CO₂ “capture areas” would therefore be located outside of the ballast shoulder on the sub-soil layer (Kolosz *et al.*, 2017, p.78), see Figure 6.3. These carbon capture areas are where additional sequestration measures such as crushed concrete for mineral carbonation could be located.

Exploration of line side vegetation is required due to the interrelations between these and the rail corridor in terms of biodiversity, ecosystem services, and additional benefits such as “increased stability and resilience of embankments and cuttings” (Hoerbinger *et al.*, 2020, p.1). In this relationship not all benefits are positive, adhesion-related paybacks caused by leaf fall are a negative relationship (Network Rail, 2021d, p.82). Rail corridor vegetation management is often not highly prioritised in railway infrastructure construction and maintenance activities (Sydney Trains, 2019, p.2). Vegetating the rail corridor with trees and bushes could increase carbon sequestration and storage potential by 40% (Blair *et al.*, 2016, p.1723). In one study a three-fold increase in sequestration potential converting bare ground to trees was found (Ghosh and Khan, 2019, p.263). This strengthens the assertion that lineside vegetation, as a very specialised part of the landscape, has a high capacity in terms of delivery of environmental services (Hoerbinger *et al.*, 2020, p.1).

Earthwork sustainability is affected by vegetation in several ways including habitats and biodiversity, the location of vegetation (crucial to avoid tree fall and leaves on the line), vegetation maintenance involving cutting and replanting, visual and acoustic screening provided by the vegetation for neighbouring areas, and engineering performance in terms of both slope failure and excessive seasonal movements (Glendinning *et al.*, 2009, p.102). The question that needs to be addressed is what types of vegetation to plant considering the ongoing changes in climate, with 2023 being reported to be the hottest on record (NASA, 2024). Many infrastructure operations, including earthworks, construction and vehicle movement along with excessive tree removal and vegetation clearance activities, have the potential to disturb stable vegetation habitats in the rail corridor (Sydney Trains, 2019, p.4). Careful planning of construction and maintenance works and liaison with ecologists is required to minimise ecological and hence biodiversity impacts of earthworks on the rail corridor. NR is undertaking such liaison via completion of environmental appraisals, examples of

these include National Vegetation Classification (NVC) Surveys (QTS Rail, 2015), Habitat Surveys, Bat, Bird, Badger & Otter Surveys, alongside detailed design summaries before works commence, such as Environmental Impact Assessments (EIA), Environmental Appraisal (QTS, 2015), and Environment and Social Management Plans (ESMP) (Network Rail, 2021f).

The Varley Report (Varley, 2018), discussed utilising rail corridor vegetation as an “operational asset” which is contrary to how vegetation is currently viewed, as a maintenance intervention. The Varley Report specifically references the NR lineside vegetation management manual (Network Rail, 2020c) which NR introduced primarily to address the issue of planned maintenance. This manual facilitates the achievement of a compliant profile to maintain the earthwork sustainability aspects of tree fall and leaf fall, despite the management of vegetation for stability and security of earthworks falling outside the manual’s scope. In addition, a tree species selection guide for specifiers was introduced alongside this manual, overviewing use of trees for carbon storage and sequestration where by the greater carbon storage advantages of healthy, fast growing and long-lived tree species are highlighted (Hirons and Sjöman, 2019, p.39). This tree guide specifically details trees suited to the transport corridor noting these have no size or environmental tolerance imposed and also that many have the co benefit of a tolerance to air pollution (Hirons and Sjöman, 2019, p.9). The additional benefit for increased sequestration of planting vegetation is also noted in the rail industry strategy route map for sustainable rail (RSSB, 2022, p.12).

When discussing any CDR, NET or NbS these cannot always be strictly divided into discrete areas. An alternative CDR method is mineral carbonation which could be located in suitable land adjacent to the rail corridor (not suited to tree plantings or other vegetation) to enable additional sequestration to be utilised, see Figure 6.3 (Kolosz *et al.*, 2017, p.78-79). Use of this method of sequestration could be beneficial on lands which are not suited to biodiversity enhancements or have other constraints such as access. In these cases additional sequestration benefits from using this method of carbon capture could be realised alongside CE benefits such as being potentially able to reuse crushed concrete from demolition of near-by infrastructure (Kolosz *et al.*, 2017, p.79).

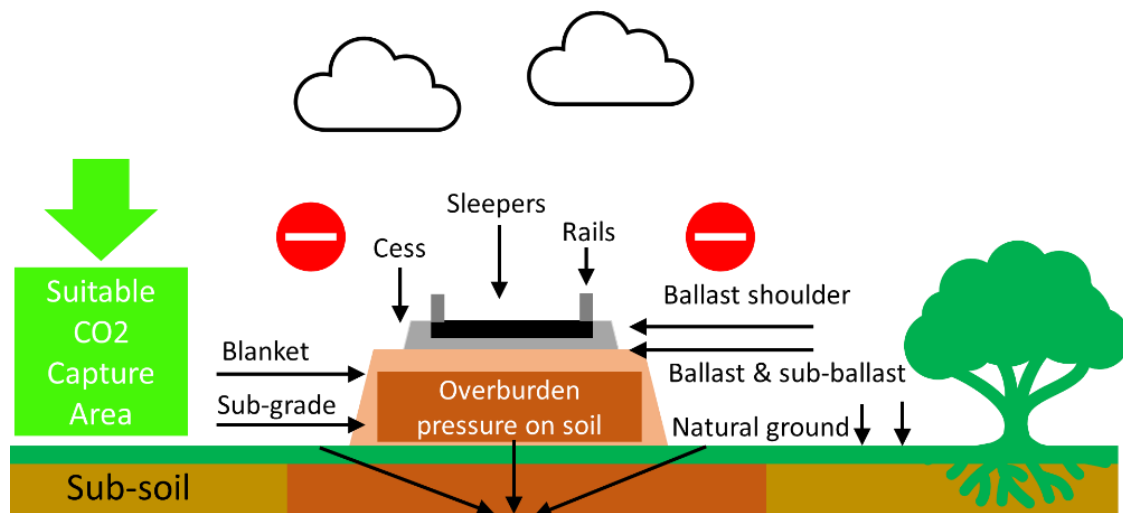


Figure 6.3 Carbon Capture Placement Guidance for Rail Track infrastructure, amended from (Kolosz *et al.*, 2017, p.78)

Reviewing the above cited rail corridor vegetation reports, identifies a gap in explicitly linking this area of research with carbon offsetting and biodiversity principles and the multitude of additional potential societal and economic benefits which come from this increased biodiversity. Increased sequestration was also clearly demonstrated in many of these studies as a beneficial outcome of increased vegetation.

Figure 6.4 illustrates the gap identified between rail corridor vegetation, increased vegetation and sequestration benefits, and linear forest formations, discussed next.

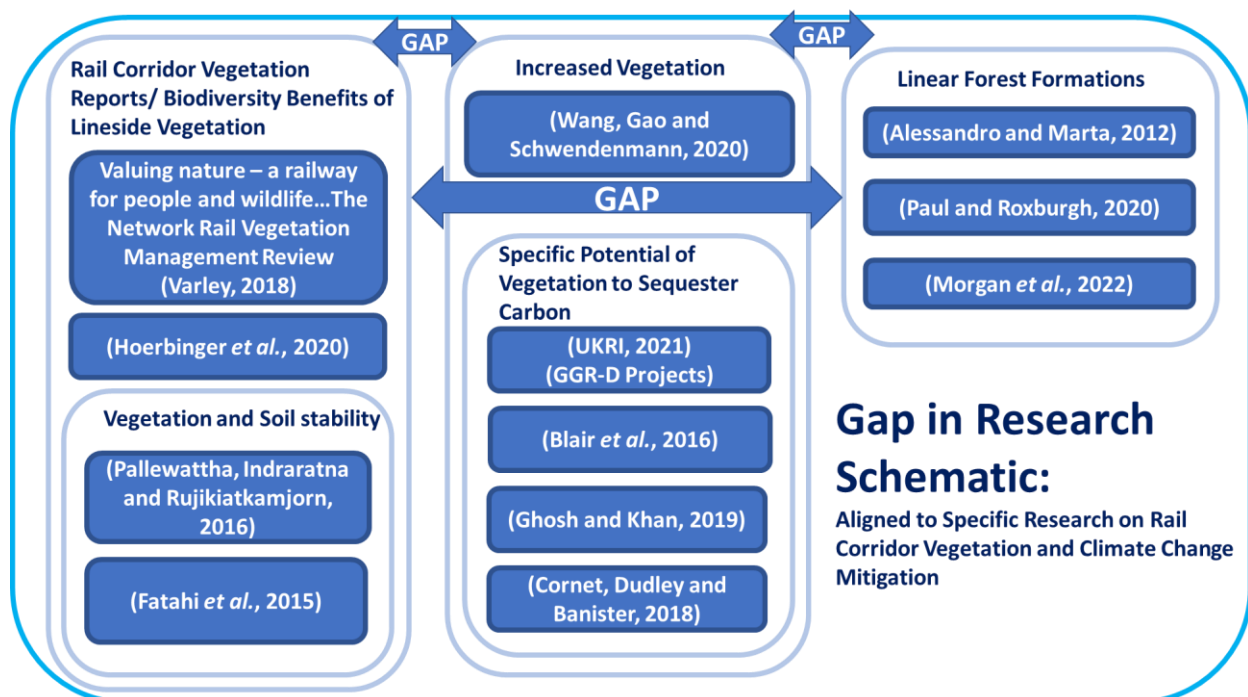


Figure 6.4 Gap in Research Schematic

6.3.1 Linear Forest Formations (LFFs) and Other Linear Vegetation

The railway as a linear forest formation (LFF) can also assist the biodiversity of an area in terms of forming a green or wildlife corridor for nature to transit along (Alessandro and Marta, 2012), alleviating some of the fragmentation effects of the rail route (Varley, 2018). Dense strands of woody biomass configured in belts (or LFFs) have carbon sequestration benefits due to benefits this configuration gives to above ground biomass (AGB) as this has a higher rate of accumulation in such a configuration compared to that of natural regeneration (Paul and Roxburgh, 2020).

Road verges (also can have LFFs and share many common features of the rail corridor) are also found to deliver a parallel ecosystem provision providing biodiversity services and storing carbon in orders of magnitude of gigatonnes (Phillips *et al.*, 2020). Road verges are able to offset between 4 and 7% (per km of road) of the carbon emitted during the construction phase of a road via grass assets adjacent to highways (Winston, Bouchard and Hunt, 2013, p.356). These grass assets also provide stormwater control, suggesting that conversion of barren or derelict land adjacent to linear infrastructure would give positive environmental benefits alongside additional sequestration benefits. Services and disservices provided by grass verges adjacent to linear infrastructure are presented in Figure 6.5.

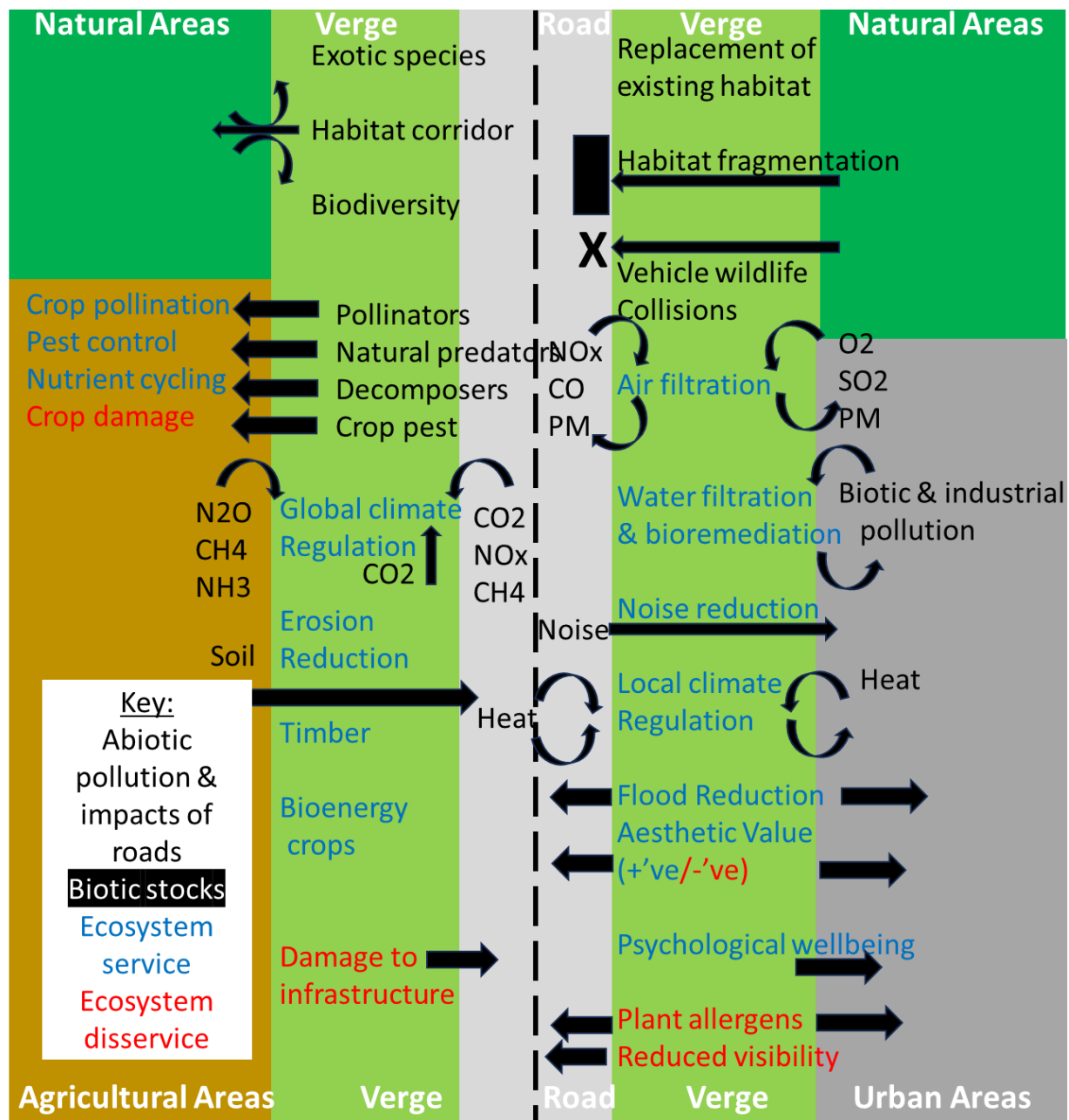


Figure 6.5 Ecosystem Services & Disservices of Verges Adjacent to Linear Infrastructure, amended from Phillips *et al.* (2020)

The three management actions being cited as methods of boosting ecosystem services at little or no extra cost (win-wins) are: reduced cutting frequency of verges, trees planted far back on wide roads, and use of verge cuttings for biogas generation. All three actions could potentially be implemented as part of a wider biodiversity initiative for NR trackside. Reduced cutting frequency gives immediate cost savings in terms of carbon emissions of machinery and staff travel to site, and their associated fiscal costs for lineside vegetation maintenance. Trees planted farther back would also potentially

give rise to reduced maintenance visits as these only need cutting back when they impinge on the railway intervention zone (Varley, 2018). See Chapter 4 for the carbon costs of vegetation management, and particularly the extrapolation exercise demonstrating the large impact this intervention type has on earthwork assets for NR.

The Varley Report, which gives rise to the intervention zones from the new standard, sets out guidance that work should “encourage the establishment of desirable lineside conditions that add value not only to the lineside but also to the surrounding environment” (Varley, 2018, p.19). The Report goes on to list these as: including providing biodiversity and improving resilience of the vegetation. Use of verge cuttings for biogas generation is an initiative that also could be investigated further by NR and their contractors to ensure zero waste to landfill of this product, and even potential gain if it can be sold on to others for biogas generation. As this is outside of the AR and EW offsets identified for exploration in this thesis, this avenue has not been explored further.

6.3.2 Sequestration via Hedgerows

Hedgerows could be one solution to increased sequestration due to their “efficient use of space for AGB C storage, when compared to other woody vegetation” (Axe, Grange and Conway, 2017, p.87). The increased above ground carbon storage offered by hedgerows suggests encouraging NR to increase their own and neighbouring hedgerows, rather than individual trees, which have their own specific issues for the railway in terms of intervention zones from the NEW standard for vegetation management, NR/L2/OTK/5201/02 (Varley, 2018, p.19). It has been shown that hedgerows can increase soil moisture storage, decrease runoff and reduce SOC loss via runoff runoff (Lenka *et al.*, 2012; Axe, Grange and Conway, 2017).

The above indicates hedgerow plantings would be beneficial for NR in terms of reduced drainage requirements trackside, resulting in lower carbon accounts for drainage works and increased SOC storage due to reduced runoff. The increased SOC could also give a win for farmers of adjacent land via increased crop yields. The situation with hedgerows is win-win-win with reduced drainage and thus reduced embodied carbon for NR carbon accounts, increased SOC and thus increased crops for farmers, and increased biodiversity for the public.

6.3.3 Choice of Vegetation

Corridors of semi-natural grasslands along linear infrastructure are increasingly important habitats as these can be rich in species diversity (Glendinning *et al.*, 2009). However there are two conflicting sets of issues regarding their maintenance, slope engineering performance, versus biodiversity maintenance (Glendinning *et al.*, 2009). As these grassland corridors are not suitable for grazing,

manual cutting, raking and removal of cuttings can be utilised to maintain the species richness and diversity, however these actions will have an associated carbon cost including fuel for relevant hand tools, strimmers and fuel for transport of staff to site. Use of fossil fuel in hand-held tools and vehicles has been shown in Chapter 4 to be major contributors to the carbon footprint of these types of vegetation management. To reduce this carbon cost low maintenance oxeye daisy grass seed could be planted as HS1 have done. Other strategies for reduced maintenance of these grasslands include low-nutrient soils which will encourage slow growing grass species and hence reduced or no mowing requirement, reducing the embodied carbon of maintaining these grassed areas alongside increasing biodiversity benefits (Stroud, Brintrup and Fancourt, 2023, p.4-5). Use of bare mineral soil can potentially lead to no maintenance requirements for decades (Sterling *et al.*, 2023, p.159) and cut and collect frequency management is advocated alongside increased planting of trees along highways (Phillips *et al.*, 2021, p.1) with additional positive ecosystem services being provided by these verges, such as mitigation of traffic pollution and additional carbon sequestration potential (Phillips *et al.*, 2020).

6.4 Applying Emissions Offsets to Case Studies

Given the aforementioned technical and feasibility reasons, the increased cumulative sequestration potential of woodland compared to grassland (Gregg *et al.*, 2021), along with the brief from NR at the outset of this project where the question of how many trees would need to be planted to offset an intervention was posed, AR, in the form of increased vegetation via tree planting, has been chosen as the primary method of offsetting. Given the prevalence of trackside potentially available to deploy EW, via mineral spreading, the area for EW has been calculated as an alternative measure to allow for comparison on an area of land basis against AR offsetting using sequestration rate data from the literature, see Section 6.2.3.

A further issue to consider when choosing sequestration routes is the permeance of the route. There are indications of higher percentage efficiency when the timescale of storage, that is, permeance is factored in. CDR efficiency of 97.2% is calculated for Dunite 50um, compared to forests 98.9% over a 100 year timescale. Using a 1,000 year timescale for a more robust comparison gives 61.9% efficiency with a large percentage “lost” to forest fires (Chiquier *et al.*, 2022).

Given the obvious challenges of including carbon sequestration amounts for every possible tree species suited to planting lineside (Hirons and Sjöman, 2019) and counting of individual trees, a more pragmatic approach was adopted using the broad tree classifications of broadleaf and conifer alongside area of land available.

To meet this pragmatic approach use of the Biodiversity Metric is advocated to ensure the Environment Act requirement to measure and enact net biodiversity gain from 2024 can also be calculated. Used alongside calculation of sequestration potential would fulfil both requirements using one metric, the Woodland Carbon Code (WCC) tool. The WCC tool calculates sequestration on a land area basis and via broader tree classification, providing flexibility to combine these differing plantings without the need for knowledge of exact tree species at time of calculation. The WCC also allows calculation of the important additional carbon emissions from soil disturbance and implementation (or deployment), which need accounting for (Brander *et al.*, 2021).

In the calculations used in this thesis assumptions have been made in line with other analyses found in the literature to estimate the initial conditions of land used for plantings. This is due to the fact that this carbon stock is highly variable and dependent on multiple factors relating to species, soil composition and previous land use (Fletcher *et al.*, 2021, p.6).

The WCC tool is used to calculate a carbon offset value in terms of the area of land for tree planting to ensure the residual carbon values, ranging from 3,699 kgCO₂e in Cove LX to 241,707 kgCO₂e in Aldercar, see Chapter 5, for each of the five renewal case studies ER EXP scenarios are offset within the first 25 years of planting, to ensure Net Zero by 2050 at the individual project level is met. This area of land required for tree planting required to offset the individual case studies is calculated and detailed in Section 6.4.1. Following this the alternative offset strategy of EW is calculated for the low, mid, and upper boundary values found and described in Section 6.2.2 and is presented in Section 6.4.2, again on an area of land basis. After the application of the two offset methods to the renewal case studies, these are applied to the whole of the NR estate in Section 6.5, where the potential of combining ER and offsets to reach Net Zero will be assessed.

6.4.1 Using WCC Method to Increase Vegetation

The WCC (UK Woodland Carbon Code, 2022), as a suitable tool for use in calculating biodiversity to meet the new Environment Act amendment (HM Government, 2020b), has been used to calculate the area of land required for planting to offset the residual carbon in the renewal case studies. The small projects sheet of the Excel spreadsheet provided by the WCC (UK Woodland Carbon Code, 2021a), suitable for projects up to 5 ha has been used as this is a project offsetting size suitable for use with the renewal case studies. This Excel sheet has been used along with user guidance documents provided by the WCC (UK Woodland Carbon Code, 2021a).

The ER EXP A0-C4 scenario values for the five renewal case studies calculated in Chapter 5 will be used to ascertain the level for D stage offsetting required to meet net zero for these case studies. The carbon sequestration has been calculated over a 25-year period to be consistent with NR meeting

their Net Zero goals by 2050 based on a planting date of 2025. The five scenarios have had their carbon expended over A0-C4 lifetime converted to tCO₂e (and rounded up in all instances) to be consistent with the units of the WCC tool and have had the first half of their postcode included, found in the rural urban classification exercise. See Appendix F.4 for details of how the country was assigned to each case study and Table 6.3 for final classifications.

Table 6.3 Country Assignment for 5 Renewal Case Studies

Renewal Case Study Name (A-Z)	ER EXP Scenario Carbon (A0-C4) kgCO ₂ e	ER EXP Scenario Carbon A0-C4 tCO ₂ e	Partial Postcode	Country Assigned Based on Postcode
Aldercar	241,707.07	242	NG16	England
Bowling Green	29,218.40	30	SK14	England
Cove LX	3,699.00	4	DG11	Scotland
Killiecrankie	31,283.40	32	PH16	Scotland
Station Plantation	35,659.84	36	LE12	England

Further guidance on how to use the WCC Excel spreadsheet, inherent assumptions within the Small Project Carbon Calculator Appendix F.5, and the results obtained can be found in Appendix F.6, F.7, and F.8.

The WCC tool is utilised to assess the carbon storage potential after 25 years for changes from one land cover type to another, with the generalised carbon storage potential of these differing land uses illustrated in Figure 6.6 (Gregg *et al.*, 2021, p.2).

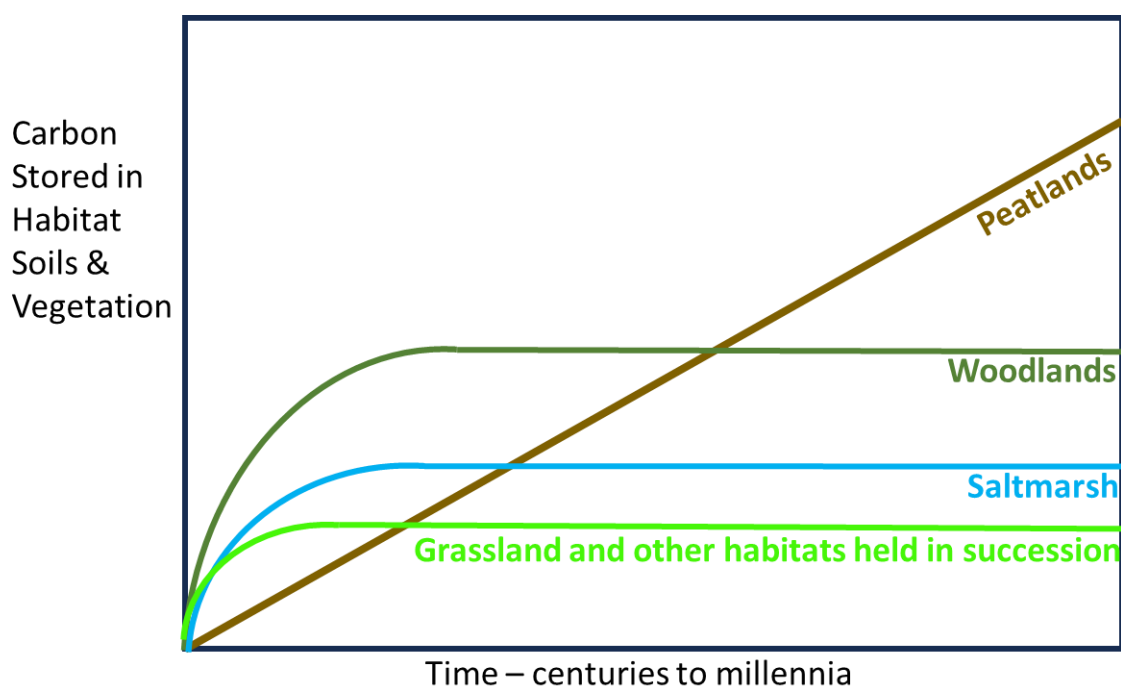


Figure 6.6 Conceptualization of differing land use carbon stocks, amended from (Gregg *et al.*, 2021, p.2)

Figure 6.6 illustrates the greater potential of woodlands to sequester and store carbon over grasslands. Peatlands are not assessed, even though their potential is the greatest, owing to their very small percentage contribution (0.46%) to the NR land assets (Dr Neil Strong, 2021). Grasslands and arable, which have greater percentage contribution to the NR estate, as found in the pixel data provided by NR (Dr Neil Strong, 2021) and therefore greater availability to change their land use, are discussed in Section 6.4.3.

An initial trial run of using the WCC tool was carried out for the smallest amount of carbon to be offset at Cove LX of 3,699 kg = 3.7 tonnes. This amount is sequestered fivefold by year 20 after planting via 5 ha of small mixed native woodland, broadleaf with no thinning, in organo-mineral soil, with seminatural previous land use, medium disturbance on site preparation, and cumulates in the sequestering of 205 tCO₂e. Therefore, differing amounts of land for planting and differing mixes of soil, previous land use and disturbance from site preparation were trialled to find the optimum, worst and mid case scenarios for Cove LX.

Full details of the scenarios ran using the WCC Excel sheet for both broadleaf and conifer plantings can be found in Appendix F.6 and F.7. Table 6.4 is a summary of all the scenarios ran for Cove LX.

Table 6.4 Differing Planting Scenarios for Cove LX to meet NZ by 2050 Carbon Sequestration with the WCC Excel Tool

Scenario Ref. in Appendix F.6&F.7	Area of Planting per ha, no Thinning	Soil Type	Previous Landuse	Site Preparation Technique (level of disturbance)	tCO ₂ e Sequestered by year 25 - Broadleaf	tCO ₂ e Sequestered by year 25 - Conifers
A	5	Organo-mineral	Semi Natural	Medium	550	494
B	0.1	Organo-mineral	Semi Natural	Medium	11***	10***
C	0.1	Mineral	Semi Natural	Meium	14	14**
D	0.1	Organo-mineral	Pasture	Medium	12	10
E	0.1	Organo-mineral	Arable	Medium	13	11
F	0.1	Organo-mineral	Semi Natural	Very High	-2	-3
G	0.1	Organo-mineral	Semi Natural	High	6*	6*
H	0.1	Mineral	Arable	Negligible	15**	14**
I	0.1	Mineral	Arable	Low	15**	14**
J	0.1	Organo-mineral	Semi Natural	Low	13	12

(*)Worst case option that meets NZ by 2050 sequestration target for this site to be offset

(**) Best case options exceeds NZ by 2050 sequestration target

(***) Mid Case option meets NZ by 2050 sequestration target)

From Table 6.4 summary table of various scenarios, a mid-case option was constructed based on the B scenarios, using a mixture of broadleaf (0.05 ha) and coniferous (0.05ha. The full details are provided below as the final choice for sequestration in Figure 6.7, giving 10 tCO₂e sequestered by 2050 which far exceeds the 4 tCO₂e required. Figure 6.8 illustrates the minimum amount of land for planting using the same constraints as per the mid case option to achieve net zero carbon for the Cove LX project and Figure 6.9 graphically represents the cumulative carbon sequestered for Cove LX.

Project Name:				Small mixed native woodland
Calculation Completed by:				Tracey Navaei
Date calculation completed:				15-Jan-24
Project Start Date (date planting was completed)				01-Jan-25
Country				Scotland
If in England, applying for Woodland Carbon Guarantee?				Please select
If in the Guarantee, 10-yearly or 5-yearly verifications?				Please select
Project Basics				
Management & Species				
Net area Broadleaf minimum intervention / no thinning (ha)			0.05	
Net area Broadleaf thinned (ha)			0.00	
Net area Conifer minimum intervention / no thinning (ha)			0.05	
Net area Conifer thinned (ha)			0.00	
Total net planting area (ha)			0.10	
Total Emissions from establishment		tCO ₂ e/ha	tCO ₂ e	
		-2.23	-0.22	
Soil type, previous landuse and establishment technique				
Soil Type			Organomineral	
Previous Landuse			Seminatural	
Site Preparation Technique			Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost			10	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e	
Total soil carbon emissions	0.10	-53.2	-5.3	

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-5	-1	-4	-40
10	-5	-1	-4	-40
15	-3	-1	-2	-20
20	4	1	3	30
25	13	3	10	100
30	20	4	16	160
35	26	5	21	210
40	31	6	25	250
45	36	7	29	290
50	42	8	34	340
55	45	9	36	360
60	48	10	38	380
65	50	10	40	400
70	51	10	41	410
75	52	10	42	420
80	53	11	42	420
85	54	11	43	430
90	55	11	44	440
95	57	11	46	460
100	57	11	46	460

Figure 6.7 Broadleaf and Conifer Planting for Cove LX Net Zero by 2050 Carbon Sequestration using WCC Carbon Calculator

Chapter 6

Project Name:			Small mixed native woodland
Calculation Completed by:			Tracey Navaei
Date calculation completed:			15-Jan-24
Project Start Date (date planting was completed)			01-Jan-25
Country			Scotland
If in England, applying for Woodland Carbon Guarantee?			Please select
If in the Guarantee, 10-yearly or 5-yearly verifications?			Please select
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)			0.02
Net area Broadleaf thinned (ha)			0.00
Net area Conifer minimum intervention / no thinning (ha)			0.02
Net area Conifer thinned (ha)			0.00
Total net planting area (ha)			0.04
Total Emissions from establishment		tCO ₂ e/ha	tCO ₂ e
		-2.23	-0.09
Soil type, previous landuse and establishment technique			
Soil Type			Organomineral
Previous Landuse			Seminatural
Site Preparation Technique			Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding
% Topsoil Carbon Lost			10
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e
Total soil carbon emissions	0.04	-53.2	-2.1

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Ash	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-2	0	-2	-50
10	-2	0	-2	-50
15	-1	0	-1	-25
20	1	0	1	25
25	5	1	4	100
30	8	2	6	150
35	10	2	8	200
40	12	2	10	250
45	14	3	11	275
50	17	3	14	350
55	18	4	14	350
60	19	4	15	375
65	20	4	16	400
70	20	4	16	400
75	21	4	17	425
80	21	4	17	425
85	22	4	18	450
90	22	4	18	450
95	23	5	18	450
100	23	5	18	450

Figure 6.8 Amount of Planting to Meet 4 tCO₂e for Net Zero by 2050 for Cove LX

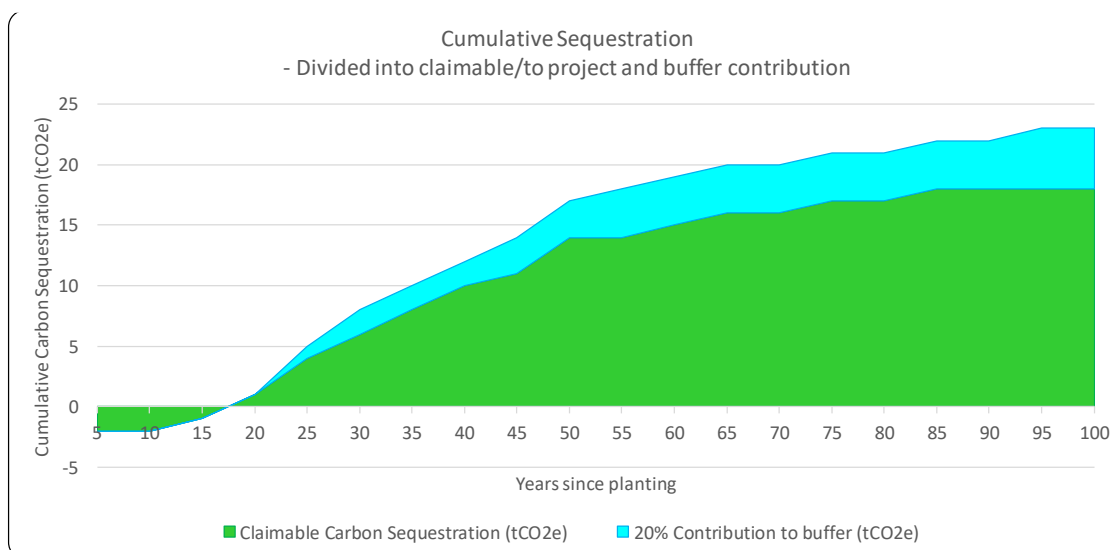


Figure 6.9 Graph of Cumulative Carbon Sequestration for Cove LX

Using this mid-case scenario the four remaining renewal sites were constructed using the WCC Excel Tool using mixed broadleaf and conifer planting, organo-mineral soil, seminatural previous landscape with medium disturbance. The areas of planting required to achieve Net Zero carbon sequestration by year 25, which would align with 2050 based on January 2025 planting date, are summarised in Table 6.5 for all five renewals and further details of the WCC Excel tool data used for each of the remaining four renewal scenarios is provided in Appendix F.8, along with cumulative sequestration graphs for each.

Table 6.5 Renewals: Area Required to Sequester Carbon to Meet Net Zero Targets

Renewal Case Study	EXP ER Scenario tCO ₂ e Expended A0-C4	Minimum Planting Area Required (ha)	Total Claimable* tCO ₂ e by year 25	Total Claimable* tCO ₂ e by year 100
Aldercar	242	2.32	242	1059
Bowling Green	30	0.28	30	128
Cove LX	4	0.04	10	18
Killiecrankie	32	0.32	34	146
Station Plantation	36	0.36	38	164

*including 20% buffer

Table 6.5 outlines the minimum planting area using the mixed broadleaf and conifer planting regime and soil, disruption characteristics found in the Cove LX trials to achieve a midpoint scenario for carbon sequestration. This table illustrates the wide range of planting areas required for the five renewals ranging from 0.04 to 2.32 ha.

With the WCC tool a 20% buffer figure is included to account for unintended consequences such as natural disturbances including: fire, wind, drought or flood, pest and disease, along with legal/social issues and species suitability in current and future climate (UK Woodland Carbon Code, 2024). To minimise any future losses a risk assessment should be carried out at project design stage and measures put in place to mitigate any risks identified.

6.4.2 Using EW – Area required to Offset Residual Carbon

To enable comparison between the land areas required for tree planting sequestration, calculated using the WCC, and that required to sequester the same amount of carbon via EW, the EW rate found in Section 6.2.3 was used. The EW rates found were then utilised, based on a 25-year application from the year 2025 to ensure net zero is reached by the 2050 deadline, in line with the method applied to tree planting sequestration. The results obtained are given in Table 6.6.

Table 6.6 Land Area Required to Sequester Carbon by 2050 for Differing EW Rates

Renewal Case Study	ER EXP (A0-C4) tCO ₂ e	Area of Land Required for EW Application (based on 25yr application from 2025) ha lower, mid and upper bound	Land Area as Percentage of Area Req'd. for Tree Planting lower, mid and upper bound
Aldercar	242	0.5378 - 0.1139 - 0.0807	23% - 5% - 3%
Bowling Green	30	0.0667 - 0.0141 - 0.0100	24% - 5% - 4%
Cove LX	4	0.0089 - 0.0019 - 0.0010	22% - 5% - 3%
Killiecrankie	32	0.0711 - 0.0151 - 0.0110	22% - 5% - 3%
Station Plantation	36	0.0800 - 0.0169 - 0.0120	22% - 5% - 3%

Table 6.6 illustrates the differing areas of land required to sequester the carbon from each renewal by the 2050 Net Zero date, with the three figures representing the demonstrated lower value, the mid value using crushed concrete which would give additional circularity benefits, and an upper theoretical value using dunite. The corresponding percentages represent the percentage of land required for EW of each lower, mid and upper bound rock material as a percentage of the corresponding land area required for sequestration via AR. This demonstrates the differing percentages from around one fifth for the lower value, to 5% and 3-4% respectively for the mid and upper values. The 3-4% area of EW required compared to AR for the higher theoretical value is of great interest as this indicates this is potentially a highly beneficial route for NR to follow to achieve its Net Zero goals.

Real life application of rock materials adjacent to track side is envisaged to follow that set out in Figure 6.3 (Kolosz *et al.*, 2017) suggesting that NR would potentially have many thousands of km of track side to utilise this strategy with. The potential for the whole of NR assets to exploit EW trackside is explored further in Section 6.5 where the potential for ER and offset combined to reach Net Zero will be discussed.

6.5 Assessing Net Zero Potential of Combined CO₂e Reduction & Offsetting

In this section the combination of ER with offsetting to reach Net Zero will be explored at the macro scale, for all NR emissions. In Section 6.4 the offsetting values have been applied to the case studies via AR and EW, and Net Zero has been demonstrated to be achievable at an individual case study level. Exploration of attaining Net Zero at a NR whole business emissions level will now be demonstrated, with EW able to potentially offset around one fifth of the residual carbon. This application of mitigation combined with offsetting, meeting Objective 5, see Section 1.2.

Further exploration of these topics can be found in Appendix F.17.

6.5.1 Applying Emission Offsets to NR Land Assets

Emission offsets via AR and EW were applied to NR land assets to give a macro scale view of these strategies.

6.5.1.1 Applying AR to NR

From the pixel data for NR 2019-20 from NR via personal correspondence (Dr Neil Strong, 2021), around 8,546.50 ha are classed as arable and 6,595.32 ha as grassland (see Appendix F.10). The WCC tool is used with the optimum set up as found for the case studies in Section 6.4.1, except for the starting conditions, which are amended from semi natural to pasture and arable as applicable, as the starting conditions are known in this scenario for this land use change to NR land assets. To maintain consistency a mixture of broadleaf (50%) and coniferous (50%) plantings, with a planting date of 1 January 2025, are input as per the case studies, and the full details are provided below as the final choice for sequestration in Appendix F.11.

The 6,595.32 ha pasture (grassland) converted to small mixed native woodland with 50% coniferous/50% broadleaf equates to cumulative sequestration of 2,255,599.44 tCO₂ by 2050. The 8,546.50 ha arable land converted to small mixed native woodland with 50% coniferous/50% broadleaf equates to cumulative sequestration of 2,982,728.50 tCO₂ by 2050. Figures used are based

on 1 ha woodland plots multiplied up to total number of hectares as the WCC Small Projects tool used is for use with small projects up to 5 ha only. It is anticipated that this method of implementing additional land use change would be via small parcels of land use change (less than 5 ha) throughout the NR land holdings.

For both grassland and arable conversion, a number of implementation strategies, from 100% of the land holding down to 10%, in 10% increments, have been calculated. The potential amounts of carbon that could be sequestered by 2050 using these differing percentages of the given land types are shown in Figure 6.10 with the data behind this graph being given in Appendix F.11.

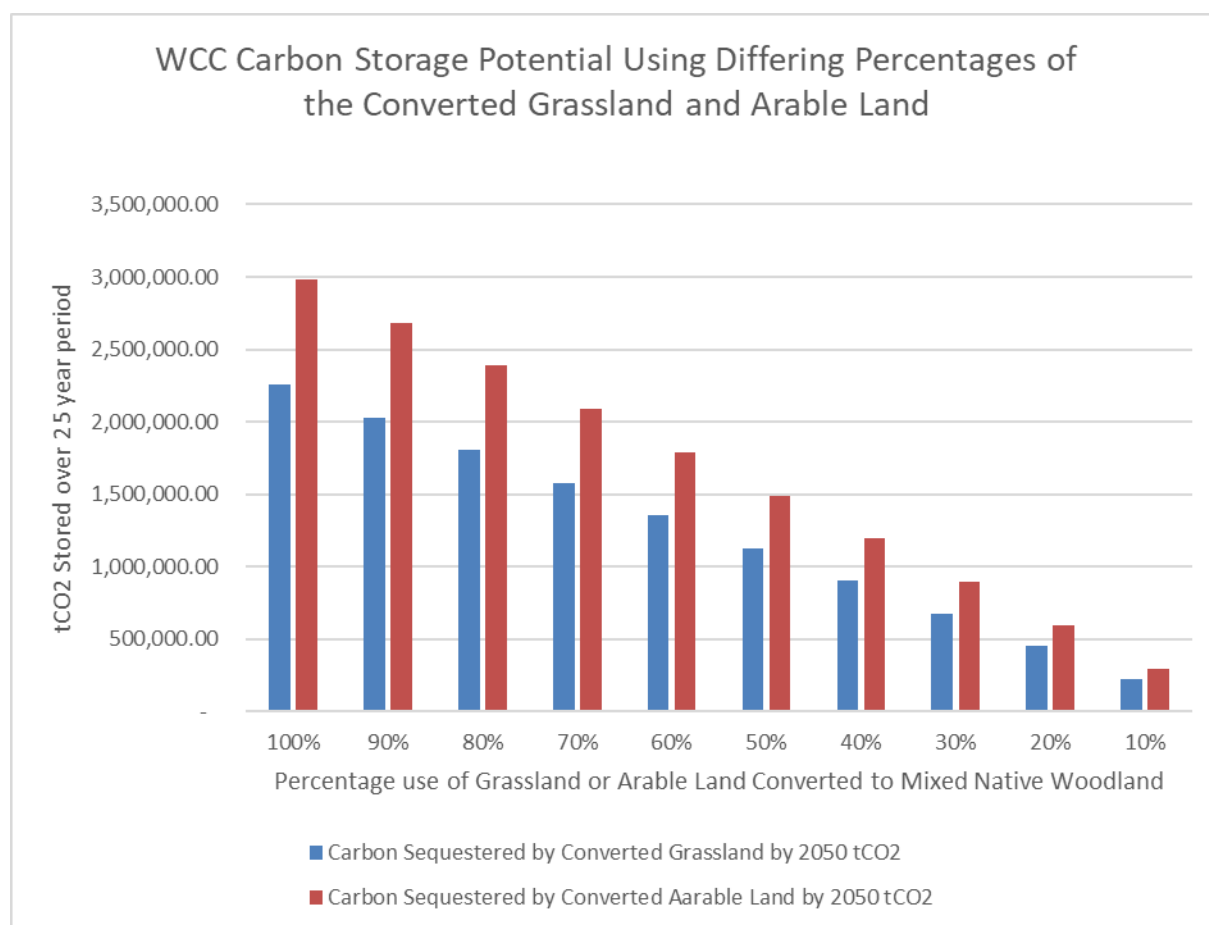


Figure 6.10 WCC Carbon Storage Potential of Converted Grassland & Arable Land

Figure 6.10 illustrates the range of potential carbon storage available up to 2050 using differing percentages of each land type of grassland and arable land.

6.5.1.2 Applying EW to NR

The route length open for traffic for NR for 2022-23 is 15,846 km (ORR, 2023). To enable an estimation using the low, mid and upper boundaries for EW, as applied to case studies, this figure can be doubled to allow for application on both sides of the track (UP and DOWN). If an arbitrary width of sequestration area is used of 1m, then the uppermost potential for application (100%) can

be calculated for the three EW values of 18, 85 and 120 tCO₂ha⁻¹yr⁻¹ based on a 25 year application in the year 2025 to allow for use of sequestered value of CO₂ in net zero by 2050 calculations, and is illustrated in Table 6.7.

Table 6.7 Application of EW Low, Mid and Upper Values to Track Side 1m Strip

Application to whole of NR Track Assets	Values	Units
NR track from ORR 2023	15,846.00	km
Assumed UP and DOWN land	31,692.00	km
Convert to m ² for 1m width either side	31,692,000.00	m ²
Convert to hectares to apply EW rates	3,169.20	ha
Storage potential in 100% of this area using lower value	1,426,140.00	tCO ₂
Storage potential in 100% of this area using mid value	6,734,550.00	tCO ₂
Storage potential in 100% of this area using upper value	9,507,600.00	tCO ₂

Using the above method, the storage potential at differing percentage storage potentials of the hypothetical 1m strip adjacent to track side for the three differing EW rates were calculated and are illustrated in Figure 6.11 with the background data behind this being given in Appendix F.9.

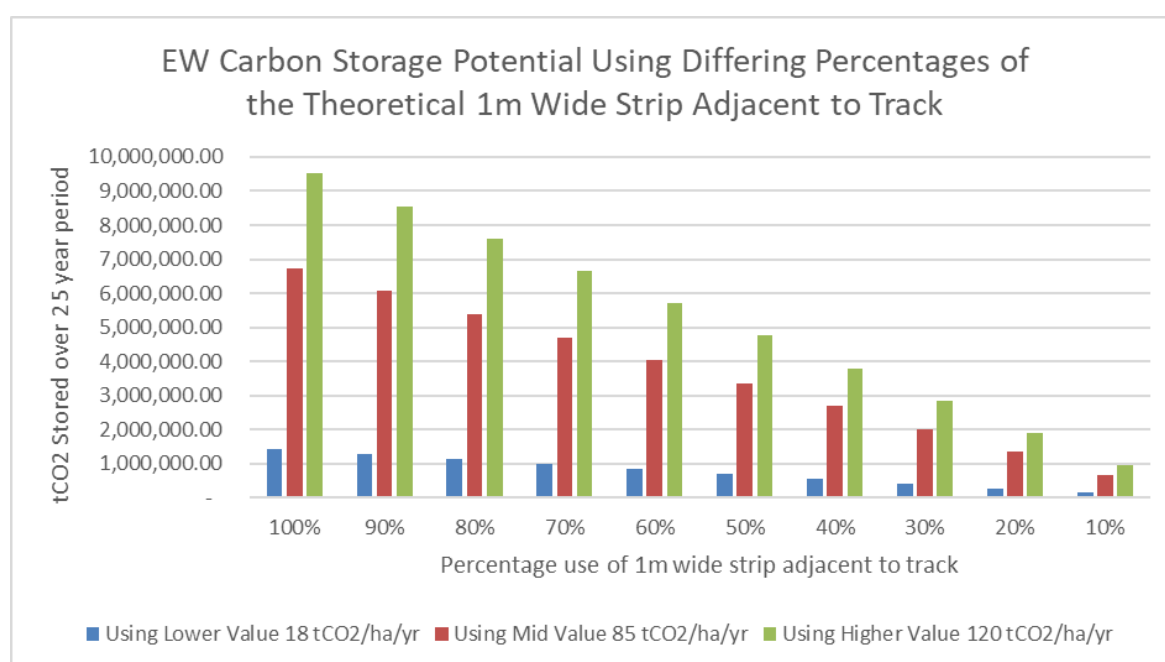


Figure 6.11 EW Carbon Storage Potential of 1m Strip Adjacent to Track

Figure 6.11 illustrates the wide range of theoretical carbon storage using EW trackside from 143,000 tonnes in the lower boundary to 0.95 million tonnes for 10% of line side offset area all the way up to 1.4 million and 9.5 million tonnes, in the 100% scenario, for lower and upper boundaries respectively. This indicates that, even via the demonstrated lower boundary, there is great potential for use of EW to assist NR in meeting their net zero by 2050 goals.

6.5.1.3 WCC Sequestration Rate Validation Exercise

Following application of the sequestration rates for AR from the WCC tool these rates have been compared to those found in the literature to assess their accuracy. Carbon sequestration rates found in the literature for woodland give values of low and high respectively for broadleaved of 7 and 14.5 $\text{tCO}_2\text{eha}^{-1}\text{yr}^{-1}$ and 11 and 20.5 $\text{tCO}_2\text{eha}^{-1}\text{yr}^{-1}$ for coniferous, giving an average value for the mid points of the two with a 50%/50% usage of 13.25 tCO_2 (Trewick and Anderson, 2023). Multiplying this value by 25 to align with the 25 years to Net Zero, a value of 331.25 $\text{tCO}_2\text{ha}^{-1}$ if found, which is within 3% of that of 342 $\text{tCO}_2\text{ha}^{-1}$ given for grassland to woodland conversion in the WCC tool. This gives confidence in use of the WCC figures as the value found aligns well with that found in the literature.

The ability of land assets of businesses to offset their carbon has been challenged in the literature by Fox *et al.* (2020) where they show that small scale plantings are not sufficient to offset small business carbon emissions.

The totals of carbon that can be offset by the NR estate changing arable and/or grassland to woodland and/or EW rates trackside at differing percentages have been assessed alongside the total NR carbon footprint multiplied over 25 years to enable comparison to see which strategy could offset the total NR global footprint of 8,071 kt = 8,071,000 t (Expedition, 2020, p.4), multiplied by 25 years = 201,775,000 tCO_2e .

- Arable to woodland sequestration potential over whole estate, if 100% of the total arable land is converted to woodland, after 25 years 2,982,728.50 tCO_2 can be sequestered and stored in these woodlands accounting for less than 1.5% of the total NR carbon footprint during that time period. This percentage is in line with that found in the literature by Fox *et al.* (2020, p.462) who found live trees at a university could only potentially offset 0.11% of the University of Georgia's carbon emissions.
- Grass land to woodland sequestration potential over whole estate, 2,255,599.44 tCO_2 accounting for around 1.1% of the total NR footprint.
- EW sequestration applied to 100% of trackside in 1m width using higher theoretical value 9,507,600 t would be able to offset around 4.7% of total NR footprint over the 25-year period, using lower value this would fall to around 0.5%.

The above illustration is made with very simplistic figures, but illustrates the point that use of offsetting, when confined to land within NR's estates alone, is not sufficient for NR to reach Net Zero. Assuming that the whole NR footprint could be reduced by the average reduction figure found in the case studies using the three differing emission reduction strategies covering materials, transport and construction of around 2/3, then the new residual figure for NR emissions over 25 years would be

67,258,333 tCO₂. The arable and, grassland to woodland and EW sequestration figures above would then represent 4.4%, 3.4%, and 14% of this figure respectively and illustrate here the potential for EW in particular to be able to offset nearly 1/7 of the residual carbon emissions. As outlined in FES2020 in their leading the way, consumer transformation and system transformation trajectories for electricity production and heavy industries showing a steady decrease year on year to Net Zero, the figures mentioned above are in reality likely to fall thereby leading to additional incremental reductions in the carbon footprint year on year of NR.

Looking in more depth at NR scope 3 reductions (Expedition, 2020) and the NR path to Net Zero (Network Rail, 2019) if these are applied to the baseline figure for all scopes in five year CPs then the total over 25 years for offset is estimated to be 86,924,670 tCO₂e, a reduction of 55.4% on the previous annual figure, based on 2019-20, multiplied by 25 years. See Appendix F.12 for reduction data calculation.

Using this revised figure over the 25 years to 2050 the following is found with the sequestration and EW for the whole NR estate.

- Arable to woodland sequestration potential over whole estate, if 100% of the total arable land is converted to woodland, after 25 years 2,982,728.50 tCO₂ can be sequestered and stored in these woodlands accounting for 3.3% of the total NR carbon footprint during that time period.
- Grass land to woodland sequestration potential over whole estate, 2,255,599.44 tCO₂ accounting for around 2.5% of the total NR footprint.
- EW sequestration applied to 100% of trackside in 1m width using higher theoretical value 9,507,600 t would be able to offset 11% of total NR footprint over the 25-year period, using lower value this would fall to 1.1%.

The above has demonstrated the potential of EW to assist NR in meeting its Net Zero by 2050 targets. ER plus EW will not be able to fully offset all estimated residual emissions without further actions such as Climate Change Adaption, an appreciation of payback times and understanding of ethics of use of NETs, all of which will now be outlined.

6.5.2 Climate Change Adaption

Climate change adaption is vital and an area that requires attention alongside that of ER and offsetting. Without action in this area, government, and societal goals, including Net Zero will not be able to be met. Further discussion on these is provided in Appendix F.13.

6.5.3 Pay Back Time

Modal shift from cars to rail has the potential to enable pay back of the carbon from construction and maintenance of rail. As the national grid decarbonises in the UK it will become increasingly more difficult to pay back the carbon expended on infrastructure by taking cars off the road (Lokesh, Densley-Tingley and Marsden, 2022b, p.9). See Section 2.3.2 where offsetting carbon payback times have been discussed against differing infrastructure projects.

A detailed understanding of the “pay back” periods for rail infrastructure also needs to be contended with to ensure that the modal shift portion of this is understood and applied consistently across projects to enable for just and fair comparison between them. With HS2 for example using a theoretical motorway comparator to the new HSR, calculating theoretical modal shift from conventional rail and car trips against a baseline of 162.9 million km of road trips removed from a theoretical 2027 baseline via phase one (HS2 Limited, 2017a, p.116). HS2 also allow for carbon offset via carbon sequestration using 2 million trees (HS2 Limited, 2017a).

Carbon calculations have been made using the RSSB RCT for Powrie (2024) illustrating pay back times for traditional and highly engineered embankments (See Appendix F.14 for calculations and assumptions). These highly engineered embankments give a payback time against air travel with radiative forcing (RF) of 3 years and without RF of 5 years. The payback time against petrol or diesel cars is 4 years; however, against BEV (as one of the lowest carbon forms of road transport) would be 31 years. These figures illustrate the increasing difficulty of achieving payback for infrastructure by modal shift from cars as these vehicles themselves decarbonise.

6.5.4 Ethics of NETs

The ethics of using NETs must also be considered when employing offset technology. It should not be employed before carbon has been reduced to its lowest possible level thereby following the Oxford Offsetting taxonomy (Axelsson *et al.*, 2024), to aid in avoiding the appeal to not reduce carbon first and just to rely on NETs to achieve Net Zero. This is particularly pertinent as some of the newer and more speculative NETs are unproven at large scale deployment, although work in the GGR-Ds is advancing to allow for large scale implementation. These NETs should not be thought of as a remedy to solve the carbon problem at some future point in time, which would draw people’s attention away from making the deep decarbonisation efforts that are required right now (McLaren *et al.*, 2019, p.4).

The case for separate measuring of reduced emissions and negative emissions while sound, needs to be used in a two-stage process. First the most carbon effective solutions are to be found and only when this path is exhausted, can negative carbon measures be utilised to ensure carbon neutrality.

During this process there is a need to be ever watchful of the issue of using negative carbon to justify use of carbon intensive materials when lesser carbon producing ones are available. All carbon needs to be locked away indefinitely and assurances need to be made that it will not be subject to rerelease at a later date and thus pushing the problem onto the next generation (McLaren *et al.*, 2019, p.4).

Recent guidance released on emissions offsetting ensuring adherence with the Net Zero by 2050 pathway and as such the SBTs is illustrated in Figure 6.12. This clearly illustrates the results of this thesis in that ER should always come before offset, with the additional clarification alluded to earlier, that avoided deforestation and habitat loss (Section 6.5.2) are part of the ER strategy rather than an offset strategy.

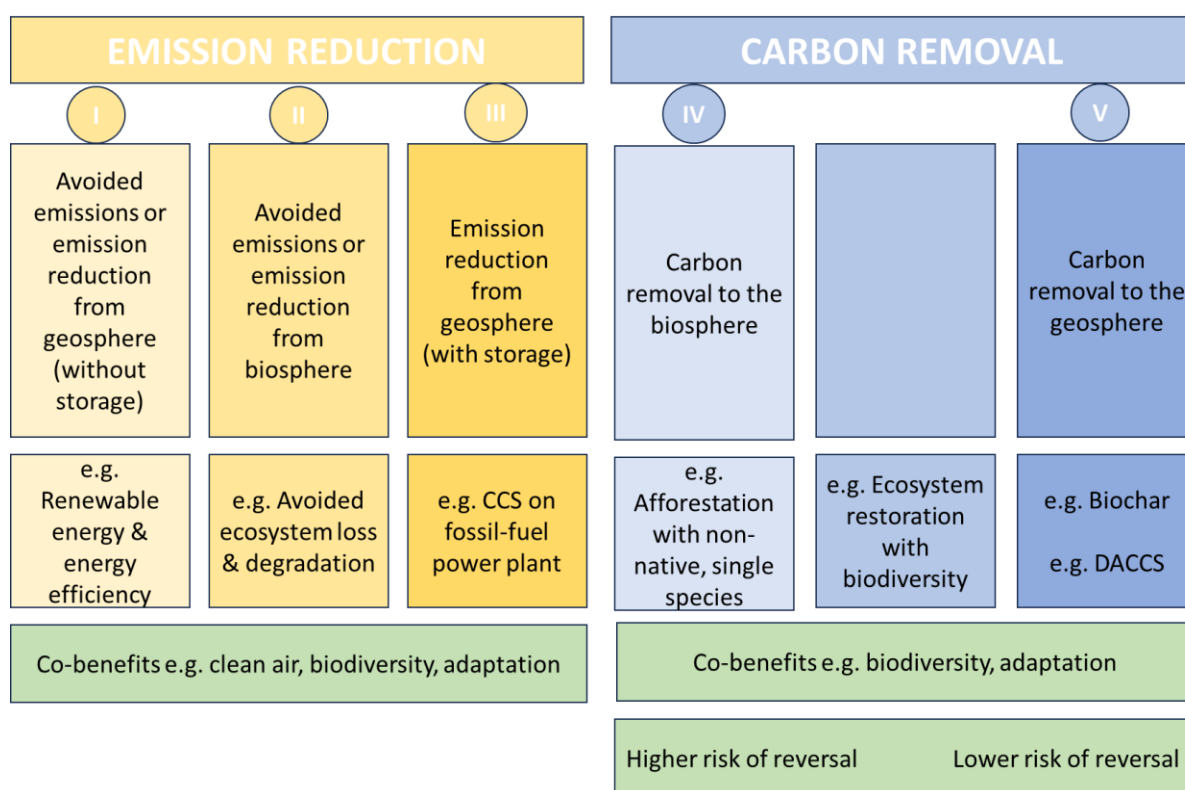


Figure 6.12 Taxonomy of ER and Carbon Removal, amended from (Axelsson *et al.*, 2024,, p.12)

Further clarification of timings of differing interventions and how their input to the global ER and offset changes over times is given by Figure 6.13.

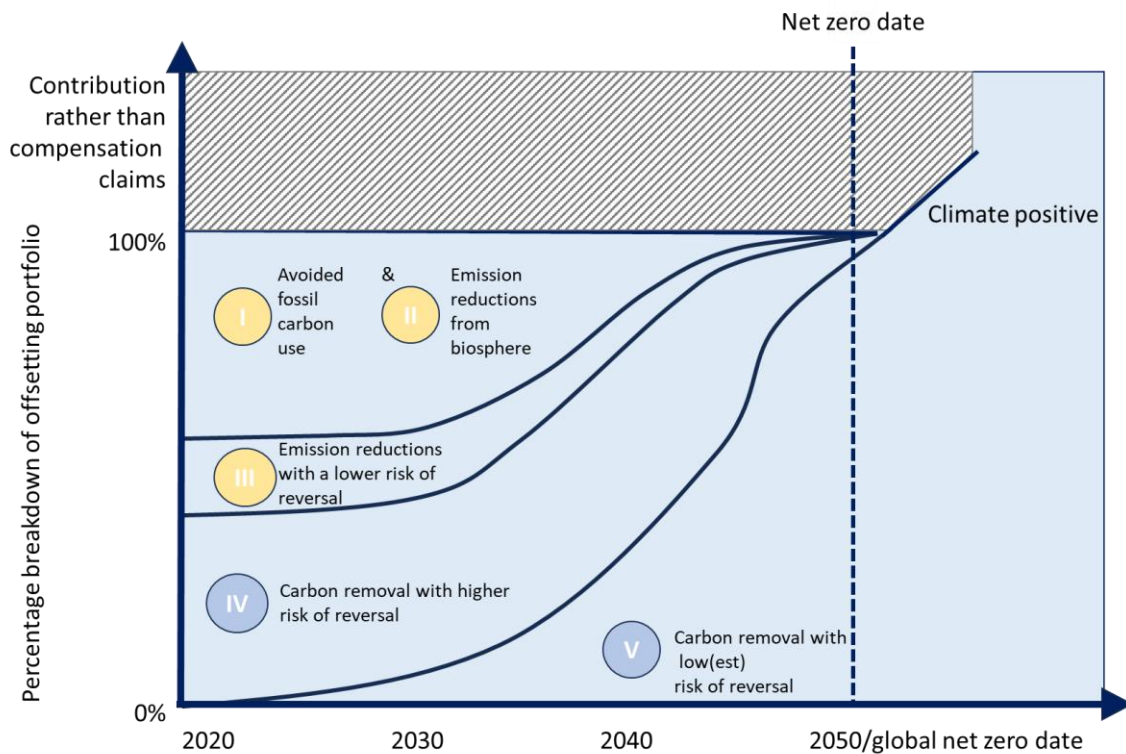


Figure 6.13 Example of Net Zero Aligned Portfolio of Offsetting Interventions, amended from (Axelsson *et al.*, 2024, p.19)

Figure 6.13 illustrates, in line with the actions advocated for NR, that emissions reductions must be used in greater proportions now, reducing as the path to net zero grows closer. Carbon removal with the highest risk of reversal, such as AR should be used in greater quantities now than in the future, with the lowest risk of reversal strategies, such as EW, gradually scaling up its inception date to 2050.

6.6 Assessing Potential Sustainability Co-Benefits of CO₂e Offsetting

In this section a succinct summary of the co-benefits of increased reforestation is provided. Further exploration of co benefits of EW, social, UNSDG, disbenefits and the circular economy can be found in Appendix F.18.

6.6.1 Increased Reforestation Co-Benefits

Benefits of “careful plant selection” (Blair *et al.*, 2016, p.1723) to green the rail corridor and increase carbon sequestration (Blair *et al.*, 2016; Ghosh and Khan, 2019; Wang, Gao and Schwendenmann, 2020) have been introduced in Section 2.6.2. Here the potential sustainability benefits of this are explored.

There is however potential for the reverse, whereby offsetting via NbS and use of land to improve biodiversity (HM Government, 2018, p.4), may potentially aid infrastructure owners in meeting the now mandatory 10% biodiversity net gain (BNG) (HM Government, 2020b). With further additional benefits for the locality including mitigating flood impacts, pollution control (for air and water) Lorenz and Lal (2012, p.153); (Blair *et al.*, 2016, p.1723) alongside benefits to the community such as recreational access for health and wellbeing purposes (Reid *et al.*, 2021, p.14).

Maintenance of high levels of biodiversity has also been shown to have the ability to enhance soil carbon sequestration (Chen *et al.*, 2018, p.4027). With the literature pointing to a rebuilding and rewilding strategy for biodiversity, rather than new forest in woodlands plantings, as the optimum pathway to amassing greater carbon stocks alongside larger areas for biodiversity and other ecosystem services such as reduced water run off (Anderson, 2021, p.33). Planted forest, in comparison to natural forest, is found to be an excellent source of both biodiversity and carbon sink potential (Gogoi, Ahirwal and Sahoo, 2021, p.1). Both strategies having metrics that point towards the linking up of NBG with working practices in NR to increase not only biodiversity but also carbon sequestration. The time lag between planting and realisation of sequestration benefits though must be borne in mind as explored in the case studies offset examples, along with the knowledge that these are not necessarily permanent solutions (Minx *et al.*, 2018) as they are a CDR strategy with a high risk of reversal and should be used as a short term intermediary to bridge the gap and prevent climate boundaries overshooting, as other novel and new offsets such as biochar and EW scale up (IPCC, 2018).

6.7 Concluding Remarks on Offsetting

In this chapter the current state of CDR has been overviewed and the two methods of AR and EW chosen for offsetting of the case studies justified. Application of these methods found that 0.04 ha – 2.32 ha of land is required for AR, or 0.08 -0.54 ha for the demonstrated lower boundary or 0.01 - 0.08 ha for the upper boundary of land required for application of EW to offset the residual individual case study carbon for the ER EXP A0-C4 renewals. This illustrates the range of land areas required to offset to net zero for projects of this size.

The whole NR estate has been assessed for its carbon sequestration potential via LULUC application. The chapter ended with two substantive discussions.

Firstly, the assessment of the potential of ER and offsetting to reach net zero. This assessment found that net zero can be achieved on a project-by-project basis. As NR land assets are not inexhaustible, offsetting will not be feasible to offset all residual carbon. The maximum carbon that can be offset in this manner is around one fifth. This was illustrated in the NR land assets expansion exercise. All

efforts should therefore be focused on increasing the ER percentage to enable the lowest possible residual carbon level to be achieved.

Secondly, an assessment of the potential sustainability co-benefits of offsetting. This assessment found that there is a plethora of additional co-benefits to offsetting including environmental (increased biodiversity, decreased soil erosion) and health related (reduced pollutants, recreation, wellbeing). These co-benefits need to be assessed against the dis-benefits addressed in this section project by project as part of the social cost assessment of a project.

Chapter 7 Conclusions

In this chapter the overarching conclusions from the thesis are presented. Section 7.1 details how the aims and objectives have been met and Section 7.2 provides an interpretation of the LCA questions posed in Figure 2.24. Alignment with the UNSDGs is provided in Section 7.3. The research impacts from this thesis will then be presented in Section 7.4, followed by comments on the future direction of research in this area in Section 7.5. Final remarks in Section 7.6 conclude this thesis.

7.1 Meeting the Aims and Objectives

The aims and objectives of this research, outlined in Section 1.2, are now revisited with details of their fulfilment, presented within this thesis.

The first aim was to identify and categorise the differing geotechnical assets. This was met via fulfilment of objectives 1 and 2.

Objective 1 has been achieved via identification and categorisation of the specific types of geotechnical solutions across the UK mainline railway to be addressed as part of this research, by asset and intervention type, and has been illustrated in Section 1.4. The scope for the thesis is clearly outlined in Figure 1.5 where determination and details of which earthworks will be addressed and included in this thesis has been given. The scope includes embankments, soil and rock cuttings, with maintenance interventions extending the asset's lifespan by two years, refurbishment interventions expected to extend their lifespan by 20 years, and renewal interventions expected to extend their lifespan by 120 years (equivalent lifespan to new build earthworks), as defined in the NR Cost and Volumes handbook.

Objective 2 concerned quantification of the BAU carbon footprint for embodied CO₂e within the differing intervention and asset types, along with identification of carbon “hotspots”. Quantification of the BAU carbon was completed via construction of a suite of 50 case studies, aligned to PAS2080 using the PAS2080 aligned templates in the RSSB RCT and the method detailed in Chapter 3, and encompassing the A1-5 lifecycle stages. The suite of 50 case studies comprised 35 maintenance, 10 refurbishment and 5 renewals, covering 20 embankments, 19 soil cuttings and 11 rock cuttings and are detailed in Chapter 4. From these 50 footprints, carbon “hotspots” were identified as the A4 stage for maintenance interventions, A1-3 & A5 for refurbishments and A1-3 for renewals, see Table 4.9.

The second aim, to assess the potential for ER and emission offset over the lifecycle of these assets, was achieved via fulfilment of Objectives 3-6.

Objective 3, exploration of the CO₂e reduction methods with potential applicability to railway embankments and cuttings has been met in Chapter 5 under the three main areas of materials, transportation, and construction machinery fuel aligning with PAS2080 lifecycle stages A1-3, A4 and A5. Wide ranging ERs have been found of between 0-590% for materials (see **Error! Reference source not found.**Appendix E.11), 67-69% for a switch to EVs for cars and vans for transport, 74% for a switch to biofuels in HGVs for transport (see Table 5.2), and 74-80% for biodiesel and bioethanol respectively for plant and machinery on site (see Table 5.3).

When these ER factors are applied to the case studies and their footprints recalculated, mean ER reduction percentages, from the BAU scenario, are found to be 65-70% across the differing earthworks for maintenance interventions, 72-79% for refurbishments and 61-64% for renewals (see Table 5.5).

ER, when applied to case studies, varies considerably for A1-3 materials (due to the wide variation in materials ER of 0-590% detailed above), giving average materials embodied carbon reductions of 13% for maintenance interventions, 28% for refurbishments, and 56% for renewals. When applied to A4 transport the reductions are found to be very similar across the three intervention types at 70% for maintenance and 71% for both refurbishment and renewal, with this closeness due to the narrower range of ER available via a switch to EV's and cars and for a switch to biofuels in HGVs. For A5 site activities, application of the ER measures gives reductions of 68%, 74% and 65% for maintenance, refurbishment and renewals respectively, again with a narrow range of ER owing to the narrow range of ER available via a switch in the A4 lifecycle stage to biodiesel and bioethanol for plant and machinery. The broad hierarchy of intervention areas in Table 5.6 provides to NR managers an initial stage of the PAS2080 lifecycle to assess the potential for emissions reduction to have the greatest benefit.

Objective 4 concerning an assessment of the applicability of differing offsetting methods applied to railway embankments and cuttings was provided in Chapter 6 via an exploration of differing rail corridor vegetation and novel CDR methods in a railway context (see Sections 6.2 and 6.3). Section 6.4 details the choice of vegetation applied to the case studies, AR as the primary method of sequestration, followed by application of a novel alternative, EW.

Objective 5, the application of offsetting via the two differing sequestration methods of AR (vegetation) and EW, applied to the ER renewal scenarios to assess whether their use was able to balance the CO₂e account, found that these renewals were able to reach net zero on a project level basis.

The potential for emissions offset in terms of area of land required to have AR applied to offset the residual carbon of the five renewal ER case studies was presented in Section 6.4. This showed that on an NR Volume basis an average of 0.35ha of land would be required to offset the residual carbon from renewals interventions with a corresponding average lower, mid and upper EW sequestration area of 0.15ha, 0.03ha, and 0.02ha per NR Asset Volume.

Future work investigating area (m^2) or volume (m^3) of intervention (to take into account differing heights of embankments and cuttings) may be beneficial to allow for ratios of intervention size in hectares to corresponding AR and EW sizes (m^2 or m^3) to be calculated.

This project (case study level) assessment of requirements to offset residual carbon was followed by application of NR estate wide sequestration against the NR whole carbon footprint to assess its ability to help NR reach net zero at this level, indicating a theoretical potential of 1/7 of the footprint being offset via application of EW.

Objective 6, the potential sustainability co-benefits of CO₂e offsetting, was explored with biodiversity gain being a key theme here and sustainability co-benefits of use of AR (using the method outlined in this thesis via use of the WCC) addressing the improved biodiversity of plants and wildlife aspect of the NR ESS core priorities and contributing towards increased biodiversity (with no net loss by 2024 and BNG by 2035) alongside assisting in the delivery of the NR priority of the low emission railway via reduced carbon footprint (Network Rail, 2020b).

The CE principles outlined in this thesis (see Section 2.5.1) such as minimal waste and sustainable use of materials give direction for NR with regards to methods and procedures to use (such as the SURPLUS app) in pursuit of greater circular practice in NR. They provide a road map for other rail infrastructure owners worldwide to follow in pursuit of greater circularity in implementation of their earthworks' interventions. The measurement of RRR (already implemented in NR regions) is key to tracking the progress of implementation of these CE principles, including minimal waste. This measurement, alongside increased measurement of carbon footprints for earthworks interventions using the RSSB RCT PAS2080 templates, will allow NR to have greater visibility of the size of its carbon footprint for earthworks interventions. It also has the potential to be able to provide additional data to the ORRs data portals rail emissions statistics requirements, as the ORR has a role in monitoring and enforcing environmental regulations, see Figure 2.5 and Section 2.3.3. The ORR has two specific duties on sustainability and the environment. These duties are detailed in the Railways Act 1993 (ORR, 2024). NR has further accountability to the ORR in "success measures that it must deliver." These measures include its carbon emissions (limited to scopes 1 and 2 only at present), and biodiversity units.

There is also a distinct legal obligation on NR in prescribed circumstances to achieve no net loss of biodiversity and indeed to achieve BNG, this is where the additional sequestration measures used for carbon offsetting will also have the dual benefit of counting towards the improved biodiversity of these sites.

7.2 Interpretation of LCA

The questions posed in the LCA interpretation stage in Figure 2.24 have been answered in pursuit of the A&O of this thesis outlined above, and are reviewed in turn here:

Are emissions reductions possible to reduce BAU/expansion scenario?

The emissions in the BAU scenarios have been reduced as evidenced in the ER scenarios under the three headings of materials, transport and construction emissions aligning with PAS2080 lifecycle stages A1-3, A4 and A5.

Total raw BAU value of all 50 case studies is 746,116 kgCO₂e (see Appendix D.1) compared to total ER value of 202,882 kgCO₂e (see Appendix E.13). This shows an absolute saving of 543,234 kgCO₂e via implementation of the suggested ER measures to these 50 case studies which encompass the equivalent of 86 NR Asset Volumes. Multiplication of this figure up to the approximate 190,000 NR Asset Volumes of geotechnical assets encompassing embankments, rock and soil cuttings (see Table 4.11) could give a carbon saving of 1,200 million kgCO₂e. Nonetheless use of the projected maintenance, refurbishment and renewal schedule as detailed in the NR “workbanks” provides a more realistic estimate of carbon savings. Applying the approximate 68% carbon saving of implementation of ER measures to the extrapolation exercise projected maintenance figures (1,466 interventions) gives a carbon saving of around 1.8 million kgCO₂e (see Section 4.1.8 & Appendix E.27).

The A1-C4 expansion for renewals details additional carbon in the life cycle B and C stages and the A0-C4 expansion for renewals details carbon in the conception A0 stage. A0 is an area that is little understood or explored in the literature at present. It is against this expansion scenario that ER is applied to the renewal interventions.

Are emissions offsets possible to reduce BAU/expansion scenario?

The ER A0-C4 renewals scenarios have had emissions offsets applied via both AR and EW to estimate the areas of land required using the two differing methods to offset the residual carbon in each project for its ER scenario.

Does any intervention lifespan have lower carbon over lifetime than an alternative lifespan?

The functional unit of kgCO₂e vol/yr was used to enable comparison between projects with differing

lifespans and sizes. Using this factor, the mean functional units were found for the BAU and ER scenarios for A1-5 stages (see Appendix G.1) and the application of these to the differing intervention types is given below:

The maintenance interventions with a 2-year expected lifespan had mean functional units for BAU and ER of 577.08 and 175 kgCO₂ vol/yr respectively with total BAU and ER over the 2-year lifespan of 1,154 and 350 kgCO₂e.

The refurbishment interventions with a 20-year expected lifespan had a mean functional unit for BAU and ER of 556.54 and 98 kgCO₂e vol/yr respectively with total BAU and ER over the 20-year lifespan of 11,160 and 1,960 kg CO₂e respectively.

The renewal interventions with a 120-year expected lifespan had a mean functional unit for BAU and ER of 352.68 and 114 kgCO₂e vol/yr respectively with total BAU and ER over the 120-year lifespan of 42,360 and 13,680 kgCO₂e respectively.

Can NR achieve carbon reduction for earthworks?

NR could potentially achieve reductions for earthworks of around 2/3 using the ER intervention strategies outlined (for materials, transport and construction activities) compared to the BAU (over A1-5 stages). The five renewals interventions when expanded (A0-C4), and using the ER scenario, indicated that potential reductions of 64-69% could be achieved via the three strategies detailed above.

Can NR achieve net zero carbon for earthworks?

Using AR to offset carbon at individual project level 0.04 -2.32 ha of land is required to reach net zero for the ER EXP A0-C4 renewals. However, as land availability for AR application is not inexhaustible there are a limited number of projects which can use this method of offset before land availability becomes an issue.

Using EW to offset the residual case study carbon at individual project level requires 0.08 to 0.54 ha of land for the demonstrated lower boundary or 0.01 to 0.08 ha of land for the upper boundary for the ER EXP A0-C4 renewals, showing the reduced land requirement using this method of offsetting. Exploration of use of EW minerals as part of ballast in addition to the line side strips discussed in this thesis is an area for future research which may aid NR in finding additional areas for EW application.

A key finding of this thesis is that the application to all NR assets shows, even if all available NR land assets are converted to AR use, net zero cannot be achieved via offsetting in this way without further emissions reductions being applied first.

7.3 Addressing the UNSDGs

In meeting the aims and objectives of this thesis, several UNSDGs have also been addressed, as detailed below:

Goal 13 Climate Action is an overarching goal stemming from policy and government legislation. The Net Zero by 2050 goal is of relevance for this research and provides the backdrop for all the calculations therein for application of ER and offsetting in pursuit of this goal.

Goal 15 Life on Land concerns the additional co-benefits of sequestration. These have been assessed in this thesis against project level carbon emissions and whole NR emissions over a 25-year period to 2050 in pursuit of Objective 5 to illustrate their potential to assist in meeting the Net Zero by 2050 legal requirement.

Goal 9 Industry, Innovation and Infrastructure has been addressed via Objective 3. This thesis contributes to the design and implementation of low carbon earthworks for NR. This is achieved by providing guidance, via the taxonomy, on which lifecycle stage to implement ER measures into first for the three differing expected lifespans.

Goal 11 Sustainable Cities and Communities has been addressed via Objective 6 being met. This research has aided NR in embedding LCA via advocating use of the PAS2080 aligned template in the RSSB RCT. The novel carbon data capture form created as part of this thesis, is the first and most vital step in ensuring all data is collected and input in a consistent manner to enable future expansion from the A1-5 BAU scenario to A0-C4 lifecycle, ensuring application of emissions reduction is consistent and therefore enabling comparisons with other footprints. The sustainability concepts introduced in this thesis via increased circularity of materials and waste (such as soil and concrete) has also been advocated in pursuit of this goal.

Goal 12 Responsible Consumption and Production has been addressed through Objective 2 and 3 with identification of carbon hotspots in differing types of earthworks intervention and identification of a hierarchy of ER measures to apply in differing lifecycle stages via the differing areas of transport, construction, and materials emissions reduction.

7.4 Research Impact

7.4.1 Meeting Net Zero by 2050

Implementation of the ER strategies outlined in Chapter 5 has shown reduction in carbon could be made in the short or medium term based on existing and proven methods in the order of 68%, 74%

and 65% for maintenance, refurbishment and renewals of earthworks respectively. This implementation aiding NR to meet its first major milestone of 25% carbon reduction in CP6 and meeting its CP8 milestone of 65% reduction from its 2019 baseline. A comparison of the NR path to net zero by 2050, see Figure 2.13, against the UK's 6th Carbon Budgets Balanced Path to Net Zero (see Appendix B.7.1) shows the NR trajectory being slightly more ambitious than the CCC's Balanced Pathway. These percentages converge later in the period, and the CCC's pathway overtakes NR ambition in 2044 and 2049 (see Figure 7.1).

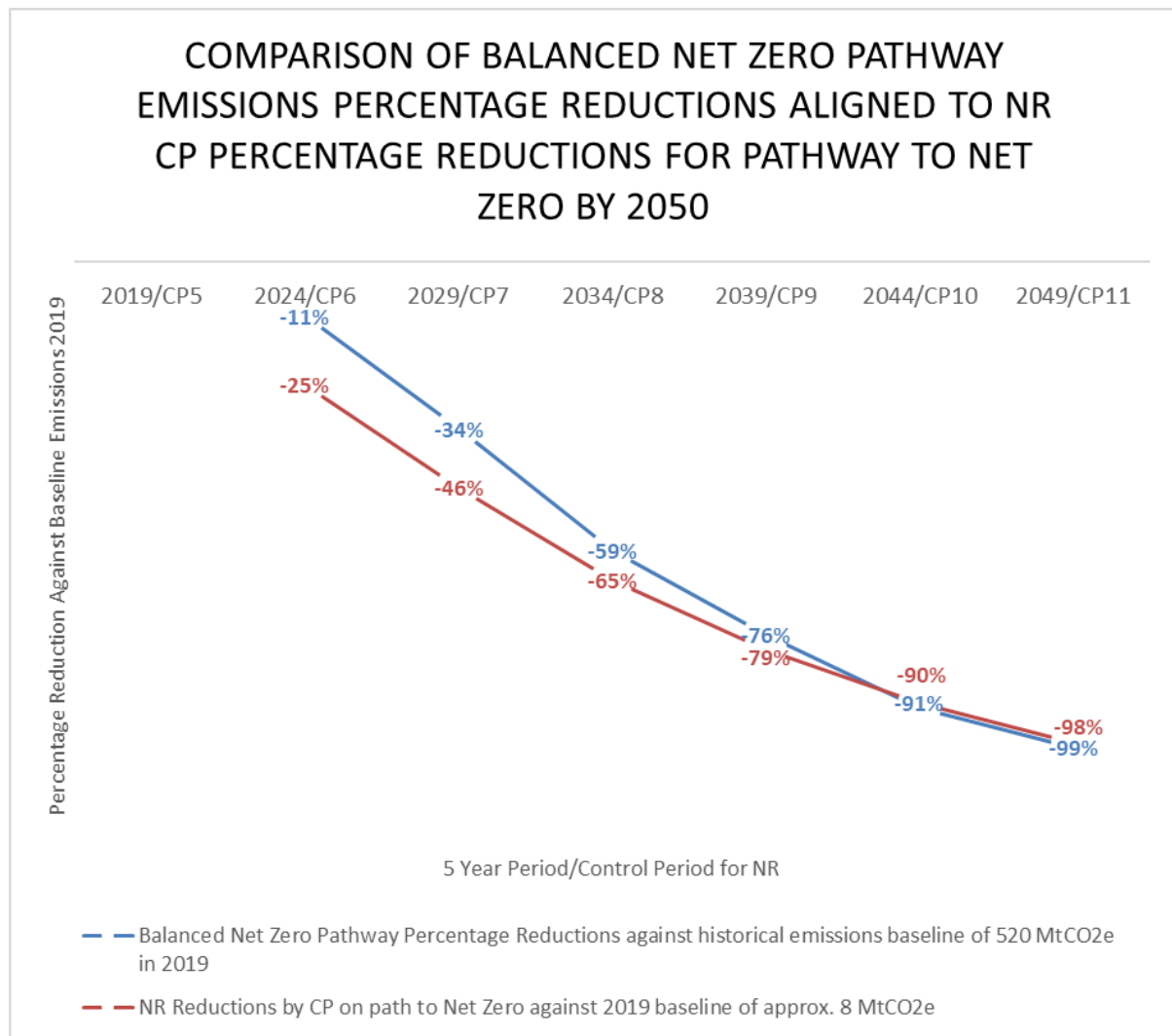


Figure 7.1 Comparison of CCC's Balanced Pathway Compared to NR's Journey to Net Zero by 2050, aligned to 5 yr CPs

Regarding use of offsetting for carbon emissions, use of EW with the higher theoretical value over the whole of the NR lineside assets of 1m width strips would give 10.9% reduction over 25 years on the total cumulative emissions for the whole of NR based on the NR reduction targets CP by CP between 2025 and 2050.

As of thesis hand in, the target for emissions reduction from 1990 figures has been increased to 81% by 2035 (BBC News, 2024; Climate Change Committee, 2024), to ensure the UK makes a “credible contribution towards limiting warming to 1.5°C above pre-industrial levels in line with the Paris Agreement” (Climate Change Committee, 2024) indicating that NR will need to increase their ambitions and potentially revisit their SBTs to ensure they too are on a compliant trajectory to net zero.

7.4.2 Sustainability Co-Benefits

The main sustainability co-benefit found is increased biodiversity with use of AR as a strategy for increased sequestration, which is a win-win for NR as it strives to meet the two legal obligations of 10% increase in biodiversity gain and net zero by 2050.

Other co-benefits of using sequestration via AR have been highlighted throughout and include reduction in water run-off in embankments, increased habitats for nature via joining up linear lineside habitats, and reduction in pollution via plants in lineside taking up pollutants and run-off.

7.5 Future Direction of Research

The arena of offsetting and decarbonisation is fast moving and influenced by a wealth of differing policy and industry actions.

Future directions of research in offsetting are to follow the latest outputs of the GGR-D projects (see Section 2.2.2) as this novel method for sequestration moves from the laboratory and small-scale tests to larger demonstration sites. This has been illustrated in the EW section as having the potential (using the higher theoretical value EW rate and assuming NR meeting its scope 3 reductions in line with those forecast) to offset up to 11% of the NR footprint over the next 25 years (see Section 6.5.1.3). This potential for EW to offset using line side strips has been reviewed and it has been shown that using smaller areas of land, greater sequestration rates can be achieved compared to AR. Use of EW material in ballast is the direction toward which future research should be focused. This is a burgeoning area of interest (Delatares, 2021), owing to the large amounts of ballast used on the network, 4,200t per 1km of track (Lokesh, Densley-Tingley and Marsden, 2022a, p.14).

In the future, innovations in materials, construction practices and energy for machinery on site along with transport of staff and materials should be regularly reviewed on a whole lifecycle basis. Where reduction is found these should be implemented in line with guidance documents such as PAS2080 and NR sustainability and environmental policies to ensure that the vital first step of carbon mitigation is followed (Axelsson *et al.*, 2024).

The development of a universal metric for comparing CO₂ in differing modes of transport over a certain distance (DfT, 2020) has been highlighted (see Section 2.2.2), although it is unclear whether this will be whole lifecycle carbon or just point of use (operating) carbon. Development of a whole lifecycle universal metric for comparing CO₂ across differing modes of transport may not be feasible at this time given the multitude of varying characteristics of differing modes' infrastructure and operating modes. Railway lines and roads having linear infrastructure comprising similar features such as embankments, cuttings, bridges and tunnels. In contrast, seaports and airports have large buildings and fixed routes. Roads and railway lines convey vehicles and trains, seaports and airports are arrival and departure points for boats and planes. This thesis has introduced the concept of a functional unit to allow for comparison between interventions of different size and expected lifespan.

Discussion regarding the five major impacts of this thesis has been communicated to NR, see Appendix G.2. Following discussion with the Carbon Team at NR (Minutes of Meeting 30.09.24) use of other metrics, rather than the linear volume metric used in this thesis, are under review. Metrics such as area or volume of earthwork are being reviewed to allow for a more accurate comparison between differing earthworks and enable more accurate carbon forecasting to take place. The hope is that in the future NR will incorporate the carbon calculation data form into its BAU operating procedure, taking the first steps in consistent and standardised carbon data collection.

An area that could be strengthened in future studies is expanding the scope of environmental indicators to include additional information as discussed in the footprint families of biodiversity and social justice for example, as a focus on one single indicator (such as CO₂e) to assess the whole environmental impact could mask the effects of other indicators (such as PM₁₀) (Trevisan and Bordignon, 2020, p.308). A single indicator approach could distort the environmental picture. Although CO₂e includes weightings for all other GHGs, a more holistic approach including not just all GHGs but also PM_{2.5} and PM₁₀, and noise pollution or social impacts for example, may provide a more detailed picture of impacts of earthworks (Trevisan and Bordignon, 2020, p.308). One method of expansion may be via use of an environmental "dashboard" of indicators with minimum levels to be met across a range of environmental services (or indeed maximums, such as for noise, not to be breached).

7.6 Final Remarks

This thesis opened with the stark message from UN Secretary General that we are in the era of global boiling. This pivotal message set the urgent tone and need to focus on exploring emissions reduction and offset in the context of NR earthworks interventions. It highlighted the importance of mitigation

before offset and emphasised that every gram of carbon matters. Using the research outputs from this thesis, inroads to carbon reduction can be made via application of the hierarchy of reduction measures by PAS2080 lifecycle stage. Use of PAS2080 is extolled repeatedly, as the need for carbon literacy in all NR staff is key to implementation of these measures. Use of the carbon calculation data form along with PAS2080 templates provides a path for project managers to follow which is not overly restrictive, allowing them the freedom to follow technologies suited to specific sites or projects. It also enables following of best practice already being implemented by similar linear infrastructure managers such as HS1, HS2 and Highways England to reduce emissions in their earthworks.

Appendix A Appendices Relating to Chapter 1

A.1 Intervention Options: Maintenance, Refurbishment & Renewal of Earthworks

A.1.1 Intervention Options to Maintain Earthworks for Two-Year Lifetime at Given Geographic Location, amended from Network Rail (2017b, p.13)

Earthworks Type	Intervention Options to Maintain Earthworks
Soil Cuttings	Drainage maintenance Vegetation management Devegetation of drains Devegetation of minor retaining structures Individual geotechnical tree removal Vermin eradication and exclusion Debris and refuse clearance Servicing engineered support (such as soil nails, netting, rock bolts) Locally clearing/repairing catch fences/netting Servicing geotechnical instrumentation array or alert/alarm systems
Rock Cuttings	Drainage maintenance Vegetation management Devegetation of drains Individual geotechnical tree removal Vermin eradication and exclusion Debris and refuse clearance Routine cess clearance Regular light scaling Servicing engineered support (such as soil nails, netting, rock bolts) Locally clearing/repairing catch fences/netting Servicing geotechnical instrumentation array or alert/alarm systems
Embankments	Drainage maintenance Vegetation management Devegetation of drains Devegetation of minor retaining structures Individual geotechnical tree removal Vermin eradication and exclusion Debris and refuse clearance Servicing engineered support (such as soil nails, netting, rock bolts) Locally clearing/repairing catch fences/netting Servicing geotechnical instrumentation array or alert/alarm systems

A.1.2 Intervention Options to Refurbish Earthworks for 20-Year Lifetime at Given Geographic Location, amended from Network Rail (2017b, p.14)

Earthworks Type	Intervention Options to Refurbish Earthworks
Soil Cuttings	Toe support - gabions Local toe retaining structure (less than 10m in length) Local regrade of slope (less than 10m in length) Shallow excavate and granular replacement (rock blanket) Limited deep excavate and granular replacement (less than 10m) Badger relocation (including backfilling) Slope drainage Crest drainage Cess containment ditch
Rock Cuttings	Local regrade of slope (less than 10m in length) Scaling Controlled rock removal Isolated dentition (less than 10m in length/10% of cutting face area) Erosion protection system Isolated rock dowels (passive) (less than 10m in length/10% of cutting face area) Isolated rock bolts/anchors (active) (less than 10m in length/10% of cutting face area) Drainage refurbishment Local rock netting (less than 10m in length/10% of cutting face area) Cess containment ditch Slope drainage Crest drainage
Embankments	Cess support – lightweight Local cess support – heavyweight (less than 10m in length) Retaining wall - gabions Local toe retaining structure (less than 10m in length) Substantial geotechnical tree removal Local regrade of slope (less than 10m in length) Toe berm Shallow excavate and granular replacement (rock blanket) Limited deep excavate and granular replacement (less than 10m) Badger relocation (including backfilling) Grouting Slope drainage Toe drainage Catch netting

A.1.3 Intervention Options to Renew Earthworks for 120-Year Lifetime at Given Geographic Location, amended from Network Rail (2017b, p.15)

Earthworks Type	Intervention Options to Renew Earthworks
Soil Cuttings	Deep excavate and granular replacement (10m or more in length) Toe retaining structure (10m or more in length, not gabions or temporary support) Regraded slope (10m or more in length) Soil nailing Ground anchors Deep slope drainage/rock ribs Cess catch fence/wall/bund
Rock Cuttings	Regraded slope (10m or more in length) Heavy scaling Dentition (at least 10m in length/10% cutting face area) Shotcrete Buttresses/anchored walling/beams Rock dowels (passive, at least 10m in length/10% cutting face area) Rock bolts/anchors/strapping (active, at least 10m in length/10% cutting face area) Cess catch fence/wall/bund Rock netting (at least 10m in length/10% cutting face area)
Embankments	Cess support – heavyweight (10m or more in length) Retaining wall (not gabions) Regraded slope (10m or more in length) Deep excavate and granular replacement (10m or more in length) Deep shear keys Soil nailing Ground anchors Soil mixing Shear piles Piled slab and embankment renewal Toe retaining structure (10m or more in length, not gabions or temporary support) Deep slope drainage/rock ribs

A.2 GWP Selected Gases

A.2.1 IPCC GWP Weightings for Selected Major GHGs Over Differing Lifetimes 20 and 100, amended from IPCC 2021

Name	Formula	Lifetime	Radiative efficiency	AGWP 20	GWP 20	AGWP 100	GWP 100
Carbon dioxide	CO ₂		1.33x10 ⁻⁵	0.0243	1	0.0895	1
Methane	CH ₄	11.8	0.000388	1.98	81.2	2.49	27.9
Nitrous Oxide	N ₂ O	109	0.0032	6.65	273	24.5	273

Units: Lifetime: yr; Radiative efficiency: W m⁻² ppb⁻¹; AGWP: pW m⁻² yr kg⁻¹; AGTP: pW m⁻² yr kg⁻¹; CGTP: yr

A.2.1 illustrates the different multipliers applicable for these main GHGs over selected lifetimes, with the two gases selected, Methane and Nitrous oxide having GWP factors of 81.2 and 273 for GWP20, and 5.38 and 233 for GWP100. These differing multipliers clearly indicate that GWP will have an impact where CO₂e is utilised.

A.2.2 IPCC GWP Weightings for Selected Major GHGs Over Differing Lifetimes 500, 50 and 100, amended from IPCC 2021

Name	AGWP 500	GWP 500	AGTP 50	GTP 50	AGTP 100	GTP 100	CGTP 50	CGTP 100
Carbon dioxide	0.314	1	0.000428	1	0.000395	1		
Methane	2.5	7.95	0.00473	11	0.00212	5.38	2730	3320
Nitrous Oxide	40.7	130	0.124	290	0.0919	233		

Units: Lifetime: yr; Radiative efficiency: W m⁻² ppb⁻¹; AGWP: pW m⁻² yr kg⁻¹; AGTP: pW m⁻² yr kg⁻¹; CGTP: yr

A.2.3 Emission Metrics for Selected Species, amended from IPCC AR6 (IPCC, 2021)

Species	Lifetime	Radiative efficiency	GWP 20	GWP100	GWP500	GTP50	GTP100	CGTP50	CGTP100
CO ₂	Multiple	$11.8 \pm 0.16 \times 10^{-5}$	1	1.000	1.000	1.000	1.000		
CH ₄ – fossil	11.8±1.8	$5.7 \pm 1.4 \times 10^{-4}$	82.5±25.8	29.8±11	10.0±3.8	13.2±6.1	7.5±2.9	2,823±1,060	3,531±1,385
CH ₄ – non fossil	11.8±1.8	$5.7 \pm 1.4 \times 10^{-4}$	80.8±25.8	27.2±11	7.3±3.8	10.3±6.1	4.7±2.9	2,701±1,057	3,254±1,364
N ₂ O	109±10	$2.8 \pm 1.1 \times 10^{-3}$	273±118	273±130	130±64	290±140	233±110		
HFC-32	5.4±1.1	$1.1 \pm 0.2 \times 10^{-1}$	2,693±842	771±292	220±87	181±83	142±51	78,175±29,402	92,888±36,534
HFC-134a	14.0±2.8	$1.67 \pm 0.32 \times 10^{-1}$	4,144±1,160	1,526±577	436±173	733±410	306±119	146,670±53,318	181,408±71,365
CFC-11	52.0±10.4	$2.91 \pm 0.65 \times 10^{-1}$	8,321±2,419	6,226±2,297	2,093±865	6,351±2,342	3,536±1,511		
PFC-14	50,000	$9.89 \pm 0.19 \times 10^{-2}$	5,301±1,395	7,380±2,430	10,587±3,692	7,660±2,464	9,055±3,128		

Units: Lifetime: yr; Radiative efficiency: W m⁻² ppb⁻¹; CGTP: yr

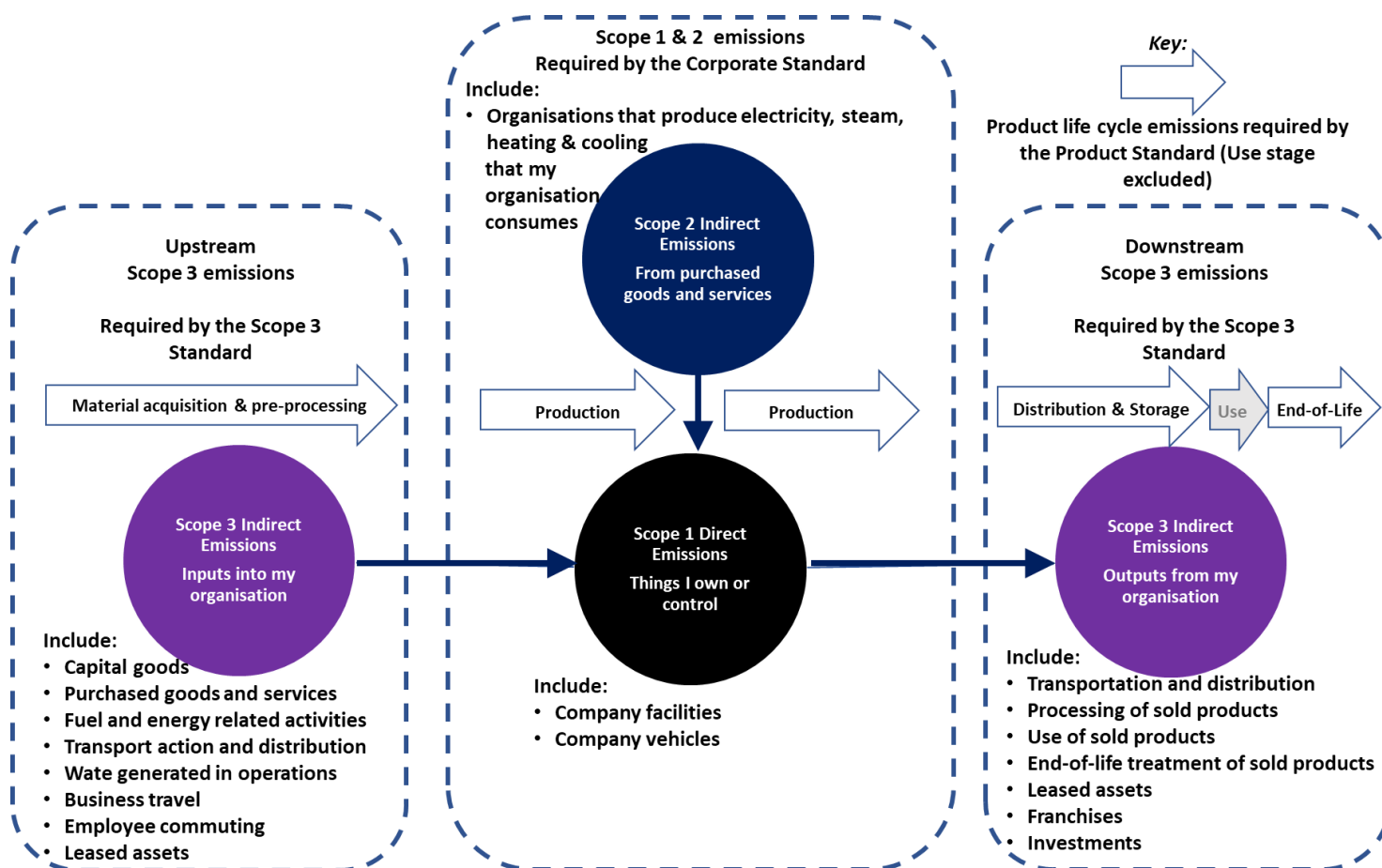
A.2.3 is presented to provide an awareness of the inherent errors that are introduced and the differing methods in calculating the weighting of differing GHGs over differing time periods.

A.3 GHG Emissions, Scopes, and Streams

There are a multitude of approaches to categorising GHG emissions, which include scopes 1, 2, & 3, direct and indirect emissions, and upstream and downstream emissions (World Business Council for Sustainable Development and the World Resources Institute, 2004).

The differing scopes of emissions can be concisely bound into scope 1, 2 and 3, direct and indirect, see Figure A.3.1 with each scope encompassing those areas detailed within its bubble. Each dashed box, adjacent to each bubble, contains the activities which are included in upstream (feeding into a company's activities) and downstream activities (resulting from a company's activities) along with indication of which scopes and activities are covered by the corporate, scope 3 and product standards of the GHG Protocol for reporting purposes. These scope 3, upstream and downstream activities can also be referred to as the "value chain" (HM Government, 2019b). Some emissions may have an element of overlap (RSSB, 2021a) and double counting (further definition available in glossary) as scope 1&2 emissions for one organisation will be the scope 3 of another organisation, furthermore corporate account emissions will inherently be included in national inventories too. To avoid "shifting environmental problems from one place to another" (Shillaber, 2016, p.21), whole LCA is of importance to ensure complete assessment of all the CO₂e associated with a particular intervention. Scope 1, 2 and 3 emissions have equivalent ISO 14064-1 certification standard terms of Direct, Energy Indirect, and Other Indirect emissions respectively (HM Government, 2019b).

A.3.1 GHG Protocol Scope 1, 2, & 3 Emissions & Direct and Indirect Emissions & Upstream and Downstream and Product and Corporate Standard, amended from (Highways England, 2021), (HM Government, 2019b), (Network Rail, 2019), (Carbon Trust, 2021a) and (Greenhouse Gas Protocol, 2011)



A.4 Boundaries

A further clarification of carbon accounts is offered in the form of a descriptive label that clarifies the lifecycle boundary, cradle to X, with most boundaries beginning in the cradle, although some such as operating carbon are just in the in-use stage. The two boundaries most commonly associated with products are cradle-to-gate and cradle-to-grave (Carbon Trust, 2021), see glossary. A third boundary that should also be considered is that of cradle-to-cradle, to incorporate recycling or reuse of products and thus bringing in the concept of the CE (Circular Ecology, 2021), along with other intermediary boundaries such as cradle-to-site and cradle-to-end of construction. All of the above boundaries are as cited by RICS (2012) in Akan, Dhavale and Sarkis (2017). It should also be noted that lifecycle carbon is another term for cradle-to-grave emissions. The above boundary definitions are also utilised when describing the embodied carbon of a product and can be measured within any of the aforementioned boundaries, although the most common boundary is cradle-to-gate for these types of datasets (RICS, 2012).

The lifecycle stages encompassed by each of the Cradle-to-X terms is given in A.4.1 illustrating the limited scopes of the first three definitions compared to the latter two. A carbon footprint is further defined in this research as all calculated CO₂e within the defined boundary and scope of a given case study.

A.4.1 Cradle-to-X Lifecycle Stages



A.5 Carbon Neutral/Net Zero

There is a need for consistency in the use of the terms net zero and carbon neutral to ensure that carbon critical business decisions are in line with the goals of the Paris Agreement (Carbon Trust,

2022b). The Science Based Target Initiative (SBTi) has previously highlighted the lack of consensus regarding an agreed definition for net zero and carbon neutral, pointing to this causing misalignment and inconsistency in net zero targets (Carbon Trust, 2022b).

These definitions are found separately in the literature as carbon neutral or carbon neutrality (Matthews *et al.*, 2020; Kortazar, Bueno and Hoyos, 2021; Watt, 2021; Lokesh, Densley-Tingley and Marsden, 2022a), as Net Zero (RSSB, 2022) (DfT, 2020) (HM Government, 2021c) and found together (HM Government, 2021d), (McLaren *et al.*, 2019) and Carbon Trust (2022a). A number of policy and governmental departments use the term net zero in their publications, potentially to ensure consistent messaging with the net zero by 2050 mandate, now enshrined in UK law (HM Government, 2019a), see Section 2.2.

Inconsistencies between the Carbon Trust, SBTi, IPCC, UN, and UK Government in terms of net zero and carbon neutrality definitions, add to the general confusion for the reader, particularly if they are trying to compare data between literature sources, which may be utilising differing definitions and therefore having differing boundaries and differing emissions included.

A.5.1 Boundary, Ambition and Residual Emissions Differences Between Carbon Neutral and Net Zero, amended from (Carbon Trust, 2022a).

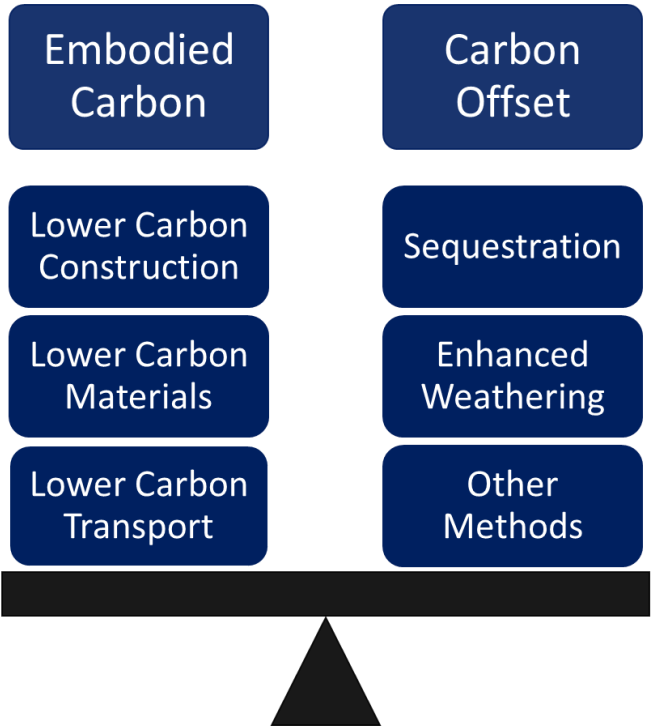
	Carbon Neutral	Net Zero
Boundary	Scope 1 and 2 minimum requirement Scope 3 “encouraged”	Must cover Scope 1, 2 & 3
Levels of ambition	No requirement to follow certain trajectory	“Must be” reducing emissions along a 1.5°C trajectory across Scope 1,2 & 3
Approach to residual emissions	Carbon offsets purchased must result in carbon reduction, efficiencies or sinks	GHG removals purchased must result in carbon sequestration from the atmosphere

This lack of consensus has been addressed at COP27 with the release of global guidance in the form of ISO International Workshop Agreement (IWA) 42 Net Zero Guidelines (ISO, 2022), and the accompanying BSI guidance document (BSI, 2022) which aims to clarify net zero terminology, with it being defined as human-caused residual GHG emissions are balanced by human-led removals over a specified time period and within specified boundaries. ISO IWA42 provides clarity and consistency in

use of nomenclature in this fast-moving area of net zero, and, via its launch at COP27, the so-called “implementation COP,” provides a trajectory to follow for all on this net zero journey.

Scales can be used to illustrate net zero balancing of anthropogenic GHG emissions with direct and indirect emissions on one side, and displaced and offset emissions of equal size on the other (UK Green Building Council, 2019). For this thesis lowering of embodied CO₂e on one side of the scales to reduce the BAU, via use of ER measures, and then CO₂e offset on the other to balance out the residual CO₂e is constructed, see A.5.2, which align with Objectives 3, 4, and 5, see Section 1.2.

A.5.2 Balanced Carbon Scales to Align with Objectives 3, 4 & 5 of Thesis

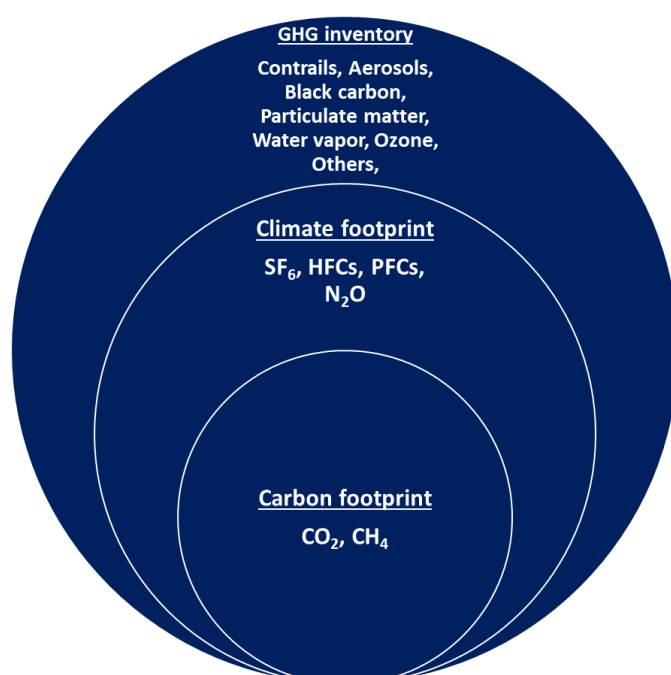


A.6 Carbon Footprint

The term carbon footprint is often associated with other members of the footprint family, such as water and energy footprints (Fang, Heijungs and de Snoo, 2013; Cheng *et al.*, 2020; Matustik and Koci, 2021), along with the material and climate footprint (Cheng *et al.*, 2020) (Mostert *et al.*, 2021) (see also Section 5.4.4). This is in contrast to the term carbon accounting which is more often used stand-alone (Brander *et al.*, 2021; Hamilton *et al.*, 2021). Wright, Kemp and Williams (2011) state that the term carbon footprint is “used interchangeably with other terms such as ‘carbon accounting’ or ‘carbon inventory’”. This poses a challenge when discussing carbon footprints to ensure that all boundaries, scopes and inventories are like-for-like. This issue is discussed throughout this thesis, see Sections 2.2, 2.4.3, 4.1.3 (functional unit) and 4.3.2 (parameters for comparison).

This lack of consensus in terminology leads to inconsistency in the way carbon footprinting calculations are performed (Wright, Kemp and Williams, 2011; Santana and Toshie Oiko, 2019; Matustik and Koci, 2021). In agreement with Rivers (2018), Matustik and Koci (2021) state that the most familiar term in use, and the one with the greatest variability in its definitions and methods, is carbon footprint, and that this leads to “chaos” in the literature. Williams *et al.* (2012) attempt to bring order to the “chaos” with a definition for carbon footprint (proposed in their earlier work with Wright and Kemp) and climate footprint. See A.6.1 indicating the progressively larger scope of gases included in each definition.

A.6.1 Carbon Footprint, Climate Footprint and GHG Inventory Boundaries, amended from (Williams *et al.*, 2012, p.57)



Appendix B Appendices Relating to Chapter 2

B.1 Timeline of UK environmental Legislative Commitments 1976-2016 , amended from HM Government (2018)

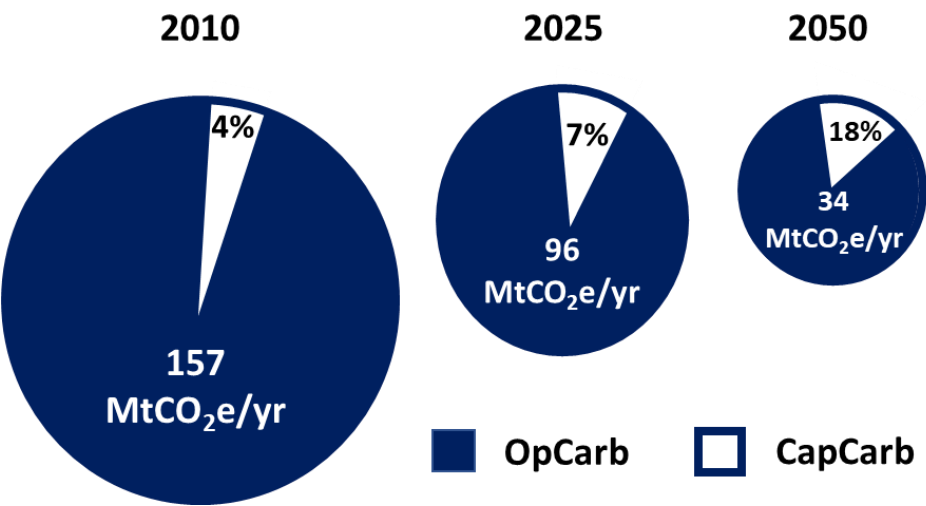


B.2 UN Sustainability Development Goals, from (UN, 2021)



B.3 Pie Charts Showing Relative Percentages of OpCarb and CapCarb

B.3.1 Increasing Significance of Capital Carbon amended from Green Construction Board (HM Treasury, 2013, p.10)



B.4 ICR Themes Mapped onto CE Thinking

B.4.1 illustrates that the production and processing, distribution and collection stages of a product or process have the potential to have circular thinking principles, and increasing circularity, via use of the 9’Rs, and that their use is not just limited to the constraints of the design, use and recycle stages. This use of CE thinking in carbon reduction is expanded on further in the Construction Playbook

B.4.1 ICR Themes Mapped onto CE Thinking, amended from Mi-ROG (2020, p.6)

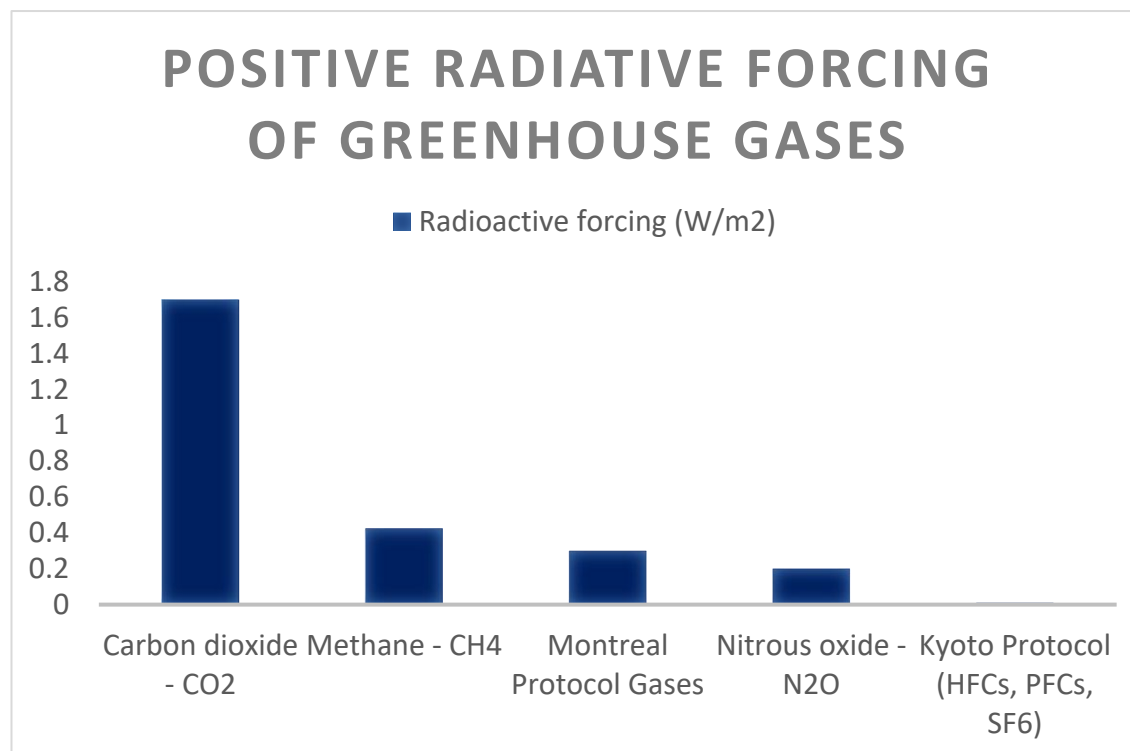
ICR Themes	Circular Economy Thinking
Build nothing Challenge root cause of the need Explore alternative approaches to achieve desired outcome	Retain Maximise use of existing assets Design for durability, longevity, adaptability
Build less Maximise use of existing assets	Re-use, reclaim, re-cover Follow hierarchy of re-use Share materials’ information

ICR Themes	Circular Economy Thinking
Build clever Design using low carbon materials Minimise resource consumption	Re-think Use less material Select local materials, minimising transport movements
Build efficiently Embrace new construction technology Eliminate waste	Optimise Use new technology for material re-use, resource efficiency, carbon storage

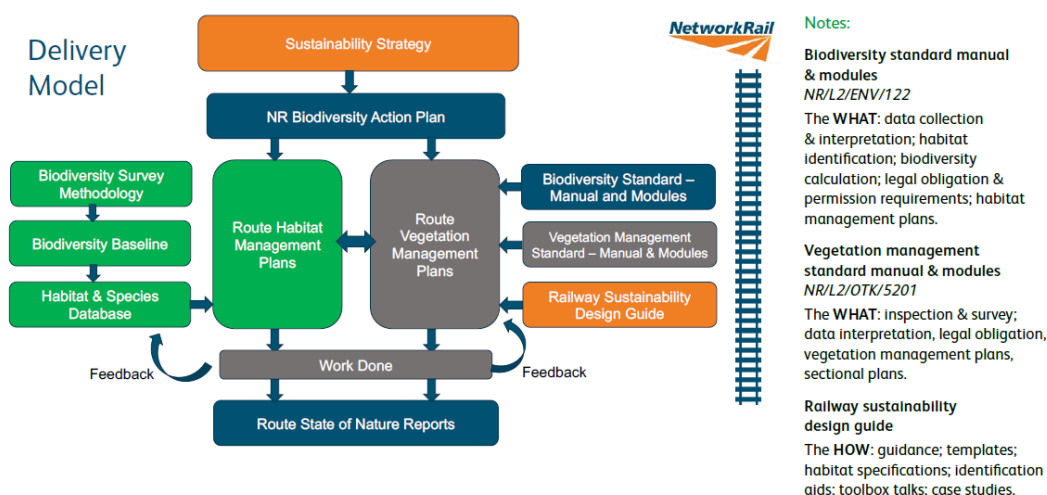
B.5 Radiative Forcing Graph

This figure illustrates the relative importance of CO₂ when compared to other GHGs, however the impact of the other gases is not insignificant. The lifespan of these other GHGs should also be taken into consideration. N₂O has a residence time of 109 years compared to 11.8 years of CH₄, and the CO₂e for the relevant GWP takes account of this.

B.5.1 Positive Radiative Forcing of Climate (1750-2005) due to Anthropogenic Emissions, amended from (Wright, Kemp and Williams, 2011) and not to scale



B.6 NR's Biodiversity Delivery Model , from (Network Rail, 2020d)



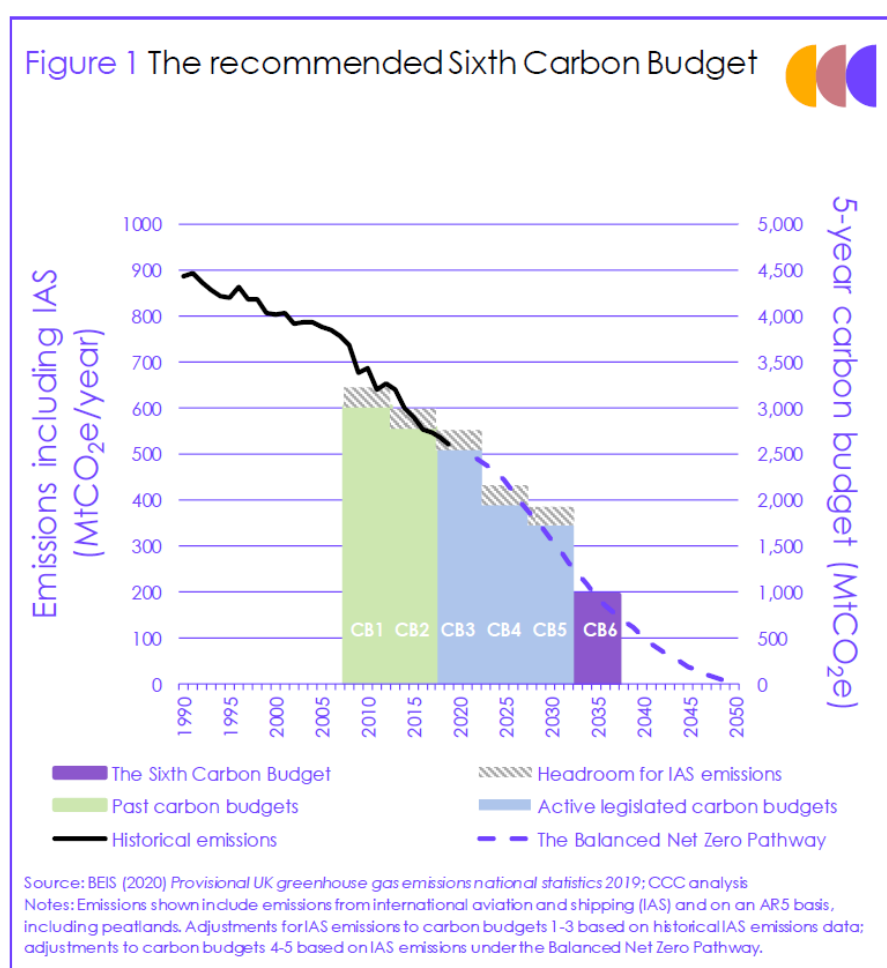
B.7 Carbon Budget/NDCs

The carbon budget quantifies the total amount of cumulative net CO₂ that can be emitted by a country within a certain time frame, in order to remain within the probability of remaining below a given temperature increase

threshold, such as 1.5°C or 2°C (IPCC, 2018). The carbon budget is also utilised to formulate NDCs, see Section 2.2.1 & 2.2.2.

There are huge uncertainties around the remaining carbon budget, see Section 1.1. For the 1.5°C warming scenario the difference between the 17th percentile and the 83rd percentile is wide, ranging from 900 GtCO₂ to 300 GtCO₂ (IPCC, 2021). The Climate Change Committee (CCC) recommended that the UK submit its next NDC for 2033-38 (Sixth carbon budget) based on their proposed path to enable the highest ambition to be met, see B.7.1

B.7.1 Pathways to Net Zero from Climate Change Committee (2020b, p.14)



The balanced net zero pathway for the UK will, by 2050, position the UK to remain within the greater than 50% likelihood range of curtailing temperature rise to 1.5°C, see B.7.1.

The CCC provide additional guidance on differing pathways and scenarios including abatement such as low carbon solutions from CO₂ capture, and offset of emissions using both land and GHG removals, see Figure 1.2. Detailed explanations of pathways and scenarios will not be presented here as these are outside the scope of this thesis,

however lower carbon solutions are examined in pursuit of Objectives 4, 5 & 6 of this thesis in Chapter 5, and offsets in Chapter 6.

From these NDCs, SBTs can be formed. SBTs are one way of showing transparency and a clear agenda in line with the relevant environmental legislation in the journey towards net zero. Signing up to the SBTi and setting verifiable interim targets, is one avenue open to companies to help enhance their competitiveness in this period of transition to net zero by 2050, alongside ensuring that the goals they set themselves are “consistent with the level of decarbonisation required to limit warming to 1.5°C or well-below 2°C” (SBTi, 2020).

National Highways plans to reduce these emissions via construction plant and compounds becoming zero emission by 2030, focusing on cement, and via use of a carbon management system “accredited to the PAS2080 methodology” and a requirement for their supply chain to implement PAS2080 and set SBTs to align with the 1.5°C target. They also aim to “embed approaches to minimise emissions” along with “lean construction practices” and “principles of the circular economy,” adding that they will “integrate whole life carbon reduction” into projects. Regarding materials’ transport, they aim to work with their suppliers including joining forthcoming zero emission HGV trials. In terms of zero emission construction sites, once again, they aim to work with suppliers to trial zero emission plant. Similar principles to this are applied to ER, see Chapter 5.

Additionally for the railway sector a potential routemap to assist in the journey to net zero by 2050 is proposed, although it is yet to have specific percentage reductions in line with the SBT added to it. See Appendix B.8 for further details. RSSB, 2022d (Sustainable Rail Strategy Prototype). This routemap provides infrastructure owners with specific actions to enable decarbonisation via identification of the performance management and industry skills required to meet each of the strategic time bound areas it identifies.

B.8 Potential Routemap to Net Zero Carbon Rail, amended from RSSB, 2022d (Sustainable Rail Strategy Prototype)

Strategic Area	Infrastructure Decarbonisation	Performance Management	Industry Skills
Strategic Aim	Rail assets, including infrastructure, trains and property, are net zero carbon over their whole lifecycle by 2050.	Decarbonisation targets and pathways in place with effective collection, analysis and reporting of carbon data.	Carbon skills across the industry are developed, with training schemes in place.
By 2050	Infrastructure fully decarbonised by 2050 Infrastructure fully decarbonised in Scotland by 2045		
By 2040	Infrastructure carbon reduced by X% by 2040		
By 2035			
By 2030	Infrastructure carbon reduced by X% by 2030 (compared with 2019 levels) 100% rail industry car and van fleet zero emission		

Strategic Area	Infrastructure Decarbonisation	Performance Management	Industry Skills
	100% government car and van fleet zero emission by 2027		
2022-2025	75% of rail industry's suppliers (by emissions) have SBTs Mandate carbon assessments for all capital projects Clear industry programme for infrastructure decarbonisation	Industry-wide carbon management system fully embedded into industry practices require all industry bodies to submit carbon data Set industry decarbonisation targets Establish industry-wide carbon performance management responsibilities within GBR Establish a system carbon optimisation framework, considering technologies such as C-DAS Establish a carbon action plan framework	Training programme established for employees working on operation and maintenance of diesel rolling stock Develop a carbon management skills training map

B.9 Errors in Footprinting

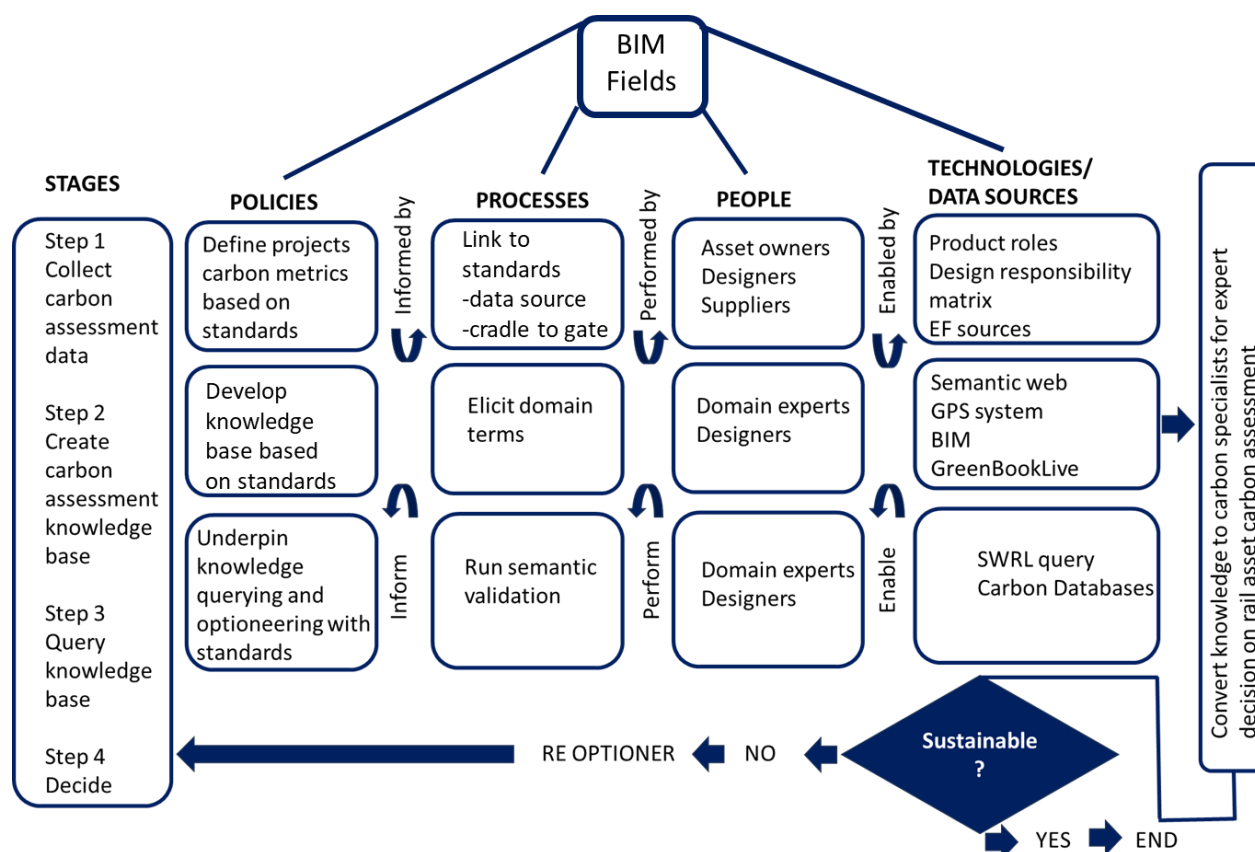
The lack of provision of an accounting or calculation methodology within the ISO14064 standard (GHG reporting standardized framework methodology) is also noted by Wright, Kemp and Williams (2011). They continue in their narrative and endorse use of a carbon footprint indicator, even if it does not give a definitive answer, as this “is better than the alternative of no indicator and decision making with ignorance” (Wright, Kemp and Williams, 2011, p.69).

One of the few references in the literature to the A0 stage is found in Akponeware *et al.* (2022) where reference to the pre-construction stage in a carbon footprint cradle-to-gate analysis is illustrated as a data requirement. Akponeware *et al.* (2022) reaffirms the theme of this thesis, that the current status quo regarding carbon assessment falls “short of driving long-term carbon reduction” and achieving net zero targets (Akponeware *et al.*, 2022, p.315), and that a “rethinking of the process of carbon assessments in the rail industry” is called for (Akponeware *et al.*, 2022, p.325). Akponeware *et al.* (2022, p.326), propose a framework to assist and guide decision makers based on “policy, process, people and technology dimensions,” see Appendix B.9.1.

Appendix B.9.1 indicates the framework advocated by Akponeware *et al.* (2022), illustrating BIM at the top of this hierarchy feeding into policies, processes, people and technologies. A limitation of the framework is the inference, under processes, that the carbon footprint is limited to cradle-to-gate and not whole lifecycle footprints, this limitation being attributed to the reliance of the study on the ICE database. Lokesh, Densley-Tingley and Marsden (2022a) note that NR need to present the carbon implications of new infrastructure utilising a whole-life approach, again pointing towards use of standards, such as PAS2080, which advocates and provide a framework via their A-D stages for evaluating this whole-life carbon.

B.9.1 Framework to Assist and Guide Policy Makers

Framework to Assist and Guide Policy Makers, amended from Akponeware *et al.* (2022)

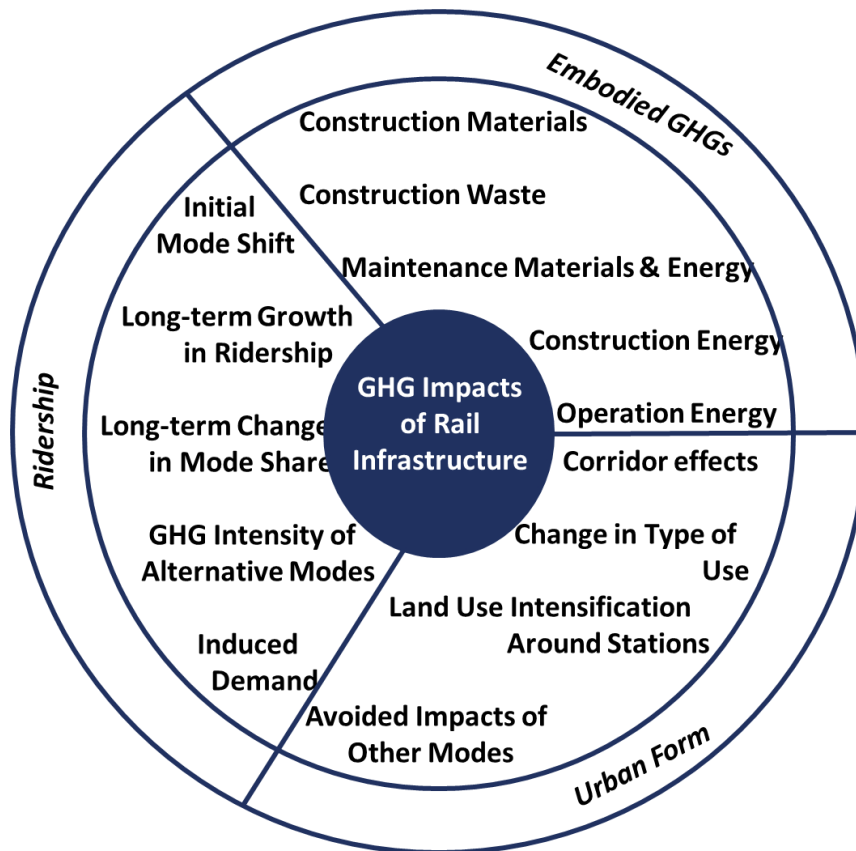


Saxe *et al.* (2015) explored GHG emissions impacts of rail projects, and, in line with Akponeware *et al.* (2022), note that the existing assessments are “often limited both in their scope and the factors considered” (Saxe *et al.*, 2015, p.171), and further acknowledge that acceptance of lifecycle thinking is growing in the construction sector. Furthermore the application of LCA for CO₂, Saxe *et al.* (2015) contend, is still limited, with some studies only examining operational emissions and others being limited by the boundary of cradle-to-site rather than cradle-to-grave (see Appendix A.4.1). Saxe *et al.* (2015) further conclude that a more holistic understanding of the GHGs emitted as part of a rail project is required in the form of a capital assessment, operational energy and maintenance assessment, along with mode shift in terms of ridership and modal share impacts, see Appendix B.9.2.

Appendix B.9.2 illustrates the split of GHG emissions via ridership, urban form and embodied, aligning approximately with the use, outside the lifecycle, and before use emissions correspondingly, of the PAS2080 lifecycle model.

B.9.2 Key Elements of GHG Impacts of Rail Infrastructure

Key Elements of GHG Impacts of Rail Infrastructure, amended from (Saxe *et al.*, 2015)



Akponeware *et al.* (2022) progress further in their analysis of the UK rail industry's carbon assessment, indicating that lack of a prescriptive approach to carbon standards, including PAS2080, is hindering comparability of results. This is due to the lack of standardisation in key comparators including boundaries, service life of assets and functional units, see Section 4.3. This lack of a prescriptive approach is impeding comparisons with the literature. Akponeware *et al.* (2022) elicit, from the sustainability experts involved in their study, a view that stricter measures going above and beyond PAS2080 are required to allow for UK rail to achieve continued carbon reduction.

Akponeware *et al.* (2022) also reiterate concerns highlighted in previous carbon studies regarding the use of the ICE database when compared to EPDs for a Passivhaus case study where significant variation in some of the data was found. This lack of comparable background data in the form of the ICE database is of great concern.

Akponeware *et al.* (2022) highlight that it is not the lack of common software that is the issue, however the provision of a common methodology would contribute towards standardisation of results and allowing for comparability of like for like between studies in terms of boundaries, service lives and functional units.

B.10 Low and Whole Carbon Initiatives

Selected NR carbon reduction internal documents are now reviewed, including the low embodied carbon steel routemap, MaGIC for NR, Zero Carbon World, and capital carbon documents (Network Rail, 2018a; Wise and Winslow, 2019; Winslow, 2020; McCann *et al.*, 2021).

Results of the Marginal Gains In Construction (MaGIC) survey (answered by 100 people from NR in 2019) suggests that this shift from BAU towards sustainability is not fully embedded in NR culture. Survey results include the viewpoint that the majority of large project leaders in NR indicated that their team did not have the skills to deliver sustainable design and construction. Conversely, over 92% of the respondents supported the position that NRs funding processes and procurement rules should have explicit consideration of whole life cost implications as a requirement, and 77% agree that NR should bolster its links with academic and industrial research organisations to foster expertise in manufacture and use of low carbon materials (Wise and Winslow, 2019). Furthermore, 1 in 4 of the staff surveyed did not feel that NR has an active and understandable sustainability plan that they could utilise (Wise and Winslow, 2019). MaGIC, with a focus on marginal gains adding up to larger gains, links to the concept of “baby steps” in the SNCF REUSE project (UIC, 2021), see Section 2.4.2.

The Zero Carbon World Tiger Team final report (McCann *et al.*, 2021) provides guidance for NR. A ‘Tiger Team’ utilising a challenge-based approach via a skilled specialist group, assesses problems and proposes solutions, to the carbon problem. The Tiger Team undertook a specialist critical review of the carbon and innovation landscape to articulate their recommendations, including acknowledging the “lack of leadership around the carbon agenda” along with a general lack of exemplar projects and carbon skills and knowledge, such as carbon literacy, see Section 2.4.5 (McCann *et al.*, 2021, p.4).

Lack of full adoption of PAS2080 principles could limit collaboration in the sector, particularly along the supply chain, and this could be behind the slow-moving implementation of innovative solutions (McCann *et al.*, 2021). Furthermore, there is a scarcity of research which considers the “interconnected nature of capital, operational and user carbon” (McCann *et al.*, 2021, p.31). The lack of a common project level carbon management tool is also noted (McCann *et al.*, 2021), with the carbon data collection form proposed in this thesis (see Appendix C.3.1), used along with the PAS2080 templates and PACE aligned PAS2080 templates, being advantageous for NR, allowing for like-for-like comparisons between projects (Network Rail, 2022c). The Carbon Innovation Initiative Register, from the Zero Carbon World project, incorporates a mixture of ideas and opportunities (including reducing embodied carbon in materials, reducing transport carbon, decarbonisation of on-site energy consumption and fully electric construction sites, explored as three discrete areas in Chapter 5) related to low carbon innovation specifically for UK infrastructure (McCann *et al.*, 2021,

pp.57-103). Opportunities in the register, explored in this thesis, include carbon estimating, standardisation, and adoption of carbon accounting tools along with use of a common project level carbon management tool, use of the RCT and embedding PAS2080 across the (rail) sector.

B.11 Carbon Accounting Methods and LULUC

Governmental guidance on reporting of carbon is available (HM Government, 2019b), providing guidance for organisations reporting their environmental impacts, including GHG emissions and waste. Guidance on what to include and how to measure, either absolute targets (comparing absolute figures in the target year to the base year), or intensity based targets (which are based on an appropriate normalising factor such as kgCO₂e per £100k spend) can be used (HM Government, 2019b). Offsets and woodland carbon units, see Chapter 6, are also outlined in this report, however these must be used with caution to avoid double counting, along with discussion regarding emitted and sequestered carbon quantities not being comparable. This governmental guidance also discusses some of the issues regarding NETs and CDR methods that will be explored further in Chapter 6 regarding additionality, avoiding leakage, permanence, validation, timing, avoidance of double counting and transparency (HM Government, 2019b). The overarching theme of the government guidance is that whole life accounting approaches are required for new railway infrastructure (Lokesh, Densley-Tingley and Marsden, 2022a).

The systemic literature review undertaken by Stechemesser and Guenther (2012) sought to derive a definition of carbon accounting over four differing scales, national, project, organisation, and product. They concluded that for the project scale measuring of non-monetary value of carbon, and offsetting from projects to inform stakeholders all aligning well with the scale of the case studies explored in this thesis. The most pertinent comment found in their work is: “To assume that a sequestered ton of carbon can compensate for an emitted ton of carbon is not a correct assumption” (Stechemesser and Guenther, 2012, p.30). This is of vital importance, as, although this thesis is looking to mitigate carbon and then assess the potential for emissions offsetting, it is important that the two amounts of carbon, emitted and sequestered, are not treated as equal. This issue is again brought to light in Marlowe and Clarke’s (2022) study on carbon accounting and the uncertainty of GHG inventories, where they contend that it is this uncertainty that leads to the inability to compare results of carbon accounting, and they pose the question: “How should carbon sequestering and sinks be calculated in these accounting systems?” (Marlowe and Clarke, 2022, p.82). This question highlights the ambiguities regarding accounting of emitted and sequestered carbon with use of efficiency ratings for CDR via differing pathways. AR has a decreasing efficiency percentage over increased timescales owing to the increased risk of forest fires and other natural disasters causing the carbon sequestered in the trees to be re-released (Chiquier *et al.*, 2022, p.4392). EW has differing

efficiencies depending on mineral type and crushed rock size (smaller size having greater efficiency) (Chiquier *et al.*, 2022, p.4397). This inequality between emitted and sequestered carbon is explored further in Chapter 6, see Section 6.1.

Further comparison of different reporting mechanisms in the waste sector by Turner, Kemp and Williams (2011) includes the GHG protocol, PAS2050, ISO, Carbon Trust and Defra Guidelines. They note the lack of commonly agreed sector-specific standard, giving rise to high levels of inconsistency and also “inaccurate, incomplete and noncomparable carbon footprints” (Turner, Kemp and Williams, 2011, p.677) with a knock on effect in information management of corporate GHGs.

B.12 UIC Ten Methodologies: Further Details

UIC REPORT REF. NO & CODE	STUDY OBJECTIVE	STUDY REF DOCUMENT	METHODOLOGICAL APPROACH & STUDY RESULTS
01 IFEU	Measuring carbon footprint and other environmental impacts of existing railway infrastructure, freight and passenger, both local-regional and high speed.	'Carbon Footprint and environmental impact of Railway Infrastructure' Tuchschnid <i>et al.</i> (2011)	Emission factors: Ecoinvent Database 2.2. Track – impact per year*km Buildings – impact per year*unit Results include CO ₂
02 UCB	Comparison between environmental impacts of road, rail and aircraft passenger transport. Both local-regional and high-speed existing infrastructures.	'Grand challenges for high-speed rail environmental assessment in the United States' (Chester and Ryerson, 2014)	LCA database: SimaPro2006 Per vehicle lifetime Per vehicle mile travelled Per passenger-mile travelled Results include GHG – CO ₂ , N ₂ O, CH ₄
03 RFF	Measuring carbon footprint of new passenger high-speed rail infrastructure.	ADEMA, RFF. SNCF; 1er ferroviaire global Bilan Carbone – La Ligne a Grande Vitesse Rhin-Rhone au service d'une Europe durable: 2011.	Emission factors: ADEME Cumulative emissions from the construction of the railway infrastructure. Results: CO ₂ eq
04 ITALFERR	Measuring carbon footprint of a railway infrastructure construction phase aimed at creating projects and programmes that allow significant CO ₂ emissions reductions. For both passenger and freight transport and both local-regional and high speed.	F. Loffredo, P. Fedele, M. Severine; The climatic mark of railway infrastructural projects; Ingegneria Ferroviaria 3/2011. (Loffredo, Fedele and Severini, 2011)	Compliant with ISO 14064 Cumulative emissions from the construction of the railway infrastructure. Results: CO ₂
05 JBV	Measuring environmental impacts connected with the construction of new rail infrastructures, for both passenger and goods transport.	MiSA AS; New Double Track Line Oslo – Ski Lifecycle Assessment of the Follo Line – Transport – Technical report Lifecycle Assessment of the Follo Line – Transport; Rev 00A, 2011. (Kjerkol and Kalager, 2011)	SimaPro using Ecoinvent inventory database Total impact Impact per pKm-tKm Results include CO ₂ eq

UIC REPORT REF. NO & CODE	STUDY OBJECTIVE	STUDY REF DOCUMENT	METHODOLOGICAL APPROACH & STUDY RESULTS
06 NTNU	Assessing environmental impacts of a future Norwegian high-speed rail infrastructure for passenger transport.	<i>'Life-cycle assessment of future high-speed rail in Norway'</i> (Grossrieder, 2011)	Ecoinvent 2.2 background systems SimaPro – emissions factors Impact per year*km Results include: Climate change – Global Warming Potential in CO ₂ eq
07 CUENTAS	Measuring environmental, social and economic impacts connected with different transport modalities in Spain. For passenger high speed infrastructures.	Alfonso Sanet zero, Pilar Vega, Miguel Mateos; Las cuentas ecologicas del transporte en Espana. Vol I + Vol II (methodology); 2014 (Alduán, Pindado and Arribas, 2016)	Energy consumption assessment per economic investment Total impact Results include: Emission of greenhouse gases CO ₂ eq
08 AEA	Measuring GHG emissions – both freight and passenger, both local-regional and high speed – resulting from future infrastructure construction and use, vehicle manufacturing, and EOL vehicles (ELVs) of different transport modes (Air, Rail, Road, Ship) and their possible influence on designing optimal routes to long-term GHG reductions from transport by 2050.	Nikolas Hill et al: the role of GG emission from infrastructure construction, vehicle manufacturing, and ELVs in overall transport sector emissions. (Hill <i>et al.</i> , 2011)	Emission factors from different sources used including SimaPro2007 and ICE (Bath University). CO ₂ /km (construction) CO ₂ /passenger (operation) Results include: CO ₂ eq
09 INECO	Measuring carbon footprint associated with new passenger High-Speed infrastructures.	INECO, Huella de carbono de la construccion de una linea ferroviaria de alta velocidad;2012 (INECO, 2012)	Ecoinvent 2.0 – indirect emissions EMIL Cornier – direct emissions CO ₂ eq per km Results include: CO ₂ eq
10 UIC	Measuring carbon footprint of new high speed rail (in comparison with road and air passenger transport).	High Speed Rail and Sustainability. Background Report: Methodology and results of carbon footprint analysis (Baron, Martinetti and Pépion, 2011)	Ecoinvent Database 2.0 -emission factors Track CO ₂ per year*km Buildings CO ₂ per year*unit Results include: CO ₂

B.13 Transparency Rating of the Methodologies, amended from (Cuenot and Hernandez, 2016)

Transparency	IFEU	UCB	RFF	ITALFERR	JBV	NTNU	CUENTAS	AEA	INECO	UIC
Illustration of calculation and assumption details	M	G	M	G	B	B	B	B	M	M
Reporting of CO2 emission factors	G	G	M	G	B	M	B	M	B	G
Indication of the emission factor data sources	G	G	M	G	B	M	M	M	B	G

Key: G = good – data fully available and traceable, M = medium – data sources published but numbers not detailed, B = bad – no source or any detailed numbering

B.14 System Boundaries Summary for Each Methodology, amended from (Cuenot and Hernandez, 2016)

Boundaries	IFEU	UCB	RFF	ITALFERR	JBV	NTNU	CUENTAS	AEA	INECO	UIC
Planning			X	X						X
Construction	X	X	X	X	X	X	X	X	X	X
Operation		X	X		X		X	X		
Maintenance	X	X	X		X			X		
Disposal					X					

**B.15 Elements of the Railway Infrastructure Included in Assessment,
amended from (Cuenot and Hernandez, 2016)**

Elements Assessed	IFEU	UCB	RFF	ITALFERR	JBV	NTNU	CUENTAS	AEA	INECO	UIC
Stations	X	X	X	X				X		X
Tunnels/ Bridges	X		X	X	X	X	X	X	X	X
Catenary	X	X	X	X	X	X	X	X		X
Signalling & telecoms	X	X	X	X	X	X	X	X		X

Appendix C Appendices Relating to Chapter 3

C.1 RSSB Tool Data Input & Training

In this thesis, use of the RSSB RCT with inventory values obtained from the Bath ICE database and Defra allows for the composition of the case studies' footprints to be transparently shown, allowing for comparability between comparative projects.

The traction decarbonisation network strategy (Network Rail, 2020f) states use of the RCT has been adopted and mandated for use in infrastructure enhancement projects to drive down volumes of carbon in infrastructure projects. This is realised in the recently released guide to managing whole life carbon in infrastructure (Network Rail, 2022c), containing a table detailing at which PACE stage and value of project the carbon assessment is required to be completed, see Table 3.1. It indicates the progression of lifecycle carbon from the current A1-3 to cover additional stages over time. In addition, NR has released a new carbon template (Project ID 775529 A NR Whole Life Carbon (PAS2080) template v1) for use within the RSSB RCT (Jones, 2021).

Further instructions on the use of the RCT can be found via the online training tools (full training available for a fee), on the RCT website via <https://www.rssb.co.uk/en/sustainability/rail-carbon-tool> and also via the NR guide (Network Rail, 2021e).

The RSSB RCT is kept updated via continuous improvements to address rail industry current and future carbon measurement requirements via the Rail Industry Carbon Management Working Group (CMWG), the custodians of the tool (Network Rail, 2021e). The specific remit of the CMWG includes effective management of carbon in rail infrastructure projects via the use of PAS2080 modular lifecycle stages, measuring and reducing carbon in rail infrastructure via development and communication of expert knowledge, monitoring effectiveness, development and awareness of RCT and any other carbon tools to aid the rail industry's overall infrastructure carbon reporting (RSSB, 2021c).

Earthworks foundations as a sub set of railway infrastructure need to have their lifecycle energy consumption, which is a useful proxy for carbon only if the materials being compared have a similar average EF (Fenner, Sykes and Ainger, 2023, p.163), bounded by the four stages of material extraction, processing of composite materials, transport between site, and construction. Once "built" no further energy is expended during operation and they do not require any further refurbishment or remediation during their anticipated lifetime (Shillaber, 2016, p.23).

Even with the advent of the new BECD, many tools are already linked into other existing databases such as the RSSB RCT with the ICE database. As such, “a unified reporting and communication system,” (aligned to PAS2080 stages) rather than unification of methodologies among databases (Takano *et al.*, 2014, p.20), would appear to be the most feasible solution moving forward to bring a level of consistency to the topic of carbon footprints of railway earthworks.

C.1.1 Other Databases

An assessment of the EcolInvent database and the uncertainty effects therein is provided by Muller *et al.* (2018) who points to the lognormal distribution which is used by default in the EcolInvent database “to model exchange uncertainly values” (Muller *et al.*, 2018, p.300) and notes that alternative distributions are available in later versions of the database, including Normal, Gamma, Uniform, Triangular and Beta PERT. This distribution has several useful properties outlined by Muller *et al.*, including it is always positive, it has a linkage to the normal distribution, as it’s right-tail distribution it is able to model large values and as such also model large uncertainties, also, its logarithmic mean and standard deviation can be retrieved via the arithmetic mean and standard deviation from a calculation of the available sample. Muller *et al.* concludes by recommending use of the default lognormal distribution to model data uncertainty and that this distribution is kept the same for both compared systems. A detailed scrutiny of EcolInvent has not been performed as its use is subject to licence and other associated costs.

Further sources of uncertainty in LCA are then highlighted by Muller *et al.* (2018) and classified: As model, scenario and parameter uncertainty while also noting that the LCA standard ISO14040 does not incorporate a “universal approval” (Muller *et al.*, 2018, p.301) to the consideration of uncertainty in LCA. A sensitivity analysis is conducted by Muller *et al.* (2018) to assess the effect of switching and conclude that the characteristics of the LCIA have a dependency on the distribution used.

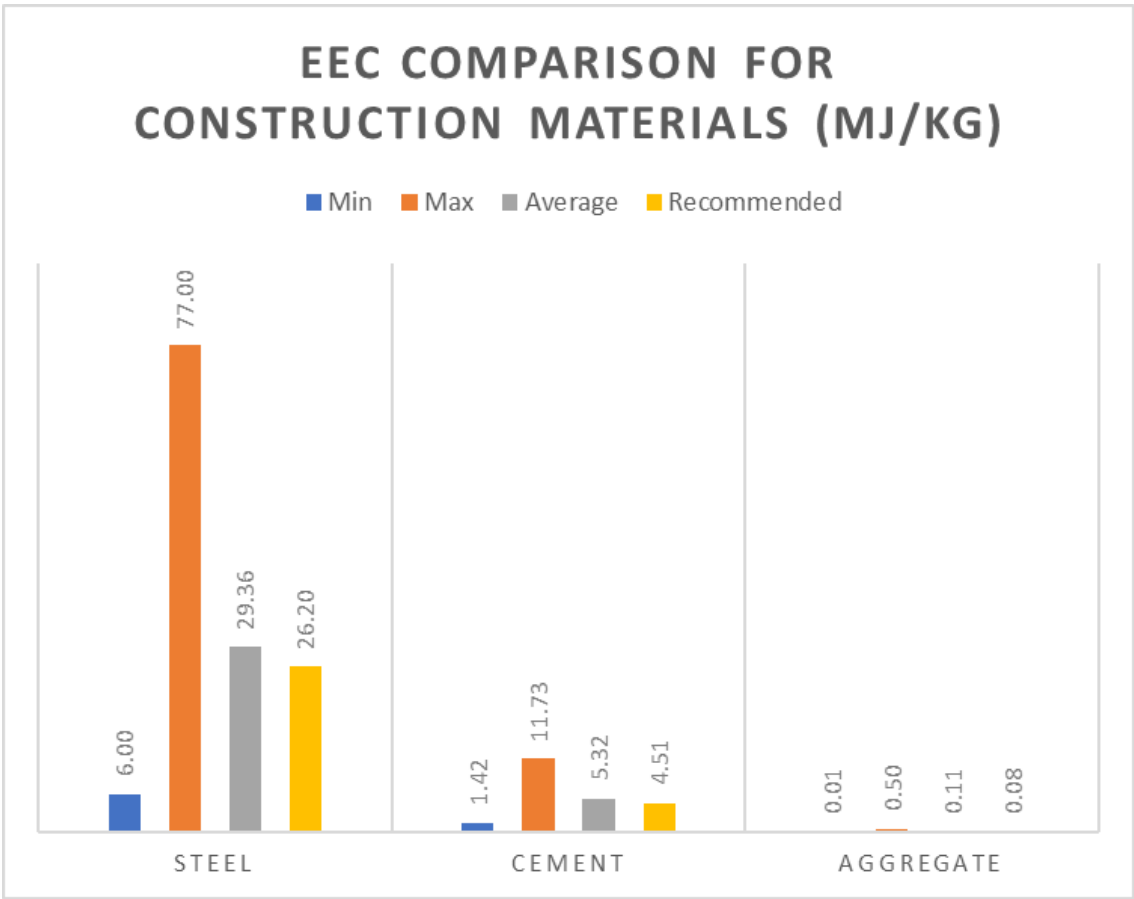
Shillaber (2016), similar to Muller *et al.* (2018), points to three major sources of uncertainty affecting energy and GHG assessments, with Shillaber’s focus being of those geotechnical assessments being made prior to construction:

- Subsurface conditions – outside thesis scope.
- Industry average EE and GHG emissions coefficients – links back to the discussion on the ICE and EcolInvent databases presented earlier.
- GHG conversions to CO₂e using GWP values – See Appendix A.2.

Shillaber (2016) notes, regarding GHG conversion, the GWP factor used must be reported owing to the difference that this can make in the final result. Shillaber (2016) also provides evidence, see

Appendix C.1.2, of differing values for EE via use of differing values for steel, cement and aggregate materials, namely minimum, maximum and average, although Shillaber does not clarify these further into UK or global, or recommend which is used.

**C.1.2 Variation in Embodied Energy for Materials in the ICE V2 Database
(amended from Hammond and Jones 2011 cited in Shillaber)**



Due to the above variations, use of EPDs should be advocated (Strippel and Uppenberg, 2010; RICS, 2012), as these will be the most accurate data for a particular case study. However, there are issues regarding obtaining item specific data in the form of EPDs. Hanson (UK supplier of building materials), for example, do not provide details by cement plant. Although they do collate this data, they will only provide UK average data to prevent one plant receiving all the orders, namely the plant with the lowest emissions factor.

A need for application of measures above and beyond PAS2080 is found in the literature to drive sustained carbon reduction in UK rail (Akponeware *et al.*, 2022). The current lack of “a standard data collection method” (Anand and Amor, 2017, p.410), means there is no common system boundary or functional unit in the construction industry which actually impedes comparability of results (Olugbenga, Kalyviotis and Saxe, 2019; Saxe and Kasraian, 2020). The ICE database is openly

acknowledged as being “limited” and used primarily for preliminary assessments alongside a consensus of reluctance by government and rail industry to share data, further highlighting the need for common solutions in the industry in the form of common methodology and common emissions factors (Akponeware *et al.*, 2022, p.325). Future research into use of digital data in the form of BIM is an area highlighted in the literature (Akponeware *et al.*, 2022).

C.2 Example of Case Study Descriptions

Summary description of each case study in a standardised format detailing the name, region, earthwork type, intervention level and lifetime, volume, brief works description, photo of the works (if available).

Airbles Station

Region: Scotland

Type: Rock Cutting

Level & Lifetime: Maintenance two years

Volume: 1 Rock Cutting Maintenance

Description: Remove overburdened materials and reinstate netting

Intervention Alignment with Cost & Volume Handbook: Rock Cutting Maintenance Relevant Activities; Vegetation management; Clearing and/or repairing locally catch fences/netting as applicable

Photo of Completed Works: None available

C.3 Example of Carbon Calculation Data Form

C.3.1 Blank Form

Blank copy of novel carbon data calculation form.

NR: Carbon Calculation Data Rev 3

Works Details

Works Name/Reference:	
Type: (please check one box)	Embankment ☐ Rock Cutting ☐ Soil Cutting ☐ Other ☐
Level & Lifetime: (please check one box)	Maintain (2yrs) ☐ Refurb (20yrs) ☐ Renew (120yrs) ☐
Size of works: (5-Chain Length is representative length for micro-case studies)	
Number of shifts & Hrs on shift:	

Brief Description of Works
(please attach photo of works site where available)

Materials required for works
(please attach data sheets for materials where available)

Description (Please include supplier, supplier part no, material and unit weight/no.)	Qty – kg or no.	Method of Transport	Distance to Site (km)

Thank you for completing this form.
 Please can you ensure all spaces are completed,
 indicating N/A where not applicable and ASSUMED where assumptions are made.

NR: Carbon Calculation Data Rev 3

Plant and Machinery required for works

(please attach data sheets for plant and machinery where available)

Description	Qty	Engine Type	Hours Running	Method of Transport	Distance to Site (km)

Transport of staff to site

Number of People	Method of Transport	Round Trip Distance to Site (in km)

Waste removal

Description (Please include separate entry for each type of waste eg soil, aggregate etc)	Qty - kg	Method of Transport	Distance to Final Destination (in km)	Final Destination eg landfill, recycling

Thank you for completing this form.
Please can you ensure all spaces are completed,
indicating N/A where not applicable and ASSUMED where assumptions are made.

C.3.2 FAQ Document

FAQs and brief instructions: Carbon Calculation Data Rev 3

Please complete the form in full. Where assumptions are made, please clearly state this. Please use metric units such as km, kg, m². Where this is not possible, please clearly indicate this; such as miles for transport distances, so these can be converted.

Appendix C

1. Please complete the data capture form – blank copy and exemplar attached.

NR: Carbon Calculation Data Rev 3

Works Details

Works Name/Reference:	
Type: (please check one box)	☐ Embankment ☐ Rock Cutting ☐ Soil Cutting ☐ Other
Level & Lifetime: (please check one box)	☐ Maintain (2yrs) ☐ Refurb (20yrs) ☐ Renew (120yrs)
Size of works: (5-Chain Length is representative length for micro case studies)	
Number of shifts & Hrs on shift:	

Brief Description of Works
(please attach photo of works site where available)

Materials required for works
(please attach data sheets for materials where available)

Description (Please include supplier, supplier part no, material and unit weight/no.)	Qty – kg or no.	Method of Transport	Distance to Site (km)

Thank you for completing this form.
Please can you ensure all spaces are completed, indicating N/A where not applicable and ASQ (MFT) where assumptions are made

NR: Carbon Calculation Data Rev 3

Plant and Machinery required for works
(please attach data sheets for plant and machinery where available)

Description	Qty	Engine Type	Hours Running	Method of Transport	Distance to Site (km)

Transport of staff to site

Number of People	Method of Transport	Round Trip Distance to Site (in km)

Waste removal

Description (Please include separate entry for each type of waste eg soil, aggregate etc)	Qty – kg	Method of Transport	Distance to Final Destination (in km)	Final Destination eg landfill, recycling

Thank you for completing this form.
Please can you ensure all spaces are completed, indicating N/A where not applicable and ASQ (MFT) where assumptions are made

2. Additionally, please provide data sheets for all materials and equipment used on site.

3. Please provide qty of fuel used for machinery used on site in addition to running hours (where possible).

4. Please identify from the list of interventions which one(s) are being addressed by your works eg soil cutting ->> maintenance ->> 1) Locally clearing/repairing catch fences

Earthworks Type	Intervention options to maintain earthworks
Soil Cuttings	Drainage maintenance Vegetation management <u>Devegetation of drains</u> <u>Devegetation of minor retaining structures</u> Individual geotechnical tree removal Vermin eradication and exclusion Debris and refuse clearance Servicing engineered support (such as soil nails, netting, rock bolts) <u>Locally clearing/repairing catch fences/netting</u> Servicing geotechnical instrumentation array or alert/alarm systems
Rock Cuttings	Drainage maintenance Vegetation management <u>Devegetation of drains</u> Individual geotechnical tree removal Vermin eradication and exclusion

5. Please identify standard details worked to for your works eg NR/CIV/SD/231 Rev B slope re-grade details

6. Please provide a photo of works post completion (if possible)

Common queries that occur are outlined below by form section to assist you in providing sufficient information to enable carbon calculation.

Materials

Please provide full details of all materials used on site.

eg rather than “rock anchors x 3”

“Rock anchors, made from steel, weight 0.5kg each, total qty used 50”

“Maccaferri mesh 50m² – see spec sheet attached for Double Twist Maccaferri Mesh”

Please attach data sheet or specification sheets where possible.

Plant and Machinery

Please confirm running hours per shift for all machinery, or qty of fuel used in litres (if known).

Please confirm whether plant left on site for duration of works, or towed back and forth weekly, or for each shift.

Please provide part number and specification sheet for plant/equipment including power type eg diesel powered 2.4hp engine or electric (battery powered) 5kw.

Transport of staff to site

Please indicate transport distances and mode of transport for all staff for all shifts. Please indicate if staff travel weekly and stay in local accommodation.

Waste removal

Can you please clarify the final destination and weight for any materials removed from site and detail what the materials removed were.

Please state if vegetation, for example, or other waste, is left in situ.

If you have any further queries regarding completion of this form please contact:

t.a.najafpour-navaei@soton.ac.uk

C.3.3 Completed Exemplar Form

Raw completed data collection form for each case study, completed by the contractor.

NR: Carbon Calculation Data Rev 3

Works Details

Works Name/Reference:	Higher Farm
Type: (please check one box)	Embankment ☐ Rock Cutting ☐ Soil Cutting ☐ Other ☐
Level & Lifetime: (please check one box)	Maintain (2yrs) ☐ Refurb (20yrs) ☐ Renew (120yrs) ☐
Size of works: (5-Chain Length is representative length for micro-case studies)	10 chain
Number of shifts & Hrs on shift:	11 x 9 hour shifts

Brief Description of Works
(please attach photo of works site where available)

Vegetation clearance, ditch clearance, regrade of embankment and installation of rabbit netting.

Materials required for works
(please attach data sheets for materials where available)

Description	Qty – kg or no.	Method of Transport	Distance to Site (km)
Rabbit Netting	200m Roll	Wagon	
Pins & Hogrings			

Thank you for completing this form.
Please can you ensure all spaces are completed,
indicating N/A where not applicable and ASSUMED where assumptions are made.

NR: Carbon Calculation Data Rev 3

Plant and Machinery required for works

(please attach data sheets for plant and machinery where available)

Description	Qty	Engine Type	Hours Running	Method of Transport	Distance to Site (km)
13t Longreach	1	Diesel	5	Flatbed	102
Telehandler	1	Diesel	5	Flatbed	102
Tower lights	2	Diesel	5	Flatbed	102
RRV	2	Diesel	5	Flatbed	102
Chipper	1	Diesel	5	Flatbed	102

Transport of staff to site

Number of People	Method of Transport	Round Trip Distance to Site (in km)
1	Van	15
1	Van	135
1	Van	112
1	Van	107
1	Van	100
1	Van	144
1	Van	100
1	van	136
1	van	102
1	van	183
1	van	183
1	van	30

Thank you for completing this form.
Please can you ensure all spaces are completed,
indicating N/A where not applicable and ASSUMED where assumptions are made.

NR: Carbon Calculation Data Rev 3

Waste removal

Description	Qty - kg	Method of Transport	Distance to Final Destination (in km)	Final Destination e.g., landfill, recycling
C&D – Mixed (17 09 04)	10,680	Skip wagon	SK14 2JP	Recycle

Thank you for completing this form.
Please can you ensure all spaces are completed,
indicating N/A where not applicable and ASSUMED where assumptions are made.

C.4 Example of Carbon Calculation Data Form Queries & Responses

Document trail of queries and subsequent responses from contractors for each case study.

Hatterlsey No. 2

NW&C Soil Cutting Maintenance (2 queries)

Materials

No queries.

Plant and Machinery

1 Can you please clarify if the 40 hours running for hedge trimmers was for each hedge trimmer, ie needs multiplying by 2 or is the total for both hedge trimmers (and also for chainsaws). **Total for all hedge trimmers**

Transport of staff to site

2 Can you please clarify that the distances provided for the 8 vans were the total round trip distance for the whole works for these vans? Or if they need multiplying by the 10 shifts. **Total distance do not multiply**

Waste removal

No queries.

C.5 Example of Assumptions Made to Case Study

Assumptions made for each case study against each section of the footprint.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	ALC1 Kenelm Road R1 BAU A1-A5 LC USING NR Whole Life Carbon Template v2															
2	SC20: ALC1 Kenelm Road - Removal of vegetation from cutting slope															
3	Description:	Qty – kg or no.	Engine Type	Hours Running	Method of Transport	Mileage to Site	Material for RSSB Tool	Unit weight for RSSB Tool	total weight kg	notes	RSSB weight per item - kg	RSSB material choice	RSSB vehicle choice per item	RSSB vehicle kilometers to site (x1.60934)	RSSB total weight per item	
4	MATERIALS															
5	N/A															
6	PLANT AND MACHINERY															
7	Strimmers (see dimbola farm for equivalent item)	2	Petrol	20 (total for both)	With Operatives	With operatives in van – see below.	assumed stihl strimmer petrol as per spec sheet provided for dimbola farm, weight 4.7kg, engine 1.01bhp			exclude transport mileage as travelled with staff and included in that transport		embodied carbon per strimmer = 0.002204613 kg co2				
8	Brush Cutters (see soulfon house)	2	Petrol	10 hours total	With Operatives	With operatives in van – see below.	brush cutter petrol as per spec sheet for soulfon house, petrol engine 2 stroke 1kW/1.35bhp using stihl saw in keller foundations for proportional			exclude transport mileage as travelled with staff and included in that transport		embodied carbon per brush cutter = 0.003002027 kg co2				
9	don't forget embodied carbon for items length of time on site - Not use															
10	TRANSPORT OF STAFF TO SITE															
11	Number of people				Method of Transport	Round Trip Distance							Van Average size			
12	1				Van	232		1296					x3.5t. Unknown			
13	1				Van	240										
14	1				Van	247										
15	1				Van	193										
16	1				Van	197										
17	1				Welfare Van	180										
18	WASTE REMOVAL															
19	n/a vegetation left in situ															
20																
21																
22																
23																
24	QUERIES															
25	none															
26	Please see attached remits for CAM south.															
27																
28	All mileages and figures given are totals for round trips and running times for machinery have been multiplied already.															
29																
30																
31																
32																
33																
34																
35																
36																
37																
38																
39																
40																
41																
42																
43																
44																
45																
46																
47																
48																
49																
50																
51																
52																
53																
54																
55																
56																
57																
58																
59																
60																
61																
62																
63																
64																
65																
66																
67																
68																
69																
70																
71																
72																
73																
74																
75																
76																
77																
78																
79																
80																
81																
82																
83																
84																
85																
86																
87																
88																
89																
90																
91																
92																
93																
94																
95																
96																
97																
98																
99																
100																
101																
102																
103																
104																
105																
106																
107																
108																
109																
110																
111																
112																
113																
114																
115																
116																
117																
118																
119																
120																
121																
122																
123																
124																
125																
126																
127																
128																
129																
130																
131																
132																
133																
134																
135																
136																
137																
138																
139																
140																
141																
142																
143																
144																
145																
146																
147																
148																
149																
150																
151																
152																
153																
154																
155																
156																
157																
158																
159																
160																
161																
162																
163																
164																
165																
166																
167																

ALC1 Kenelm Rd SC20 NW&C
Aldercar E120 EASTERN
Appley Locks E2 NW&C
Aughton Park RC2 NW&C
Bathpool Reservoir E2 NW&C

C.6 Example of A-Z .csv data download from RSSB RCT

Download of Footprint from RSSB RCT in .csv format, for each BAU A1-5 case study.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Level number	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Name	Units	Quantity	Single CO ₂ e	Total CO ₂ e	Project CO ₂ e	Missing CO ₂ e	Library Name	Source	State	Region	Carbon Factor Value
2	1	SC2 Dalton Junction R1 BAU	A1-A5 LC USING NR Whole Life	SC2 Dalton Junction R1 BAU							4951.93	4951.93	4951.93						
3	2		A1-A3 - BEFORE USE - Product Embodied Carbon	A1-A3 - BEFORE USE - Product Embodied Carbon							921.785	921.785	921.785						
4	3		Items Procured as Prefabricated Building Elements	Items Procured as Prefabricated Building Elements							0	0	0						
5	4		Prefabricated element #1	Prefabricated element #1							0	0	0						
6	4		Prefabricated element #2	Prefabricated element #2							0	0	0						
7	4		Prefabricated element #3	Prefabricated element #3							0	0	0						
8	3		Items Procured as Manufactured Construction Raw Materials	Items Procured as Manufactured Construction Raw Materials							0	0	0						
9	3		Items procured as construction raw materials	Items procured as construction raw materials							900	900	900						
10	4		MOT Type 1	MOT Type 1							10	90	900	900					
11	5		Limestone - General	Limestone - General							90	90	900		Limestone Bath ICE	United States		0.09 kgCO ₂ e/kg	
12	3		Construction-phase Consumable Products and Materials Transport (To-From)	Construction-phase Consumable Products and Materials Transport (To-From)							0	0	0						
13	3		Proportional embodied carbon for construction-phase Consumable Products and Materials Transport (To-From)	Proportional embodied carbon for construction-phase Consumable Products and Materials Transport (To-From)							21.785	21.785	21.785						
14	4		Embodied Carbon in Chains	Embodied Carbon in Chains							3	0.005	0.015	0.015					
15	5		Carbon Dioxide	Carbon Dioxide							0.005	0.005	0.015		Carbon Dioxide	Defra	UK	1 kgCO ₂ e/kgGHG	
16	4		Embodied Carbon in RRV - M	Embodied Carbon in RRV - M							1	19.15	19.15	19.15					
17	5		Carbon Dioxide	Carbon Dioxide							19.15	19.15	19.15		Carbon Dioxide	Defra	UK	1 kgCO ₂ e/kgGHG	
18	4		Embodied Carbon in Tower	Embodied Carbon in Tower							2	1.31	2.62	2.62					
19	5		Carbon Dioxide	Carbon Dioxide							1.31	1.31	2.62		Carbon Dioxide	Defra	UK	1 kgCO ₂ e/kgGHG	
20	2		A4 - BEFORE USE - Construction Stage - Transport	A4 - BEFORE USE - Construction Stage - Transport							2429.6	2429.6	2429.6						
21	3		Products and Materials Transport (To-From)	Products and Materials Transport (To-From)							68.16	68.16	68.16						
22	4		Prefabricated Elements	Prefabricated Elements							0	0	0						
23	5		Element #1	Element #1							0	0	0						
24	5		Element #2	Element #2							0	0	0						
25	5		Element #3	Element #3							0	0	0						
26	4		Manufactured Construction	Manufactured Construction							0	0	0						
27	4		Construction Raw Materials	Construction Raw Materials							68.16	68.16	68.16						
28	5		MOT Type 1	MOT Type 1							1	68.16	68.16	68.16					
29	6		Road Freight: HGV, Unknown	Road Freight: HGV, Unknown							68.16	68.16	68.16		Road Freight: HGV, Unknown	Defra	UK	0.1136 kgCO ₂ e/tkm	
30	3		Plant & Equipment Transport (To-From)	Plant & Equipment Transport (To-From)							1020.27	1020.27	1020.27						
31	4		RRV	RRV							1	935.155	935.155	935.155					
32	5		Road Freight: HGV	Road Freight: HGV, Unknown							935.155	935.155	935.155		Road Freight: HGV, Unknown	Defra	UK	0.1136 kgCO ₂ e/tkm	
33	4		Tower Lights - Diesel	Tower Lights - Diesel							2	42.5591	85.1182	85.1182					
34	5		Road Freight: HGV	Road Freight: HGV, Unknown							42.5591	42.5591	85.1182		Road Freight: HGV, Unknown	Defra	UK	0.1136 kgCO ₂ e/tkm	
35	3		Waste Transport (From)	Waste Transport (From)							681.6	681.6	681.6						
36	4		MOT Type 1	MOT Type 1							10	68.16	681.6	681.6					
37	5		Road Freight: HGV	Road Freight: HGV, Unknown							68.16	68.16	681.6		Road Freight: HGV, Unknown	Defra	UK	0.1136 kgCO ₂ e/tkm	
38	3		Worker Travel (To-From)	Worker Travel (To-From)							659.564	659.564	659.564						
39	4		Transit Van Travel via Unknown	Transit Van Travel via Unknown							2571	0.25654	659.564	659.564					
40	5		Van: Average size	Van: Average size <3.5t							0.25654	0.25654	659.564		Van: Average size <3.5t	Defra	UK	0.25654 kgCO ₂ e/vkm	
41	2		A5 - BEFORE USE - Construction Stage - Site Activity	A5 - BEFORE USE - Construction Stage - Site Activity							1600.55	1600.55	1600.55						
42	3		Fossil fuel use for mobile plant & equipment	Fossil fuel use for mobile plant & equipment							1600.55	1600.55	1600.55						
43	4		RRV 1 no	RRV 1 no							15	100.73	1510.95	1510.95					
44	5		Diesel Engine - 12	Diesel Engine - 125kW / 16h							100.73	100.73	1510.95		Diesel Engine - 125kW / 16h	EMEP/EE	Europe	100.73 kgCO ₂ e/hr	
45	4		Tower lights 2 no	Tower lights 2 no							15	5.973	89.595	89.595					
46	5		Diesel Engine - 7	Diesel Engine - 7kW / 9.45h							5.973	5.973	89.595		Diesel Engine - 7kW / 9.45h	EMEP/EE	Europe	5.973 kgCO ₂ e/hr	
47	3		Fossil fuel use for fixed/static plant	Fossil fuel use for fixed/static plant							0	0	0						
48	3		Grid electricity use by plant / equipment	Grid electricity use by plant / equipment							0	0	0						
49	3		Mains water use for site operations	Mains water use for site operations							0	0	0						
50	3		Waste treatment / disposal carbon footprint	Waste treatment / disposal carbon footprint							0	0	0						

Dalton Junction BAU R1 A1-A5

C.7 Example of A-Z .pdf report download from RSSB RCT

RSSB

Page 1 of 13

 Rail Carbon Tool				
Name	Quantity	kgCO ₂ e		
		Single	Total	Project
Portland Cement	4,250 kg	0.91	3,876	3,876
Cement - CEM I - Portland Cement		0.91	0.91	3,876
Raw material #2		0	0	0
Raw material #3		0	0	0
Construction-phase Consumable Products (excluding fuel & water)		0	0	0
Proportional embodied carbon for construction plant & equipment manufacture		52	52	52
Embodied Carbon in Compressor	1 no.	8.2	8.2	8.2
Carbon Dioxide		8.2	8.2	8.2
Embodied Carbon in 8t Excavator	1 no.	44	44	44
Carbon Dioxide		44	44	44
A4 - BEFORE USE - Construction Stage - Transportation		2,030	2,030	2,030
Products and Materials Transport (To)		513	513	513
Prefabricated Elements		0	0	0
Element #1		0	0	0
Element #2		0	0	0
Element #3		0	0	0
Manufactured Construction Products		150	150	150
Moncaster Macferry PVC Coated Hexagonal Wire Mesh		128	128	128
Lorry Transport to Site	186 km	0.69	128	128
Road Freight: Articulated HGV. Unknown size. Average Load		0.69	0.69	128
Galvanised Rebar U Pins		16	16	16
Flat Bed Transport to Site	186 km	0.08	16	16
Road Freight: Rigid HGV. Unknown size. Average Load		0.08	0.08	16

Page 2 of 13



Rail Carbon Tool



Name	Quantity	kgCO ₂ e		
		Single	Total	Project
Hog Ring Clips		6.8	6.8	6.8
Carrier Box Van Transport to Site	200 km	0.03	6.8	6.8
Van: Average size. <3.5t. Unknown fuel.		0.03	0.03	6.8
Construction Raw Materials		363	363	363
Grout - Portland Cement		363	363	363
Flatbed transit van transport to site	155 km	2.3	363	363
Van: Average size. <3.5t. Unknown fuel.		2.3	2.3	363
Material #2		0	0	0
Material #3		0	0	0
Plant & Equipment Transport (To-From)		390	390	390
Compressor XAS68-135 CFM		66	66	66
Towed by Van to Transport to-from site		66	66	66
Towed by Van	160 km	0.41	66	66
Van: Average size. <3.5t. Unknown fuel.		0.41	0.41	66
8t Excavator Hitachi ZX130 LCN-6		324	324	324
Low Loader Used to Transport to-from Site		324	324	324
Low Loader	160 km	2.0	324	324
Road Freight: Articulated HGV. 3.5 - 33t. Average Load		2.0	2.0	324
Plant #3		0	0	0
Waste Transport (From)		47	47	47
8cu yd skip		47	47	47
8cu yd Skip	50 km	0.94	47	47
Road Freight: Rigid HGV. Unknown size. 100% Load		0.94	0.94	47

Page 3 of 13



Rail Carbon Tool



Name	Quantity	kgCO ₂ e		
		Single	Total	Project
Worker Travel (To-From)		1,081	1,081	1,081
Ford Connect Type Van		542	542	542
Ford Connect	2,100 km	0.26	542	542
Car - MPV - Unknown Fuel		0.26	0.26	542
Ford Transit Type Van		539	539	539
Ford Transit	2,100 km	0.26	539	539
Van: Average size. <3.5t. Unknown fuel.		0.26	0.26	539
A5 - BEFORE USE - Construction Stage - Site Activities		11,797	11,797	11,797
Fossil fuel use for mobile plant & equipment / vehicle operations on site				
Compressor - XAS 68 - 135CFM	1 no.	3,478	3,478	3,478
Diesel Engine - 30kW / 40.5hp		3,478	3,478	3,478
8t Excavator - Hitachi ZX130LCN-6	1 no	8,148	8,148	8,148
Construction - Plant & Machinery - Excavator 13 tonne	1 no	8,148	8,148	8,148
Diesel Engine - Agricultural - 70kW / 94.5hp		8,148	8,148	8,148
Fossil fuel use for fixed/static plant & equipment for site operations and welfare		0	0	0
Grid electricity use by plant / equipment / services for site operations and welfare		0	0	0
Mains water use for site operations and welfare		0	0	0
Waste treatment / disposal carbon footprint (excluding transport)		171	171	171
8 cu yd Skip		171	171	171
8 cu yd Skip	1 8 cu yd	171	171	171
Waste - Refuse - Commercial and industrial waste		171	171	171
B1 - USE STAGE - Emissions from installed materials		0	0	0
Equipment / systems with potential for fugitive GHG emissions		0	0	0

Page 4 of 13



Rail Carbon Tool



Name	Quantity	kgCO ₂ e		
		Single	Total	Project
📁 B2 - USE STAGE - Maintenance		0	0	0
📁 Maintenance - Products Stage (A1-A3 equivalent)		0	0	0
📁 Replacement of Items Procured as Prefabricated Building Elements		0	0	0
📁 Prefabricated element #1		0	0	0
📁 Prefabricated element #2		0	0	0
📁 Prefabricated element #3		0	0	0
📁 Replacement of Items Procured as Manufactured Construction Products / Components		0	0	0
📁 Product #1		0	0	0
📁 Product #2		0	0	0
📁 Product #3		0	0	0
📁 Replacement of items procured as construction raw materials		0	0	0
📁 Raw material #1		0	0	0
📁 Raw material #2		0	0	0
📁 Raw material #3		0	0	0
📁 Replacement-phase Consumable Products (excluding fuel & water)		0	0	0
📁 Replacement-phase proportional embodied carbon for construction plant & equipment		0	0	0
📁 Maintenance - Transportation Stage (A4 equivalent)		0	0	0
📁 Products and Materials Transport		0	0	0
📁 Prefabricated Elements		0	0	0
📁 Element #1		0	0	0
📁 Element #2		0	0	0
📁 Element #3		0	0	0
📁 Manufactured Construction Products		0	0	0

Page 5 of 13



Rail Carbon Tool



Name	Quantity	kgCO ₂ e		
		Single	Total	Project
📁 Product #1		0	0	0
📁 Product #2		0	0	0
📁 Product #3		0	0	0
📁 Construction Raw Materials		0	0	0
📁 Material #1		0	0	0
📁 Material #2		0	0	0
📁 Material #3		0	0	0
📁 Plant & Equipment Transport (To-From)		0	0	0
📁 Plant #1		0	0	0
📁 Plant #2		0	0	0
📁 Plant #3		0	0	0
📁 Worker Travel		0	0	0
📁 Waste Transport		0	0	0
📁 Maintenance - Site Activities (A5 equivalent)		0	0	0
📁 Fossil fuel use for mobile plant & equipment / vehicle operations on site		0	0	0
📁 Fossil fuel use for fixed/static plant & equipment for site operations and welfare		0	0	0
📁 Grid electricity use by plant / equipment / services for site operations and welfare		0	0	0
📁 Mains water use for site operations and welfare		0	0	0
📁 Waste treatment / disposal carbon footprint (excluding transport)		0	0	0
📁 B3 - USE STAGE - Repair		0	0	0
📁 Repair - Products Stage (A1-A3 equivalent)		0	0	0
📁 Replacement of Items Procured as Prefabricated Building Elements		0	0	0
📁 Prefabricated element #1		0	0	0

Page 6 of 13

Name	Quantity	kgCO ₂ e		
		Single	Total	Project
 Prefabricated element #2		0	0	0
 Prefabricated element #3		0	0	0
 Replacement of Items Procured as Manufactured Construction Products / Components		0	0	0
 Product #1		0	0	0
 Product #2		0	0	0
 Product #3		0	0	0
 Replacement of items procured as construction raw materials		0	0	0
 Raw material #1		0	0	0
 Raw material #2		0	0	0
 Raw material #3		0	0	0
 Replacement-phase Consumable Products (excluding fuel & water)		0	0	0
 Replacement-phase proportional embodied carbon for construction plant & equipment		0	0	0
 Repair - Transportation Stage (A4 equivalent)		0	0	0
 Products and Materials Transport		0	0	0
 Prefabricated Elements		0	0	0
 Element #1		0	0	0
 Element #2		0	0	0
 Element #3		0	0	0
 Manufactured Construction Products		0	0	0
 Product #1		0	0	0
 Product #2		0	0	0
 Product #3		0	0	0
 Construction Raw Materials		0	0	0

Page 7 of 13

Name	Quantity	kgCO ₂ e		
		Single	Total	Project
 Material #1		0	0	0
 Material #2		0	0	0
 Material #3		0	0	0
 Plant & Equipment Transport (To-From)		0	0	0
 Plant #1		0	0	0
 Plant #2		0	0	0
 Plant #3		0	0	0
 Worker Travel		0	0	0
 Waste Transport		0	0	0
 Repair - Site Activities (A5 equivalent)		0	0	0
 Fossil fuel use for mobile plant & equipment / vehicle operations on site		0	0	0
 Fossil fuel use for fixed/static plant & equipment for site operations and welfare		0	0	0
 Grid electricity use by plant / equipment / services for site operations and welfare		0	0	0
 Mains water use for site operations and welfare		0	0	0
 Waste treatment / disposal carbon footprint (excluding transport)		0	0	0
 B4 - USE STAGE - Replacement		0	0	0
 Replacement - Products Stage (A1-A3 equivalent)		0	0	0
 Replacement Items Procured as Prefabricated Building Elements		0	0	0
 Prefabricated element #1		0	0	0
 Prefabricated element #2		0	0	0
 Prefabricated element #3		0	0	0
 Replacement Items Procured as Manufactured Construction Products / Components		0	0	0
 Product #1		0	0	0

Page 8 of 13

Appendix C

Name	Quantity	kgCO ₂ e		
		Single	Total	Project
Product #2		0	0	0
Product #3		0	0	0
Replacement items procured as construction raw materials		0	0	0
Raw material #1		0	0	0
Raw material #2		0	0	0
Raw material #3		0	0	0
Replacement-phase Consumable Products (excluding fuel & water)		0	0	0
Replacement-phase proportional embodied carbon for construction plant & equipment		0	0	0
Replacement - Transportation Stage (A4 equivalent)		0	0	0
Products and Materials Transport		0	0	0
Prefabricated Elements		0	0	0
Element #1		0	0	0
Element #2		0	0	0
Element #3		0	0	0
Manufactured Construction Products		0	0	0
Product #1		0	0	0
Product #2		0	0	0
Product #3		0	0	0
Construction Raw Materials		0	0	0
Material #1		0	0	0
Material #2		0	0	0
Material #3		0	0	0
Plant & Equipment Transport (To-From)		0	0	0

Page 9 of 13

Name	Quantity	kgCO ₂ e		
		Single	Total	Project
Plant #1		0	0	0
Plant #2		0	0	0
Plant #3		0	0	0
Worker Travel		0	0	0
Waste Transport - if different to Replacement C2		0	0	0
Replacement - Site Activities (A5 equivalent)		0	0	0
Fossil fuel use for mobile plant & equipment / vehicle operations on site				
Fossil fuel use for fixed/static plant & equipment for site operations and welfare		0	0	0
Grid electricity use by plant / equipment / services for site operations and welfare		0	0	0
Mains water use for site operations and welfare		0	0	0
Waste treatment/disposal carbon footprint (excluding transport) - if different to Replacement C3-C4		0	0	0
Replacement - Transportation of decommissioned materials - Stage C2 equivalent		0	0	0
Replacement - Treatment of decommissioned materials - Stage C3 equivalent		0	0	0
Replacement - Disposal of decommissioned materials - Stage C4 equivalent		0	0	0
B5 - USE STAGE - Refurbishment		0	0	0
Refurbishment - Products Stage (A1-A3 equivalent)		0	0	0
Refurbishment as Prefabricated Building Elements		0	0	0
Prefabricated element #1		0	0	0
Prefabricated element #2		0	0	0
Prefabricated element #3		0	0	0
Refurbishment as Manufactured Construction Products / Components		0	0	0
Product #1		0	0	0
Product #2		0	0	0

Page 10 of 13



Rail Carbon Tool

 PARTNERSHIP
 WITH
 Atkins

Name	Quantity	kgCO ₂ e		
		Single	Total	Project
Product #3		0	0	0
Refurbishment as construction raw materials		0	0	0
Raw material #1		0	0	0
Raw material #2		0	0	0
Raw material #3		0	0	0
Refurbishment-phase Consumable Products (excluding fuel & water)		0	0	0
Refurbishment-phase proportional embodied carbon for construction plant & equipment		0	0	0
Refurbishment - Transportation Stage (A4 equivalent)		0	0	0
Products and Materials Transport		0	0	0
Prefabricated Elements		0	0	0
Element #1		0	0	0
Element #2		0	0	0
Element #3		0	0	0
Manufactured Construction Products		0	0	0
Product #1		0	0	0
Product #2		0	0	0
Product #3		0	0	0
Construction Raw Materials		0	0	0
Material #1		0	0	0
Material #2		0	0	0
Material #3		0	0	0
Plant & Equipment Transport (To-From)		0	0	0
Plant #1		0	0	0

Page 11 of 13



Rail Carbon Tool

 PARTNERSHIP
 WITH
 Atkins

Name	Quantity	kgCO ₂ e		
		Single	Total	Project
Plant #2		0	0	0
Plant #3		0	0	0
Worker Travel		0	0	0
Waste Transport - if different to Refurbishment C2		0	0	0
Refurbishment - Site Activities (A5 equivalent)		0	0	0
Fossil fuel use for mobile plant & equipment / vehicle operations on site		0	0	0
Fossil fuel use for fixed/static plant & equipment for site operations and welfare		0	0	0
Grid electricity use by plant / equipment / services for site operations and welfare		0	0	0
Mains water use for site operations and welfare		0	0	0
Waste treatment / disposal carbon footprint (excluding transport) - if different to Refurb C3-C4		0	0	0
Refurbishment - Transportation of decommissioned materials - Stage C2 equivalent		0	0	0
Refurbishment - Treatment of decommissioned materials - Stage C3 equivalent		0	0	0
Refurbishment - Disposal of decommissioned materials - Stage C4 equivalent		0	0	0
B6-B7 - USE STAGE - Operational Utilities Consumption		0	0	0
B6 - Operational Electricity Consumption		0	0	0
B6 - Operational Fixed Plant Fuel Consumption		0	0	0
B7 - Operational Water Consumption		0	0	0
B8 - USE STAGE - Other Operational Emissions		0	0	0
B9 - USE STAGE - User Utilization of Infrastructure		0	0	0
C1 - END of LIFE - Deconstruction Site Activities (including Transport to support demolition)		0	0	0
Plant & Equipment Transport (To-From)		0	0	0
Plant #1		0	0	0
Plant #2		0	0	0

Page 12 of 13

Name	Quantity	kgCO ₂ e		
		Single	Total	Project
Plant #3		0	0	0
Worker Travel (To-From)		0	0	0
Fossil fuel use for mobile plant & equipment / vehicle operations on site				
Fossil fuel use for fixed/static plant & equipment for site operations and welfare		0	0	0
Grid electricity use by plant / equipment / services for site operations and welfare		0	0	0
Mains water use for site operations and welfare		0	0	0
Waste Transport - if different to C2		0	0	0
Waste treatment / disposal carbon footprint (excluding transport) - if different to C3-C4		0	0	0
C2 - END of LIFE - Transportation of Deconstructed Materials		0	0	0
C3 - END of LIFE - Treatment of Deconstructed Materials		0	0	0
C4 - END of LIFE - Disposal of Deconstructed Materials		0	0	0
D - BEYOND LIFECYCLE - Carbon emissions / benefits from other infrastructure functions		0	0	0

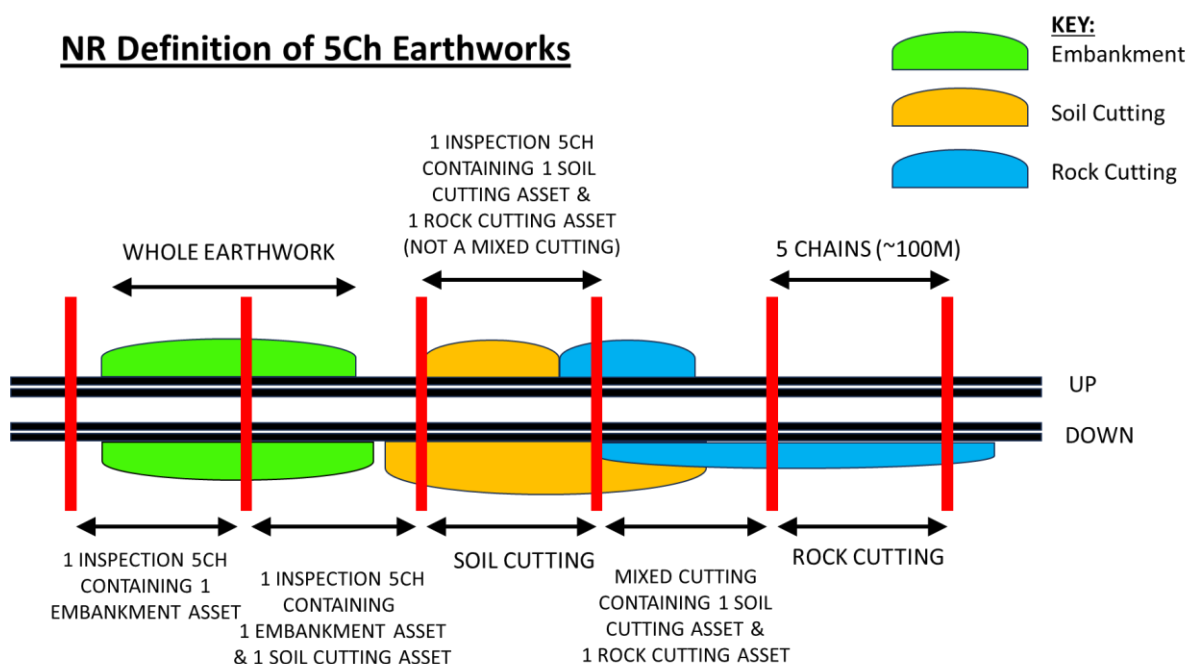
railcarbontoolsupport@r5sb.co.uk
www.railindustrycarbon.com

Page 13 of 13

C.8 Definition of 5Ch Earthworks

NR go into greater detail in their cost and volumes handbook to define earthworks, with further definitions being provided in the glossary and the unit of measurement – the chain - being detailed below.

C.8.1 Definition of 5Ch Earthworks



C.9 Evolution of Carbon Calculation Data Form

The evolution of the form was:

- R0 Initial pilot version.
- R1 Further details added to level of works in works details, lifetime of works now requested, size of works box added to list, number of shifts and hours on shift combined into one.
- R2 Further text added to materials required for works section with “please include supplier, supplier part no material and unit weight/no” being added to description box. And “please include separate entry for each type of waste e.g. soil, aggregate etc” added to waste removal description.
- R3 addition of reference to text in works details work name box and addition of check boxes for type of earthworks and level and lifetime. Clarification text added under size of works (5-Chain Length is representative length). The wording of mileage to site was altered to avoid confusion with units, to read distance to site (km).

C.10 Details Tracking Sheet for Case Studies

Tracking of data collection over such a large number of case studies was undertaken using Excel and the Data Collection Tracker sheet (DCT).

In this sheet a record was kept for every identified case study organised primarily alphabetically by name and then by region, expected lifespan (in years) and volume along with a unique case study number. Details of whether the carbon data capture form had been received and whether queries were outstanding were also tracked in this sheet along with any notes of contacts. An example screen shot is provided below showing the headings which could all be sorted for ease of use.

C.10.1 Example Headings from Tracking Sheet LHS

Case Study No	Region	Case Study Name	Intervention Type	works details	worded temporal life span	Temporal Type Life Sp	Volumes	Carbon Data Capture Form Received
46	NW&C	ALC1 Kenelm Road Cutting	Soil cutting	earthwork repair	maintenance	2	1	yes
71	Eastern	Aldercar	Embankment	embankment other - cess retnection - renewal	Renew	120		yes

C.10.2 Example Headings from Tracking Sheet RHS

Form Received From	Queries Noted	Email sent date and	Reply Received	All queries resolve	ready to begin footprint proce
highlighted on excel sheet sent by HR 26.10.25	No queries ready to footprint	No queries ready to footprint	No queries ready to footprint	No queries ready to footprint	yes
AF 30.11.22	5 quereies noted - passed onto AF in 7.12.22 meeting	07.12.22	17.01.23	yes	yes

C.11 Differentiation of Footprints by Rural-Urban Classification

The data will now be differentiated by rural-urban classification to explore the differences in carbon footprint between these two differing classifications of site, to investigate whether this classification affects the carbon in the A4 transport lifecycle.

The results of this exercise are presented in C.11.2 along with the percentage contribution of all transport carbon towards the raw BAU footprint to illustrate the difference between urban and rural sites. To preserve confidentiality of contractors who worked on these sites, only the first half of all postcodes are presented in the table, however the full postcode is used to plot site locations on the map presented in Figure C.11.3 **Error! Reference source not found.** Sites highlighted in green are classified as rural, black are classified as urban.

C.11.1 Method for Assigning Rural/Urban Classification

The rural urban classification index from the ONS, has been used as the primary source for rural urban classification of the case study sites. To enable this, a postcode has been aligned with each site. Where NR was unable to provide postcodes, the Engineer's Line Reference (ELR) & mileages, grid references, and eastings and northings provided by NR are used to identify the nearest relevant postcodes. To convert Grid Reference and eastings and northings to postcodes, GridReference Finder (Grid Reference Finder, 2023) was utilised. To convert ELR & Mileage (in miles and chains), railwaycodes.org (Railway Codes, 2023) was used with the line (ELR) being looked up and then the nearest station to the given mileage was chosen and the coordinates/grid reference for this inserted into GridReference Finder to find the relevant postcode.

To find the rural urban classification the Lower Layer Super Output Area 2011 (LSOA 2011) reference was found for each postcode using the Office for National Statistics (ONS) Postcode Directory Look Up Tool (ONS, 2023). Once found this LSOA data was then located in the 2011 Rural Urban Classification lookup tables for all geographies (HM Government, 2011b) and the classification associated with the LSOA read off and noted as rural or urban.

For Scottish sites, once the relevant LSOA data was found in the ONS Postcode Directory Look Up Tool, this data was used in the small user Scotland postcode look up table 2023 (Gov.Scot, 2018) to find the relevant 6-fold and 8-fold Scottish rural and urban classifications, which were then simplified to either urban or rural to align with England and Wales postcodes' 2-fold classifications.

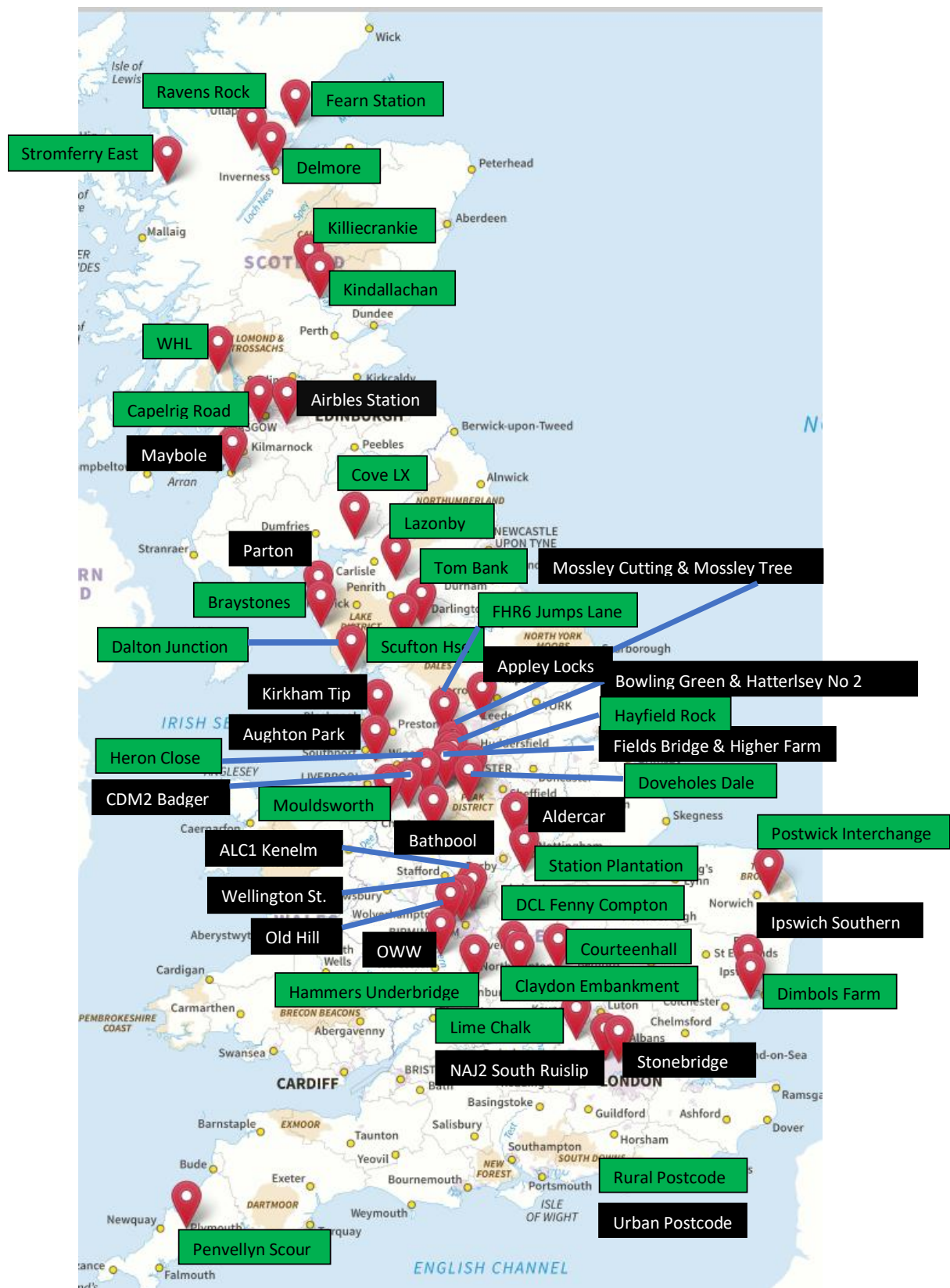
C.11.2 Rural Urban Classification: Descending Order of A4 Transport to Raw BAU

Case Study Name	NR Region	Earthwork Type	Temporal Intervention Type	Raw Data Format	Postcode (first half only)	% Contribution of A4 Transport to Raw BAU	Rural Urban Classification
DCL Fenny Compton - Survey	NW&C	E	2	ELR & Mileage	CV47	100.00	Rural
Mouldsworth to Little Barrow- Badger Mitigation	NW&C	SC	2	ELR & Mileage	CH3	100.00	Rural
Claydon Embankment	NW&C	E	20	ELR & Mileage	OX17	91.86	Rural
Kindallachan	Scotland	E	2	Postcode	PH9	90.85	Rural
FHR6 Jumps Lane DOWN	NW&C	RC	2	ELR & Mileage	OL14	89.60	Rural
Scufton House	NW&C	SC	2	ELR & Mileage	LA8	89.28	Rural
Lazonby	NW&C	RC	20	ELR & Mileage	CA10	86.08	Rural
Delmore	Scotland	SC	2	Postcode	IV3	76.64	Rural
Ravens Rock	Scotland	SC	2	Postcode	IV14	75.49	Rural
Cove LX	Scotland	E	120	Postcode	DG11	66.00	Rural
Heron Close - Badger Mitigation	NW&C	SC	2	ELR & Mileage	WA16	65.57	Rural
Tom Bank	NW&C	RC	2	Grid Reference	CA17	62.08	Rural
Postwick interchange	EASTERN Anglian	SC	2	ELR & Mileage	NR13	60.12	Rural
Hayfield Rock	NW&C	RC	2	ELR & Mileage	S33	54.06	Rural
Lime Chalk Embankment	NW&C	E	2	ELR & Mileage	HP16	47.26	Rural
Dalton Junction Overhang	NW&C	SC	2	ELR & Mileage	LA13	41.86	Rural
Courteenhall	NW&C	E	2	ELR & Mileage	NN7	37.37	Rural

Case Study Name	NR Region	Earthwork Type	Temporal Intervention Type	Raw Data Format	Postcode (first half only)	% Contribution of A4 Transport to Raw BAU	Rural Urban Classification
Capelrig Road	Scotland	E	2	Postcode	G77	36.10	Rural
WHL	Scotland	RC	20	Postcode	G84	35.50	Rural
Stromferry East	Scotland	SC	2	Postcode	IV53	32.67	Rural
Station Plantation - cess	Eastern	E	120	Grid Reference	LE12	21.38	Rural
Fearn Station	Scotland	SC	2	Postcode	IV20	20.53	Rural
Killiecrankie	Scotland	SC	120	Postcode	PH16	18.29	Rural
Doveholes Dale	NW&C	SC	2	Eastings and Northings	SK17	16.29	Rural
Braystones	NW&C	SC	20	Eastings and Northings	CA21	12.74	Rural
Dimbols farm foot crossing	EASTERN Anglian	E	2	ELR & Mileage	CO11	8.19	Rural
Penvellyn - Scour -	W&W	E	20	Postcode	PL26	5.91	Rural
Hammers Underbridge - Burrowing -	W&W	E	20	Postcode	GL55	4.30	Rural
CDM2 Badger Environmental Management - Survey	NW&C	E	2	ELR & Mileage	CW8	100.00	Urban
NAJ2 South Ruislip	NW&C	E	2	Eastings and Northings	HA4	100.00	Urban
OWW Evaluations	NW&C	RC	2	ELR & Mileage	WR9	100.00	Urban
Parton	NW&C	RC	2	ELR & Mileage	CA28	100.00	Urban
Ipswich southern tunnel portal	EASTERN Anglian	SC	2	Postcode	IP2	96.38	Urban
Airbles Station	Scotland	RC	2	Postcode	ML1	92.93	Urban

Case Study Name	NR Region	Earthwork Type	Temporal Intervention Type	Raw Data Format	Postcode (first half only)	% Contribution of A4 Transport to Raw BAU	Rural Urban Classification
Appley Locks	NW&C	E	2	ELR & Mileage	BD10	84.47	Urban
ALC1 Kenelm Road Cutting	NW&C	SC	20	ELR & Mileage	B73	84.20	Urban
Mossley Tree Removal	NW&C	RC	2	Eastings and Northings	OL5	80.20	Urban
Bathpool Reservoir	NW&C	E	2	ELR & Mileage	ST7	70.55	Urban
Hattersley No. 2	NW&C	SC	2	ELR & Mileage	SK14	68.42	Urban
Mossley Cutting	NW&C	RC	2	ELR & Mileage	OL5	63.25	Urban
Maybole	Scotland	E	2	Postcode	KA7	52.45	Urban
Old Hill	NW&C	E	2	ELR & Mileage	B64	47.15	Urban
Aughton Park Station	NW&C	RC	22	ELR & Mileage	L39	36.67	Urban
Kirkham Tip	NW&C	SC	2	ELR & Mileage	PR4	33.74	Urban
Stonebridge	NW&C	E	2	ELR & Mileage	NW10	23.83	Urban
Wellington Street	NW&C	E	2	Eastings and Northings	B66	19.28	Urban
Bowling Green	NW&C	SC	120	ELR & Mileage	SK14	14.81	Urban
Fields Bridge	NW&C	SC	20	ELR & Mileage	SK7	12.92	Urban
Higher Farm	NW&C	SC	20	ELR & Mileage	SK7	9.86	Urban
Aldercar - cess	Eastern	E	120	Grid Reference	NG16	7.45	Urban

C.11.3 Map of all 50 Case Studies Rural/Urban Classification



C.11.4 Rural Urban Classification Discussion

Following on from the rural-urban classification exercise; 28 sites are classified as rural and 22 as urban (see C.11.3). Some 27 case studies can attribute more than 50% of their total BAU carbon footprint to A4 transport mileage, with the rural-urban split of these sites being 14 rural (50%) and 13 urban sites (59%) (see C.11.5). These results are not as expected, it was hypothesised that the rural locations, owing to their rurality and postulated extended travel distances, would have much larger percentage of A4 transport carbon in their total BAU carbon footprint. This may be because distance from an NR maintenance depot is more important than urban/rural location, or because NR maintenance staff live in a few concentrated locations, meaning that some urban areas do not have any local resident staff and as such travel distances are extended.

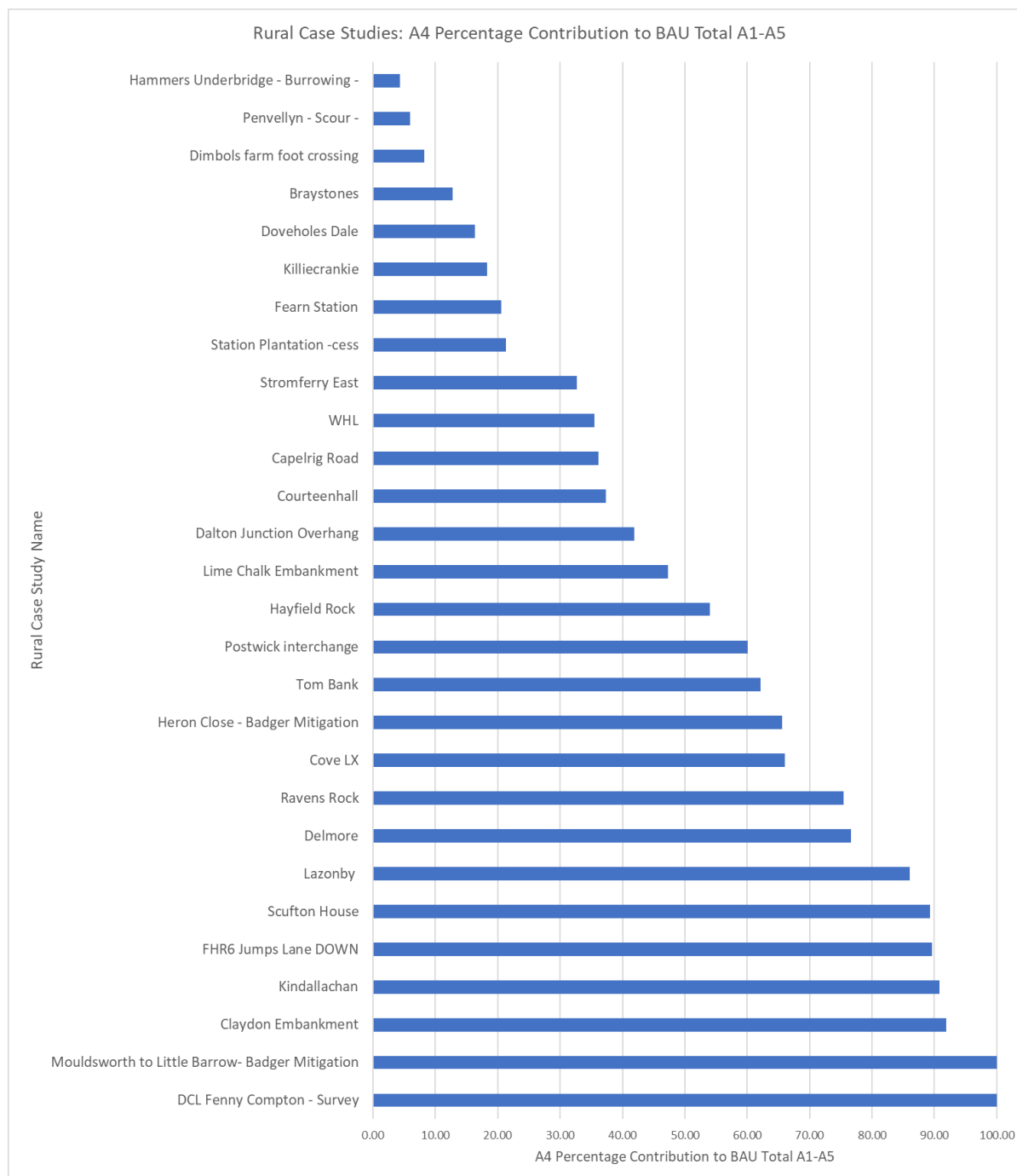
For all case studies that are surveys the BAU carbon footprint is 100% of their transport carbon and fifteen of the 50 case studies have less than 1/3 of their total BAU carbon footprint attributable to A4 transport, with the 15 case studies split; 9 rural and 6 urban.

For those sites lying in the Scottish Region, 9 of the 10 sites are classified as rural, with 5 of these 9 being further classified as remote or very remote rural locations, and the remaining 4 as accessible rural areas, highlighting the logistical challenges facing sites located in Scotland.

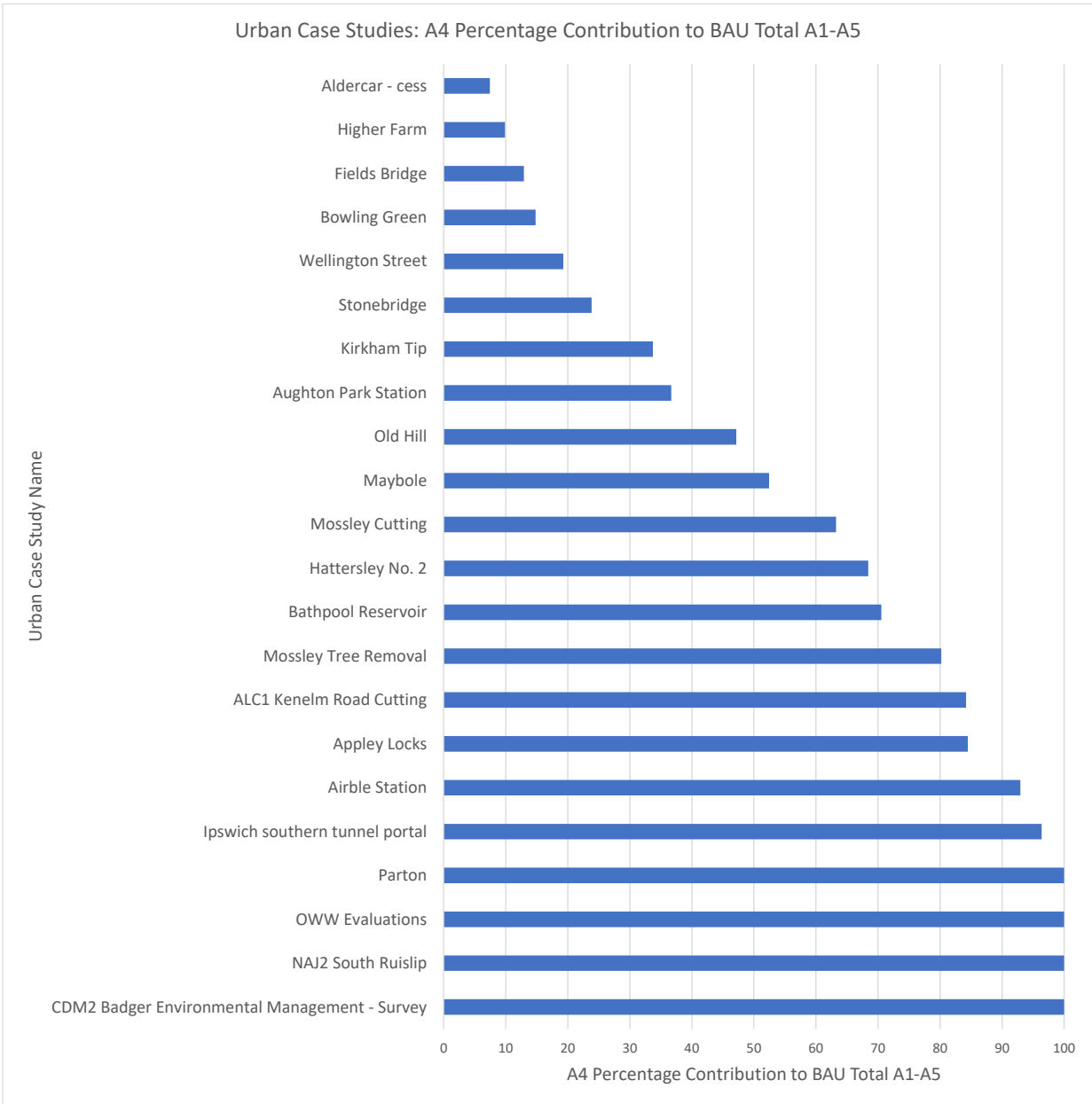
When looking at rural classified case studies there does not appear to be any patterns regarding percentage raw BAU attributable to A4 transport for the differing earthwork types, as a mixture of embankments, soil cuttings and rock cuttings are dispersed across the range of differing percentages of A4 attributable to A4 transport. When the interventions expected lifespan is delved into there once again is no discernible pattern. It was hypothesised that renewals would have the highest percentage and maintenance the lowest percentage of A4 transport as a percentage of BAU footprint, but this is not the case, there is a mixture of intervention types across the differing percentages.

The results of the rural-urban classification are presented in descending order of A4 transports' percentage contribution to total BAU carbon (see Figure C.11.5 for rural Figure C.11.6 for urban).

C.11.5 Percentage Contribution of A4 Transport to Raw BAU A1-5 for Rural Sites



C.11.6 Percentage Contribution of A4 Transport to Raw BAU A1-5 for Urban Sites



Following an extensive cross referencing exercise (see Appendix D.5), with all case studies against the listed NR interventions as detailed in Appendix A.1, the intervention type for the 28 rural classifications were identified and quantified for the top 14 (greater than 50% contribution to A4), and bottom 14 sites (less than 50% contribution to A4), in order of percentage contribution of A4 transport to Raw BAU A1-5 and the results are presented C.11.7.

*note that Badger Management has been grouped with vermin eradication and animal exclusion owing to there not being a separate intervention type in the Cost and Volume handbook (Network Rail, 2021a) for protected species, so it must be borne in mind that actions for protected species such as badgers, bats and newts will be different to those for vermin and may involve additional carbon in the form of specialist surveys.

C.11.7 Top 5 Intervention Types for Rural Classification Case Studies

Top Five Most Frequent Rural Intervention Types	Number of Interventions in Top 14 Rural Sites (by % contribution to A4)	Number of Interventions in Bottom 14 Rural Sites (by % contribution to A4)
Debris and refuse clearance	2	2
Devegetation of drains and vegetation management	5	4
Vermin eradication and exclusion *	2	0
Scaling	3	0
Drainage maintenance	0	2

C.11.7 illustrates the prevalence of debris clearance and revegetation interventions in rural sites. highlighting once more the increased transport distances tending to be associated with these works whether they have high transport carbon or not, with 7 and 6 interventions respectively in the top 14 (greater than 50% contribution to A4) and bottom 14 (less than 50% contribution to A4) rural sites.

The same cross referencing exercise detailed in Appendix D.5, with all case studies against the listed NR interventions, was then used to find the intervention type for the 22 urban classifications which were split top 13 (greater than 50% contribution to A4) and bottom 9 sites (less than 50% contribution to A4), in order of percentage contribution of A4 transport to Raw BAU and the results are presented in C.11.8.

C.11.8 Top 5 Intervention Types for Urban Classification Case Studies

Top Five Most Frequent Urban Intervention Types	Number of Interventions in Top 13 Urban Sites (by % contribution to A4)	Number of Interventions in Bottom 9 Urban Sites (by % contribution to A4)
Debris and refuse clearance	2	0
Devegetation of drains and vegetation management	7	2
Vermin eradication and exclusion*	0	1
Regrade slope	0	3
Drainage maintenance	1	1

C.11.8.illustrates the prevalence of both debris and revegetation works in urban sites, highlighting the increased transport carbon (and hence distances) tending to be associated with these works, with 9 of such interventions in the top 13 sites.

By aligning urban and rural case studies with earthwork intervention types, urban classified case studies vegetation management interventions dominate the top 13 case studies with 7 examples, when ranked high to low by A4 transport percentage of BAU raw total, whereas local regrade of slope falls in the bottom 9 of urban case studies with 3 examples. For both urban and rural the 2 surveys DCL Fenny Compton and CDM2 Badger Survey were in top place with 100% of their A4 lifecycle stage accounting for 100% of the total BAU footprint

Both access issues and noise prevention in rural vs urban sites were deemed to be outside of scope for this research, with the focus being carbon footprinting, however these issues may be of interest for exploration in the future as part of the whole footprint family of a site.

C.12 Proportional Embodied Carbon in Plant & Machinery

Proportional embodied carbon for plant and machinery is included in all case studies where these were used. It has been found in the literature that this carbon is excluded, as for each individual project the amounts of carbon are small (Shillaber, 2016, p.64), however when multiplied up over a substantial number of projects this carbon may no longer be inconsequential. This embodied carbon has been calculated using the Keller Foundations methodology (EFFC, 2023b, p.14). Proportional embodied carbon will be different for each case study, even for the same item of equipment, as it is dependent on time on site. Appendix C.12.1 provides a step-by-step calculation example from the Hammers Underbridge case study. The amount of carbon calculated (8.2kg) being input into the RCT as item name “Carbon Dioxide” under “Embodied Carbon in Compressor.” See Appendix C.7 (screen shot page 2 of 13) for example in the Hammers Underbridge carbon footprint.

C.12.1 Embodied Carbon in Plant and Machinery Calculation

Calculation Method	Hammers Underbridge
Formula from Keller Foundations Methodology for apportioning embodied carbon in plant	Quantity of plant x (weight of machine in t x (time on site in weeks)/(150 days use per year *machine lifetime in yrs))
Compressor apportioned quantity	$1 \times 1t \times (7 \text{ weeks} / (150 \text{ days use per year} \times 10 \text{ yr lifetime}))$ $= 1 \times 1t \times (7 / 1,500)$ $= 0.0046666$
Compressor Embodied carbon in plant = carbon factor x apportioned quantity	$= 1.759 \times 0.0046666$ $= 0.0082085 \text{ t/CO}_2\text{e}$ =8.2085 kg/CO₂e

Although other methods are available for calculating apportioned carbon, see Appendix C.12.2, given that the Keller method was actively being utilised by NR contractors in other projects, the same method was adopted for use in the case studies

C.12.2 Other Methods of Calculating Apportioned Carbon

Not all carbon tools contain EFs for calculating the embodied carbon in plant and machinery. A very simplistic method of calculating embodied carbon in plant and machinery would be a simple weight of steel multiplied by the material embodied steel EF and then apportioning that to the time on site out of the products lifetime. The EFFC Carbone tool does have a method, similar to that of Keller used for the case studies, therefore the EFFC DFI Carbon Calculator Tool v4.0 was downloaded and the method used therein for calculation of embodied emissions in machinery evaluated (EFFC, 2023a) and detailed below to allow comparison between Keller, EFFC and the simplistic method.

For example, a 1 tonne compressor on site for 7 weeks:

- Using Keller method (EFFC, 2023b, p.14):
 - Formula for apportioning of embodied carbon in plant
 - Qty of plant x (weight of machine in t x (time on site in weeks)/(150 days use per year *machine lifetime in yrs))
 - For compressor = $1 \times 1\text{t} \times (7 \text{ weeks} / (150 \text{ days use per year} \times 10 \text{ yr lifetime}))$
 - $= 1 \times 7 / 1500$
 - $= 0.0046666$
 - **For compressor**
 - $= 1.759 \times 0.0046666$
 - $= 0.0082085 \text{ t/CO}_2\text{e}$
 - $= 8.2085 \text{ kg/CO}_2\text{e}$
- Using simplistic method:
 - A 1 tonne compressor using a steel factor $2.89 \text{ kgCO}_2\text{e/kg}$ from RSSB RCT for the simplistic method and EFFC
 - Steel EF x Apportioned time on site (as per Keller)
 - 2.89×0.0046666
 - $= 0.01349 \text{ t/CO}_2\text{e}$
 - $13.5 \text{ kg/CO}_2\text{e}$
- Using EFFC method (EFFC, 2023a)
 - Formula for apportioning of embodied carbon in plant
 - Qty of plant x (weight of machine in t x (time on site in days)/(150 days use per year *machine lifetime in yrs))
 - For compressor = $1 \times 1\text{t} \times (49 \text{ days} / (150 \text{ days use per year} \times 10 \text{ yr lifetime}))$
 - $= 1 \times 49 / 1500$
 - $= 0.0326$

Appendix C

- **For compressor**
- $= 3.667 \times 0.0326$
- $= 0.1195442 \text{ t/CO}_2\text{e}$
- $= 11.95 \text{ kg/CO}_2\text{e}$

The figures calculated above for the three methods are presented in the table below for comparison. While a full analysis of this portion of carbon is outside the scope of this thesis it is concerning that different methods result in different emissions factors as such, similar to the differences found between EFs

C.12.3 Comparison Table of Embodied Carbon Factors

	EF kgCO ₂ e/ per kg	Machine Weight (t)	Weeks/ Days Use	Days Use in Year	Lifespan (Years)	Apportioned Time Factor	kgCO ₂ e
Keller	1.759	1	7 weeks	150	10	0.0046666	8.2
EFFC	3.667	1	49 days	150	10	0.00066	11.95
Simple Steel Method	2.89	1	7 weeks	150	10	0.0046666	13.5

The background to the EFFC EF could not be found owing to this coming from the Billet Carbone which is a pay to use database. Also note Billet Carbone uses days rather than weeks in its calculator.

Appendix D Appendices Relating to Chapter 4

D.1 Complete Data Set of 50 Case Studies

Complete data set of 50 case studies in descending order of raw BAU A1-5 kgCO₂e, detailing the case study name, NR region, earthwork type (RC Rock Cutting, SC Soil Cutting, E Embankment), expected lifespan (in years), total raw BAU A1-5 in kgCO₂e and BAU A1-5 in kgCO₂e/volume.

Case Study Name	NR Region	Earthwork Type	Expected Lifespan (in years)	Total Raw BAU A1-5 kgCO ₂ e	Raw BAU A1-5 kgCO ₂ e/Volume
Aldercar – cess	Eastern	E	120	406,120.59	135,373.53
Penvellyn - Scour -	W&W	E	20	96,009.93	48,004.97
Hammers Underbridge - Burrowing -	W&W	E	20	45,018.69	11,254.67
Station Plantation - cess	Eastern	E	120	35,572.31	35,572.31
Higher Farm	NW&C	SC	20	24,044.45	24,044.45
Killiecrankie	Scotland	SC	120	22,761.25	22,761.25
Bowling Green	NW&C	SC	120	15,378.29	15,378.29
Fearn Station	Scotland	SC	2	16,419.78	8,209.89
Doveholes Dale	NW&C	SC	2	12,287.87	4,095.96
Fields Bridge	NW&C	SC	20	11,335.70	11,335.70
WHL	Scotland	RC	20	8,942.33	8,942.33
Tom Bank	NW&C	RC	2	7,092.22	3,546.11
Dalton Junction Overhang	NW&C	SC	2	4,338.49	4,338.49
Stromferry East	Scotland	SC	2	4,082.41	1,360.82
Lazonby	NW&C	RC	20	3,318.60	3,318.60
Aughton Park Station	NW&C	RC	22*	3,229.29	1,614.64
Dimbols farm foot crossing	EASTERN	E	2	2,947.79	982.60
Wellington Street	NW&C	E	2	2,860.06	2,860.06
Courteenhall	NW&C	E	2	2,666.13	2,666.13

Case Study Name	NR Region	Earthwork Type	Expected Lifespan (in years)	Total Raw BAU A1-5 kgCO ₂ e	Raw BAU A1-5 kgCO ₂ e/ Volume
Cove LX	Scotland	E	120	2,522.29	2,522.29
Hayfield Rock	NW&C	RC	2	2,292.93	2,292.93
Braystones	NW&C	SC	20	2,188.43	2,188.43
Delmore	Scotland	SC	2	2,117.67	2,117.67
Heron Close - Badger Mitigation	NW&C	SC	2	2,023.72	1,011.86
Stonebridge	NW&C	E	2	1,690.87	1,690.87
Mouldsworth to Little Barrow- Badger Mitigation	NW&C	SC	2	798.61	798.61
Hattersley No. 2	NW&C	SC	2	791.86	197.96
Capelrig Road	Scotland	E	2	735.23	735.23
Maybole	Scotland	E	2	700.11	350.05
Mossley Cutting	NW&C	RC	2	682.27	682.27
Bathpool Reservoir	NW&C	E	2	635.75	105.96
Ravens Rock	Scotland	SC	2	611.80	305.90
Scufton House	NW&C	SC	2	582.07	145.52
Postwick interchange	EASTERN	SC	2	469.42	78.24
Kirkham Tip	NW&C	SC	2	412.90	206.45
ALC1 Kenelm Road Cutting	NW&C	SC	20	394.89	394.89
Claydon Embankment	NW&C	E	20	356.16	356.16
Kindallachan	Scotland	E	2	286.78	286.78
Parton	NW&C	RC	2	233.45	233.45
CDM2 Badger Environmental Management - Survey	NW&C	E	2	224.99	224.99
Mossley Tree Removal	NW&C	RC	2	189.38	189.38
FHR6 Jumps Lane DOWN	NW&C	RC	2	140.29	140.29

Case Study Name	NR Region	Earthwork Type	Expected Lifespan (in years)	Total Raw BAU A1-5 kgCO ₂ e	Raw BAU A1-5 kgCO ₂ e/ Volume
Appley Locks	NW&C	E	2	133.94	66.97
NAJ2 South Ruislip	NW&C	E	2	87.74	87.74
Lime Chalk Embankment	NW&C	E	2	86.85	86.85
Airbles Station	Scotland	RC	2	80.56	80.56
Old Hill	NW&C	E	2	78.90	78.90
Ipswich southern tunnel portal	EASTERN	SC	2	68.38	68.38
DCL Fenny Compton - Survey	NW&C	E	2	56.18	56.18
OWW Evaluations	NW&C	RC	2	15.39	15.39

*Aughton Park station consisted of a two year maintenance intervention and 20 year refurbishment intervention – with both interventions for vegetation, therefore as exact split of data unknown, this was classified as refurbishment, but value of 22 years used for calculating functional unit

D.2 Rankings: Staff Hours, Staff Transport, Functional Unit

D.2.1 Rankings of 35 Maintenance Case Studies

BELOW SORTED BY TOTAL STAFF HOURS

Ranking	Total staff hrs	Case Study Name
Highest to	for case	
Lowest	study	
1	2016	Doveholes Dale
2	720	Hattersley No. 2
3	648	Hayfield Rock
4	495	Tom Bank
5	450	Dalton Junction Overhang
6	432	Dimbols farm foot crossing
7	378	Stonebridge
8	350	Scufton House
9	300	Stromferry East
10	270	Wellington Street
11	225	Postwick interchange
12	200	Bathpool Reservoir
13	189	Maybole
14	165	Fearn Station
15	162	Mouldsworth to Little Barrow- Badger Mitigation
16	144	Parton
17	144	Ravens Rock
18	108	Courteenhall
19	90	Mossley Cutting
20	72	Capelrig Road
21	72	Heron Close - Badger Mitigation
22	72	NAJ2 South Ruislip
23	63	Appley Locks
24	63	Mossley Tree Removal
25	56	Delmore
26	48	Airbles Station
27	45	FHR6 Jumps Lane DOWN
28	36	CDM2 Badger Environmental Management - Survey
29	27	Kirkham Tip
30	27	Lime Chalk Embankment
31	27	Old Hill
32	20	Ipswich southern tunnel portal
33	18	DCL Fenny Compton - Survey
34	18	Kindallachan
35	9	OWW Evaluations

SORTED BY STAFF HOURS PER VOLUME

Ranking Highest to Lowest for staff hrs per vol	Staff Hours per Vol for case study	Case Study Name	Volume
1st	672.0	Doveholes Dale	3
2nd	648.0	Hayfield Rock	1
3rd	450.0	Dalton Junction Overhang	1
4th	378.0	Stonebridge	1
5th	270.0	Wellington Street	1
6th	247.5	Tom Bank	2
7th	180.0	Hattersley No. 2	4
8th	162.0	Mouldsworth to Little Barrow- Badger Mitigation	1
9th	144.0	Dimbols farm foot crossing	3
10th	144.0	Parton	1
11th	108.0	Courteenhall	1
12th	100.0	Stromferry East	3
13th	94.5	Maybole	2
14th	90.0	Mossley Cutting	1
15th	87.5	Scufton House	4
16th	82.5	Fearn Station	2
17th	72.0	Ravens Rock	2
18th	72.0	Capelrig Road	1
19th	72.0	NAJ2 South Ruislip	1
20th	63.0	Mossley Tree Removal	1
21st	56.0	Delmore	1
22nd	48.0	Airbles Station	1
23rd	45.0	FHR6 Jumps Lane DOWN	1
24th	37.5	Postwick interchange	6
25th	36.0	Heron Close - Badger Mitigation	2
26th	36.0	CDM2 Badger Environmental Management - Survey	1
27th	33.3	Bathpool Reservoir	6
28th	31.5	Appley Locks	2
29th	27.0	Lime Chalk Embankment	1
30th	27.0	Old Hill	1
31st	20.0	Ipswich southern tunnel portal	1
32nd	18.0	DCL Fenny Compton - Survey	1
33rd	18.0	Kindallachan	1
34th	13.5	Kirkham Tip	2
35th	9.0	OWW Evaluations	1

BELOW SORTED BY TOTAL STAFF TRANSPORT MILEAGE KM

Ranking	Total Staff Transport Higest to Lowest	mileage for case study km	Case Study Name
1		8877	Tom Bank
2		5014	Doveholes Dale
3		3113	Mouldsworth to Little Barrow- Badger Mitigation
4		2571	Dalton Junction Overhang
5		2332	Heron Close - Badger Mitigation
6		2292	Fearn Station
7		2112	Hattersley No. 2
8		2073	Scufton House
9		1979	Wellington Street
10		1836	Ravens Rock
11		1740	Bathpool Reservoir
12		1585	Stonebridge
13		1523	Stromferry East
14		1482	Maybole
15		1404	Courteenhall
16		1187	Hayfield Rock
17		1100	Postwick interchange
18		960	Dimbols farm foot crossing
19		910	Parton
20		877	CDM2 Badger Environmental Management - Survey
21		864	Kindallachan
22		648	Mossley Cutting
23		592	Mossley Tree Removal
24		543	Kirkham Tip
25		490	FHR6 Jumps Lane DOWN
26		441	Appley Locks
27		342	NAJ2 South Ruislip
28		338	Delmore
29		314	Airbles Station
30		260	Ipswich southern tunnel portal
31		240	DCL Fenny Compton - Survey
32		160	Lime Chalk Embankment
33		145	Old Hill
34		124	Capelrig Road
35		60	OWW Evaluations

SORTED BY STAFF TRANSPORT MILEAGE (KM) PER VOLUME

Ranking Highest to Lowest for staff transport mileage per vol	Staff Transport per Vol for case study km	Case Study Name	Vol
1st	4438.5	Tom Bank	2
2nd	3113.0	Mouldsworth to Little Barrow- Badger Mitigation	1
3rd	2571.0	Dalton Junction Overhang	1
4th	1979.0	Wellington Street	1
5th	1671.0	Doveholes Dale	3
6th	1585.0	Stonebridge	1
7th	1404.0	Courteenhall	1
8th	1187.0	Hayfield Rock	1
9th	1166.0	Heron Close - Badger Mitigation	2
10th	1146.0	Fearn Station	2
11th	918.0	Ravens Rock	2
12th	910.0	Parton	1
13th	877.0	CDM2 Badger Environmental Management - Survey	1
14th	864.0	Kindallachan	1
15th	741.0	Maybole	2
16th	648.0	Mossley Cutting	1
17th	592.0	Mossley Tree Removal	1
18th	528.0	Hattersley No. 2	4
19th	518.3	Scufton House	4
20th	507.7	Stromferry East	3
21st	490.0	FHR6 Jumps Lane DOWN	1
22nd	342.0	NAJ2 South Ruislip	1
23rd	338.0	Delmore	1
24th	320.0	Dimbols farm foot crossing	3
25th	314.0	Airbles Station	1
26th	290.0	Bathpool Reservoir	6
27th	271.5	Kirkham Tip	2
28th	260.0	Ipswich southern tunnel portal	1
29th	240.0	DCL Fenny Compton - Survey	1
30th	220.5	Appley Locks	2
31st	183.3	Postwick interchange	6
32nd	160.0	Lime Chalk Embankment	1
33rd	145.0	Old Hill	1
34th	124.0	Capelrig Road	1
35th	60.0	OWW Evaluations	1

BELOW SORTED BY FUNCTIONAL UNIT PER VOL/PER YR

Ranking	Functional Unit BAU	
Highest to	Kg CO2e per	
Lowest	Volume/Per Year	Case Study Name
1st	4104.95	Fearn Station
2nd	2169.24	Dalton Junction Overhang
3rd	2047.98	Doveholes Dale
4th	1773.06	Tom Bank
5th	1430.03	Wellington Street
6th	1333.07	Courteenhall
7th	1146.46	Hayfield Rock
8th	1058.83	Delmore
9th	845.43	Stonebridge
10th	680.59	Stromferry East
11th	505.93	Heron Close - Badger Mitigation
12th	491.30	Dimbols farm foot crossing
13th	399.30	Mouldsworth to Little Barrow- Badger Mitigation
14th	367.61	Capelrig Road
15th	341.13	Mossley Cutting
16th	175.03	Maybole
17th	152.95	Ravens Rock
18th	143.39	Kindallachan
19th	116.73	Parton
20th	112.49	CDM2 Badger Environmental Management - Survey
21st	103.23	Kirkham Tip
22nd	98.98	Hattersley No. 2
23rd	94.69	Mossley Tree Removal
24th	72.76	Scufton House
25th	70.14	FHR6 Jumps Lane DOWN
26th	52.98	Bathpool Reservoir
27th	43.87	NAJ2 South Ruislip
28th	43.42	Lime Chalk Embankment
29th	40.28	Airbles Station
30th	39.45	Old Hill
31st	39.12	Postwick interchange
32nd	34.14	Ipswich southern tunnel portal
33rd	33.48	Appley Locks
34th	28.09	DCL Fenny Compton - Survey
35th	7.70	OWW Evaluations

D.2.2 Rankings of 10 Refurbishment Case Studies

BELOW SORTED BY TOTAL STAFF HOURS

Ranking	Total staff hrs	Case Study Name
Higest to	for case	
Lowest	study	
1st	2450	Hammers Underbridge - Burrowing -
2nd	1512	Fields Bridge
3rd	1188	Higher Farm
4th	1008	Aughton Park Station
5th	1000	Penvellyn - Scour -
6th	196.875	WHL
7th	180	Claydon Embankment
8th	144	Lazonby
9th	135	Braystones
10th	108	ALC1 Kenelm Road Cutting

SORTED BY STAFF HOURS PER VOLUME

Ranking Highest to Lowest for staff hrs per vol	Staff Hours per Vol for case study hrs	Case Study Name	Volume
1st	1512.0	Fields Bridge	1
2nd	1188.0	Higher Farm	1
3rd	612.5	Hammers Underbridge - Burrowing -	4
4th	504.0	Aughton Park Station	2
5th	500.0	Penvellyn - Scour -	2
6th	196.9	WHL	1
7th	180.0	Claydon Embankment	1
8th	144.0	Lazonby	1
9th	135.0	Braystones	1
10th	108.0	ALC1 Kenelm Road Cutting	1

BELOW SORTED BY TOTAL STAFF TRANSPORT MILEAGE KM

Ranking

Highest to

Lowest Total Staff Transport Case Study Name

1st	10480	Penvellyn - Scour -
2nd	8619	WHL
3rd	4214	Aughton Park Station
4th	4200	Hammers Underbridge - Burrowing -
5th	3795	Fields Bridge
6th	2824	Lazonby
7th	1347	Higher Farm
8th	1296	ALC1 Kenelm Road Cutting
9th	1270	Claydon Embankment
10th	213	Braystones

SORTED BY STAFF TRANSPORT MILEAGE (KM) PER VOLUME

Ranking Highest

to Lowest for
staff transport
mileage per volStaff Transport per
Vol for case study
km

Case Study Name

Volume

1st	8619.0	WHL	1
2nd	5240.0	Penvellyn - Scour -	2
3rd	3795.0	Fields Bridge	1
4th	2824.0	Lazonby	1
5th	2107.0	Aughton Park Station	2
6th	1347.0	Higher Farm	1
7th	1296.0	ALC1 Kenelm Road Cutting	1
8th	1270.0	Claydon Embankment	1
9th	1050.0	Hammers Underbridge - Burrowing -	4
10th	213.0	Braystones	1

BELOW SORTED BY FUNCTIONAL UNIT PER VOL/PER YR

Ranking	Functional Unit BAU	
Highest to	CO2e per	
Lowest	Volume/Per Year	Case Study Name
1st	2400.25	Penvellyn - Scour -
2nd	1202.22	Higher Farm
3rd	566.78	Fields Bridge
4th	562.73	Hammers Underbridge - Burrowing -
5th	447.12	WHL
6th	165.93	Lazonby
7th	109.42	Braystones
8th	73.39	Aughton Park Station
9th	19.74	ALC1 Kenelm Road Cutting
10th	17.81	Claydon Embankment

D.2.3 Rankings of 5 Renewal Case Studies

BELOW SORTED BY TOTAL STAFF HOURS

Ranking	Total	
Highest to	staff hrs	
Lowest	for case	
	study	Case Study Name
1st	10680	Aldercar - cess
2nd	1680	Station Plantation -cess
3rd	1485	Bowling Green
4th	228	Killiecrankie
5th	144	Cove LX

SORTED BY STAFF HOURS PER VOLUME

Ranking Highest to Lowest for staff hrs per vol	Staff Hours per Vol for case study hrs	Case Study Name	Volume
1st	3560.0	Aldercar - cess	3
2nd	1680.0	Station Plantation -cess	1
3rd	1485.0	Bowling Green	1
4th	228.0	Killiecrankie	1
5th	144.0	Cove LX	1

BELOW SORTED BY TOTAL STAFF TRANSPORT MILEAGE KM

Ranking	Total Staff Transport Case Study Name
Highest to	
Lowest	
1st	76752 Aldercar - cess
2nd	16258 Station Plantation -cess
3rd	8240 Killiecrankie
4th	6675 Bowling Green
5th	4500 Cove LX

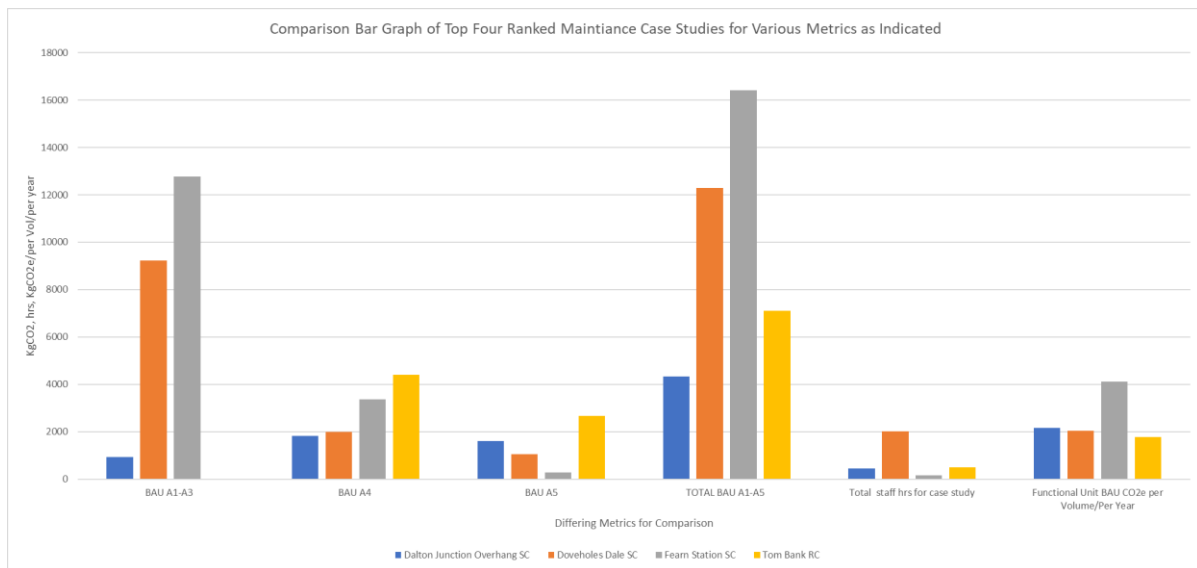
SORTED BY STAFF TRANSPORT MILEAGE (KM) PER VOLUME

Ranking Highest to Lowest for staff transport mileage per vol	Staff Transport per Vol for case study km	Case Study Name	Volume
1st	25584.1	Aldercar - cess	3
2nd	16257.8	Station Plantation -cess	1
3rd	8239.8	Killiecrankie	1
4th	6675.0	Bowling Green	1
5th	4500.0	Cove LX	1

BELOW SORTED BY FUNCTIONAL UNIT PER VOL/PER YR

Ranking	Functional Unit	Case Study Name
Highest to	BAU CO2e per	
Lowest	Volume/Per Year	
1st	1128.11	Aldercar - cess
2nd	296.44	Station Plantation -cess
3rd	189.68	Killiecrankie
4th	128.15	Bowling Green
5th	21.02	Cove LX

D.2.4 Comparison Graph of Top Four Maintenance Rankings

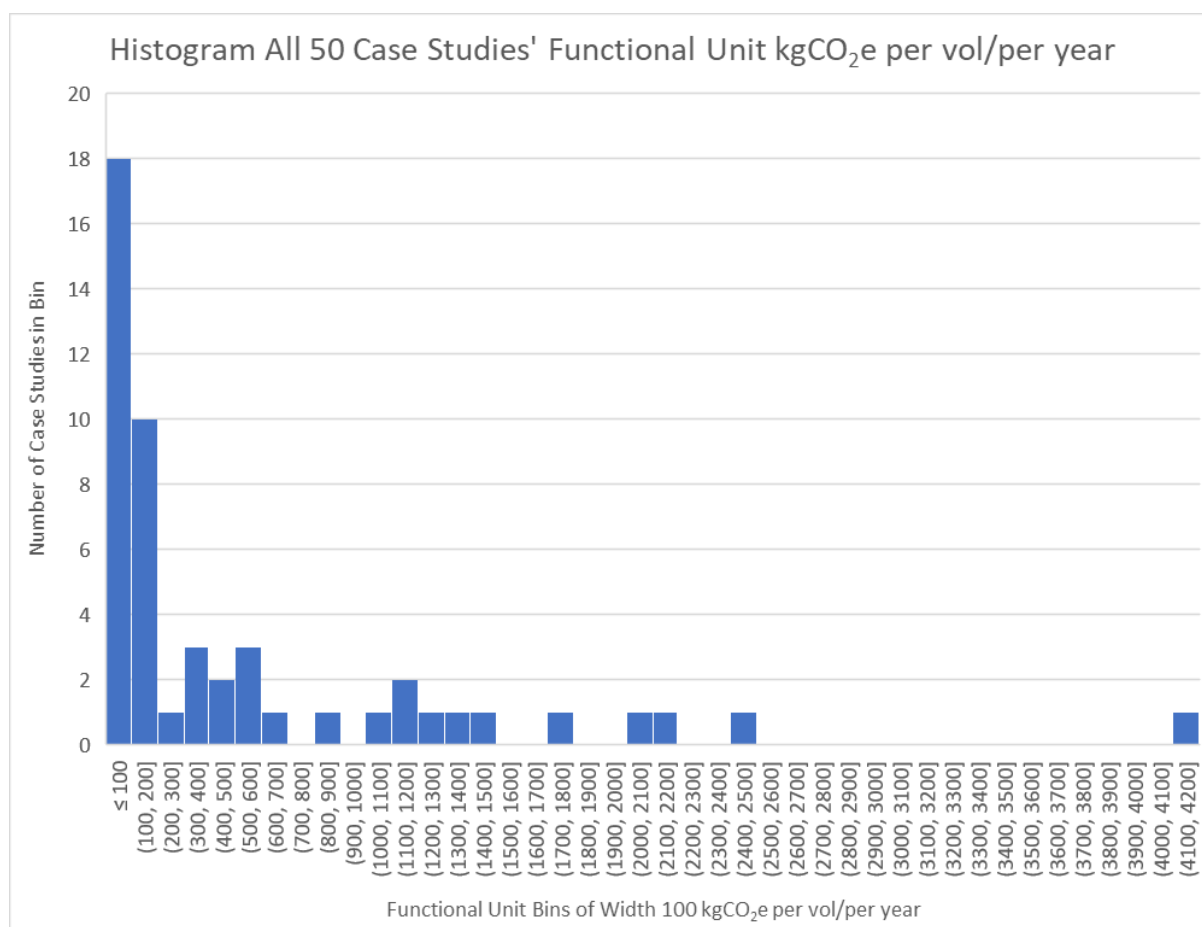


D.3 Descriptive Statistics of Raw BAU A1-5

Maintenance Descriptive Statistics Total BAU A1-5		Refurbishment Descriptive Statistics Total BAU A1-5	
Mean	1,965.27	Mean	19,483.85
Standard Error	591.5104973	Standard Error	9580.940936
Median	635.74538	Median	6130.46788
Mode	#N/A	Mode	#N/A
Standard Deviation	3499.423294	Standard Deviation	30297.59549
Sample Variance	12245963.39	Sample Variance	917944292.2
Kurtosis	9.805634709	Kurtosis	4.786453708
Skewness	3.038273137	Skewness	2.175062357
Range	16404.3876	Range	95653.76882
Minimum	15.3924	Minimum	356.1613357
Maximum	16419.78	Maximum	96009.93016
Sum	68784.45462	Sum	194838.478
Count	35	Count	10
Confidence Level(95.0%)	1202.09396	Confidence Level(95.0%)	21673.59416
Whole Data Set Descriptive Statistics Total BAU A1-5		Renewal Descriptive Statistics Total BAU A1-5	
Mean	14,919.55	Mean	96,470.95
Standard Error	8291.619634	Standard Error	77597.36917
Median	1244.73783	Median	22761.251
Mode	#N/A	Mode	#N/A
Standard Deviation	58630.6047	Standard Deviation	173512.9923
Sample Variance	3437547807	Sample Variance	30106758507
Kurtosis	42.61647812	Kurtosis	4.905143457
Skewness	6.364258556	Skewness	2.2094937
Range	406105.1976	Range	403598.3003
Minimum	15.3924	Minimum	2522.2897
Maximum	406120.59	Maximum	406120.59
Sum	745977.6639	Sum	482354.7313
Count	50	Count	5
Confidence Level(95.0%)	16662.63349	Confidence Level(95.0%)	215444.8358

D.4 Histogram for all 50 Case Studies' Functional Unit

Histogram shows the same clustering of data points in the first two data intervals (bins) for the previous data sets of Raw BAU A1-5, total staff hours and total staff transport mileage.



D.5 Cross Reference Exercise of Case Studies Against NR Interventions

D.5.1 Maintenance Soil Cutting

Case Study Name	Drainage maintenance	Vegetation management	Devegetation of drains	Devegetation of minor retaining structures	Individual geotechnical tree removal	Vermin eradication and exclusion	Debris and refuse clearance	Servicing engineered support (such as soil nails, netting, bolts)	Locally clearing/repairing catch fences/netting	Servicing geotechnical instrumentation array or alert/alarm
Dalton Junction Overhang		1								
Delmore							1		1	
Doveholes Dale (mixed SC and RC)							1			
Fearn Station	1		1							
Hattersley No. 2		1								
Heron Close - Badger Mitigation						1				
Ipswich Southern Tunnel Portal		1								
Kirkham Tip	1									
Mouldsworth to Little Barrow- Badger Mitigation							1			
Postwick Interchange		1								
Ravens Rock			1							
Scufton House			1							
Stromferry East					1					
Totals: SC Maint	2	4	3	0	1	1	3	0	1	0
	Drainage maintenance	Vegetation management	Devegetation of drains	Devegetation of minor retaining structures	Individual geotechnical tree removal	Vermin eradication and exclusion	Debris and refuse clearance	Servicing engineered support (such as soil nails, netting, rock bolts)	Locally clearing/repairing catch fences/netting	Servicing geotechnical instrumentation array or alert/alarm systems
	A	B	C	K	E	F	G	H	I	J
				unique to SC	E and SC only					

D.5.2 Maintenance Rock Cutting

Case Study Name	Drainage maintenance	Vegetation management	Devegetation of drains	Individual geotechnical tree removal	Vermin eradication and exclusion	Debris and refuse clearance	Routine cess clearance	Regular light scaling	Servicing engineered support (such as soil nails, netting, locally clearing/repairing catch	Servicing geotechnical instrumentation array or alert/alarm	
Airbles Station		1							1		
FHR6 Jumps Lane Down		1									
Hayfield Rock		1						1			
Mossley Cutting		1									
Mossley Tree Removal						1					
OWW Evaluations - Survey only											
Parton									1	1	
Tom Bank								1			
Doveholes Dale (mixed SC and RC)						1			1		
Totals: RC Maint	0	4	0	0	0	2	0	2	1	3	0
	Drainage maintenance	Vegetation management	Devegetation of drains	Individual geotechnical tree removal	Vermin eradication and exclusion	Debris and refuse clearance	Routine cess clearance	Regular light scaling	Servicing engineered support (such as soil nails, netting, rock bolts)	Locally clearing/repairing catch fences/netting	Servicing geotechnical instrumentation array or alert/alarm systems
	A	B	C	E	F	G	L	M	H	I	J
							unique to RC	unique to RC			

D.5.3 Maintenance Embankment

Case Study Name	Drainage maintenance	Vegetation management	Devegetation of drains	Devegetation of minor retaining structures	Individual geotechnical tree removal	Vermine eradication and exclusion	Debris and refuse clearance	Servicing engineered support (such as soil nails, netting, bolts)	Locally clearing/repairing catch fences/netting	Servicing geotechnical instrumentation array or alert/alarm
Appley Locks		1								
Bathpool Reservoir + Survey		1								
Capelrig Road	1						1			
CDM2 Badger Env. Man. Survey Only										
Courteenhall		1								
DCL Fenny Compton - Survey only										
Dimbols Farm		1								
Kindallachan						1				
Lime Chalk Embankment		1								
Maybole	1						1			
NAJ2 South Ruislip		1								
Old Hill		1								
Stonebridge		1				1				
Wellington Street					1					
Totals: E Maint	2	8	0	0	1	2	2	0	0	0
	Drainage maintenance	Vegetation management	Devegetation of drains	Devegetation of minor retaining structures	Individual geotechnical tree removal	Vermine eradication and exclusion	Debris and refuse clearance	Servicing engineered support (such as soil nails, netting, rock bolts)	Locally clearing/repairing catch fences/netting	Servicing geotechnical instrumentation array or alert/alarm systems
	A	B	C	D	E	F	G	H	I	J
				E and SC only						

D.5.4 Maintenance Summary

Totals across SC, RC and E Maintenance Interventions			
Drainage maintenance	A		4
Vegetation management	B		16
Devegetation of drains	C		3
Devegetation of minor retaining structures	D		0
Individual geotechnical tree removal	E	E and SC only	1
Vermin eradication and exclusion	F		3
Debris and refuse clearance	G		7
Servicing engineered support (such as soil nails, netting, rock bolts)	H		1
Locally clearing/repairing catch fences/netting	I		4
Servicing geotechnical instrumentation array or alert/alarm systems	J		0
Devegetation of minor retaining structures	K	unique to SC	0
Routine cess clearance	L	unique to RC	0
Regular light scaling	M	unique to RC	2
Survey Only			3
NB: more than one intervention may be undertaken on the same case study			

D.5.5 Refurbishment Soil Cutting

[illegible]

D.5.6 Refurbishment Rock Cutting

[illegible]

D.5.7 Refurbishment Embankment

[illegible]

D.5.8 Refurbishment Summary

Totals across SC, RC and E Refurbishment Interventions			
Toe support - gabions	A	unique to SC	0
Local toe retaining structure (less than 10m in length)	B		1
Local regrade of slope (less than 10m in length)	C		3
Shallow excavate and granular replacement	D		1
Limited deep excavate and granular	E		0
Badger relocation (including backfilling)	F		1
Slope drainage	G		0
Crest drainage	H		0
Cess containment ditch	I		0
Scaling	J	unique to RC	1
Controlled rock removal	K	unique to RC	1
Isolated dentition (less than 10m in length/10% of cutting face area)	L	unique to RC	0
Erosion protection system	M	unique to RC	0
Isolated rock dowels (passive) (less than 10m in length/10% of cutting face area)	N	unique to RC	0
Isolated rock bolts/anchors (active) (less than 10m in length/10% of cutting face area)	O	unique to RC	0
Drainage refurbishment	P	unique to RC	0
Local rock netting (less than 10m in length/10% of cutting face area)	Q	unique to RC	0
Cess support – lightweight	R	unique to E	0
Local cess support – heavyweight (less than 10m in length)	S	unique to E	0
Retaining wall - gabions	T	unique to E	0
Substantial geotechnical tree removal	U	unique to E	0
Toe berm	V	unique to E	0
Grouting	W	unique to E	1
Toe drainage	X	unique to E	0
Catch netting	Y	unique to E	0
			9
NB: more than one intervention may be undertaken on the same case study			
Aughton Park and ACL1 excluded from alignment exercise as commeserte refub alignment could not be found.			

D.5.9 Renewal Soil Cutting

[illegible]

D.5.11 Renewal Embankment

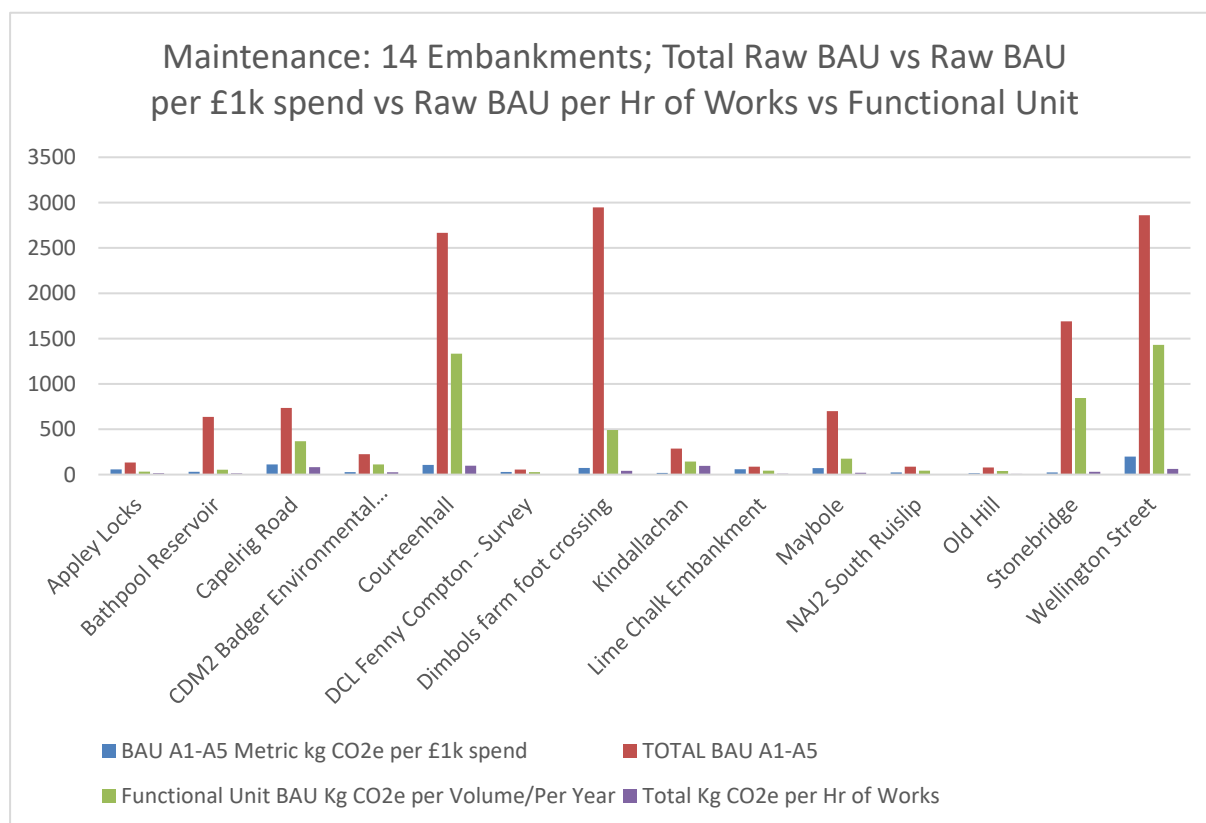
[illegible]

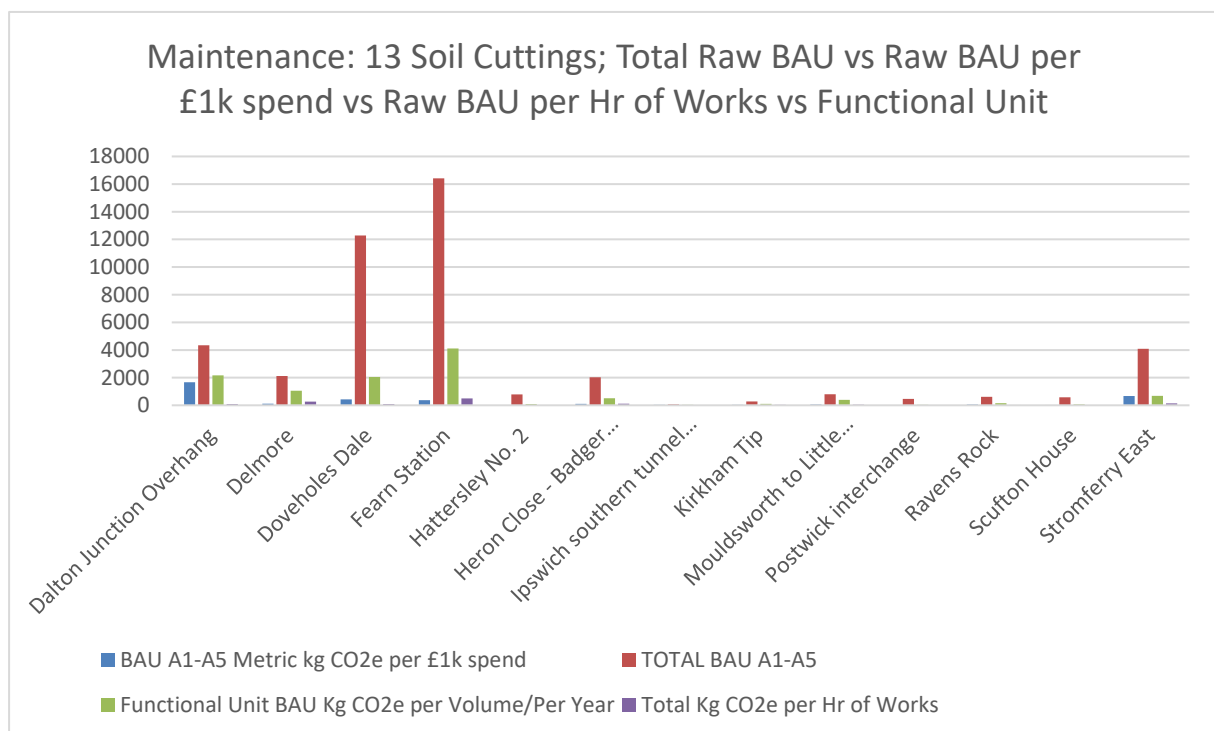
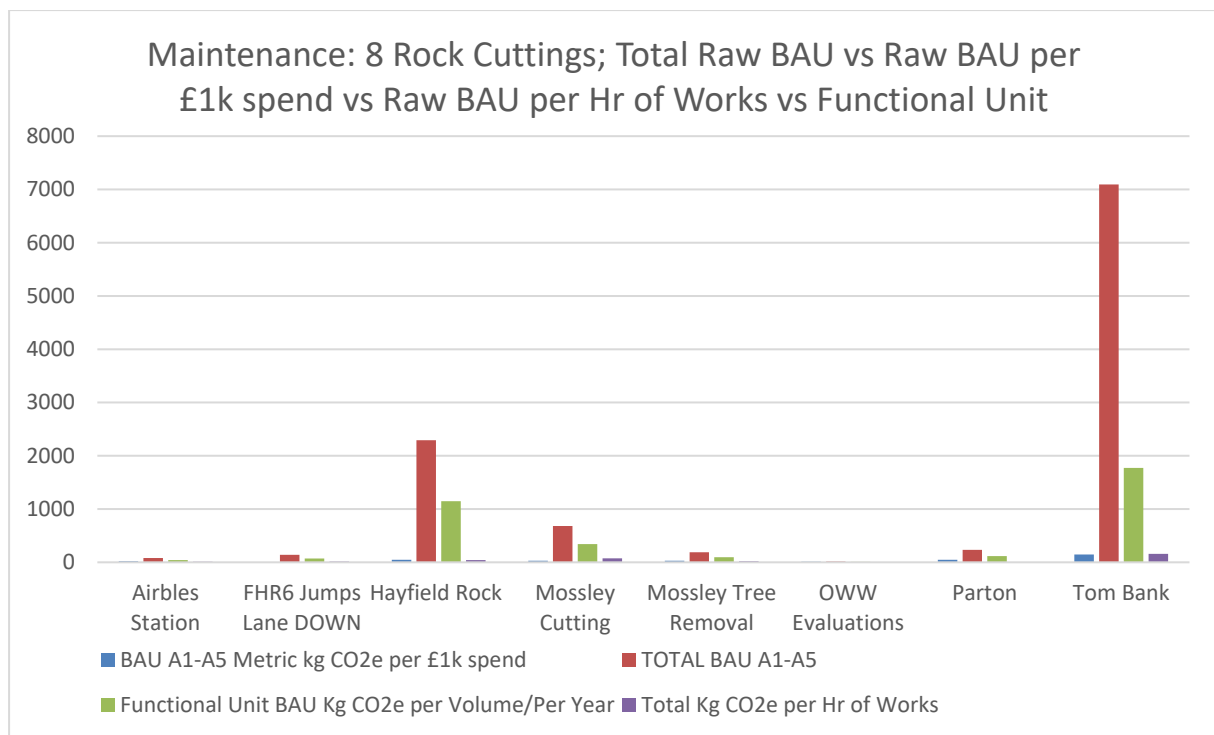
D.5.12 Renewal Summary

Totals across SC, RC and E Renewal Interventions			
Deep excavate and granular replacement (10m or more in length)	z	0	SC & E only
Toe retaining structure (10m or more in length)	aa	0	SC & E only
Regraded slope (10m or more in length)	ab	1	SC & E only
Soil nailing	ac	0	SC & E only
Ground anchors	ad	0	SC & E only
Deep slope drainage/rock ribs	ae	1	SC & E only
			SC & RC
Cess catch fence/wall/bund	af	1	only
			Unique to
Regraded slope (10m or more in length)	ag	0	RC
			Unique to
Heavy scaling	ah	0	RC
Dentition (at least 10m in length/10% cutting face area)	ai	0	Unique to
			RC
			Unique to
Shotcrete	aj	0	RC
			Unique to
Buttresses/anchored walling/beams	ak	0	RC
			Unique to
Rock dowels (passive, at least 10m in length/10% cutting face area)	al	0	RC
			Unique to
Rock bolts/anchors/strapping (active, at least 10m in length/10% cutting face area)	am	0	RC
Rock netting (at least 10m in length/10% cutting face area)	ao	0	Unique to
			RC
Cess support – heavyweight (10m or more in length)	ap	2	Unique to E
Retaining wall (not gabions)	aq	0	Unique to E
Deep shear keys	at	0	Unique to E
Soil mixing	aw	0	Unique to E
Shear piles	ax	0	Unique to E
Piled slab and embankment renewal	ay	1	Unique to E
		6	
NB: more than one intervention may be undertaken on the same case study			

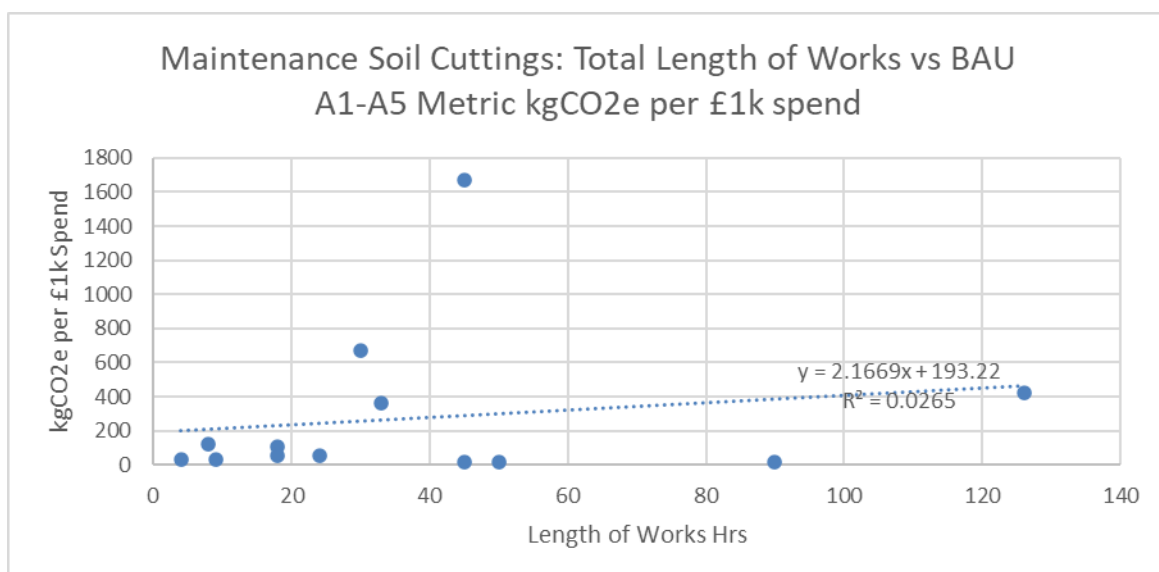
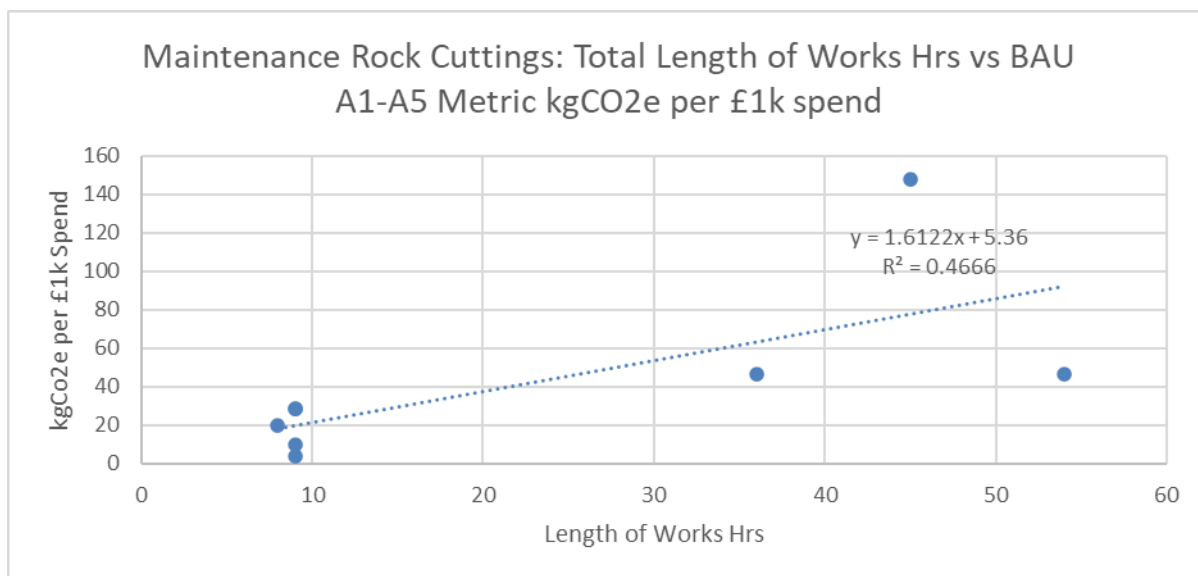
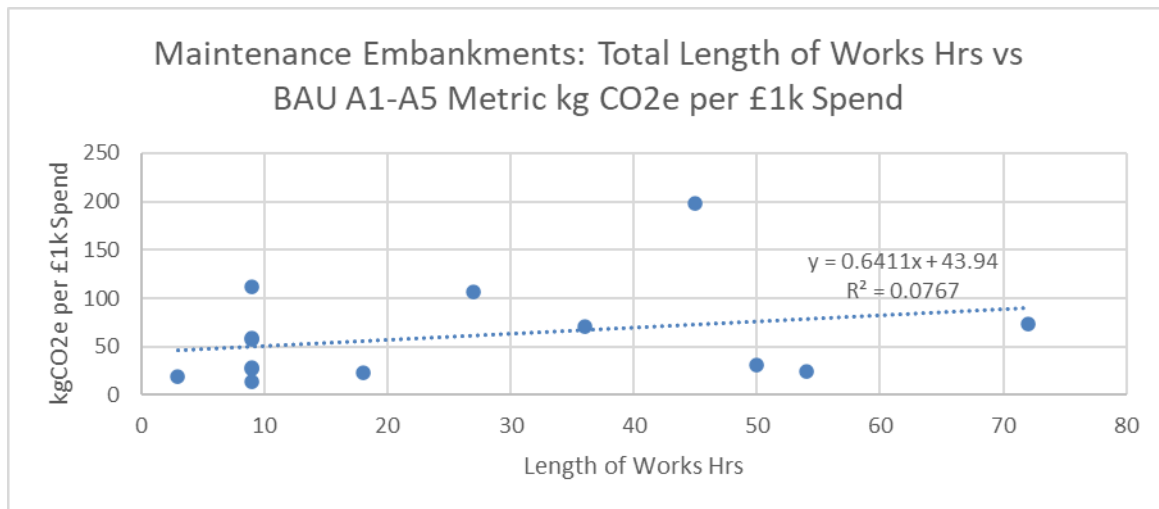
D.6 Maintenance Bar Graphs

The bar graphs below illustrate the relationship between differing metrics, disaggregated by maintenance interventions types; embankment, rock cutting and soil cutting respectively and with the differing metrics explored being total raw BAU, Raw BAU per £1k spend, Raw BAU per hour of works, and the functional unit kgCO₂e per volume/per year.





D.7 Correlation Length of Works Hrs vs BAU A1-A5 Metric kgCO₂e/£1k Spend



The correlation graphs above illustrate the correlation between total length of works in hours and the BAU A1-A5 metric of kgCO₂e per £1k spend showing a positive linear correlation in all cases. The correlation coefficient, R-Squared value and equation of trendline being illustrated in D.7.1 for each.

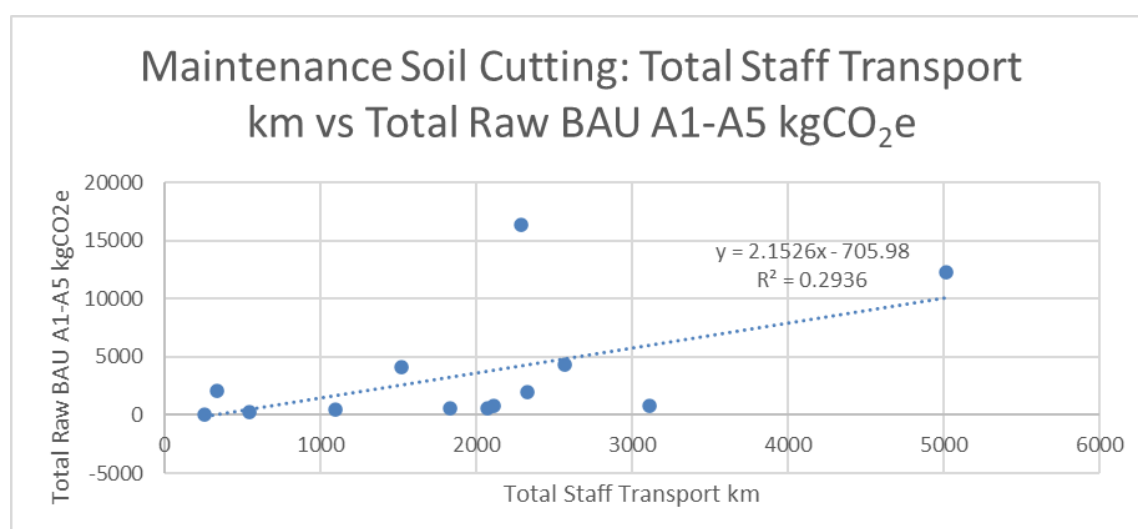
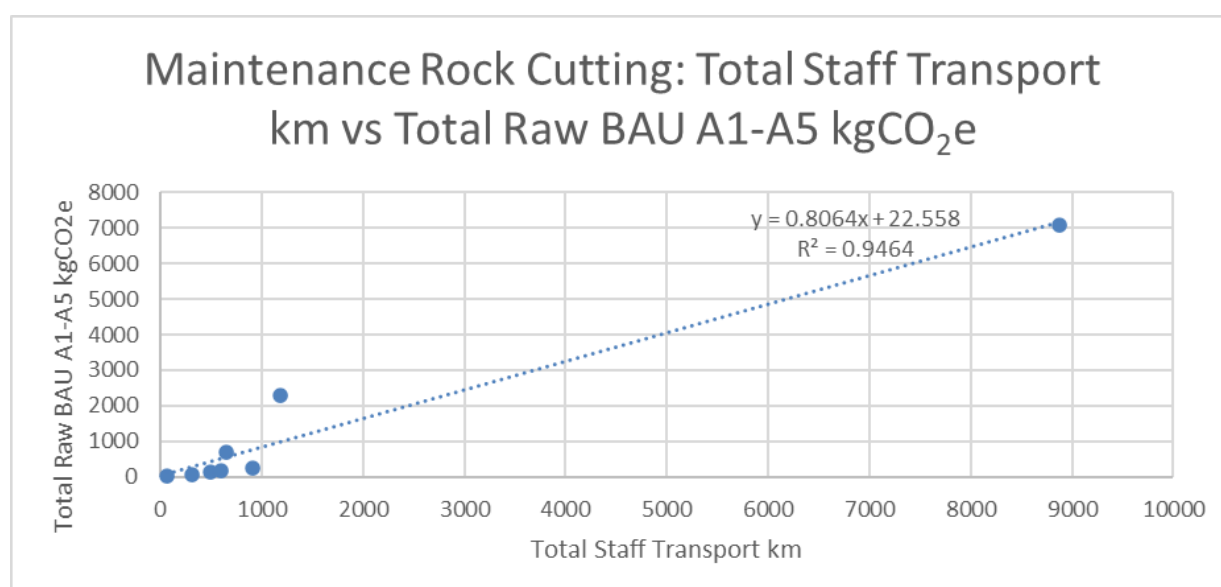
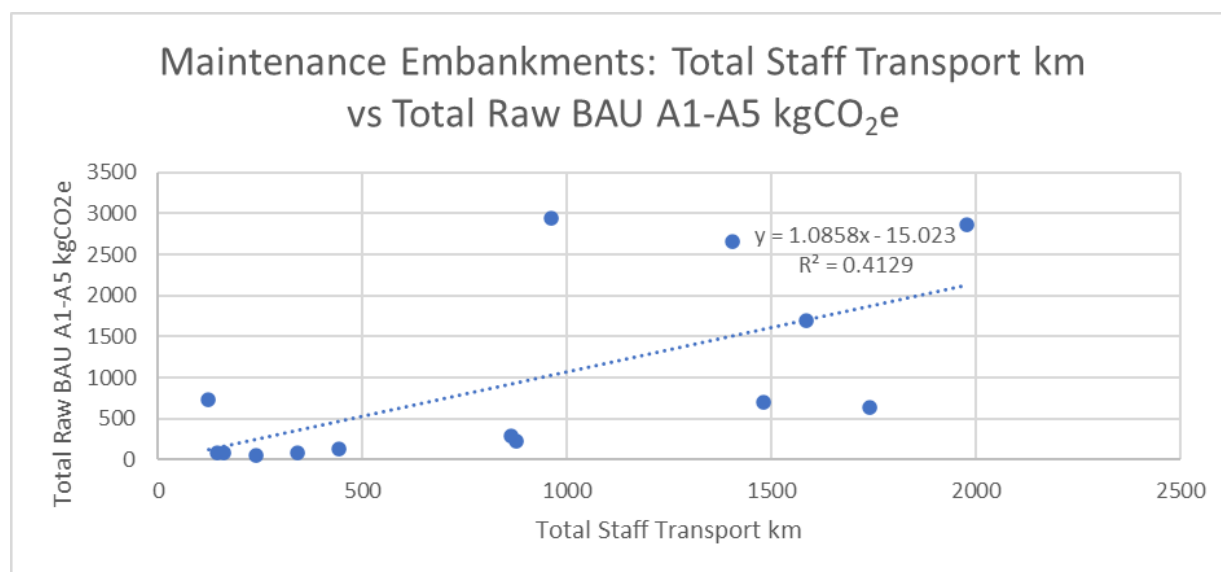
D.7.1 R, R2 and Equations of Trend Line for Different Maintenance Earthworks:
Variables are Total Length of Works vs BAU A1-A5 Metric of kgCO₂e per
£1k Spend

Maintenance Intervention Type	R – Correlation Value	R-Squared	Equation of Trend Line
Embankments	0.2770	0.0767	$y = 0.6411x + 43.94$
Rock Cuttings	0.6831	0.4666	$y = 1.6046x + 5.7053$
Soil Cuttings	0.1628	0.0265	$y = 2.1669x + 193.22$

D.7.1 illustrates that regarding the correlation value, for maintenance interventions of embankments and soil cuttings, the total length of works has a weak correlation to the metric of kgCO₂e per 1K spend. For maintenance interventions of rock cuttings the two variables are moderately correlated.

With regards the R-Squared value, this indicates that for embankments and soil cuttings, 8% and 2% respectively of the variation in the metric of kgCO₂e per £1k spend can be associated with the length of works, whereas for rock cuttings this value rises to 46% of the variation associated with the length of works. Indicating that the length of works affects the kgCO₂e per £1k of spend to a greater extent for rock cuttings than soil cuttings. Embankments' kgCO₂e per £1k of spend here increase gradually from a relatively higher starting point than rock or soil cuttings, indicating slow growth, whereas rock cuttings' kgCO₂e per £1k of spend start low but grows faster than embankments as length of works increases. Soil cuttings' kgCO₂e per £1k of spend start very high and grow the fastest as time on site increases.

D.8 Correlation Staff Transport km vs Total Raw BAU A1-A5



This Appendix illustrates the correlation between total staff transport in kilometres and the total raw BAU A1-A5 carbon footprint, again showing a positive linear correction in all cases. The correlation coefficient, R-Squared value and equation of trendline being illustrated in D.8.1 for each.

D.8.1 R, R2 and Equations of Trend Line for Different Maintenance Earthworks :

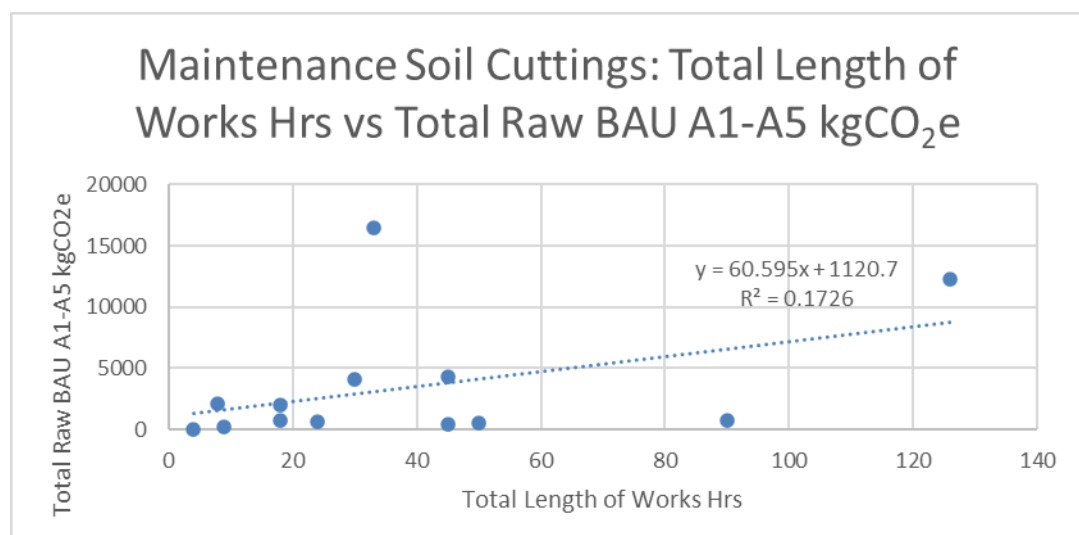
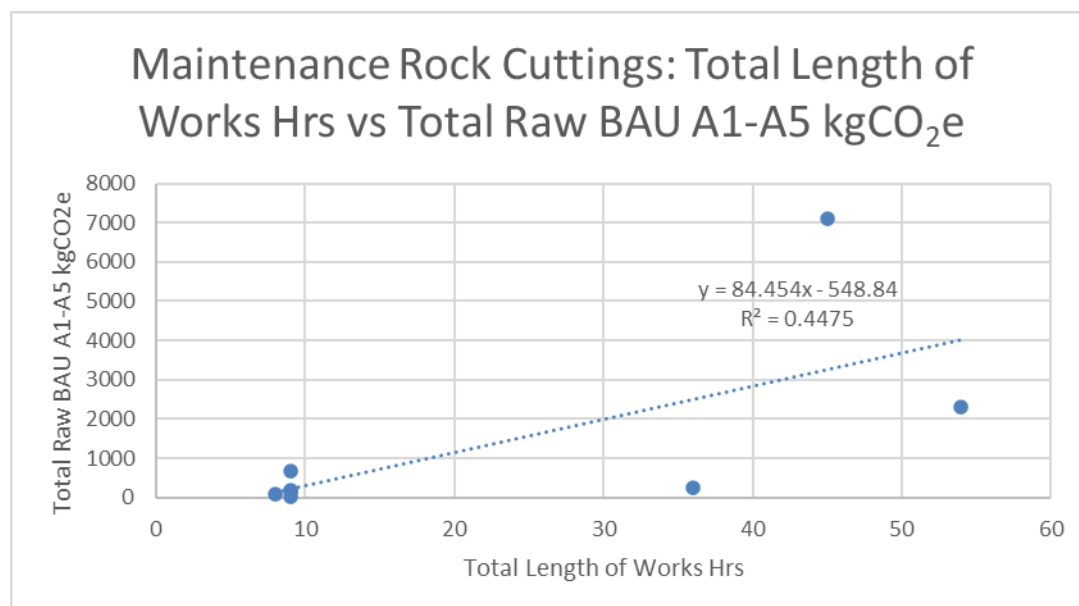
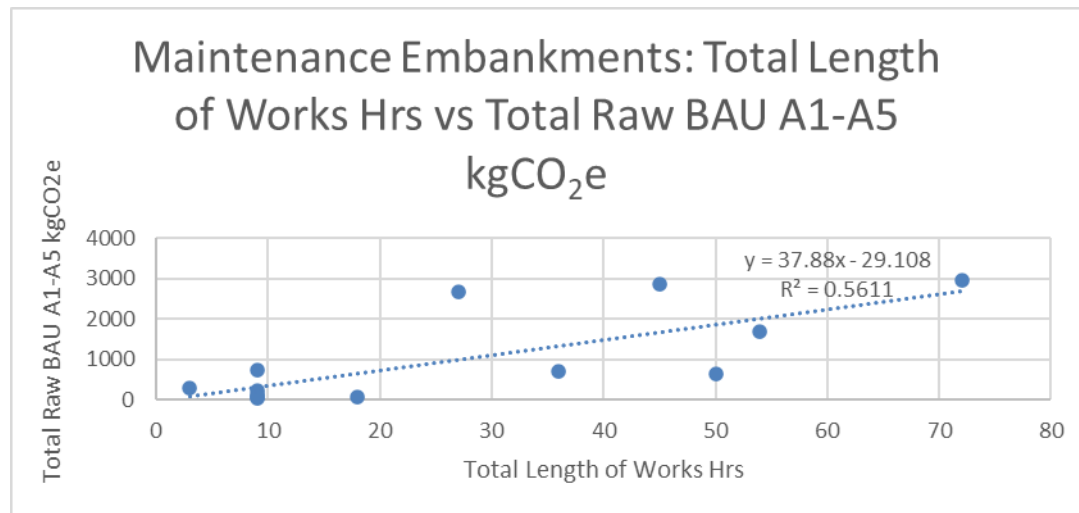
Variables are Total Staff Transport Mileage vs Total Raw BAU A1-A5

Maintenance Intervention Type	R – Correlation Value	R-Squared	Equation of Trend Line
Embankments	0.64	0.41	$y = 1.0858x - 15.023$
Rock Cuttings	0.97	0.95	$y = 0.8064x + 22.558$
Soil Cuttings	0.54	0.29	$y = 2.1526x - 705.98$

D.8.1 illustrates that for maintenance interventions of embankments and soil cuttings the total staff transport mileage variable is moderately correlated to total raw BAU A1-5 value, and for rock cuttings there is a near perfect linear correlation between these two variables. The R-squared values for these interventions show that 33% and 41% of the variation in the total raw BAU for soil cuttings and embankments respectively is attributable to the staff mileage, compared to 95% for rock cuttings indicating that the mileage variable is a good indicator of the BAU total raw footprint for maintenance rock cutting interventions.

The slightly larger R squared values given for these scatter plot, indicate that there may be a better correlation between these two variables than seen for hours on site vs kgCO₂e per £1k spend previously.

D.9 Correlation Length of Works vs Total BAU: Embankment, Rock & Soil Cutting



This Appendix illustrates the correlation between total length of works and the total raw BAU A1-A5, as with their previous correlation to the metric of kgCO₂e per £1k spend, the correlation is positive and linear in all cases. The correlation coefficient, R-Squared value and equation of trendline being illustrated in D.9.1 for each.

D.9.1 R, R2 and Equations of Trend Line for Different Maintenance Earthworks:
Variables are Total Length of Works vs Total Raw BAU A1-A5

Maintenance Intervention Type	R – Correlation Value	R-Squared	Equation of Trend Line
Embankments	0.75	0.56	$y = 37.88x - 29.108$
Rock Cuttings	0.67	0.45	$y = 84.454x - 548.84$
Soil Cuttings	0.45	0.17	$y = 60.595x + 1120.7$

D.9.1 illustrates that for maintenance interventions of embankments the total length of works variable is highly correlated to total raw BAU A1-A5 value, and for rock cuttings there is a moderate correlation and for soil cuttings a low linear correlation between these two variables. The R-squared values for these interventions show that 56% and 45% of the variation in the total Raw BAU for embankments and rock cuttings respectively is attributable to the length of works, compared to just 20% for soil cuttings indicating that the length of works is a not good indicator of the BAU total raw footprint for maintenance soil cutting interventions.

D.10 Eastern Assets Extrapolation to All of NR

D.10.1 Raw Data Provided for Eastern Region

Raw data provided by CR of Eastern Region.

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Rock Scaling	TJC1	150.0000 to 150.0220	6	NO	13			ROCK CUTTING VOLUME - Refurb	1	1
De-vegetation following Yr3 Inspections	ECM1	031.0880 to 031.0990	1	NO	6			ROCK CUTTING VOLUME - Maintain	1	1
De-vegetation following Yr3 Inspections	ECM1	095.0770 to 095.0880	1	NO	13			ROCK CUTTING VOLUME - Maintain	1	1
Removal of low-lying vegetation, light scale, clear cess	PED5	019.0770 to 019.1100	1	NO	6			ROCK CUTTING VOLUME - Refurb	1	1

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Devegetation of rock netting	LEN3	088.0110 - 088.0330	1	NO	#N/A			ROCK CUTTING VOLUME - Maintain	2	2
Gas, grouting and Netting	PMJ	009.0770 to 009.0880	1					EMBANKMENT VOLUME - Refurb	1	1
Vermin Eradication and vegetation clearance	NOG1	111.1280 to 111.1430	1	NO				EMBANKMENT VOLUME - Refurb	2	10
Gas, grouting and Netting	NOG1	108.0990 to 108.1210	1	NO				EMBANKMENT VOLUME - Refurb	2	2
Badger Exclusion Works	DBP1	020.0990 to 20.1210	1	NO				EMBANKMENT VOLUME - Refurb	2	2
				NO	#N/A					0
Crest vegetation management	PED5	020.0382 to 020.0739	1		44 - Y4			ROCK CUTTING VOLUME - Maintain	4	4
Clear loose blocks from the cess and provide price for light hand scale of loose blocks on slope	TJC1	150.0000 to 150.0220	1					ROCK CUTTING VOLUME - Refurb	4	13

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Deveg and rock removal	LEN3	97.1110 to 97.1440	1		Y3			ROCK CUTTING VOLUME - Maintain	3	3
Design of ballast retention	HDB	12.0783 to 12.0233	1		Y3					
De-vegetation and light scale following Yr3 Inspections	ECM1	103.0770 to 103.1650	1		10			ROCK CUTTING VOLUME - Refurb	2	
Gas, grouting and Netting	GSM2	103.1540 to 104.0000	1	NO				EMBANKMENT VOLUME - Refurb	2	2
Gas, grouting and Netting	GSM2	100.0550 to 100.0880	1	NO				EMBANKMENT VOLUME - Refurb	3	3
Geotechnical Tree Removal and Remote Monitoring Plan	PMJ	001.1320 to 002.0000	12	NO				EMBANKMENT VOLUME - Maintain	1	3
Scour Assessment and Form A	NSS	018.0990 to 18.1100	1	NO						
Tree removal and scaling	SPD2	079.0880 to 079.1100	1					ROCK CUTTING VOLUME - Refurb	2	2

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Design for Embankment Repair Works.	PED5	016.0770 to 016.1200	1	NO	3			EMBANKMENT VOLUME - GIA	4	4
Design	DOL2	182.0992 to 182.1002	1	NO	46 - Y4			GIA	1	1
Design of rock slope remedial works (full extents TBC).	PEH	012.1054 to 012.1060	1	NO	46 - Y4			ROCK CUTTING VOLUME - GIA	1	1
Debris removal behind catch fence	NOB1	001.0880 to 001.1320	1					ROCK CUTTING VOLUME - Maintain	4	4
Cutting crest ditch clearance	ECM7	009.0330 to 009.0915	1	NO	45 - Y4			SOIL CUTTING VOLUME - Maintain	6	6
Cutting crest ditch design	ECM7	009.0330 to 009.0915	1	NO	9			SOIL CUTTING VOLUME - GIA	1	1
Vermin Eradication	SPC1	041.1540 to 042.0110	1					SOIL CUTTING VOLUME - Maintain	3	3
Remove loose block and reinstate fence	TJC1	148.1429 to 148.1461	1	NO	10			ROCK CUTTING VOLUME - Refurb	1	1

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Rock netting management and refurbishment	CHS	001.0220 to 001.0440	7	NO	6			ROCK CUTTING VOLUME - Refurb	2	2
Crest ditch clearance	ECM1	050.0550 to 050.1100	1	NO	43 - Y4			EMBANKMENT VOLUME - Maintain	2	2
Blanket vegetation clearance	NSS	029.1290 to 029.1335	1	NO				EMBANKMENT VOLUME - Maintain	1	1
Vermin Eradication	PBS1	137.0695 to 137.0880	1	NO	44 - Y4			EMBANKMENT VOLUME - Refurb	2	2
Vegetation management	SPC6	118.1320 to 118.1460	1	NO	48 - Y4			ROCK CUTTING VOLUME - Maintain	2	2
Rock Scaling	SPC8	147.0440 to 147.0550	1	NO	46 - Y4			ROCK CUTTING VOLUME - Refurb	1	1
Rock Scaling	SPC3	078.0440 to 078.0550	1	NO	46 - Y4			ROCK CUTTING VOLUME - Refurb	1	0

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Rock Scaling	SPC8	137.1100 to 137.1320	1	NO	46 - Y4			ROCK CUTTING VOLUME - Refurb	2	2
Rock Scaling	RAC	135.0990 to 135.1320	1	NO	47 - Y4			ROCK CUTTING VOLUME - Refurb	2	2
Rock Cutting Assessment and Devegetation Works	SPC8	134.0990 to 134.1210	1	NO	51 - Y4			ROCK CUTTING VOLUME - GIA	2	2
Rock Scaling	GSM1	080.1210 to 080.1650	1	NO	51 - Y4			ROCK CUTTING VOLUME - Maintain	4	4
Vermin Eradication	VAR	VAR	1		#N/A			EMBANKMENT VOLUME - Maintain	92	92
Crest Ditch Clearance	VAR	VAR	1	NO	#N/A			SOIL CUTTING VOLUME - Maintain	40	40
Toe Ditch Clearance	VAR	VAR	1	NO	#N/A			EMBANKMENT VOLUME - Maintain	196	196

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Veg Clearance & Eco Survey	VAR	VAR	1	NO	#N/A			EMBANKMENT VOLUME - Maintain	95	95
Crest Ditch Clearance	VAR	VAR	1	NO	#N/A			SOIL CUTTING VOLUME - Maintain	35	35
Clear Cess of Fallen Material	VAR	VAR	1					ROCK CUTTING VOLUME - Maintain	16	16
Dentition work	ECM5	61.1158	1	NO	4			ROCK CUTTING VOLUME - Maintain	1	0
Badger Sett spoil removal	ECM3	181.1077	1	NO	3			SOIL CUTTING VOLUME - Maintain	1	1
Badger survey with TQ recommendations	HBS	031.0500 to 031.0945	1	NO	2					
Bespoke vegetation clearance	GSM1	085.0110 to 085.0440	1	NO	52 - Y4			EMBANKMENT VOLUME - Maintain	6	6
Implementation of rock netting design under 7050_LNE_CML	HUL3	9.1747 to 10.0060	10		9			ROCK CUTTING	1	1

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
								VOLUME - Renew		
Design	MAC3	049.0880 to 049.0990	12		20	21				
Ecology survey and Deveg works	SPC1	38.1540 to 39.0880	1	NO	52 - Y4			EMBANKMENT VOLUME - Maintain	2	
Drainage Clearance works	SPC3	88.0110 to 88.0365	1	NO	3			EMBANKMENT VOLUME - Maintain	6	6
Badger exclusion and vermin eradication works	NOG1	109.0000 to 109.0330	1	NO	3			EMBANKMENT VOLUME - Refurb	2	2
Slope regrade and removal of retaining wall	PED5	20.1550 to 20.1560	1	NO	2			SOIL CUTTING VOLUME - Refurb	1	1
Deveg and badger survey	SPC5	113.0220 to 114.0110	1	NO	3			SOIL CUTTING VOLUME - Maintain	15	15
Catch fence clearance and light scaling	ILK1	204.0110 to 204.0330	1	NO	9			ROCK CUTTING VOLUME - Refurb	1	1
PCIP Production	Various	Various	1	NO	4					0

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Rock Cutting Assessment and removal of rock from cess	AJM1	144.1320 to 144.1430	1	NO	5			ROCK CUTTING VOLUME - GIA	2	2
Vermin treatment / badger exclusion	YMS	007.1540 to 008.1100	1	NO	3			EMBANKMENT VOLUME - Maintain	11	0
Rock Cutting Assessment, Scaling and Devegetation Works	AJM1	143.1650 to 144.0130	1	NO	5			ROCK CUTTING VOLUME - GIA	5	5
Rock Cutting Assessment and existing netting checks	AJM1	143.1054 to 143.1320	1	NO	5			ROCK CUTTING VOLUME - GIA	3	3
Rock Cutting Assessment, Scaling and Devegetation Works	SPC8	134.0550 to 134.0660	1	NO	5			ROCK CUTTING VOLUME - GIA	2	2
Clear crest drain / cess	ECM1	UP = 029.0190 - 029.0453. DN = 029.0149 - 029.0880	1	NO	7			SOIL CUTTING VOLUME - Maintain	10	10
Light Scaling and localised tree removal	PSE	145.0770 to 146.0330	2	NO	13			ROCK CUTTING	19	19

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
								VOLUME - Maintain		
Weasal Hall Cutting Adverse Weather Resilience Works	MVN2	022.1430 to 023.0880	1	NO	9					0
Slope monitoring installation.	NEC2	028.0220 to 028.0330	2	NO	16					0
REMINDER: Issue to Dywidag once 8683 has completed.				NO	#N/A					0
Rabbit treatment / grouting	GSM1	074.0660 to 074.1100	2	NO	5			SOIL CUTTING VOLUME - Maintain	4	4
Additional works from Year 4 TQ.			1	NO	#N/A					0
Eco survey and tree removal	ECM1	49.1149	3	NO	8			SOIL CUTTING VOLUME - Maintain	1	1
Eco survey and tree removal	ECM1	050.0040 to 050.0090	3	NO	8			SOIL CUTTING VOLUME - Maintain	1	1
Eco survey and tree removal	ECM1	47.011	3	NO	8			SOIL CUTTING VOLUME - Maintain	1	1

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Partial regrade	TJC3	184.1615 to 185.0000	1	NO	#N/A			ROCK CUTTING VOLUME - Refurb	2	0
Scaling and Vegetation Management	BKS	000.0440 to 000.1100	9	NO	13			ROCK CUTTING VOLUME - Refurb	3	3
De-veg, vermin treatment and site visit with AE.	LEN3	077.1210 to 077.1430	6	NO	9			SOIL CUTTING VOLUME - Maintain	4	4
Installation of passive draped rockfall netting	ILK1	203.1430 to 203.1650	16	NO	20			ROCK CUTTING VOLUME - Renew	1	1
Vermin Treatment, Deveg, Ditch Clearance & Badger Surveys	VAR	VAR	8	NO	#N/A			EMBANKMENT VOLUME - Maintain	33	33
Install half pipe drainage system	MRB	032.0660 to 032.0880	6	NO	7			SOIL CUTTING VOLUME - Refurb	1	1
Stump and Root Ball Removal	MAS	153.1650 to 154.0000	6	YES	11			SOIL CUTTING VOLUME - Maintain	1	1

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Claypole Crossing Design GI	ECM1	115.0505 to 115.0528	1	NO	45 - Y4					0
LiDAR and Photogrammetry	SSK1	032.0550 to 032.0955	6	YES	#N/A					0
Design - Rock Netting / Catch Fence	MRB	033.1650 to 034.1100	6	YES	#N/A					0
Design - Form A	NEC2	051.0640 to 051.0650	6	NO	13					0
Drain Survey and de-veg.	ECM1	006.0470 to 006.0220	6	NO	14			EMBANKMENT VOLUME - Maintain	1	
Rock netting management and scaling	CHR	146.1298 to 146.1430	7	NO	11			ROCK CUTTING VOLUME - Refurb	2	2
Crest drain clearance and vegetation management	NOB3	014.0220 to 014.0330	2	NO	50 - Y4			SOIL CUTTING VOLUME - Maintain	1	1
Scaling and Removal of Fallen Blocks	ILK1	204.0660 to 204.0990	4	NO	51 - Y4			ROCK CUTTING VOLUME - Refurb	2	2

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Ecological & Badger Survey with devegetation	ECM1	030.1320 to 031.0370	7	NO	13			EMBANKMENT VOLUME - Maintain	16	16
Eco survey and tree removal	ECM5	036.1120 to 037.0010	7	NO	10			EMBANKMENT VOLUME - Refurb	5	5
Eco survey and tree removal	ECM5	34.07	7	NO	19			EMBANKMENT VOLUME - Refurb	2	2
Gas Grout and Netting	GSM3	104.0990 to 104.1540	7	NO	7			EMBANKMENT VOLUME - Refurb	4	4
Badger exclusion	GSM2	098.0220 to 98.0550	7	NO	7			EMBANKMENT VOLUME - Refurb	3	3
Badger exclusion	DBP1	022.0050 to 022.1010	7	NO	7			EMBANKMENT VOLUME - Refurb	1	1
PCIP	SPD3	93.1700 to 94.0110	7	NO	21					0
Badger Exclusion Works	GRS1	110.0990 to 110.1210	1	NO	1			EMBANKMENT VOLUME - Refurb	2	2

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Veg clearance and concrete bag removal	SPC1	018.0770 to 018.0990	1	NO	43 - Y4			SOIL CUTTING VOLUME - Maintain	2	2
Monitoring	PMJ	001.1430 to 001.1650	8	NO	9					0
Rock Fall removal / spray up.	SPD2	079.1210 to 079.1320	9	NO	19					0
De-veg and rabbit treatment	MAC3	063.0220 to 063.0770	9	NO	12			EMBANKMENT VOLUME - Maintain	10	10
Badger Survey	YMS	10.0990 to 10.1100	7	NO	9					0
Badger exclusion including netting and artificial sett	LEH1	005.1270 to 005.1430	10	YES	#N/A			SOIL CUTTING VOLUME - Refurb	3	3
Badger Survey	CAW	005.0870 to 005.1540	1	NO	43 - Y4					0
				NO	#N/A					0
Design of Slope Drainage	NEC2	049.1421 to 050.0187		NO	#N/A					0

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Inspection, Clear debris, sandbags and tidy up the slopes.	TJC1	151.1170 to 152.1070	11	YES	#N/A			SOIL CUTTING VOLUME - Refurb	2	2
Vegetation Clearance and Rock Slope Assessment	SPD2	079.1210 to 079.1320	13	NO	17			ROCK CUTTING VOLUME - GIA	1	1
Vegetation Clearance and Rock Slope Assessment	AJM1	144.0440 to 144.0460	13	NO	20			ROCK CUTTING VOLUME - GIA	2	2
Back of portal ditch clearance	ECM1	10.0475	13	NO	19			SOIL CUTTING VOLUME - Maintain	1	1
Rabbit treatment and exclusion	LEH1	011.0000 to 011.0152	13	NO	21			EMBANKMENT VOLUME - Maintain	2	2
Badger Exclusion, Grouting, Netting including Deveg and Survey	YMS	008.0790 to 008.1210	13	NO	18			EMBANKMENT VOLUME - Refurb	3	0
De-veg and options report from Pell Frischman	ECM7	063.1184 to 063.1222	13	NO	21					0
Eco survey and tree removal	ECM1	88.1430 to 89.0300	13	YES	#N/A			SOIL CUTTING VOLUME - Refurb	1	1

Work Scope Details	ELR	Mileage	Remit issued (week)	Is Estimate overdue	Week Estimate Received in Monitor	Week Issued to RE(G) Team	Asset intervention	Volume Type	Baseline Volume Quantity	Latest Volume Quantity
Eco survey and tree removal	NOB1	019.1260 to 020.0300	13	NO	19			EMBANKMENT VOLUME - Refurb	2	2
Crest ditch clearance	ECM1	010.1430 to 011.0000	16	YES	#N/A			SOIL CUTTING VOLUME - Maintain	5	5
Tree removal	ECM2	166.0120 to 166.0180	17	NO	19			EMBANKMENT VOLUME - Refurb	1	1
Badger spoil removal	ECM5	54.0041	23	NO	#N/A			SOIL CUTTING VOLUME - Maintain	1	1

D.10.2 Extrapolation Exercise

Following analysis of above the following raw data was found for the 141 interventions identified.

	Maintenance	Refurbishment	Renewal	GIA	Design	Other	Totals
Eastern for CP -01	59	49	2	11	11	9	141
Eastern Extrapolated to 5 years (whole CP)	293	243	12	56	56	44	705
Extrapolated to all NR for whole CP	1466	1217	62	281	281	218	3525

From the quantities of differing maintenance interventions found in Eastern the following percentage contributions to maintenance were found and applied to arrive at anticipated number of these types of interventions over the CP for all of NR

Intervention	Percentage Contribution to Maintenance	Anticipated No of Interventions over NR for Whole CP
Vegetation Management	36.2	531
Vermin Eradication	23.4	343
Surveys	21	308
Drainage Maintenance	23	337

D.11 Renewals BAU A1-5 to EXP Scenario A1-C4 Actions Per Stage

Expansion A1-C4	Aldercar E120	Action to Expand	Bowling Green SC120	Action to Expand	Cove LX E120	Action to Expand	Killiecrankie SC120	Action to Expand	Station Plantation E120	Action to Expand
Brief Description of Works	Embankment Cess Renewal - retention added via h section pile, armco barrier and kee clamp		Install 6G Drainage Blanket, regularise slope profile		Scour protection		Removal of debris following landslip and installation of gabion baskets at toe of soil cutting, along with new catch fence netting, cables and erosion matting.		Embankment cess renewal. Cess retention using universal columns, armco barrier and kee klamp barrier.	
A1-A3	H section piles	Dispose/Recycle same weights of materials in C4	Pallisade fencing	Leave in situ	Coir matting	N/A as materials left in situ	Gabion Basket	N/A as materials left in situ	H section piles	Dispose/Recycle same weights of materials in C4
A1-A3	Armco barrier 3mm	Dispose/Recycle same weights of materials in C4	Postmix	Leave in situ	fence posts wooden	N/A as materials left in situ	Erosion Matting	N/A as materials left in situ	Armco barrier 3mm	Dispose/Recycle same weights of materials in C4
A1-A3	Kee klamps various sizes	Dispose/Recycle same weights of materials in C4	Terram	Leave in situ	Metal posts	N/A as materials left in situ	Galvanised wire rope	N/A as materials left in situ	Kee klamps various sizes	Dispose/Recycle same weights of materials in C4

Expansion A1-C4	Aldercar E120	Action to Expand	Bowling Green SC120	Action to Expand	Cove LX E120	Action to Expand	Killiecrankie SC120	Action to Expand	Station Plantation E120	Action to Expand
A1-A3			6G Stone	Leave in situ	Timber pegs	N/A as materials left in situ	Bulldog wire rope	N/A as materials left in situ		
A1-A3			Ballast	Leave in situ	Jay pegs for coir matting	N/A as materials left in situ	Macferri mesh	N/A as materials left in situ		
A1-A3					Type 1 aggregates	N/A as materials left in situ	Steel dowel	N/A as materials left in situ		
A1-A3					Postcrete	N/A as materials left in situ	Cement	N/A as materials left in situ		
A1-A3	Embodied carbon in plant and equipment	Same figure in C1 - deconstruction site activities	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	N/A as materials left in situ	Embodied carbon in plant and equipment	Same figure in C1 - deconstruction site activities
A4	Product and material transport	Same figure in C2 - transportation of deconstructed materials	Product and material transport	N/A as materials left in situ	Product and material transport	N/A as materials left in situ	Product and material transport	N/A as materials left in situ	Product and material transport	Same figure in C2 - transportation of deconstructed materials

Expansion A1-C4	Aldercar E120	Action to Expand	Bowling Green SC120	Action to Expand	Cove LX E120	Action to Expand	Killiecrankie SC120	Action to Expand	Station Plantation E120	Action to Expand
A4	Worker travel	Same figure in C1 - Deconstruction site activities	Worker travel	N/A as materials left in situ	Worker travel	N/A as materials left in situ	Worker travel	N/A as materials left in situ	Worker travel	Same figure in C1 - Deconstruction site activities
A4	Plant and equipment transport	Same figure in C1 - Deconstruction site activities	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	N/A as materials left in situ	Plant and equipment transport	Same figure in C1 - Deconstruction site activities
A5	Fossil fuel for mobile plant and equipment	Same figure in C1 - Deconstruction site activities	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	N/A as materials left in situ	Fossil fuel for mobile plant and equipment	Same figure in C1 - Deconstruction site activities

D.12 Average Functional Unit for Maintenance Interventions BAU Scenarios

D.12.1 Embankment Vegetation Intervention

In the calculations for the maintenance lifecycle stage for the actual intervention of cess retention is set to zero, however as this sits adjacent to vegetation it was deemed necessary to recalculate this taking into account biannual vegetation management. From Chapter 4 it is known that there are 8 vegetation management type interventions (standard details) in the data set for embankments and using this an average value for the functional unit was found. Using the figures found for such interventions an additional 360.38 kgCO₂e carbon would be allocated to maintenance as indicated in the table below.

Aldercar is 3 volumes in size, as such the average functional unit would need multiplying by 3 (volumes) and the 120 year lifespan of the renewal intervention, giving 129,735 kgCO₂e over the 120 anticipated life of the embankment based on BAU carbon allocated to the B stage maintenance.

Maintenance Embankment Case Study Name	Functional Unit BAU kg CO ₂ e per Volume/Per Year
Appley Locks	33.48
Bathpool Reservoir	52.98
Courteenhall	1333.07
Dimbols farm foot crossing	491.30
Lime Chalk Embankment	43.42
NAJ2 South Ruislip	43.87
Old Hill	39.45
Stonebridge	845.43
Average	360.38

D.12.2 Soil Cutting Vegetation Intervention

In calculating the maintenance stage for the soil cutting renewals four maintenance case studies were identified as being maintenance de vegetation as such their average functional unit was used to calculate the B LC stages for the expansion scenario as illustrated below.

Soil Cutting Case Study Name	Functional Unit BAU kg CO ₂ e per Volume/Per Year
Dalton Junction Overhang	2169.24
Hattersley No. 2	98.98
Postwick interchange	39.12
Ipswich southern tunnel portal	34.14
Average	585.37

D.12.3 Scour Refurbishment Intervention

In calculating the B maintenance LC stage for the scour protection renewal, Cove LX, only one case study pertained to scour maintenance, Claydon, as such the functional unit for this maintenance intervention was used to calculate the B LC stages as indicated below.

Soil Cutting Case Study Name	Functional Unit BAU kg CO ₂ e per Volume/Per Year
Claydon Embankment	17.81

D.13 Breakdown of Lifecycle Stage Carbon for BAU Scenarios

Case Study Name	Materials Left in Situ or Deconstructed	Earthwork Type and Volume	Total Raw BAU A1-A5 kgCO ₂ e	Total (EXP) Expanded Exc. B stages, A1-C4 kgCO ₂ e	B stages Based on Average for BAU kgCO ₂ e	Total A1-C4 kgCO ₂ e	Percentage Increase in Footprint BAU – EXP A1-C4
Aldercar	Deconstructed	E, 3 volumes	406,121	625,562	129,737	755,299	86%
Bowling Green	Left in situ	SC, 1 volume	15,378	15,378	70,244	85,622	457%
Cove LX	Left in Situ	E, 1 volume	2,522	2,522	2,137	4,659	85%
Killiecrankie	Left in Situ	SC, 1 volume	22,761	22,761	70,244	93,005	309%
Station Plantation	Deconstructed	E, 1 volume	35,572	51,128	43,246	94,374	165%
Mean values	Mixture of above	Per volume	42,321	60,062	45,823	105,885	150%

D.14 Renewal Type Interventions: A0 Stages' Estimated Carbon Allocation

Methodology and Calculations based on BAU scenarios for below Table of renewal type interventions

A0 stages estimated carbon allocation

Pre Site Stage	Pre Site Sub Stage	Methodology	Estimated Carbon Allocation
Desk Study Stage	Including photos, geological survey data	Office and homeworking carbon values (Circular Ecology, 2023)	33.02 kgCO ₂ e/ week
	Potentially several meetings with consultants/contractors	Location of meetings unknown assumed office based and distance for average travel distance to site used as proxy. Van carbon = 0.25654 kgCO ₂ e per vkm as per RSSB RCT For 2 and 3 days.	Mileage for 4 vans travelling average 109km per day. This is average daily staff transport figure from all 50 case studies.
	Walk over survey up to 5 differing groups – asset engineer, contractors, designers, ecologists)	Travel distance based on average daily distance from the 5 renewal case studies. Van carbon = 0.25654 kgCO ₂ e per vkm as per RSSB RCT	Mileage for 5 vans travelling average 109km per day.
Ground Investigation	Potentially further secondary ecological survey	Use average travel distance figure from all survey type case studies (all of 1 volume size): CDM2 Badger Mitigation (225 kgCO ₂ e 1 shift), Courteenhall borehole sampling (2,666 kgCO ₂ e 3 shifts), DCL Fenny Compton ecological survey (56 kgCO ₂ e 1 shift)and OWW evaluation surveys (15 kgCO ₂ e 1 shift).	Based on average per day carbon value for the four survey type activities =296 kgCO ₂ e per shift
	Sample transport to laboratories	Assumed included in above travel distances	Assumed included in above
Ground Interpretation	Return monthly for at least 3 months to read instrumentation	Use average travel distance figure from all survey type case studies of 109km x 3 visits x van carbon figure above	84 kgCO ₂ e
Design	Detailed scheme design	Office and homeworking carbon values (Circular Ecology, 2023)	33.02 kgCO ₂ e/ week

D.15 Breakdown of Lifecycle Stage Carbon Using A0 & EXP Data

Case Study Name	Materials Left in Situ or Deconstructed	Earthwork Type and Volume	Total A0 Carbon Higher Limit	Total Raw BAU A1-A5 kgCO ₂ e	Total (EXP) Expanded Exc. B stages, A1-C4 kgCO ₂ e	B stages Based on Average for BAU kgCO ₂ e	Total A1-C4 kgCO ₂ e	Total A0-C4 kgCO ₂ e	Percentage Increase in Footprint BAU – EXP A0-C4
Aldercar	Deconstructed	E, 3 volumes	18,189	406,121	625,562	129,737	755,299	773,488	90%
Bowling Green	Left in situ	SC, 1 volume	6,063	15,378	15,378	70,244	85,622	91,685	496%
Cove LX	Left in Situ	E, 1 volume	6,063	2,522	2,522	2,137	4,659	10,722	325%
Killiecrankie	Left in Situ	SC, 1 volume	6,063	22,761	22,761	70,244	93,005	99,068	335%
Station Plantation	Deconstructed	E, 1 volume	6,063	35,572	51,128	43,246	94,374	100,437	182%
Mean values (per volume)	Mixture of above	Per volume	6,063	42,321	60,062	45,823	105,885	111,948	165%

D.16 BAU Expansion Scenario kgCO₂e per Stage

Renewal Case Study Name	A0	A1-A5	B	C1-4	A0-C4 total
Aldercar	18,189.00	406,121.00	129,736.80	219,441.00	773,487.80
Bowling Green	6,063.00	15,378.00	70,244.00	-	91,685.00
Cove LX	6,063.00	2,522.00	2,137.20	-	10,722.20
Killiecrankie	6,063.00	22,761.00	70,244.00	-	99,068.00
Station Plantation	6,063.00	35,572.00	43,245.60	15,556.00	100,436.60

D.17 BAU Expansion Scenario Percentage Contribution per Stage

Renewal Case Study Name	A0	A1-A5	B	C1-4	A0-C4 total
Aldercar	2.4%	52.5%	16.8%	28.4%	100.0%
Bowling Green	6.6%	16.8%	76.6%	0.0%	100.0%
Cove LX	56.5%	23.5%	19.9%	0.0%	100.0%
Killiecrankie	6.1%	23.0%	70.9%	0.0%	100.0%
Station Plantation	6.0%	35.4%	43.1%	15.5%	100.0%

D.18 End-of-Life Pathways for Concrete and Steel

In this section the differing pathways for EOL of concrete and steel, two of the largest contributors in the materials section to the renewals' footprints, are discussed in general, and in relation to the renewal case studies. Concrete's large contribution was expected, as concrete production accounts for around 8-9% of global anthropogenic emissions (Miller, 2018), similarly, steel has been recognised as a carbon hotspot in the literature (Pons *et al.*, 2020). Steel accounted for around half of the A1-5 footprint for Aldercar, Bowling Green and Station Plantation, and cement (key constituent of concrete) forming around one tenth of BAU A1-3 for Killiecrankie and one third for Cove LX. For concrete, both left in situ and removed from site, the differing waste hierarchy paths available will now be overviewed. For steel the differing waste paths only will be overviewed, as it is assumed steel will always be removed from site at EOL.

In the renewal examples concrete (and its constituent parts of aggregates and cement) has been assumed to be left in situ, resulting in no additional carbon being expended for its removal. Where this is not possible, and removal from site is required, there are differing EOL pathways to be considered. For concrete the main pathways at EOL are reuse, recycling, and disposal.

In the renewal examples steel has been assumed to be deconstructed and removed from site, resulting in additional carbon from machinery, staff transport and waste disposal. Other waste routes for steel and their relative carbon impacts are given below.

Steel can take a variety of routes at EOL which, counter-intuitively, may be lower carbon than primary production depending on the steel production method, with the electric arc furnace (EAF) used for scrap steel having a carbon footprint of about 0.3 tCO₂/t crude steel versus the blast furnace (BF-BOF) route used for virgin steel having a carbon footprint of about 2.2 tCO₂/t crude steel (Suer, Traverso and Jäger, 2022, p.2). NR is already making inroads in adopting utilisation of this technology (Expedition, 2020) as scrap steel for recycling is on an upwards trajectory and virgin steel production on a downwards trajectory to 2050 (Winslow, 2020, p.6). The realisation of this upwards trajectory for scrap steel usage depends on sourcing of scrap steel, which is currently insufficient (Worldstainless, 2023, p.3). In the European market, the steel innovation technological pathways, for transformation to a CO₂ neutral European steel industry, with the CE overarching all of the carbon initiatives from smart carbon usage to carbon direct avoidance, are starting to be communicated for future implementation (EUROFER, 2019, p.4).

A viewpoint on alternative lower emissions versions of these materials along with other used in the case studies is presented in Section 5.4.

D.19 Confidence in Results

Prior to comparison with the literature, confidence in the results is discussed. The RSSB report on the UK mainline rail industry whole carbon footprint (RSSB, 2021b) provides a table to illustrate their confidence in the data utilised. This has been amended and the confidence and magnitude of impact of the data collected for the case studies added (see Appendix D.19.1 and Appendix D.19.2).

D.19.1 Data Confidence amended from (RSSB, 2021b, p.42)

Data Confidence/ Availability of Data	Guideline from RSSB	For the 50 Case Studies
Low	There are known issues with the data, such as outdated carbon factor	
Medium	Data is good quality apart from some minor known issues	Data collected on the novel data capture form is of good quality. There are known issues and assumptions made regarding the data as detailed in earlier sections.
High	Good quality data provided	

Appendix D

Appendix D.19.1 illustrates that the data confidence level for the data collected for the case studies is aligned to medium level, owing to the known issues and assumptions made with the data, such as engine size and vehicles used to transport staff, materials, and plant outlined for each case study in Appendix C.5 and more generically in Section 3.4.5.

D.19.2 Magnitude of Data amended from (RSSB, 2021b, p.42)

Magnitude of Impact	Guideline from RSSB	For the 50 Case Studies
Low	Less than 5% of baseline of NR total carbon 2019-20.	Total for all 50 BAU A1-A5 = 746,141 kg which is less than 5% of the NR baseline.
Medium	More than 5% of baseline of NR	
High	More than 10% of baseline of NR	

Appendix D.19.2 illustrates that for the data set of 50 cases studies their carbon footprint is less than 5% of the NR baseline found in T1197 Decarb Carbon Measurements, of 5,390,161 tCO₂e (RSSB, 2021a, p.43). This percentage may alter in the future as these footprints are scaled up across NR to all interventions for earthworks in the NR Cost and Volume Handbook and potentially all LC stages A0-C4, and these small interventions may then be found to have a higher magnitude of impact as shown for maintenance interventions in Section 4.1.8.

The A0-C4 figures found in Section 4.2.2 for renewals have been recalculated using the same expansion methodology, for ER scenario, in Chapter 5. Offsetting, residing in the D stages, is explored in Chapter 6. This will then be applied to the expanded life cycle footprints using the ER scenario and A0 scenario, with ER principles applied. The next section will focus on comparisons of the BAU and expanded data renewal scenarios with the literature.

D.20 A0-C4 Expansion of Renewal Examples Comparison with (Kaewunruen, Sresakoolchai and Peng, 2020, p.7)

Four Stages of HSR Earthworks LC from (Kaewunruen, Sresakoolchai and Peng, 2020, p.7)	Beijing-Shanghai HSR Earthwork (kt CO ₂) from (Kaewunruen, Sresakoolchai and Peng, 2020, p.7)	Earthwork % Contribution	PAS2080 LC Stage	Renewal Aldercar A0-C4 LC Stage Carbon (kg CO ₂ e)	Renewal % Contribution of each LC Stage for Aldercar	Renewal Station Plantation A0-C4 LC Stage Carbon (kg CO ₂ e)	Renewal % Contribution of each LC Stage for Station Plantation
Conception	35.59	<1%	A0	18,189	2.4%	6,063	6.0%
Construction	8,317.33	71%	A1-5	406,121	52.5%	35,572	35.4%
Operation & Maintenance	2,864.48	25%	B	129,737	16.8%	43,246	43.1%
Disposal	451.29	4%	C	219,441	28.4%	15,556	15.5%
Totals	11,668.69	100%		773,487.80	100%	100,437	100%

D.21 Comparative Literature Assessment Against Suitability Factors

This table includes both those literature included in the comparison as they meet the relevant suitability factors, those that do not meet the suitability factors are also included below for completeness.

Case Study	Reference	Temporal: Post 2017/ Lifetime	Spatial: UK Based	Asset Type: Embankment or Cutting	Asset Size: Known & Adjusted to Functional Unit	Climate Change Factor: CO ₂ e	Include in Comparison
HS2 Phase 1	(HS2 Limited, 2022d)	YES	YES	YES	Euston Station to Old Oak Common Station	YES	YES
Carbon Assessment: Network Rail North West and Central Works Delivery Team; Confidential	Mott MacDonald (2021)	YES	YES			YES	YES
A Whole Life Carbon Model for Railway Track System Interventions	Rempelos (2023)	YES	YES			YES	YES
Measuring railway infrastructure carbon – A 'critical' in transports journey to net zero	(Lokesh, Densley-Tingley and Marsden, 2022a)	YES	YES	1km of track: ballasted or ballastless split by materials, material transport, construction, operation and maintenance	Whole life carbon of 1km of track 2,024.3 tCO ₂ eq ballasted 1,662.2 tCO ₂ eq for ballastless track	CO ₂ e per km of track	YES

Case Study	Reference	Temporal: Post 2017/ Lifetime	Spatial: UK Based	Asset Type: Embankment or Cutting	Asset Size: Known & Adjusted to Functional Unit	Climate Change Factor: CO2e	Include in Comparison
Greenhouse gas emissions from high-speed rail infrastructure construction in Korea	(Lee, Lee and Chun, 2020)	YES	NO Korea	Earthwork (noting that their definition of earthwork may be different to NR)	65.4km earthworks over HSR line For earthworks tCO ₂ e Materials 231,538 Equipment 107,991 Total 339,529	BOMS approach used 3.7MtCO ₂ eq for whole project 92% from materials 5,192 tCO ₂ e/km for earthworks on this project Data multiplied by 1000 = kg/km then divided by 10 to get NR vol equivalent	NO Note different energy mix in Korea

Case Study	Reference	Temporal: Post 2017/ Lifetime	Spatial: UK Based	Asset Type: Embankment or Cutting	Asset Size: Known & Adjusted to Functional Unit	Climate Change Factor: CO ₂ e	Include in Comparison
Dynamic energy and carbon footprints of urban transportation infrastructures: Differentiating between existing and newly-built assets	Wei and Chen (2020)	YES	NO China	Railway all stages extraction, construction, maintenance and disposal	1km length in baseline year 2017	LCA GHGs	NO NB: only percentages available in their paper, no hard quantities
A study for the measurement of environmental impact resulting from railway construction	(Morita <i>et al.</i> , 2011)	NO	NO Japan (Tokyo),	YES Earth structure: Embankment	Multiplied up from basic unit of 6.02 ton/CO ₂ /m embankment: H=6m, W=10.7m	NO CO ₂ Only	NO
A study for the measurement of environmental impact resulting from railway construction	(Morita <i>et al.</i> , 2011)	NO	NO Japan, (Tokyo),	YES Earth Structure: Cut	Multiplied up from basic unit of 3.29 ton/CO ₂ /m cut: H=6m, W=10.3m	NO CO ₂ Only	NO

Case Study	Reference	Temporal: Post 2017/ Lifetime	Spatial: UK Based	Asset Type: Embankment or Cutting	Asset Size: Known & Adjusted to Functional Unit	Climate Change Factor: CO ₂ e	Include in Comparison
Open calculator for environmental and social footprints of rail infrastructures link to calculator https://www.life-huellas.eu/calc/index_en.php tool assessed – due to boundary differences unable to use this for comparative purposes here 750kg rockfill embankment with material from loans =1.93 kg CO₂ eq	Barrientos et al., (2017)	YES	EU Study to produce modelling tool using their EPD factors	Earthwork	Cradle-to-gate EPD In Earthworks, embankment was found (compare to E2 Kindlachallen)	Kg CO ₂ eq	NO Model does not use data in same format as RSSB RCT, comparisons can therefore not be made.
Knowledge-based minimization of railway infrastructures environmental impact	Barrientos et al., (2016)	NO	NO Spain	Substructure	N/A case studies used to created indicators for model.	Carbon Footprint	NO

Case Study	Reference	Temporal: Post 2017/ Lifetime	Spatial: UK Based	Asset Type: Embankment or Cutting	Asset Size: Known & Adjusted to Functional Unit	Climate Change Factor: CO ₂ e	Include in Comparison
Greenhouse gas considerations in rail infrastructure in the UK	Saxe et al., (2015)	NO Refers back to work by Chester 2008 (Boston, Green Line), Paris and de Silva, 2010 (Crossrail)	NO Discusses range of case studies from around the globe. Some references to UK.	Whole LC of rail infrastructure with focus on metro rail transit.	Unknown.	GHGs	NO
Greenhouse gas emissions in the construction industry: An analysis and evaluation of a concrete supply chain	Akan, Dhavale and Sarkis, (2017)	YES	NO Turkey	N/A focus on concrete LC emissions – tunnels specifically	Some potentially useful tables on emissions of trucks at differing average speeds	CO ₂ and CO ₂ e	NO
Life-Cycle assessment of Future Highspeed Rail in Norway	(Grossrieder, 2011) (UIC06)	NO References pre 2017 literature	NO Norway	Open Sections – no further breakdown into earthworks	Case study based kg CO ₂ eq per m ³ *y Results give infrastructure gCO ₂ eq per pk for 2010 of 104.74	Climate Change percentages presented for construction, maintenance and EOL for open sections	NO Results show carbon reductions due to changes in technology in materials production

Case Study	Reference	Temporal: Post 2017/ Lifetime	Spatial: UK Based	Asset Type: Embankment or Cutting	Asset Size: Known & Adjusted to Functional Unit	Climate Change Factor: CO ₂ e	Include in Comparison
Screening Lifecycle Assessment to compare CO ₂ and Greenhouse Gases emissions of air, road, and rail transport: An exploratory study	Trevisan and Bordignon (2020)	NO All studies referenced are pre 2017 However good comparative rail graph that my data could potentially be plotted against.	NO Global from literature Infrastructure %'s CO ₂ eq Yue 11% Schlaupitz 31% Chester 24.9% CO ₂ Baron et al. 39.1% Pritchard 20.5%	Rail – studies cover various aspects of construction, operation and maintenance with further breakdown to infrastructure only provided.	Variety of figures presented in CO ₂ (g) and GHG (g CO ₂ eq)	gCO ₂ per passenger km - uses literature spanning from 2005 - 2016	NO graph of percentage allocations
Railway infrastructure and its environmental effects in the Alps (1945-today) Some data on emissions for France, Italy and Switzerland split by construction, ops and maint. but no further disaggregation	Gratzer (2021)	NO Data used is from Tuchschnid 2011	NO Alpine Region of Europe	Earthwork new double tracks	Earthwork new double tracks kg/y*km 9.791 CO ₂	CO ₂	NO
Historic vs highly engineered embankment	Powrie, W., Proctor Lecture 2024	YES	YES	Embankment		YES	NO data excludes A4 transport

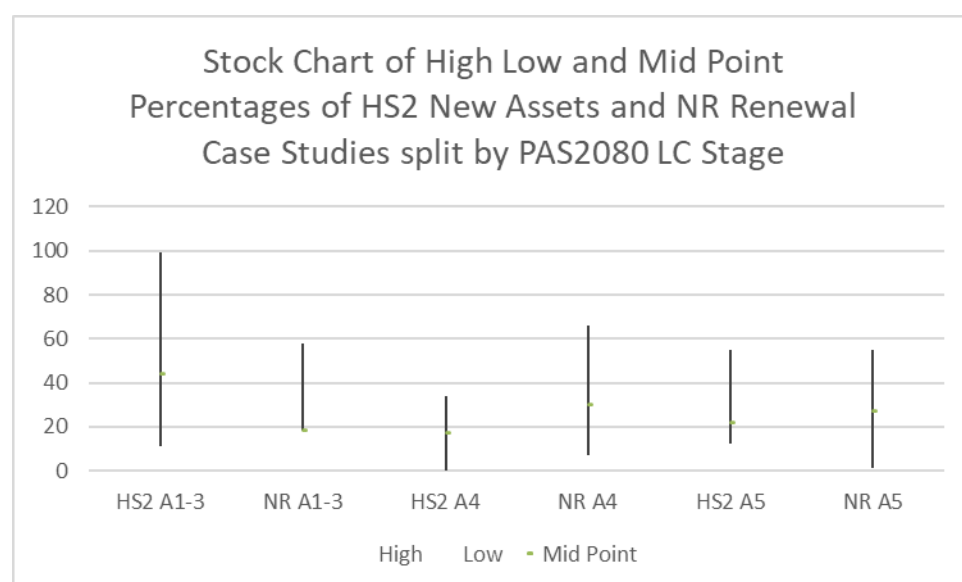
Case Study	Reference	Temporal: Post 2017/ Lifetime	Spatial: UK Based	Asset Type: Embankment or Cutting	Asset Size: Known & Adjusted to Functional Unit	Climate Change Factor: CO ₂ e	Include in Comparison
Environmental footprints of high-speed railway construction in China: a case study of the Beijing–Tianjin Line	Lin <i>et al.</i> (2020)	NO Based on construction 2005-2008	NO China	Subgrade – but no further definition of subdivision of this item	“The whole-length of the Beijing–Tianjin intercity HSR is 120 km, of which 83.8% are bridges (100.6 km) and 16.2% are subgrades (19.4 km).”	CO ₂	NO
Literature review of 22 publications, 57 case studies	Olugbenga, Kalyviotis and Saxe (2019)	NO Model based on 2009-2019 data	NO Literature review over 3 continents	At grade	~941(+/-168~)tCO ₂ e per km of rail at grade	CO ₂ e	NO
Life Cycle Cost, Energy and Carbon Assessments of Beijing-Shanghai High-Speed Railway	Kaewunruen, Sresakoolchai and Peng (2020)	NO 2008-2011 construction period	NO China	Earthwork (conception, construction, O&M, disposal split of in CO ₂ kt for entire rail system)	11,668.68kt CO ₂ whole Split 35.59 conception 8317.33 construction 2864.48 o&m 451.29 disposal		NO
EPDs for the Bothnia Line	Strippel and Uppenberg (2010)	NO pre 2010 data	NO Sweden	Track foundation processes (including earth cuttings and rock cuttings)		CO ₂ e	NO

D.22 HS2 Rail Infrastructure Carbon Emissions by PAS Lifecycle Stages from HS2 Data Set (HS2 Helpdesk, 2022(HS2 Limited, 2021))

Asset Name	Life-cycle Stage					TOTAL
	A1-A3Product stage	A4Transport	A5Construction	B2Maintenance	B4Replacement	
Brackbury Cutting	0	233,753	233,753	0	0	233,753
Copthall Cutting	8,707,797	18,928,598	29,202,777	0	0	28,419,586
Gatehead Embankment	510,079	1,556,464	2,479,853	0	0	2,273,198
West Ruislip Retained Embankment	3,215,805	7,219,880	11,927,139	0	0	11,181,413
Colne Valley South Embankment	136,745	573	1,014	0	767	139,099
Colne Valley North Embankment	6,988	744	1,456	0	3,864	13,052
Tilehouse Lane Cutting	4,049	5,008	4,218	0	1,860	15,135
West Hyde Embankment	125,172	3,028	53,168	0	9,481	190,850
Chiltern Tunnel South Cutting	535	10	1,863	0	0	2,408
Agricultural Centre Embankment	1,117	438	128	34	0	1,717

D.23 Comparison of NR and HS2 by Lifecycle Stage Percentage Contribution

HS2 Asset Name/NR Case Study Name	A1-3 Percentage Contribution.	A4 Percentage Contribution	A5 Percentage Contribution
HS2: Gatemead Embankment	11	34	55
HS2: West Ruislip Retained Embankment	14	32	53
HS2: Colne Valley South Embankment	99	0	1
HS2: Colne Valley North Embankment	76	8	16
HS2: West Hyde Embankment	69	2	29
HS2: Agricultural Centre Embankment	66	26	8
NR: Alder car	46	7	46
NR: Bowling Green	54	15	31
NR: Cove LX	22	66	12
NR: Killiecrankie	27	18	55
NR: Station Plantation	58	21	21



D.24 Descriptive Statistics for HS2 Data Set vs NR Renewals**Functional Unit**

	HS2 Data set	NR Case Studies Renewals
Mean	112.19	352.68
Standard Error	70.61	198.93
Median	18.73	189.68
Standard Deviation	199.72	444.81
Kurtosis	5.23	4.03
Skewness	2.29	1.96
Sum	897.53	1763.40
Count	8	5
Largest(1)	576.38	1128.11
Smallest(1)	7.72	21.02

Appendix E Appendices Relating to Chapter 5

E.1 Comparison of BEV vs PHEV in RSSB Tool

An exploration of the total emissions emanating from these vehicles over all scopes using the 2023 HM Government GHG conversion factors is given in E.1.1.

E.1.1 Emission Factors for EVs per km (A+C or B+C)

Tabs in 2023 GHG Conversion Factors Spreadsheet	Scopes covered	PHEV kgCO ₂ e/km	BEV kgCO ₂ e/km
A: Passenger Vehicles	Scope 1	0.06588	0.0
A: UK electricity for EVs	Scope 2	0.02579	0.05043
A: UK electricity T&D for EVs	Scope 3	0.00223	0.00437
C: WTT-Pass Vehs & Travel - Land	Scope 3	0.0244	0.01215
Total A+C	All Scopes	0.11830	0.06695
B: Business Travel – land	Sum of Scope 1 & 2 plus Scope 3 elec T&D losses	0.093916	0.054796
C: WTT-Pass Vehs & Travel - Land	Only Scope 3	0.0244	0.01215
Total B+C	All Scopes	0.118316	0.066946

E.1.1 demonstrates that BEVs have a significant carbon savings over PHEVs when all scopes are accounted for, and has the advantage of zero scope 1 emissions, further solidifying the choice of BEVs for the EV section of the emissions reduction taxonomy.

E.2 Determination of EF to Use for BEVs

In determining the emissions factor to use for EVs in the RSSB RCT, the 0.07469 kgCO₂e/km given in the tool is the figure which takes precedence, however, before using this figure in the ER scenario validation of this figure is required. Validation is achieved via comparison with the figures in the GHG Conversion Factors 2023 which come second in the order of precedence when choosing suitable ER EFs.

When calculating emissions factors for vehicles all scopes need to be accounted for to give a complete picture of the emissions associated with a vehicle. However, this total vehicle figure will then fall under Scope 3 value chain emissions for NR, and, crucially, also be counted in the sub-contractors GHG inventory as their own Scope 1 emissions from their own owned and operated vehicles (Williams *et al.*, 2012). This is where double counting of emissions occurs at the company (or

project) level. However, as company reporting is split into these different scopes, duplication of scopes should be avoided at country level.

To calculate the emissions from the sub-contractor vehicles for staff transport (cars and vans), and supplier vehicles for transport of materials and plant (vans and HGVs), emissions factors falling under scope 3 upstream indirect need to be accounted for along with scope 2 indirect for the indirect emissions from the production of electricity to power the BEVs, see A.3.1 along with the scope 1 emissions for vehicles, which are set to 0 for BEVs but are included here for completeness.

The method for assessing emissions of PHEV and BEV vehicles is outlined in the Passenger Vehicles tab (HM Government, 2023c) whereby factors from both A and C (or B+C) are required to account for all emissions emanating from a vehicle, as detailed in E.2.1.

E.2.1 Calculation of EF for PHEV Car and BEV Car & Van using 2023 GHG

Conversion Factors (HM Government, 2023c)

Tabs in 2023 GHG Conversion Factors Spreadsheet	Scopes covered	2023 PHEV Car kgCO ₂ e/ km	2023 BEV Car Avg. kgCO ₂ e/ km	2023 BEV Van. Avg. kgCO ₂ e/ km
A: Passenger Vehicles/ Delivery Vehicles	Scope 1	0.06588	0.0	0.0
A: UK electricity for EVs	Scope 2	0.02579	0.05043	0.06762
A: UK electricity T&D for EVs	Scope 3	0.00223	0.00437	0.00586
C: WTT-Pass Vehs & Travel – Land	Scope 3	0.0244	0.01215	N/A
C: WTT -Delivery Vehs and Freight	Scope 3	N/A	N/A	0.01633
Total	Scopes 1, 2&3	0.1183	0.06695	0.08981

E.2.1 illustrates the emissions factor to apply to BEVs as per the 2023 GHG conversion factors is 0.06695 kgCO₂/km which when compared to the figure of 0.07469 kgCO₂/km in the tool for EVs is within -10% of this value which appears reasonable to use as the BEV figures are using DEFRA 2018 conversion factors which may explain their higher value. To check this the 2018 conversion factors were also found for cars and compared to those of 2023 and the RCT and are also illustrated in E.2.2 and as can be seen tally exactly with the figure used in the tool thereby validating its use. However, the 10% reduction found using the 2023 figure is a promising indication of future emissions, as this

indicates that further substantial savings can potentially be made via continued use of EVs as the grid itself continues to decarbonise.

E.2.2 Calculation of EF for PHEV Car and BEV Car & Van using 2018 GHG

Conversion Factors (ref 2018 conv factors)

Tabs in 2023 GHG Conversion Factors Spreadsheet	Scopes covered	2018 PHEV Car Avg. kgCO ₂ e/km	2018 BEV Car Avg. kgCO ₂ e/ km	2018 BEV Van Avg. <3.5t kgCO ₂ e/km
A: Passenger Vehicles	Scope 1	0.07096	0.0	0.0
A: UK electricity for EVs	Scope 2	0.04531	0.05993	0.06381
A: UK electricity T&D for EVs	Scope 3	0.00386	0.00511	0.00544
C: WTT-Pass Vehs & Travel – Land	Scope 3	0.02651	0.00965	N/A
C: WTT -Delivery Vehs and Freight	Scope 3	N/A	N/A	0.01027
Total	Scopes 1, 2&3	0.14664	0.07469	0.07952

For a BEV Van the Defra all scope figure for 2018 in the RSSB RCT is given as 0.07951 kgCO₂e/vkm which was once again was validated using the GHG conversion factors for 2018 figures given in E.2.2. Using this validation method an emissions saving can be seen, this time of an additional -11% from the 2018 to 2023 figures. In the ER scenario BEV vans with this EF will be used.

For a PHEV Car the 2018 figure for scope 1, 2 and 3 above at 0.14664 can be compared with that in the tool for all scope at 0.07469 kgCO₂e/km, where it is found to be higher, however this is explained when scope 1 emissions are removed and a value of 0.07568 kgCO₂e/km is found for PHEV cars in 2018, which then aligns with the tool accounting for scope 1 or 3 only for this type of vehicle.

E.3 Analysis of EV EFs from the Literature and Comparison to Tool

To enable confidence in use of an EV emissions figure in the RSSB RCT tool a concise analysis of the differing emissions factors for the whole lifecycle of both fossil fuel vehicles and EVs in the literature is presented, cumulating in a summary table of emissions factors from the literature.

For ICEV results, where the fuel is unknown, Peng *et al.* (2017) find a figure which is around one quarter of that found by Pipitone, Caltabellotta and Occhipinti (2021) and also that of Ambrose *et al.* (2020). Whereas Onat, Kucukvar and Tatari (2014) find a figure for ICEV that is twice that of the aforementioned authors, illustrating the contrast in figures for fossil fuel vehicles. Note that these

differing studies used differing boundaries and differing life spans so comparisons should be made with caution.

For ICEV vehicles where the fuel is known figures for petrol and diesel powered vehicles are found in Johrens and Helms (2014) and Peng *et al.* (2017) which have good alignment for gasoline and slight disparity for diesel. Figures from Moro and Helmers (2017) for gasoline are approximately two thirds that of Johrens and Helms (2014) and Peng *et al.* (2017), whereas Moro and Helmers (2017) find a diesel figure that is three quarters that of Johrens and Helms (2014) and nearly half that of Peng *et al.* (2017). The gasoline figure given by Jursova, Burchart-Korol and Pustejovska (2019) was the highest and nearly 50% higher than that of the lowest figure of Moro and Helmers (2017). Again, illustrating a stark contrast and range in emissions figures for fossil fuel vehicles.

BEVs are the category of EVs overviewed with a range between 78.3 and 320 CO₂eg/km in the literature. The lowest figure being presented by Moro and Helmers (2017), the highest from Onat, Kucukvar and Tatari (2014). Peng *et al.* (2017) gives a range which aligns well with the highest and lowest figures at 79-293 gCO₂e/km. Moro and Helmers (2017) and Pipitone, Caltabellotta and Occhipinti (2021) have similar figures of around 100 gCO₂e/km. It is notable that Moro presents two figures, the lower being WTW and the higher being WTW plus the battery footprint. These two figures highlight that the battery footprint forms a considerable percentage of the material footprint of the vehicle, which is also echoed in work by Vitta (2021) and Sen *et al.* (2019), with Pipitone, Caltabellotta and Occhipinti (2021) attributing half of the production phase for BEVs to battery production.

The national electricity mixes influence on the lifecycle footprint is also important as detailed by Burchart-Korol and Folega (2020) and Wu *et al.* (2021) highlighting that as the electric grid decarbonises, and brings in more renewables, this figure will lower in line with that. The trade off in increasing electric powertrains to curtail tailpipe emissions and the corresponding increase in embedded emissions in these vehicles is outlined by Sharma *et al.* (2013) who find that class B and E BEVs have lower emissions than ICEV, almost half the emissions in the case of the Class B BEV. Once all embedded emissions are accounted for in the battery production and electricity generation for charging, BEVs (in China) can have higher lifetime emissions of around 150% of ICEV (Peng *et al.*, 2017).

A summary table of figures from the above review of the literature pertaining to the carbon footprint of differing powered vehicles are now presented in the comparison table, E.3.1, along with figures from the RSSB RCT.

E.3.1 Comparison of Emissions from Differing Powered Vehicles from Sources as Listed (gCO₂e/km)

Source	ICEV (fuel not detailed)	ICEV (gasoline / diesel)	BEV
(Peng <i>et al.</i> , 2017, pp.15-16)	49.9	278/262	79–293 BEV Range BEV NMC 75.0 BEV LFP 75.9
(Pipitone, Caltabellotta and Occhipinti, 2021) (based on 150,000 km)	187		107*
(Ambrose <i>et al.</i> , 2020)	191.5		
(Onat, Kucukvar and Tatari, 2014)	~430		~320
(Johrens and Helms, 2014)		245/ 195	
(Jursova, Burchart-Korol and Pustejovska, 2019)		342.3	215.3
(Moro and Helmers, 2017) (WTW)		178/ 145	78.3
(Moro and Helmers, 2017) (WTW + battery footprint)			96.6
(Wong <i>et al.</i> , 2021) based against 5kg H ₂ tank with 500km range			
(Sharma <i>et al.</i> , 2013) (t over lifetime)	62 (t over lifetime)		Class B 32t, Class E 52t
RSSB RCT (DEFRA 2018 All Scopes)	(Car average fuel unknown) 226.58	Car average Petrol/Diesel 233.53/ 219.49	Car average 74.69 Van 79.51

*based on EU-28 electricity mix

**based on scenario 1 based on existing electricity power infrastructure in US

E.3.1 illustrates the breadth of differing carbon emissions figures found in the literature alongside those figures found in the RSSB RCT for battery EV car and van. Comparing the BEV car figure of around 67g from E.2.1 to figures in E.3.1 (in gCO₂e/km) we find that this is just below (Peng *et al.*, 2017, pp.15-16) range of 79-293 for BEV and around (Moro and Helmers, 2017) WTW figure of 78.3, it is also within 10% of the RSSB RCT figure (of 75g).

E.4 Literature Review Analysis of Biofuels

In research by Puricelli *et al.* (2021), the environmental impacts of biofuels in Europe for light-duty vehicles (LDVs) were assessed. LDVs includes passenger cars and light-commercial vehicles (vans). Biofuels are suitable, in the majority of instances, for use in current ICEVs. Examples of biofuels analysed include biodiesel, bioethanol, HVO, upgraded biogas and bio-ETBC (Puricelli *et al.*, 2021).

Biofuels are generally subdivided into three generations (Puricelli *et al.*, 2021):

- Conventional made from food and feed energy crops such as corn,
- Non-food and non-feed energy crops such as straw
- Algae.

The degree of technological maturity of these biofuels must also be taken into consideration (Puricelli *et al.*, 2021, p.9). The two most promising biofuels in terms of CO₂eq reductions were found to be biohydrogen and UBG. Also, the ILUC CO₂ sequestration losses must be taken into consideration as these may negate the carbon benefits of these biofuels partially or even completely.

The literature on biofuels is generally classified into three generations of feedstock (Puricelli *et al.*, 2021); First generation – These are well established technologies, however the ongoing “food vs. fuel” debate is of concern when thinking of using these. These tend to fall under food and feed crops. Examples include corn, palm oil. Second generation – These are relatively mature technologies but with more complex and expensive production. These tend to fall under non-edible crops and non-edible crops suitable for marginal/desertic areas. Examples include straw, wastes etc.

The first and second generation feedstocks have the additional complication of requiring land, water, energy and fertilizers. Third generation tend to fall under wastes and residues, and algae examples include biofuels from cyanobacteria and higher alcohols. Examples of biofuels from these feedstocks are biodiesel from vegetable oils or animal fats. Biodiesel, HVO, bioethanol and biomethane can be generated from all three generations of feedstock (Puricelli *et al.*, 2021, p.3).

In terms of available literature on the differing fuels, bioethanol, FAME and upgraded biogas account for the majority of the 86 studies analysed by Puricelli *et al.* (2021, p.10). When discussing use of biofuels in place of fossil fuels DeCicco (2015) states that “although the carbon in a biofuel was recently removed from the atmosphere, that does not guarantee that it represents a net removal, the extent of which can only be ascertained by quantifying the relevant CO₂ sources and sinks” (DeCicco, 2015, p.110), which points to the need to have a full cradle-to-cradle LCA on the carbon emissions to determine this, which can be seen in Table E.6.1 where the biofuels have their differing

EFs assessed using scope 1, scope 1&3 and Scope 1& 3 and out of scope, with out of scope giving increased rather than reduced emissions.

There is a plethora of differing low carbon technologies under development and potentially more to come. This research will be concerned with additional analysis of those greener fuel options that are currently commercially available for deployment now and overviewing those that may be available soon (10-15 years) and would therefore be available for use in the path to net zero for NR. In terms of available pathways in the UK, savings of up to 95% of GHGs can be attained via the use of waste wood as a feedstock (Velazquez Abad, 2016). Biofuels accounted for some 4.5% of the energy consumption in road transport, and, of equal importance to this research, NRMM (Puricelli *et al.*, 2021). Table E.4.1 indicates the percentages of these greener fuels that were consumed in the EU in 2018 (which is prior to the introduction in 2021 of E10 petrol at UK forecourts (HM Government, 2021b), having already been introduced in the EU in 2011 as part of the European Union's Fuel Quality Directive 1 Directive 98/70/EC (European Union, 1998)) alongside their average percentage emission savings (Puricelli *et al.*, 2021).

E.4.1 Consumption of Feedstocks & Average Emissions Savings adapted from Puricelli *et al.* (2021)

Biofuel Feedstock	Percentage consumed in EU 2018	Percentage average emission savings
Biodiesel	62	41
BE (Bioethanol)	17.5	7-54
HVO (Hydrotreated Vegetable Oil)	16.6	Unknown
Upgraded biogas	1.7	63
Bio-ETBE (Ethyl-Tertiary-Butyl Ether)	1.1	unknown

A commensurate EF for biofuels, taking into account their reduction potential from the literature review which will be presented next along with comparison to government biofuel data, has been applied to HGVs in the case studies. Full details of the calculations used follow.

Current research on biofuels in vehicles has been overviewed, cumulating in a comparison of the government biofuels statistics and figures from the literature to arrive at a reduction percentage to apply to the case studies for a move from 100% diesel to 100% biofuel.

From the literature reviewed above, a summary table is provided in Appendix E.5 which illustrates the breadth of figures available for biofuels. These figures must be compared with caution owing to differing boundaries in comparison. The DfT figures here are used as these align well with the literature (average) and also from a FOI to HS2 ((HS2 Limited, 2023)) are from the same data set used by them in their carbon emissions footprinting for biofuels on site. The emissions reductions for

biofuels range from 9% for B20 based on NSPS soy oil plants (Pang *et al.*, 2021, p.271), to -50% (an increase of half). For some advanced biofuels specific biofuels need to be chosen to enable the largest GHG savings (Fairley, 2011). These figures must be compared with caution owing to differing boundaries in the comparison table which some account for Scope 3, some include ILUC and some are not stated.

E.5 Table showing Biofuel Carbon Emissions Factors /% Reductions from the Literature as cited

Type of Bio Fuel	Replacing	Boundary	Emissions Reduction	Emissions Factor	Source
Bioethanol		Inc ILUC	60% GHG reduction (by carbon intensity as per notes in the document)	Carbon intensity inc ILUC gCO ₂ e/MJ 38	DfT (2023) Renewable Fuel Statistics 2023
Biodiesel	Diesel	Inc ILUC	86% GHG reduction	Carbon intensity inc ILUC gCO ₂ e/MJ 14	DfT (2023) Renewable Fuel Statistics 2023
Bioethanol		Scope 3, WTT		0.57502 kg CO ₂ e per litre	HM Government (2023c) GHG Conversion Factors 2023
Biodiesel ME	Diesel	Scope 3, WTT		0.44759 kg CO ₂ e per litre	HM Government (2023c) GHG Conversion Factors 2023
Biodiesel ME from used cooking oil	Diesel			0.37381 kg CO ₂ e per litre	HM Government (2023c) GHG Conversion Factors 2023
Biodiesel ME from Tallow	Diesel			0.65984 kg CO ₂ e per litre	HM Government (2023c) GHG Conversion Factors 2023
Biodiesel HVO	Diesel			0.27844 kg CO ₂ e per litre	HM Government (2023c) GHG Conversion Factors 2023
B20 – based on NSPS soy oil plants	Petroleum Diesel		9% CO ₂ emissions reduction for Construction Equipment and Vehicles		Pang (2008, p.271)
B100	Diesel		42% CO ₂ emissions reduction for Construction Equipment and Vehicles		Pang (2008, p.271)
HVO100	Diesel MK1	WTT 2017	86% reduction potential identified from benchmark levels		Karlsson, Rootzén and Johnsson (2020, p.9)
Biobased heavy transport fuel	Fossil diesel	WTT various sources	36%-90% reduction potential identified from benchmark levels		Karlsson, Rootzén and Johnsson (2020, p.8) (graph)
YGME				Approx. 6 Kg CO ₂ /100km	Heinen and Johnson (2008, p.258)

Type of Bio Fuel	Replacing	Boundary	Emissions Reduction	Emissions Factor	Source
Palm oil/Rape oil biodiesel	Diesel			Approx. 14 Kg CO ₂ /100km	Heinen and Johnson (2008, p.259)
Biofuel	Fossil Fuels		GHG savings range from +85% to -30%		Hammond and Seth (2013, p.549)
Bioethanol (cellulosic)	Petrol (gasoline)		50% lower CO ₂ emissions		Hammond and Seth (2013, p.554)
First generation biofuels	Fossil fuels - gasoline		78% reduction in GHG		Highina, Bugaje and Umar (2014, p.26)
Second generation biofuels	Fossil fuels - gasoline		94% reduction in GHG		Highina, Bugaje and Umar (2014, p.26)
Biodiesel from Jatropa oil	Fossil Fuels	(non edible crop)	>70% saving in GHG emissions	23.9kg per FU (GJ of output energy when biofuel is combusted in the engine)	Eshton and Katima (2015, p.672)
Bioethanol from sugarcane molasses	Fossil Fuels - gasoline	Sugar production waste	76.1% saving in GHG emissions	17.4kg per FU	Eshton and Katima (2015, p.679)
Biofuel replacing Diesel	N/A		52.85 (GHG emissions savings when replaced with a biofuel (kg GJ-1 of fossil fuel))	76.7 Carbon footprint in CO ₂ eq kg GJ-1 of fossil fuels - diesel	Eshton and Katima (2015, p.679)
Biofuel replacing Gasoline	N/A		55.32 (GHG emissions savings when replaced with a biofuel (kg GJ-1 of fossil fuel))	72.7 Carbon footprint in CO ₂ eq kg GJ-1 of fossil fuels - gasoline	Eshton and Katima (2015, p.679)
Rape Methyl Ester (RME) biodiesel.	Diesel		(2.7 kg CO ₂ eq per kg of RME which is only 36.6% of total LC emissions)	Whole LC 7.38 kg CO ₂ eq per kg (uncertainty range 5.03 – 8.44)	Acquaye <i>et al.</i> (2011, p.2471 & p.2475)
Biodiesel from soybean, canola and carinata oils	Diesel			Lifecycle GHG emissions reduction range from 40-69% inc LUC	Xu <i>et al.</i> (2022, p.7512)
Advanced biofuels	Fossil fuels		Range from 120% reduction in emissions to -50% compared to fossil fuels		Fairley (2011) page s5 graph interpretation

Type of Bio Fuel	Replacing	Boundary	Emissions Reduction	Emissions Factor	Source
Conventional biofuels	Fossil fuels		Range from 110% reduction to -20% compared to fossil fuels		Fairley (2011, p.S5) page s5 graph interpretation
Renewable Diesel	Diesel		50-90%, 90% based on waste and residue raw materials such as used cooking oil	Nb use of GHGH savings defined by RED II does not account for differences in engine efficiency between different biofuels. It sets fuel in use emissions as zero due to CO ₂ sequestration.	Neste Corporation (2020, p.40) Table 8
Biodiesel	Diesel		.	67-444 gCO ₂ e/km Range for biodiesels including waste oil, jatropha, Fischer-Tropsch. NB: vehicle & fuel cycle included in LCA	Peng <i>et al.</i> (2017, p.16)
Bioethanol blend 10-100%	Petrol		.	210-275 gCO ₂ e/km Range for ethanols including sweet sorghum, cassava and corn. NB: vehicle & fuel cycle included in LCA	Peng <i>et al.</i> (2017, p.16)
Generation II biofuel vehicles	Gasoline/diesel		72-97% gasoline reduction 65-93% diesel reduction		Peng <i>et al.</i> (2017, p.14)
Biodiesel	Diesel			41%	Puricelli <i>et al.</i> (2021)
Bioethanol blend 10-100%	Petrol			7-54%	Puricelli <i>et al.</i> (2021)

E.6 Calculation of EF Percentage Reduction to Use for Biofuels Using Mileage From Case Studies

The determination of ER to use for biofuels is outlined following a comparative analysis using the total mileage from the case studies and converting to litres of fuel as outlined in E.6.1.

E.6.1 Total Carbon for all 50 Case Studies using Fossil Fuels and Biofuels for Scope 1, Scope 3, Scope 1 & 3 and Scope 1&3+Out Of Scope (OOS)

Metric/ Fuel	Diesel	Biodiesel	Petrol	(Bio)ethanol
Total Mileage (all 50 Case studies)	201,211	201,211	201,211	201,211
Mileage per litre of fuel	14.77		12.80	
Conversion to Litres	Total Mileage/ Mileage per litre of fuel	Litres Diesel x 1.3*	Total Mileage/ Mileage per litre of fuel	Litres Petrol x 1.7*
Litres of fuel	13,623	17,710	15,720	26,724
Carbon Emissions kgCO ₂ e/l (Scope 1)	2.51	0.16751	2.1	0.00901
Calculation	Total L x Carbon Emissions	Total L x Carbon Emissions	Total L x Carbon Emissions	Total L x Carbon Emissions
kgCO ₂ e Based on CO ₂ e per litre Scope 1 only	34,194	2,967	33,011	241
% emissions saving biofuel to fossil fuel using CO ₂ e/l	N/A	-91%	N/A	-99%
Carbon Emissions kgCO ₂ e/l (Scope 1 & 3)	3.12101	0.6151	2.68094	0.58403
Calculation	Total L x Carbon Emissions	Total L x Carbon Emissions	Total L x Carbon Emissions	Total L x Carbon Emissions
kgCO ₂ e Based on CO ₂ e per litre Scope 1& 3	42,518	10,893	42,144	15,608
% emissions saving biofuel to fossil fuel using CO ₂ e/l	N/A	-74%	N/A	-63%
Carbon Emissions kgCO ₂ e/l (Scope 1&3 out of scope)	3.26101	3.0051	2.80094	2.10403
Calculation	Total L x Carbon Emissions	Total L x Carbon Emissions	Total L x Carbon Emissions	Total L x Carbon Emissions

Metric/ Fuel	Diesel	Biodiesel	Petrol	(Bio)ethanol
kgCO ₂ e Based on CO ₂ e per litre Scope 1&3 and OOS	44,425	53,220	44,031	56,228
% emissions saving biofuel to fossil fuel using CO ₂ e/l	N/A	+20%	N/A	+28%

E.7 Determination of EF to use for Biofuel

A recap on scopes is given here to enable clear navigation of this complex arena. Scopes have been overviewed in Appendix A.3, however a brief recap to ensure the correct scopes are chosen is necessary at this juncture. Scope 1 emissions are those directly emitted by a business, scope 2 are those emitted from energy production and scope 3 are in the value chain, upstream from inputs into the organisation such as transport activities and distribution, and fuel and energy related activities.

Scope 3 is where the transport for staff to site, transport of materials to site and transport to and from site of plant and equipment would be attributed to as the vehicles are not directly owned or controlled by NR. However, as detailed earlier, project level whole LCA emissions are being counted here so all scopes will be included. Again the scope 1 direct emissions of the subcontractor will be the scope 3 emissions for NR at company level GHG reporting and as such some double counting will be taking place due to nature of carbon reporting at company level (Williams *et al.*, 2012, p.59). This double counting in itself is acceptable as it “reflects the reality that there are several leverage points at which emissions can be reduced” (Hertwich and Wood, 2018, p.3), that is by both the purchaser of the service and the provider. In calculating the emission of vehicles, all of their scopes will need accounting for, so scope 1 in use and scope 3 in use along with Scope 3 emissions for both the extraction, refinery, transport of fuel to the vehicle (WTT) will be accounted for.

Using GHG conversion factors 2023 (HM Government, 2023c) the CO₂e per litre of fuel, including for both upstream and downstream scope 3 and outside of scope, can be found and a total calculated for each fuel as detailed in E.7.1. Along with these figures an additional line is given to present the kgCO₂e/L for biodiesel and bioethanol found in the RSSB RCT.

In the RSSB RCT emissions factors are available for biofuels; biodiesel HVO, biodiesel Methyl Ester and bioethanol given in kgCO₂e/L at 0.03558, 2.8605 and 0.8165 respectively. The following sections will look to these figures to validate use of the GHG conversion factors figures and conversion of mileages in the tool, in assumed diesel vehicles for HGVs, into litres of diesel, and then converted to litres of biodiesel before applying the relevant EF.

Mileage will be converted to litres of diesel using the km per litre factors found via comparison of scope 1 and 3 and then converting to biofuel by multiplying by relevant fossil to biofuel factors.

E.7.1 Emissions Factors for Fuels (per Litre) from 2023 GHG Conversion Factors and RSSB RCT

Tabs in 2023 GHG Conversion Factors Spreadsheet	Scopes covered	Diesel Average biofuel blend kgCO ₂ e/l	Biodiesel kgCO ₂ e/l	Petrol Average biofuel blend kgCO ₂ e/l	(Bio)ethanol kgCO ₂ e/l
Fuels	Scope 1	2.51		2.10	
WTT-Fuels (Up)	Scope 3	0.61101	N/A	0.58094	N/A
Bioenergy	Scope 1		0.16751		0.00901
WTT-Bioenergy (Up)	Scope 3	N/A	0.44759	N/A	0.57502
Total	Scope 1&3	3.12101	0.6151	2.68094	0.58403
Biofuel emission factors from RSSB RCT	HVO Methyl Ester		0.03558 2.8605		0.8165
Biofuel % Reduction From Fossil Fuel		N/A	80.29%	N/A	78.22%
Outside of Scopes (kgCO ₂ e of CO ₂ per unit) from 1179	Out of Scope	0.14	2.39	0.12	1.52
Total	Scope 1&3 + Out of Scope	3.26101	3.0051	2.80094	2.10403

The out of scopes emissions are detailed here for information only as these are not found in any of the RSSB RCT BAU calculations and for consistency across data comparison these are excluded, however a brief discussion around these will be presented at the end of this appendix. However, it is worth noting here that their inclusion negates any potential emissions savings of their use, opening up a debate about, with their inclusion, if there are any emission reduction benefits to the use of biofuels.

The percentage reduction based on just the EFs per L, without taking into account conversion between litres of fossil fuel and litres of biofuel, are given in E.7.1 at 80.29% and 78.22% for diesel to biodiesel and petrol to bioethanol respectively.

These EFs align well with the literature (ref here) and the figures espoused by the (DfT, 2023) renewable fuel statistics, which on closer inspection are based on EFs per MJ which is a property tied into the volume of liquid required, as biofuels have inherently lower energy values per L, more litres of the biofuel are required hence negating or even reversing their emissions reduction potential. The figures for biodiesel from the GHG conversion factors for scope 1&3, falls between the two values presented in the RCT for HVO and Methyl Ester, and the value for bioethanol scope 1&3 from the GHG conversion factors is within about 28% of the EF in the RCT.

Using GHG conversion factors 2023 (HM Government, 2023c) the CO₂e per km of travel for cars/passenger vehicles, including for Scope 1 & 3 can be found and a total calculated for each fuel as detailed in E.7.2 using both 2023 conversion factors as the most recent figures and figures from the 2018 conversion factors which align with other transport data in the RCT.

E.7.2 Emissions Factors for Fossil Fuels 2023 Factors (2018 in brackets)

Tabs in 2023 GHG Conversion Factors Spreadsheet	Scopes covered	Diesel kgCO ₂ e/km	Petrol kgCO ₂ e/km
Passenger Vehicles (Car Avg)	Scope 1	0.16983 (0.17753)	0.16391 (0.18368)
WTT-Pass Vehs & Travel – Land	Scope 3	0.04145 (0.04196)	0.04551 (0.04985)
Total	Scope 1 & 3	0.21128 (0.21949)	0.20942 (0.23353)
Delivery vehicles (all HGVs Avg Laden)	Scope 1	0.87205 (0.87287)	N/A
WTT – delivery vehs & freight (All HGVs Avg Laden)	Scope 3	0.21135 (0.20776)	N/A
Total	Scope 1 & 3	1.0834 (1.08063)	N/A

In GHG conversion factors 2023 (HM Government, 2023c) there is also an outside of scopes tab to account for the direct CO₂ impact of burning of biofuels and biomass, however these are not included in the above table as they are not available per km of travel for comparison and would therefore not aid in this exercise to find emissions reduction data using GHG conversion tables for use of biofuels.

Using the data given for differing fuels in E.7.1 and E.7.2, the mileage (in km) per litre of fuel can be calculated as illustrated in E.7.3. Note that only scope 1 and 3 have been used to ensure comparability in this calculation with figures used in the RSSB RCT tool which do not account for out of scope emissions. Note also that the efficiency of the fuel is considered to be the same between all types of fossil fuel and biofuel for these calculations. In addition, mpg figures from HM government Department of Transport statistics have been added to the bottom of E.7.3. to investigate if the km/L figures found using this equivalency exercise are reasonable to use (HM Government, 2017a}{HM

Government, 2021 #1677)) (HM Government, 2017a{HM Government, 2021 #1677)) (HM Government, 2021a).

E.7.3 Metrics for Diesel and Petrol to Calculate Mileage per Litre of Fuel

Metric/Fuel Type	Scopes	Diesel Car	Diesel HGV	Petrol Car
kgCO ₂ e/km	1 & 3	0.21128	1.0834	0.20942
kgCO ₂ e/litre	1 & 3	3.12101	3.12101	2.68094
		kgCO ₂ e/litre /kgCO ₂ e/km	kgCO ₂ e/litre /kgCO ₂ e/km	kgCO ₂ e/litre /kgCO ₂ e/km
Calculation		3.12101/0.21128	3.12101/1.0834	2.68094/0.20942
Mileage per litre of fuel (km)		14.77	2.88	12.80
mpg from HM Gov Department for Transport Statistics		56.1 (2020 fig)	9.2 (2016 figs)	52.6 (2020 figs)
km per Litre converted from above		19.9	3.3	18.6

The figures in E.7.3 for a diesel car appear reasonable when compared to Department for Transport Statistics data (HM Government, 2021a), whereby the average miles per gallon for diesel cars is stated at 56.1 for the year 2020 which equates to 19.9 km/L which is around 26% higher than the mileage value found using the equivalency exercise above. Reasons for this discrepancy may be that the Department for Transport Statistics figures are from “carefully controlled laboratory conditions” and do not necessarily reflect real life conditions (HM Government, 2021a). In contrast the passenger land vehicles figures (which form part of the total figure for scope 1 & 3 emissions) include “an uplift to account for differences between these and real-world driving performance emissions” (HM Government, 2023a, p.48). Further details of how the mpg figures differ from real-world were not available. It is therefore concluded that it is reasonable to use the mileage figure of 14.77 km/litre for diesel cars in the subsequent calculations of emissions reduction between diesel and biodiesel cars.

For diesel HGVs the figure arrived at in the equivalency exercise also appears reasonable when compared to Department for Transport Statistics regarding HGV fuel consumption (HM Government, 2017a), where average miles per gallon for rigid vehicles is given as 9.2 mpg for 2016, which equates to 3.3 km/L, using conversion factor 1km/L = 2.8248094 UK mpg (asknumbers.com, 2023). This 3.3 km/L figure is 13% higher than that found using the GHG conversion factors scope 1&3 methodology above. Reasons behind this are unclear as the figures in Table ENV0104 (HM Government, 2017a) are based on the gallons of fuel purchased by hauliers along with records of miles travelled during a given survey week, and the figures from the GHG conversion factors include uplifts and reduction depending on loading and these can vary for a >17t rigid HGV by ± 19% between full laden and empty

compared to the average, half laden figure (HM Government, 2023a, p.79) and this uplift/reduction can be up to $\pm 25\%$ for $>33\text{t}$ articulated HGBs. Due to this variation due to loading, it does not appear reasonable to use these EFs and subsequent km/L values in subsequent calculations.

For petrol cars the figure arrived at using GHG conversion factors 2023 data appears reasonable to use as it lies within 31% of the Department for Transport statistics figure which as alluded to earlier these Department of Transport figures are from carefully controlled laboratory conditions and as such do not reflect real world conditions where the fuel efficiency may not be as good and hence the mileage in the GHGs figures will be lower.

Using the figures for diesel car and petrol car given in E.7.3, the mileages from the case studies can be converted to litres of petrol or diesel and then equivalent emission factor per litre of biodiesel factored in using the factor of $\times 1.3$ to convert diesel to biodiesel and $\times 1.7$ petrol to ethanol found in the Renewables 2018 Global Status Report (REN21, 2018). This increased amount of bioethanol compared to biodiesel to achieve the same energy output is found in Eshton and Katima (2015, p.679) thereby providing confidence in using the above multipliers.

Validation of the use of these multipliers is found using the fuel properties found in the 2023 Conversion factors and converting the Net CV kWh/litre of fuel to Net CV GJ/litre of fuel using the multiplier of 0.0036 as illustrated in E.7.4.

E.7.4 Net and Gross CV per kWh and GJ per litre of fuel

Fuel	Net CV kWh/ litre	Gross CV kWh/ litre	Net CV GJ/ litre	Gross CV GJ/ litre
Diesel (100% mineral diesel)	9.92	10.55	0.035712	0.03798
Diesel (average biofuel blend)	9.89	10.51	0.035604	0.037836
Petrol (100% mineral petrol)	9.22	9.70	0.033192	0.03492
Petrol (average biofuel blend)	8.97	9.46	0.032292	0.034056
Biodiesel (ME)	9.20	9.57	0.03312	0.034452
Biodiesel (BtL or HVO)	9.53	9.93	0.034308	0.035748
Bioethanol	5.91	6.55	0.021276	0.02358

Using GJ/litre values, when biodiesel ME is multiplied by 1.3 and then compared to the diesel 100% mineral oil blend, the figure found is within 21% and for bioethanol against petrol 100% mineral blend the figure found is within around 9% of the petrol value. It is therefore deemed reasonable to use these multipliers in the equivalency exercises, but to bear in mind these percentage differences when interpreting the results.

Using the conversion factors detailed above for both mileage to km per litre and the multipliers for fossil fuels to biofuels, the potential fossil fuel and biofuel emissions from using these differing fuels

in the case studies will be presented. The total staff transport mileage for all 50 case studies is 201,211 km, split between cars and vans using fuel unknown in the RSSB RCT. For this biofuels emissions reduction exercise, the carbon factor for diesel, petrol, (bio)ethanol and biodiesel will be applied to this total mileage and the results compared as illustrated in E.7.5. Further calculations are given in the appendices for scope 1 only, scope 3 only and scope 1&3 + OOS for comparison.

E.7.5 Total Carbon for all 50 Case Studies using Fossil Fuels and Biofuels for Scope 1&3

Metric/ Fuel	Diesel	Biodiesel	Petrol	(Bio)ethanol
Total Mileage (all 50 Case studies)	201,211	201,211	201,211	201,211
Mileage per litre of fuel	14.77		12.80	
Conversion to Litres	Total Mileage/ Mileage per litre of fuel	Litres Diesel x 1.3*	Total Mileage/ Mileage per litre of fuel	Litres Petrol x 1.7*
Litres of fuel	13,623	17,710	15,720	26,724
Carbon Emissions kgCO ₂ e/l (Scope 1 & 3)	3.12101	0.6151	2.68094	0.58403
Calculation	Total L x Carbon Emissions	Total L x Carbon Emissions	Total L x Carbon Emissions	Total L x Carbon Emissions
kgCO ₂ e Based on CO ₂ e per litre Scope 1& 3	42,518	10,893	42,144	15,608
% emissions saving biofuel to fossil fuel using CO ₂ e/l	N/A	-74%	N/A	-63%

NB: Carbon emissions kgCO₂e/l for fossil fuels Scope 3 and Out of Scope factors from (HM Government, 2023c) and Biofuels conversion from Renewables 2018 Global Status Report (REN21, 2018)

E.7.5 illustrates the complexities of conversions and potential errors being introduced with multi step conversion to carbon per km and converting litres of fossil fuel to litres of biofuel. Both scope 1&3 emissions are included in the calculations to ensure full and appropriate accounting of all the emissions associated with production and use of fuel, and the potential emissions reductions found are 74% and 63% respectively for biodiesel and bio-ethanol compared to their fossil fuel equivalents. However, all emissions savings are lost, and an increase in emissions is seen, when out of scope emissions factors are incorporated with scope 1&3 giving increased emissions of 20% and 28% respectively for biodiesel and bioethanol. Indicating that careful attention must be paid to what scopes are being used in carbon footprint tools to ensure equivalency and full accounting of

Appendix E

emissions associated with transport which would mean that scope 1 and 3 are the most appropriate to include to ensure full accounting of transport related emissions.

The biodiesel percentage GHG emissions reduction on diesel of between 74% for scope 1 & 3 and 91% for scope 1 illustrated in E.7.5 align well with those from the literature presented in E.5 where biodiesel including ILUC has an 86% GHG reduction (based on carbon intensity) on diesel fuel from the renewable fuel statistics tables (DfT, 2023). What follows is the details of the figures currently in the RCT and the calculation to reduce this in line with the above findings.

The BAU case study scenarios use the following EF for Plant transport – road freight HGV; 0.1136 kgCO₂e/tkm (weight tonnes * distance km*cf scope 1 or 3 DEFRA 2018). This EF is used in the footprint for freighting of a specified tonnage in the given vehicle.

Using the above methodology from the equivalency exercise this road freight emissions factor will be reduced by 74% to encompass all scopes (scope 1&3 emissions factor reduction calculated will be used) giving a factor of **0.029536 kgCO₂e/tkm**. The case studies were then manually recalculated using this figure for HGV movements assuming a 100% change to biofuels and achievement of this 74% emissions reduction for the biofuel used.

The calculation used for each HGV movement to be adjusted was EF x km X t with this data being taken from the existing HGV entry and adjusted as per the Calcs for ER R1.1 tab in the case studies document register R1.

For freight van movements as for Bathpool Reservoir a Van/LCV EF of 0.26866 kgCO₂e/vkm was reduced by 74% to **0.069852**.

At the start of this section carbon in staff and plant and material transport (PAS2080 lifecycle stage A4) was stated as being around 91 tonnes over the BAU 50 case studies, from the above this can be reduced by approximately 67% and 69% for staff transport by car and van respectively, and 74% for HGVs. These reductions have been applied to EFs and added to the taxonomy in Section 5.2.3.

E.8 Calculations to Determine L of Biodiesel for Diesel Machinery based on kWh

For the case studies, the kilowatt-hours (kWh) of machinery and hours running are known, however litres (L) of fuel are not. The kWh of machinery was therefore converted to L of diesel used to then allow for conversion to L of biodiesel and associated carbon emissions of biodiesel. A direct conversion of kWh to litres of diesel is found, however this factor is adjusted as engine efficiency is not 100%, and then once litres of fuel are known this is converted to equivalent litres of biofuel, and finally the carbon emission factor for the biofuel applied.

Step 1: Find kWh per litre of fuel

One litre of diesel average biofuel blend is 9.89kWh/litre (Net CV) (HM Gov, 2023)

GHG Conversion Factors gives this figure and net used as this is the practical amount of energy as opposed to gross which is the energy under laboratory conditions.

Step 2: Adjust kWh due to Engine Efficiency of around 40%

9.89kWh reduced by 60% gives 3.956 kWh per litre of diesel

Most Non Road Vehicles have 40% max efficiency (Nokka, 2018, p.16)

Large diesel engines could exceed 40% efficiency (Everett, Peake and Warren, 2021, p.281)

Typical diesel powered car engine efficiency is 32% (Everett, Peake and Warren, 2021, p.289)

Step 3: Find litres of diesel per kWh

Therefore each kWh = $1/3.956 = 0.252781$ L of fuel.

Step 4 apply to example to get total fuel

Example: Aldercar

Colmar T100000FS Piling Extension 155 kW for 400 hours

$155 \times 400 = 62,000$ kWh

$62,000 \times 0.252781 = 15,672.4$ L diesel

Step 5 convert fuel to biofuel

Conversion of fuel to biofuel is multiply by 1.3

Biofuels conversion by energy is 1.3x diesel for biodiesel and 1.7x petrol for bioethanol (REN21, 2018)

$15,672.4 \times 1.3 = 20,374.12$ L of biofuel

Step 6 Calculate emissions of biofuel

$20,374.12\text{L} \times \text{EF of biofuel from E.7.1.}$

$20,374.12 \times 0.6151$ (Scope 1 and 3 from 2023 GHG Conversion Factors) = 12,532.12 kgCO₂e over 400hrs

=31.33 kgCO₂e/hr

$20,374.12 \times 0.16751$ (Scope 1 from 2023 GHG Conversion Factors) = 3,412.87 kgCO₂e over 400hrs

= 8.53 kgCO₂e/hr

Scope 1&3 and Scope 1 only have been calculated to ensure the same methodology applied to transport emissions is applied here for plant and machinery running on biofuel.

Step 7 Choice of EF to Use in Tool

The scope of fuel for plant and equipment is unknown in the RSSB RCT for the machinery chosen in the BAU scenario. Therefore, a suitable percentage reduction for use of biofuels will need to be applied. Using the 86% reduction factor which is reduction factor from HM Gov 2023, Biofuels Factors, this percentage reduction falls between the two values calculated for Scope 1 and Scope 1&3 at 16.59 kgCO₂e/hr. The Scope 1&3 factor 31.33 kgCO₂e/hr aligns almost exactly with the 74% reduction applied to transport, thereby providing reassurance that the scope 1&3 value is valid to use an also ensuring that the biofuels' emissions are reduced in line with government factors and the literature previously overviewed.

E.8.1 Diesel Engine - Calculation of kgCO₂e/hr Using Differing EFs

To ascertain if this figure aligns with 74% found in the equivalency exercise for vehicles, and whether it is reasonable for the same calculation to be applied in this research. The results of the calculations made are presented in Appendix E.8.2.

E.8.2 kgCO₂e/hr Using Differing EFs

	BAU EF in RSSB RCT	Scope 1 EF Biofuel	Scope 1+ 3 EF Biofuel	86% Reduction on EF from GHG Renewable Statistics
Diesel	118.5			
Biofuel		8.53	31.33	16.59
Percentage Reduction in EF from BAU		92.80%	73.56%	86%

E.8.2 illustrates the differing percentage reductions using the GHG Conversion Factors for Biofuels factor of 86% and the two EFs calculated for Scope 1 and Scope 1&3 emissions.

The 86% reduction figure of 16.59 kgCO₂e/hr lies within the two factors calculated above of 31.33 kgCO₂e/hr and 8.53 kgCO₂e/hr and as further details of exact engine type and efficiency are unknown the 31.33 kgCO₂e/hr factor which incorporates emissions from scope 1 and 3 of the fuel shall be used for this example 155kW machine and for all other case studies with diesel engines, their respective EF in the tool will be reduced by 74% which aligns with the method used for vehicles using biofuels.

E.9 Calculations to Determine L of Bioethanol for Petrol Machinery based on kWh

The above method was replicated for Petrol Engine for Scope 1&3 emissions and comparison with the -60% for bioethanol made in Government Renewable fuel statistics for comparison.

Using the same method as for diesel (using the petrol conversion factors) the calculation for litres of bioethanol required for a given kWh of petrol machine was conducted.

Step 1: Find kWh per litre of fuel

One litre of petrol average biofuel blend is 8.97 kWh/litre (Net CV) (HM Gov, 2023)

GHG Conversion Factors gives this figure and net used as this is the practical amount of energy as opposed to gross which is the energy under laboratory conditions.

Step 2: Adjust kWh due to Engine Efficiency of 35%

8.97 kWh reduced by 65% gives 3.1395 kWh per litre of diesel

Appendix E

Typically in a petrol car efficiency is around 24% (Everett, Peake and Warren, 2021, p.289)

Typical gasoline car efficiency is 35% (AAA Automotive, 2023)

Petrol engines typically have 35-50% efficiency (Bach, 2019)

Step 3: Find litres of petrol per kWh

Therefore each kWh = $1/3.1395 = 0.318522$ L of fuel.

Step 4 apply to example to get total fuel

Example: Courteenhall

Drilling Rig Petrol 200 kW running for 5 hours

$$200 \times 5 = 1,000 \text{ kWh}$$

$$1,000 \times 0.318522 = 318.522 \text{ L diesel}$$

Step 5 convert fuel to biofuel

Conversion of fuel to biofuel is multiply by 1.3

Biofuels conversion by energy is 1.3x diesel for biodiesel and 1.7x petrol for bioethanol (REN21, 2018)

$$318.522 \times 1.7 = 541.4874 \text{ L of biofuel}$$

Step 6 Calculate emissions of biofuel

$$541.4874 \text{ L} \times \text{EF of biofuel from E.7.1.}$$

$$541.4874 \times 0.58403 \text{ (Scope 1 and 3 from 2023 GHG Conversion Factors)} = 316.24 \text{ kgCO}_2\text{e over 5hrs}$$

$$= 63.25 \text{ kgCO}_2\text{e/hr}$$

$$541.4874 \times 0.00901 \text{ (Scope 1 from 2023 GHG Conversion Factors)} = 4.88 \text{ kgCO}_2\text{e over 5hrs}$$

$$= 0.98 \text{ kgCO}_2\text{e/hr}$$

Scope 1&3 and Scope 1 only have been calculated to ensure the same methodology applied to transport emissions is applied here for plant and machinery running on biofuel.

Step 7 Choice of EF to Use in Tool

The scope of fuel for plant and equipment is unknown in the RSSB RCT for the machinery chosen in the BAU scenario which is 319.7 kgCO₂e/hr. Therefore, a suitable percentage reduction for use of biofuels will need to be applied. Using the 60% reduction factor which is reduction factor from HM

Gov 2023, Biofuels Factors, this percentage reduction falls outside the two values calculated for Scope 1 and Scope 1&3 at 127.88 kgCO₂e/hr. The Scope 1&3 factor 63.25 kgCO₂e/hr is higher than the 60% reduction factor at just over 80% so is within 20% of the GHG Renewable Fuel Statistics figure. When compared to the literature for biofuels previously presented this 80% factor is higher than the 50% reduction on petrol emissions from cellulosic biofuels found by (Hammond and Seth, 2013, p.554), however falls between the 78% reduction on petrol for first generation biofuels and 94% reduction on petrol for second generation fuels, found by Highina, Bugaje and Umar (2014, p.26). As such the 80% reduction factor shall be applied to plant and machinery currently using petrol.

E.9.1 Petrol Engine - Calculation of kgCO₂e/hr Using Differing EFs

The figures found for EFs are illustrated in E.9.2.

E.9.2 kgCO₂e/hr Using Differing EFs for Petrol vs Biofuel

	BAU EF in RSSB RCT	Scope 1 EF Biofuel	Scope 1+ 3 EF Biofuel	60% Reduction on EF GHG Renewable Statistics
Petrol	319.7			
Biofuel		0.98	63.25	127.88
Percentage Reduction in EF from BAU		99.69%	80.22%	60%

E.9.2 illustrates the differing percentage reductions using the GHG Conversion Factors for Biofuels factor of 60% and the two EFs calculated for Scope 1 and Scope 1&3 emissions.

The 60% reduction figure of 127.88 kgCO₂e/hr lies outside the two factors calculated above of 63.25 kgCO₂e/hr and 0.98 kgCO₂e/hr and as further details of exact engine type and efficiency are unknown the 63.25 kgCO₂e/hr factor which incorporates emissions from scope 1 and 3 of the fuel shall be used for case studies with this engine size powered via petrol, for all other case studies with petrol engines, their respective EF in the tool will be reduced by 80% which falls between the percentage reductions outlined in the literature and is within 17% of the 63% reduction factor used for vehicles using bioethanol.

E.10 Emissions Reduction from Materials

E.10.1 Selected Materials' Percentage Contributions to A1-3 Stage for BAU

Scenario : Aggregates, Granite and Limestone, Sand, Slate, Stone and Gravel

Material	Percentage Contribution of Material Embodied Carbon to BAU A1-3 LC	Case Study Name
Aggregates	84.14%	Courteenhall
Granite	99.85%	Penvellyn
Gravel - Stone	2.03%	Bowling Green
Limestone	98.08%	Fearn Station
Limestone	97.64%	Dalton Junction
Limestone	97.50%	Doveholes Dale
Limestone	87.98%	Braystones
Limestone	48.05%	Cove LX
Limestone	40.37%	Killiecrankie
Limestone	10.77%	Bowling Green
Sand	21.14%	Claydon Embankment
Sand	0.21%	Doveholes Dale
Sand	0.14%	Fearn Station
Slate	100%	Kindallachan

E.10.2 EF Review of Aggregates, Granite, Limestone, Sand, Slate, Stone and Gravel

E.10.3 Aggregates, Granite, Limestone, Sand, Slate, Stone, Gravel BAU EF & ER EF from Other Sources with ER Figure Bold and Underlined

Material	BAU EF RSSB RCT (kgCO ₂ e/ kg)	ER EF (kgCO ₂ e/ kg)	Source	Region	Reference
Aggregates and Sand - Expanded Clay	0.39321		Bath ICE 3.0 (2019)	Europe	
Aggregates and Sand – Secondary Resources		<u>0.06332</u>	Bath ICE 3.0 (2019)	Europe	RSSB RCT
Aggregates and Sand Mix Recycled and Secondary Resources		0.01418	Bath ICE 3.0 (2019)	N. America	RSSB RCT
Primary Route		0.00775	2023 GHG Conversion Factors	UK	(HM Government, 2023c)

Material	BAU EF RSSB RCT (kgCO ₂ e/ kg)	ER EF (kgCO ₂ e/ kg)	Source	Region	Reference
Secondary Route Re used Closed loop source		0.00221 0.00319	2023 GHG Conversion Factors	UK	(HM Government, 2023c)
Granite	0.7		Bath ICE 2.0 (2011)	UK	RSSB RCT
Granite General Lower		0.006	Bath ICE 1.6a (2008)	Global	RSSB RCT
Crushed Rock Production		0.0030	Trade Body	UK	(MPA, 2022)
UK Granite Production		0.0929	Literature	UK	(Crishna, Banfill and Goodsir, 2011)
Granite Rock Production		0.00292	Literature	Thailand	(Kittipongvises, Chavalparit and Sutthirat, 2016)
Gravel – Stone (Gravel Chippings)	0.017		Bath ICE 1.6a (2008)	Global	RSSB RCT
Gravel (land won)		0.0027	Trade Body	UK	(MPA, 2022)
Gravel		0.00218	Literature	China	Chen <i>et al.</i> (2022, p.5)
Limestone - General	0.09		Bath ICE 2.0 (2011)	US region	RSSB RCT
Ground Limestone		0.034	Bath ICE 2.0 (2011)	UK	RSSB RCT
Limestone quarrying operations		0.00313	Literature using GHG Protocol	Thailand	(Kittipongvises, 2017)
Limestone quarrying operations		0.00276	Literature using IMPACT2002+	Thailand	(Kittipongvises, 2017)
Sand - General	0.0051				RSSB RCT
Sand – land won		0.0027	Trade Body	UK	(MPA, 2022)
Slate - General - Mid	0.035		Bath ICE 2.0 (2011)	UK	RSSB RCT
Slate – General - Lowe		0.007	Bath ICE 2.0 (2011)		RSSB RCT
Slate	0.232	0.232		UK	Crishna, Banfill and Goodsir (2011)

E.10.3 illustrates the 2019 Bath ICE ER EF available for aggregates via secondary resources for the European region in the RSSB RCT and so this figure will be used. An ER EF is available in the RSSB RCT for mix recycled and secondary, however this figure is for North America, and as such will not be utilised as the region is outside the UK and Europe. Figures are available in the 2023 GHG conversion

factors for the UK and these are shown for comparison, however the RSSB tool figure will take precedence.

For granite there is a lower EF figure, however this is from the Bath ICE launched in 2008. Due to its age, a more timely figure from the UK trade body the MPA in 2022 will be used as this also takes precedence over the figures found in the literature, presented again for comparative purposes. Note however the closeness of the Thai figure to the trade body figure and that the UK figure, which is not as timely, from 2011, gives a figure 30 times lower than that from the trade body, the MPA.

Gravel figures from the Trade Body, the MPA, will be used as no lower figures could be found in the RSSB RCT or GHG conversion factors. The trade body figures take precedence over those from the literature which were found for China which would not be readily comparable to the UK.

Regarding limestone, a second figure was found in the RSSB RCT which has a lower footprint and will therefore be used as taking precedence over other figures found. The literature figures were from Thailand and therefore not suitable for use in a UK context.

For sand, a lower figure could not be found in the RSSB RCT therefore the trade body's figure was used as no figure could be found in the HM Government (2023c) 2023 GHG conversion factors, which would have taken precedence, for sand either.

The 2011 Bath ICE 2.0 database gives a figure for slate embodied carbon of 0.035 kgCO₂/kg which includes extraction and processing of the slate. This figure is classified in the RSSB RCT tool as the middle figure of a range of provided values and the database also contains an upper and lower value at 0.063 and 0.007 respectively. For the ER factor the lower RSSB RCT value detailed here will be utilised as this takes precedence over the literature figure found.

E.10.4 Emission Factor Review of Bricks

Material	BAU EF RSSB RCT (kgCO ₂ e/ kg)	ER EF (kgCO ₂ e/ kg)	Source	Region	Reference
Bricks - General	0.213		Bath ICE 3.0 (2019)	UK	RSSB RCT
Bricks Primary Production		0.24175	2023 GHG Conversion Factors	UK	(HM Government, 2023c)
Light colour Marshalls Brick		<u>0.1309</u>	EPD	UK	Marshalls Bricks & Masonry (2021)

Material	BAU EF RSSB RCT (kgCO ₂ e/ kg)	ER EF (kgCO ₂ e/ kg)	Source	Region	Reference
Portuguese brick cradle to gate GWP100		0.141	Literature	Portugal	(Almeida <i>et al.</i> , 2010)
K-BRIQ [®]		0.0070	From start up associated with Heriot Watt University	UK	(KENOTEQ, 2024)

E.10.4 illustrates Bricks BAU EF and ER EF from Other Sources with ER Figure Bold and Underlined.

The values above in grey were found post ER scenario production, illustrating the fast moving pace of the carbon reduction market.

E.10.5 Emission Factor Review of Concrete & Cement

Green Concrete

Several solutions for green concrete, including use of Recycled Coarse Aggregate (RCA) and SCMs are now reviewed, see Figure 5.2. The three categories of waste (agricultural, industrial and municipal) that can be utilised are highlighted in Liew, Sojobi and Zhang (2017, p.1065). They provide in depth analysis of the multitude of approaches to greener concrete alongside highlighting the need to reduce depletion of nature sources and the limited (and decreasing) landfill spaces for construction waste.

Ecological concrete can be defined as “concrete with aggregates derived from recycled waste” (Vieira, Calmon and Coelho, 2016, p.658) which aligns to use of RCA and SCMs, and sits well with the circular economy principles outlined in Figure 2.18. Waste reuse closing the loop of circularity, is one of several types of greener concrete that will be explored here (Vieira, Calmon and Coelho, 2016, p.658). Use of RCA and SCMs needs to be well understood and LCA utilised to enable the whole life footprint to be compared, as the use of recyclables in concrete do contribute towards the CE “but do not per se reduce” the GHG emissions and resource consumption at the same time (Gallego-Schmid *et al.*, 2020, p.2).

Use of recycled concrete (RC) would aid in decarbonisation of concrete and RC can contain recycled aggregates from demolished and crushed concrete from buildings and structures at their EOL, which means that NR could use this as a route to circularity when demolishing concrete structures at EOL. Climate and resource footprints of RC find that the use of RC does reduce the material footprint (see Glossary) by up to half, whereas with the climate footprint (see Appendix A.6.1) reduction is limited

(Mostert *et al.*, 2021, p.1). Use of RC may require additional cement, therefore overall GHG emissions may even be higher than for concrete using natural aggregates (NA) (Mostert *et al.*, 2021, p.10). The change in GHG emissions of concrete made with RA compared to NA can range from -25% to +35%, and transport distances of the concrete need to be considered as this is a significant factor in their footprint (Mostert *et al.*, 2021, p.2).

When travel distances exceed 15km by road for RAs, this negates any emissions savings from using RAs (The Concrete Centre, 2020). Therefore, the transportation distances of raw materials need to be paid special attention to. The reason being the potential for approaching a distant supplier (with low GHG product) actually increasing the emissions of the final product, and vice versa for high emissions product sourced from a geographically close source (Deschamps *et al.*, 2018). To achieve additional emissions savings, suppliers of raw materials may need incentivising to utilise producers of such materials in geographically close locations to achieve decarbonisation in line with net zero by 2050 timescales (Akan, Dhavale and Sarkis, 2017).

Mode of transport will also be a key factor in transport emissions with use of rail potentially giving a decrease in emissions compared to road transport (Miller, 2018). This is an area for NR to galvanise further as they have the desirable position of potentially being able to use rail transport for materials, giving them direct access to the work site via the rail network.

Material truck haul distance affects total CO₂ emissions on construction projects. As the material truck haul distance increases the percentage of total CO₂ emissions attributable to materials transport increases in a linear fashion, with the total absolute CO₂ emissions increasing in a linear manner also (Shillaber, 2016, p.153). With tripling of materials transport distances producing an increase of less than 7% in the total CO₂ emissions (Shillaber, 2016, p.156). Use of actual distances where possible, as conducted for the case studies in this thesis, should be used when calculating the carbon footprint. The tendency, illustrated with some larger projects, to use an arbitrary blanket transport distance, must be dissuaded (HS2 Limited, 2013b, p.19).

In the case studies with emissions from aggregates, these contributed between 12% and 99% to the A1-3 total, see Appendix E.10.6. Due to the impact of transport emissions on aggregates, additional analysis of the A1-3 and A4 contribution of aggregates to various footprint stages has been conducted, illustrated in Appendix E.10.7. The varying contributions of aggregates and stones to both the A1-3 embodied carbon stage and A4 transport stage is given in Appendix E.10.7. The transport of these materials accounts for up to around half of all transport emissions and the materials themselves account for between half and nearly all of the embodied carbon emissions.

Appendix E.10.8 illustrates the range of percentage contributions of A1-3, A4 and A1-4 towards the total BAU A1-5 footprint and shows that the contribution of these aggregates is a significant proportion of the total footprint for two of the case studies investigated; Fearn Station and Penvellyn.

Green Cement

Cement is included in the materials of several of the case studies as detailed in Appendix E.10.6. Research into lower carbon products is ongoing and new innovations are being pursued by academia, including low clinker cements and other alternatives to Portland cement, see ongoing work by Steel (2021), and Birkinshaw and Jarvis (2021) and, for self-healing concretes (Basilisk, 2022). Use of green cement using SCMs as outlined in Figure 5.2 will also make greener concrete as a constituent part of this material.

LCA of concrete identified several stages which add to the embodied carbon in this material including transportation of raw ingredients to concrete production plant, transportation to construction site, the in service phase. This is followed by the demolition and waste phase which ends with transportation and waste disposal in the environment, or re-use via the waste processing plant back to the concrete production plant (Vieira, Calmon and Coelho, 2016).

The Concrete Centre (2020) outline the GHG contribution of the constituent parts of concrete with the cement contribution being the “controlling constituent material” in term of embodied CO₂ compared to aggregates, which are two orders of magnitude lower (SCMs range from one order to two orders of magnitude lower than the cement constituent (The Concrete Centre, 2020, p.14)). SCMs include three main groups as illustrated in Figure 5.2: Group 1 is industrial waste such as GGBFS, fly ash, silica fume. Group 2 is agricultural waste such as RHA, corn cob ash and sawdust ash. Group 3 is municipal waste includes glass and plastics (Liew, Sojobi and Zhang, 2017, p.1065).

E.10.6 Concrete and Cement Percentage Contributions to A1-3 Stage for BAU Scenario

Material	Percentage Contribution of Material Embodied Carbon to BAU A1-3	Case Study Name
Cement	6.55%	Bowling Green
Cement	32.46%	Cove LX
Cement	0.29%	Fearn Station
Cement	12.39%	Hammers Underbridge
Cement	9.88%	Killiecrankie
Cement	100%	Kirkham Tip
Cement	94.90%	Maybole Road
Cement	99.98%	Stonebridge
Cement	3.50%	Wellington Street

Material	Percentage Contribution of Material Embodied Carbon to BAU A1-3	Case Study Name
Concrete	10.49%	Braystones

E.10.7 Percentage contribution of Aggregates to A1-3 & A4 Stages in Selected Case Studies

Case Study	Item	% Contribution of Aggregates to A1-3	% Contribution of Aggregates to A4
Killiecrankie	Gabion Baskets	47%	7%
Fearn Station	Gabion Stone	98%	24%
Penvellyn	Salix Rock Rolls	99%	47%

E.10.8 Percentage Contribution of Aggregates to A1-5 BAU Selected Case Study Totals

Case Study	Item	% Contribution of Aggregates to Total BAU A1-5	% Contribution of Aggregates A4 to Total BAU A1-5	% Contribution of Aggregates A1-A4 to Total BAU A1-5
Killiecrankie	Gabion Baskets	12.5%	1.3%	13.8%
Fearn Station	Gabion Stone	73.6%	5.6%	79.2%
Penvellyn	Salix Rock Rolls	80.1%	2.8%	82.9%

E.10.9 Concrete BAU EF and ER EF from Other Sources with ER Figure Bold and Underlined

Material	BAU EF RSSB RCT (kgCO ₂ e/ kg)	ER EF (kgCO ₂ e/ kg)	Source	Region	Reference
Concrete - RC40/50 - C40/50 MPa - Cement Replacement - 0%	0.169		Bath ICE 1.6a	Global	RSSB RCT
Concrete - Reinforced - modification factors*	0.077 *		Bath ICE 2.0	UK	RSSB RCT
Concrete - Precast (prefabricated) concrete - modification factors*	0.029 *		Bath ICE 2.0	UK	RSSB RCT

Material	BAU EF RSSB RCT (kgCO ₂ e/ kg)	ER EF (kgCO ₂ e/ kg)	Source	Region	Reference
Total Concrete BAU Sum of Above	0.275				
Concrete - RC40/50 - C40/50 MPa - Cement Replacement - Blast Furnace Slag -50%		0.101	Bath ICE 1.6a	Global	RSSB RCT
Concrete - RC40/50 - MPa – 70% Blast Furnace Slag*		0.072*	Bath ICE 3.0	Europe	RSSB RCT
Concrete - RC40/50 - C40/50 MPa - Cement Replacement – Fly Ash - 50%		0.096	Bath ICE 1.6a	Global	RSSB RCT
Primary Production Route		0.13175	GHG Conversion Factors 2023	UK	(HM Government, 2023c)
Secondary Production Route		0.00319	GHG Conversion Factors 2023	UK	(HM Government, 2023c)
Total Concrete ER Sum of *		0.178			

**E.10.10 EF Percentage Difference from Differing Portland Cement Mixes amended
from The Concrete Centre (2020) for Cements used in Case Studies**

Cement Types in BS 8500 – Produced at Cement Factory	Secondary Main Constituent or Addition (Low-High Content %)	Embodied CO ₂ SMC Content Low -High kgCO ₂ /t	Difference in EF from Portland Cement EF - LOW	Difference in EF from Portland Cement EF – HIGH
CEM I Portland cement		860	0	
CEM II/A-LL or L Portland limestone cement	6-20 limestone	842-721	2.1%	16.2%

E.10.11 Cement BAU EF and ER EF from Other Sources with ER Figure Bold and Underlined

Material	BAU EF RSSB RCT (kgCO ₂ e/ kg)	ER EF (kgCO ₂ e/ kg)	Source	Region	Reference
Cement - CEM I - Portland Cement	0.912		Bath ICE 3.0 (2019)	UK	RSSB RCT
CEM I		<u>0.860</u>	Trade Body		The Concrete Centre (2020)
Cement - CEM II/A-L - Portland-Limestone - 13% Limestone	0.799		Bath ICE 3.0 (2019)	UK	RSSB RCT
CEM II/A-L		0.842-0.721	Trade Body		The Concrete Centre (2020)
Cement CEM II/A-M Portland Composite – 16% Cement Replacement		0.774	Bath ICE 3.0	Europe	RSSB RCT
Cement CEM II/A-M Portland Composite – 28% Cement Replacement		<u>0.666</u>	Bath ICE 3.0	Europe	RSSB RCT
Cement 80% GGBS CEM II/B		0.26	Bath ICE 2.0	UK	RSSB RCT

E.10.12 Emission Factor Review of Geotextiles Geogrid BAU EF and ER EF from Other Sources with ER Figure Bold and Underlined

Material	BAU EF RSSB RCT (kgCO ₂ e/ kg)	ER EF (kgCO ₂ e/ kg)	Source	Region	Reference
Polyethylene - General	2.54				RSSB RCT
Polypropylene (PP)	2				RSSB RCT
Geogrid Woven		<u>2.36</u>	Literature		(Raja <i>et al.</i> , 2015, p.398)
Geogrid Extruded		2.97	Literature		(Raja <i>et al.</i> , 2015, p.398)
Geogrids Nonwoven Average		2.35	Literature		(Raja <i>et al.</i> , 2015, p.398)

E.10.13 EF Review of Steel Percentage Contributions of Steel to BAU A1-3 Stage of Selected Case Studies

Material	Percentage Contribution of Material Embodied Carbon to BAU A1-3 LC	Case Study Name
Steel General and Sheet	99.08%	Aldercar
Steel General and Galvanised Sheet	97.73%	Station Plantation
Steel Wire	90.48%	Fields Bridge
Steel Wire and Stainless Steel	87.29%	Hammers Underbridge
Steel Sheet	85.12%	Wellington St
Steel Sheet	77.81%	Bowling Green
Steel Wire and Stainless Steel	71.60%	Higher Farm
Steel Wire	58.20%	Airbles
Steel Wire and Stainless Steel	45.77%	Killiecrankie
Steel Coil and Steel General	9.91%	Cove LX

Steel production inherently generates vast quantities of CO₂ owing to the large amounts of energy required in production. Making steel from scrap metal, via the use of an electric arc furnace (EAF), produces one third of carbon required to make the virgin steel from iron ore, via the blast furnace or Basic Oxygen Furnace (BOF) route (The Concrete Centre (2020). Steel has a (potential) 100% recovery rate (meaning that it can be practically re-used over and over again) (Wei and Chen, 2020). However, its re-use in the production of further steel is subject to constraints in collection and removal of contaminants. See Equation 2 and Equation 3 for recovery and recycling rates (Dovetail Partners, 2015, p.4):

Equation 2

$$\text{Recovery Rate (\%)} = \frac{\text{quantity of scrap recovered}}{\text{quantity of scrap available}} \times 100$$

Equation 3

$$\text{Recycling Rate (\%)} = \frac{\text{quantity of scrap reprocessed}}{\text{quantity of scrap available}} \times 100$$

Scrap steel is subclassified into home scrap (trimmings from the steel mill), new scrap (from steel manufacturing plants), and old scrap (steel discarded at EOL) (Dovetail Partners, 2015, p.4). These three diverse routes mean that is plenty of scope for collection of “scrap” steel and potential re-use. Figures for scrap availability for EU28 are found in EUROFER (2019, p.13) with this being comprised of predominantly obsolete scrap (from EOL products), then prompt scrap (production scrap) followed by home scrap (waste and errors) in total quantities for 2030, 2040 and 2050 of 122 Mt, 135 Mt and 147Mt respectively (EUROFER, 2019, p.13) and recycling rates of 90% given in (EUROFER, 2023, p.2).

NR undertake steel recycling at their rail recycling centre which typically has 40-50 wagon loads of scrap steel components delivered weekly (UIC, 2021). The NR recycling centre at Whitemoor

currently recycles track panels, sleepers, rails, small steel components and switches and crossing units (UIC, 2021, p.13) amounting to some 93,000 tonnes of scrap metal recycled nationally in 2016/17 (Network Rail, 2018d). NR needs to continue and expand this approach, given that integrating more recycled steel into the rails (and reinforced concrete structures) has the potential to make embodied carbon savings of between 20-35% (Marsden, Lokesh and Densley-Tingley, 2022, p.7). From the case studies no instances of scrap metals being sent to one of the three network rail recycling plants (Whitemoor, Crewe, or Westbury) could be found (Network Rail, 2018d). If it can be confirmed that at EOL any steel components would be sent into this circular process then the applicable circular EFs could be applied to these quantities of steel at removal from site. If left in situ, as has been assumed in several of the expansion scenarios, then there are no associated demolition and removal activities emissions or disposal of material emissions to account for. One factor that could be considered moving forward is an emissions penalty for not recycling materials left in situ. This penalty would account for the “opportunity cost” of not taking this action, because resources are finite in supply. Energy required for crude steel production has the potential to be reduced by 7.49% to 11.15% depending on the technology chosen (Gao *et al.*, 2020, p.8).

One potential route to focus decarbonisation efforts of steel on for NR is working with steel manufacturers who are looking to develop an electric arc furnace dedicated to produce rail components fed by NR scrap rail (Expedition, 2020, p.12). Use of EAF plus zero carbon electricity have the potential to reduce emissions from steel production to 0.1 tCO₂e per tonne of steel, compared to the current BOF route of 2.3 tCO₂e per tonne of steel (Expedition, 2020, p.7). To decarbonise the steel sector a number of novel approaches have been found, including the product as a service approach. This is where steel installed in railways remains the property of the steel manufacturers, thus encouraging them to provide the longest possible lifespan (UIC, 2021). Other approaches being potential vertical integration into British Steel to bring track supply in house, driving the decarbonisation agenda (Expedition, 2020, p.12). Quantifiable quantities of emissions reduction are not given against these novel approaches, however the emissions figures presented above give an indication of the potential reduction in emissions from engaging with the current lowest carbon emission route proposed (EAF + zero carbon electricity). These figures exclude the fabrication figures, noted in the literature as “relatively old,” and that updated data should be used where possible. EPDs for steel, which would be against specific fabrication methods, would enable more accurate calculation of the footprint of these items.

E.10.14 Steel BAU EF and ER EF from Other Sources with ER Figure Bold and Underlined

Material	BAU EF RSSB RCT (kgCO ₂ e/ kg)	ER EF (kgCO ₂ e/ kg)	Source	Region	Reference
Stainless Steel – General	6.52		Bath ICE (2.0)	Global	RSSB RCT
Stainless Steel – Global (inc Scope 1, 2, & 3)		6.82 using 30% scrap 3.28 using 50% scrap 2.42 using 75% scrap <u>2.08</u> using 85% scrap	Trade Body	Global	(Worldstainless, 2023, p.8)
Steel - Sheet - Galvanised - Virgin	3.01		Bath ICE (2.0)	UK	RSSB RCT
Steel - Coil - Galvanised - World Average Recycled Content	2.03		Bath ICE (2.0)	Global	RSSB RCT
Steel – Coil – Sheet – Galvanised Average Recycled Content		<u>1.54</u>	Bath ICE (2.0)	UK	RSSB RCT
Steel - Wire – Virgin	3.02		Bath ICE (2.0)	UK	RSSB RCT
Steel General Virgin	2.89		Bath ICE (2.)	UK	RSSB RCT
Steel General Recycled		<u>0.47</u>	Bath ICE (2.)	UK	RSSB RCT
Steel	4.01 (primary production)	1.56 (closed loop source)	GHG Conversion Factors 2023	UK	(HM Government, 2023c)
Steel	2.3 (BOF)	0.6 (EAF)	HM Report 2015	UK	(WSP Parsons Brinckerhoff, 2015)

No reduced emissions factor could be found in Bath ICE or the GHG conversion factors for stainless steel or steel wire. For stainless steel the trade body's factors using increasing amounts of recycled scrap were used and the lowest possible figure taken as the optimum one to use. For steel wire the factors from the RSSB tool for steel general recycled were used as no recycled factors for wire could be sourced. The virgin factor for steel general is also included to illustrate its relevance to steel wire virgin. For galvanised sheet and coil the Bath ICE average recycled content for the UK for coil and sheet galvanised was used.

E.10.15 Emission Factor Review of Timber: Wood BAU EF and ER EF from Other Sources with ER Figure Bold and Underlined

Material	BAU EF RSSB RCT (kgCO ₂ e/ kg)	ER EF (kgCO ₂ e/ kg)	Source	Region	Reference
Timber - Softwood - Exc. CS	0.263		Bath ICE 3.0	N. America	RSSB RCT
Timber – Softwood – Inc. CS		<u>-1.29</u>	Bath ICE 3.0	N. America	RSSB RCT
Primary production of wood		0.313	GHG Conversion factors 2023	UK	(HM Government, 2023c)
Closed loop wood		0.113	GHG Conversion factors 2023	UK	(HM Government, 2023c)
Reused wood		0.039	GHG Conversion factors 2023	UK	(HM Government, 2023c)

For the case studies timber softwood excluding carbon storage is utilised, for the ER EF a second figure is available in the RSSB RCT for wood including sequestration which gives a negative carbon figure. This will be utilised as it takes precedence over the figures found in the GHG conversion tables which are lower than the tool excluding carbon, but higher than the figure which includes carbon storage.

E.11 Summary Table of Materials' ER Emissions Factors

E.11.1 Table of Materials in Case Studies with BAU EF from RSSB RCT and ER EF Value from Cited Source with ER Figure Bold and Underlined

RSSB RCT Library Name (A-Z)	BAU Carbon Factor Value kgCO ₂ e/kg	ER Carbon Factor Value kgCO ₂ e/kg	% Emissions Reduction on BAU Value	Source of ER Value
Aggregates and Sand - Expanded Clay	0.39321	<u>0.06332</u>	83.90%	RSSB RCT Bath ICE 3.0
Bricks - General	0.213	<u>0.1309</u>	38.54%	EPD from (Almeida <i>et al.</i> , 2010); Marshalls Bricks & Masonry (2021)
Cement - CEM I - Portland Cement	0.912	<u>0.860</u>	5.70%	The Concrete Centre (2020)

RSSB RCT Library Name (A-Z)	BAU Carbon Factor Value kgCO ₂ e/kg	ER Carbon Factor Value kgCO ₂ e/kg	% Emissions Reduction on BAU Value	Source of ER Value
Cement - CEM II/A-L - Portland-Limestone - 13% Limestone	0.799	<u>0.666</u>	16.65%	RSSB RCT Bath ICE 3.0
Concrete - RC40/50 - C40/50 MPa - Cement Replacement - 0%	0.169	<u>0.072</u>	57.40%	RSSB RCT Bath ICE 3.0
Concrete - Reinforced - modification factors	0.077	0.077	0%	RSSB RCT Bath ICE 2.0
Concrete - Precast (prefabricated) concrete - modification factors	0.029	0.029	0%	RSSB RCT Bath ICE 2.0
Granite	0.7	<u>0.0030</u>	99.57%	Trade Body (MPA, 2022)
Limestone - General	0.09	<u>0.034</u>	62.22%	RSSB RCT Bath ICE 2.0
Paint - General	2.91	<u>2.54</u>	12.71%	RSSB RCT Bath ICE 2.0
Geogrid (Terram) PE 30% of 2.54 PP 70% of 2	0.762+1.4=2.162	2.97(extruded geogrids) <u>2.36</u> (woven geogrid)	-9.16%	Raja <i>et al.</i> (2015)
Sand - General	0.0051	<u>0.0027</u>	47.06%	MPA (2022)
Stainless Steel – General	6.52	<u>2.08</u>	68.10%	(Worldstainless, 2023, p.8)
Slate - General – Mid	0.035	<u>0.007</u>	80.00%	RSSB RCT Bath ICE 2.0
Steel - Coil - Galvanised - World Average Recycled Content	2.03	<u>1.54</u>	24.14%	RSSB RCT Bath ICE 2.0
Steel - Sheet - Galvanised – Virgin	3.01	<u>1.54</u>	48.84%	RSSB RCT Bath ICE 2.0
Steel - Wire – Virgin	3.02	<u>0.47</u>	84.44%	RSSB RCT Bath ICE 2.0
Stone - Gravel/Chippings	0.017	<u>0.0027</u>	84.12%	(MPA, 2022)

RSSB RCT Library Name (A-Z)	BAU Carbon Factor Value kgCO ₂ e/kg	ER Carbon Factor Value kgCO ₂ e/kg	% Emissions Reduction on BAU Value	Source of ER Value
Timber - Softwood - Exc. CS	0.263	<u>-1.29</u>	590.49%	RSSB RCT Bath ICE 3.0

E.12 ER Actions Applied to Each Case Study by Stage A1-3, A4 and A5

Case Study Name	A1-3 ER	A4 ER	A5 ER
Airbles Station	None suitable for reduction of emissions from PP etc.	Vans and/or cars changed to battery EVs.	Waste soil used in situ for landscaping (still has a land use change emissions factor) see above section on LULUC. Using 1015 WCC carbon calculation spreadsheet. Peli lights are battery powered.
ALC1 Kenelm Road Cutting	No materials to reduce emissions from.	Vans and/or cars changed to battery EVs.	Petrol brush cutters and strimmer's changed to battery powered.
Aldercar - cess	Steel and galvanised steel changed to recycled versions.	Vans and/or cars changed to battery EV HGV EF changed to biodiesel reduced figure.	NRMMs recalculated using biofuel factors.
Appley Locks	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors.
Aughton Park Station	Steel and galvanised steel changed to recycled versions.	Vans and/or cars changed to battery EV. HGV EF changed to biodiesel reduced figure.	NRMMs recalculated using biofuel factors.
Bathpool Reservoir	No materials to reduce emissions from.	Vans and/or cars changed to battery EV. Freight van changed to biodiesel reduced figure.	Petrol hand-held tools recalculated using biofuel factors.
Bowling Green	Galvanised steel hanged to recycled version. Postmix changed to lower carbon cement. Terram EF used for geogrid. Lower EF stone and gravel used.	Vans and/or cars changed to battery EV. HGV EF changed to biodiesel reduced figure.	NRMMs recalculated using biofuel factors.

Case Study Name	A1-3 ER	A4 ER	A5 ER
Braystones	Concrete changed to lower carbon concrete. Lower EF stone used.	Vans and/or cars changed to battery EV. HGV EF changed to biodiesel reduced figure.	NRMMs recalculated using biofuel factors.
Capelrig Road	No materials to reduce emissions from.	Vans and/or cars changed to battery EV. HGV EF changed to biodiesel reduced figure.	NRMMs recalculated using biofuel factors.
CDM2 Badger Environmental Management - Survey	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	No plant or NRMMs to reduce emissions from.
Claydon Embankment	PP left at BAU value. Sand changed to MPA value.	Vans and/or cars changed to battery EV. Freight van changed to biofuel reduced figure.	Petrol hand-held tools recalculated using biofuel factors.
Courteenhall	Lower EF aggregates used to replace Bentonite.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Cove LX	Coir matting left at BAU value. Steel and galvanised steel changed to recycled EF. Wood changed to softwood including carbon sequestration. Aggregate changed to lower EF value and lower carbon cement value used for postcrete.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Dalton Junction Overhang	Lower EF Limestone used.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
DCL Fenny Compton – Survey	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	No plant or NRMMs to reduce emissions from.
Delmore	No materials to reduce emissions from.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Dimbols farm foot crossing	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors. Diesel plant recalculated using biofuel factors.

Case Study Name	A1-3 ER	A4 ER	A5 ER
Doveholes Dale	Terram EF used for geogrid. Lower EF stone and sand used.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Fearn Station	Terram EF used for geogrid. Lower EF bricks used. GRP same as BAU. Lower EF sand and stone and lower carbon cement used.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
FHR6 Jumps Lane DOWN	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors.
Fields Bridge	Steel changed to recycled EF.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	Petrol hand-held tools recalculated using biofuel factors. NRMMs recalculated using biofuel factors.
Hammers Underbridge - Burrowing -	Steel changed to recycled EF. Stainless steel changed to lower EF. Lower carbon cement used.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Hattersley No. 2	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors.
Hayfield Rock	No materials to reduce emissions from.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Heron Close - Badger Mitigation	No materials to reduce emissions from.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Higher Farm	Steel changed to recycled EF. Stainless steel changed to lower EF.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Ipswich southern tunnel portal	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors.
Killiecrankie	Steel changed to recycled EF. Stainless steel changed to lower EF. Lower ER stone used. PP remains as BAU. Lower carbon cement chosen.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.

Case Study Name	A1-3 ER	A4 ER	A5 ER
Kindallachan	Lower carbon slate.	Vans and/or cars changed to battery EV. Freight van changed to biofuel reduced figure	No plant or NRMMs to reduce emissions from.
Kirkham Tip	Lower carbon cement value used for postcrete.	Vans and/or cars changed to battery EV.	No plant or NRMMs to reduce emissions from.
Lazonby	No materials to reduce emissions from.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Lime Chalk Embankment	Lower carbon paint used.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors.
Maybole	Lower carbon cement value used for postcrete.	Vans and/or cars changed to battery EV. Tractor EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors. Petrol hand-held tools recalculated using biofuel factors.
Mossley Cutting	No materials to reduce emissions from.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Mossley Tree Removal	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors.
Mouldsworth to Little Barrow- Badger Mitigation	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	No plant or NRMMs to reduce emissions from.
NAJ2 South Ruislip	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	No plant or NRMMs to reduce emissions from.
Old Hill	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors.
OWW Evaluations	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	No plant or NRMMs to reduce emissions from.
Parton	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	No plant or NRMMs to reduce emissions from.
Penvellyn - Scour -	Lower EF rock used.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Postwick interchange	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors.
Ravens Rock	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors.

Case Study Name	A1-3 ER	A4 ER	A5 ER
Scufton House	No materials to reduce emissions from.	Vans and/or cars changed to battery EV.	Petrol hand-held tools recalculated using biofuel factors. Battery hand-held equipment remains same as BAU.
Station Plantation - cess	Steel and galvanised steel changed to recycled EF.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Stonebridge	Lower carbon cement value used for grout.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	Petrol hand-held tools recalculated using biofuel factors.
Stromferry East	No materials to reduce emissions from.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors. Petrol hand-held tools recalculated using biofuel factors.
Tom Bank	No materials to reduce emissions from.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.
Wellington Street	Galvanised steel changed to recycled EF. Lower EF brick used. Lower carbon cement used for postcrete and mortar.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	Petrol hand-held tools recalculated using biofuel factors. C&D waste EF remains same as BAU.
WHL	No materials to reduce emissions from.	Vans and/or cars changed to battery EV. HGV EF changed to biofuel reduced figure.	NRMMs recalculated using biofuel factors.

E.13 ER New A1-5 Totals for all 50 Case Studies

Case Study Name	ER Value (kgCO ₂ e)	RP % from BAU	ER Functional Unit (kgCO ₂ e/per vol/per year)
Airbles Station	27	67	13.5
ALC1 Kenelm Road Cutting	116	71	5.8
Aldercar - cess	123,699	70	343.6
Appley Locks	39	71	9.8
Aughton Park Station	916	72	20.8
Bathpool Reservoir	176	72	14.7
Bowling Green	6,370	59	53.1
Braystones	716	67	35.8
Capelrig Road	202	72	101

Case Study Name	ER Value (kgCO ₂ e)	RP % from BAU	ER Functional Unit (kgCO ₂ e/per vol/per year)
CDM2 Badger Environmental Management - Survey	70	69	35
Claydon Embankment	110	69	5.5
Courteenhall	619	77	309.5
Cove LX	881	65	7.3
Dalton Junction Overhang	1,283	70	641.5
DCL Fenny Compton – Survey	18	68	9
Delmore	556	74	278
Dimbols farm foot crossing	746	75	124.3
Doveholes Dale	4,493	63	748.8
Fearn Station	2,913	82	728.3
FHR6 Jumps Lane DOWN	42	70	21
Fields Bridge	2,963	74	148.2
Hammers Underbridge - Burrowing -	12,245	73	153.1
Hattersley No. 2	218	72	27.3
Hayfield Rock	645	72	322.5
Heron Close - Badger Mitigation	562	72	140.5
Higher Farm	6,363	74	318.2
Ipswich southern tunnel portal	21	68	10.5
Killiecrankie	8,435	63	70.3
Kindallachan	85	71	42.5
Kirkham Tip	301	27	75.3
Lazonby	905	73	45.3
Lime Chalk Embankment	34	61	17
Maybole	308	56	77
Mossley Cutting	189	72	94.5
Mossley Tree Removal	55	71	27.5
Mouldsworth to Little Barrow- Badger Mitigation	248	69	124
NAJ2 South Ruislip	27	69	13.5
Old Hill	20	74	10
OWW Evaluations	4.8	69	2.4
Parton	72	69	36
Penvellyn - Scour -	5,500	94	137.5
Postwick interchange	125	74	10.4
Ravens Rock	175	71	43.8
Scufton House	175	70	21.9

Case Study Name	ER Value (kgCO ₂ e)	RP % from BAU	ER Functional Unit (kgCO ₂ e/per vol/per year)
Station Plantation - cess	11,406	68	95.1
Stonebridge	1,298	23	649
Stromferry East	1,086	73	181
Tom Bank	1,974	72	493.5
Wellington Street	1,345	53	672.5
WHL	2,105	76	105.3

E.14 ER Scenario Renewal Type Interventions: A0 Stages' Estimated Carbon Allocation Methodology and Calculations

Pre Site Stage	Pre Site Sub Stage	Methodology	Estimated Carbon allocation	Estimated ER Scenario Carbon Allocation
Desk Study Stage	Including photos, geological survey data	Office and homeworking carbon values (Circular Ecology, 2023)	33.02 kgCO ₂ e/ week	66-100 kgCO ₂ e
	Potentially several meetings with consultants/contractors	Location of meetings unknown assumed office based and distance for average travel distance to site used as proxy. Van BEV carbon = 0.07951 kgCO ₂ e per vkm as per RSSB RCT	Mileage for 4 vans travelling average 109km per day. This is average daily staff transport figure from all 50 case studies. For 2 and 3 days.	69-104 kgCO ₂ e
	Walk over survey up to 5 differing groups – asset engineer, contractors, designers, ecologists)	Travel distance based on average daily distance from the 5 renewal case studies. Van BEV carbon = 0.07951 kgCO ₂ e per vkm as per RSSB RCT	Mileage for 5 vans travelling average 109km per day.	43 kgCO ₂ e

Pre Site Stage	Pre Site Sub Stage	Methodology	Estimated Carbon allocation	Estimated ER Scenario Carbon Allocation
Ground Investigation	Potentially further secondary ecological survey	Use average travel distance figure from all survey type case studies (all of 1 volume size): CDM2 Badger Mitigation (70 kgCO ₂ e 1 shift), Courteenhall borehole sampling (619 kgCO ₂ e 3 shifts), DCL Fenny Compton ecological survey (18 kgCO ₂ e 1 shift) and OWW evaluation surveys (4.8 kgCO ₂ e 1 shift).	Based on average per day carbon value for the four survey type activities =119 kgCO ₂ e per shift	1,190 – 1,785 kgCO ₂ e
	Sample transport to laboratories	Assumed included in above travel distances	Assumed included in above	Assumed included in above
Ground Interpretation	Return monthly for at least 3 months to read instrumentation	Use average travel distance figure from all survey type case studies of 109km x 3 visits x van carbon figure above	x 3 visits x van carbon figure above	26 kgCO ₂ e
Design	Detailed scheme design	Office and homeworking carbon values (Circular Ecology, 2023)	33.02 kgCO ₂ e/ week	66-100 kgCO ₂ e
Totals ER Scenario				1,460 – 2,158 kgCO ₂ e

E.15 Descriptive Statistics for ER Scenarios Split by Temporal Intervention Type

Maintenance descriptive stats for FU ER		Refurbishment descriptive stats for FU ER		Renewal descriptive stats for FU ER		All 50 descriptive stats for FU ER	
Column1		Column1		Column1		Column1	
Mean	175.0602381	Mean	97.52806818	Mean	113.875	Mean	151.7503
Standard Error	40.46089248	Standard Error	30.78402089	Standard Error	59.19302	Standard Error	29.06041
Median	43.75	Median	75.25	Median	70.29167	Median	61.6875
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	239.369868	Standard Deviation	97.34762154	Standard Deviation	132.3596	Standard Deviation	205.4881
Sample Variance	57297.9337	Sample Variance	9476.559419	Sample Variance	17519.07	Sample Variance	42225.38
Kurtosis	0.812039218	Kurtosis	1.947751964	Kurtosis	3.9399	Kurtosis	2.025204
Skewness	1.494735553	Skewness	1.313310543	Skewness	1.904981	Skewness	1.757104
Range	746.4333333	Range	312.65	Range	336.2667	Range	746.4333
Minimum	2.4	Minimum	5.5	Minimum	7.341667	Minimum	2.4
Maximum	748.8333333	Maximum	318.15	Maximum	343.6083	Maximum	748.8333
Sum	6127.108333	Sum	975.2806818	Sum	569.375	Sum	7587.514
Count	35	Count	10	Count	5	Count	50
Largest(1)	748.8333333	Largest(1)	318.15	Largest(1)	343.6083	Largest(1)	748.8333
Smallest(1)	2.4	Smallest(1)	5.5	Smallest(1)	7.341667	Smallest(1)	2.4
Confidence Level(95.0%)	82.22642658	Confidence Level(95.0%)	69.63829335	Confidence Level(95.0%)	164.3462	Confidence Level(95.0%)	58.39908

E.16 Descriptive Statistics for ER Scenarios Split by Temporal

Intervention Type & Earthwork Type for Carbon Amounts

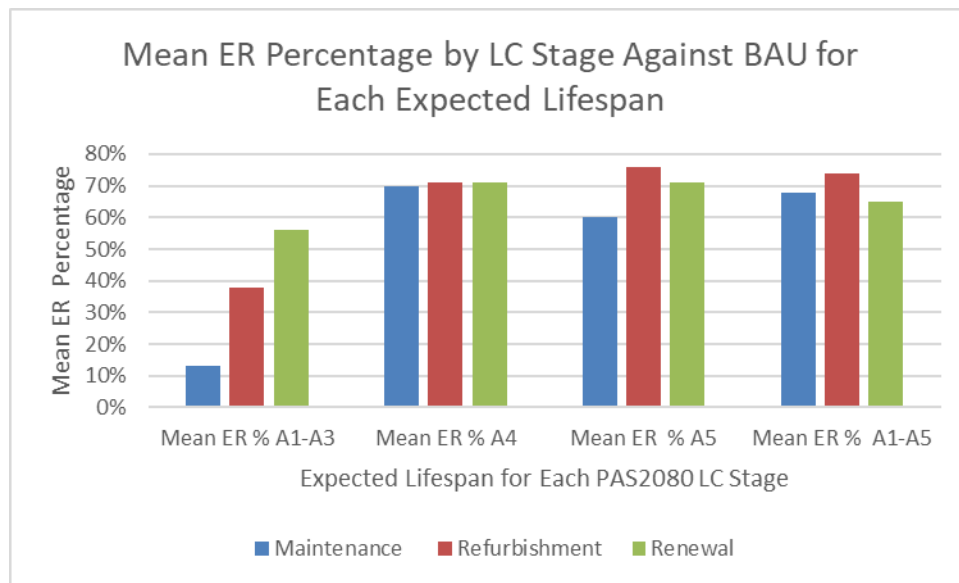
Maintenance: Embankment			Maintenance: Rock Cutting			Maintenance : Soil Cutting	
Column1			Column1			Column1	
Mean	65.08512		Mean	70.30776		Mean	68.17815
Standard Error	3.720936		Standard Error	0.699472		Standard Error	3.614683
Median	69.91553		Median	70.67445		Median	71.39142
Mode	#N/A		Mode	#N/A		Mode	#N/A
Standard Deviation	13.92247		Standard Deviation	1.978406		Standard Deviation	13.03292
Sample Variance	193.8351		Sample Variance	3.91409		Sample Variance	169.8571
Kurtosis	6.382673		Kurtosis	-0.24677		Kurtosis	9.870234
Skewness	-2.37268		Skewness	-0.75227		Skewness	-2.94225
Range	53.54823		Range	5.678587		Range	54.89879
Minimum	23.23463		Minimum	66.73112		Minimum	27.10121
Maximum	76.78286		Maximum	72.4097		Maximum	82
Sum	911.1917		Sum	562.462		Sum	886.3159
Count	14		Count	8		Count	13
Largest(1)	76.78286		Largest(1)	72.4097		Largest(1)	82
Smallest(1)	23.23463		Smallest(1)	66.73112		Smallest(1)	27.10121
Confidence Level(95.0%)	8.038594		Confidence Level(95.0%)	1.653989		Confidence Level(95.0%)	7.875717
Refurbishment: Embankment			Refurbishment: Rock Cutting			Refurbishment: Soil Cutting	
Column1			Column1			Column1	
Mean	78.76684		Mean	73.59921		Mean	71.4656
Standard Error	7.821133		Standard Error	1.462679		Standard Error	1.577028
Median	72.80062		Median	72.7304		Median	72.36819
Mode	#N/A		Mode	#N/A		Mode	#N/A
Standard Deviation	13.5466		Standard Deviation	2.533435		Standard Deviation	3.154056
Sample Variance	183.5104		Sample Variance	6.418291		Sample Variance	9.948071
Kurtosis	#DIV/0!		Kurtosis	#DIV/0!		Kurtosis	-0.45353
Skewness	1.597467		Skewness	1.361725		Skewness	-1.01646
Range	25.04504		Range	4.838252		Range	6.652308
Minimum	69.22743		Minimum	71.61449		Minimum	67.23686
Maximum	94.27247		Maximum	76.45274		Maximum	73.88917
Sum	236.3005		Sum	220.7976		Sum	285.8624
Count	3		Count	3		Count	4
Largest(1)	94.27247		Largest(1)	76.45274		Largest(1)	73.88917
Smallest(1)	69.22743		Smallest(1)	71.61449		Smallest(1)	67.23686
Confidence Level(95.0%)	33.65162		Confidence Level(95.0%)	6.2934		Confidence Level(95.0%)	5.018807
Renewal: Embankment			Renewal: Rock Cutting			Renewal: Soil Cutting	
Column1			Not Applicable - No Data			Column1	
Mean	67.51522					Mean	60.76183
Standard Error	1.30714					Standard Error	2.18387
Median	67.93293					Median	60.76183
Mode	#N/A					Mode	#N/A
Standard Deviation	2.264033					Standard Deviation	3.088458
Sample Variance	5.125847					Sample Variance	9.538575
Kurtosis	#DIV/0!					Kurtosis	#DIV/0!
Skewness	-0.80198					Skewness	#DIV/0!
Range	4.469894					Range	4.36774
Minimum	65.07142					Minimum	58.57796
Maximum	69.54131					Maximum	62.9457
Sum	202.5457					Sum	121.5237
Count	3					Count	2
Largest(1)	69.54131					Largest(1)	62.9457
Smallest(1)	65.07142					Smallest(1)	58.57796
Confidence Level(95.0%)	5.624171					Confidence Level(95.0%)	27.7487

E.17 Descriptive Statistics for ER Scenarios Percentage Reduction on BAU Split by Temporal Intervention Type & Earthwork Type

Maint: A1-A3 ER % Red on BAU		Maint: A4 ER % Red on BAU		Maint: A5 ER % Red on BAU	
Column1		Column1		Column1	
Mean	13.2627361	Mean	69.89008412	Mean	60.13588701
Standard Error	4.47897528	Standard Error	0.309421044	Standard Error	5.669695581
Median	0	Median	69.06327303	Median	74.53059894
Mode	0	Mode	#N/A	Mode	0
Standard Deviation	26.4979751	Standard Deviation	1.830559581	Standard Deviation	33.5423714
Sample Variance	702.142683	Sample Variance	3.35094838	Sample Variance	1125.090679
Kurtosis	1.60731537	Kurtosis	-0.757287394	Kurtosis	-0.242295526
Skewness	1.7751099	Skewness	0.853661373	Skewness	-1.270527721
Range	84.7857271	Range	6.012446347	Range	100
Minimum	0	Minimum	67.74046126	Minimum	0
Maximum	84.7857271	Maximum	73.7529076	Maximum	100
Sum	464.195763	Sum	2446.152944	Sum	2104.756045
Count	35	Count	35	Count	35
Largest(1)	84.7857271	Largest(1)	73.7529076	Largest(1)	100
Smallest(1)	0	Smallest(1)	67.74046126	Smallest(1)	0
Confidence Level(95.0%)	9.10237291	Confidence Level(95.0%)	0.628819217	Confidence Level(95.0%)	11.52220771
Refurb: A1-A3 ER % Red on BAU		Refurb: A4 ER % Red on BAU		Refurb: A5 ER % Red on BAU	
Column1		Column1		Column1	
Mean	37.7989029	Mean	71.26468723	Mean	75.7694559
Standard Error	12.4738987	Standard Error	0.765816764	Standard Error	0.986927682
Median	34.6899625	Median	70.67259443	Median	74.02633105
Mode	0	Mode	#N/A	Mode	#N/A
Standard Deviation	39.4459312	Standard Deviation	2.421725245	Standard Deviation	3.120939362
Sample Variance	1555.98149	Sample Variance	5.864753161	Sample Variance	9.740262499
Kurtosis	-1.8669123	Kurtosis	2.23697653	Kurtosis	-1.142577059
Skewness	0.26603671	Skewness	1.458867207	Skewness	1.005415072
Range	99.4203637	Range	7.80490556	Range	7.844659897
Minimum	0	Minimum	69.02030536	Minimum	72.92457087
Maximum	99.4203637	Maximum	76.82521091	Maximum	80.76923077
Sum	377.989029	Sum	712.6468723	Sum	757.694559
Count	10	Count	10	Count	10
Largest(1)	99.4203637	Largest(1)	76.82521091	Largest(1)	80.76923077
Smallest(1)	0	Smallest(1)	69.02030536	Smallest(1)	72.92457087
Confidence Level(95.0%)	28.2179193	Confidence Level(95.0%)	1.732397878	Confidence Level(95.0%)	2.232585525
Renew: A1-A3 ER % Red on BAU		Renew: A4 ER % Red on BAU		Renew: A5 ER % Red on BAU	
Column1		Column1		Column1	
Mean	56.4819934	Mean	71.27021486	Mean	71.20582887
Standard Error	4.40434111	Standard Error	0.695127581	Standard Error	2.784162958
Median	61.3258272	Median	70.65455601	Median	73.99506966
Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	9.84840611	Standard Deviation	1.554352524	Standard Deviation	6.225577635
Sample Variance	96.9911029	Sample Variance	2.416011769	Sample Variance	38.75781689
Kurtosis	-3.143473	Kurtosis	3.751358951	Kurtosis	4.999946522
Skewness	-0.5372273	Skewness	1.918336469	Skewness	-2.236053051
Range	19.928976	Range	3.701504304	Range	13.92795165
Minimum	45.0043578	Minimum	70.26289404	Minimum	60.06919191
Maximum	64.9333338	Maximum	73.96439834	Maximum	73.99714357
Sum	282.409967	Sum	356.3510743	Sum	356.0291443
Count	5	Count	5	Count	5
Largest(1)	64.9333338	Largest(1)	73.96439834	Largest(1)	73.99714357
Smallest(1)	45.0043578	Smallest(1)	70.26289404	Smallest(1)	60.06919191
Confidence Level(95.0%)	12.2284113	Confidence Level(95.0%)	1.92998357	Confidence Level(95.0%)	7.730075617

E.18 Summary Table & Graph of Descriptive Statistics for ER Scenarios Split by Temporal Intervention Type & Earthwork Type for Percentage Reduction on BAU

	Mean ER % A1-A3	Mean ER % A4	Mean ER % A5	Mean ER % A1-A5
Maintenance	13%	70%	60%	68%
Refurbishment	38%	71%	76%	74%
Renewal	56%	71%	71%	65%



E.19 Descriptive Statistics for ER & BAU Scenarios Split by Temporal Intervention Type

Descriptive Statistic Type for Functional Unit	50 Case Studies	35 Maintenance Interventions	15 Refurbishment Interventions	5 Renewal Interventions
Mean BAU	551	577	558	353
Mean ER	152	175	98	114
Largest BAU	4105	4105	2400	1128
Largest ER	749	749	318	344
Smallest BAU	8	8	18	21
Smallest ER	2	2	6	7

E.20 Descriptive Statistics for ER Scenarios Split by Temporal Intervention Type for Carbon Amounts

Descriptive stats maint kgCO ₂ in ER scenario		Descriptive stats refurb kgCO ₂ in ER scenario		Descriptive stats renew kgCO ₂ in ER scenario	
Column1		Column1		Column1	
Mean	575.7657143	Mean	3193.9	Mean	30158.2
Standard Error	158.16901	Standard Error	1220.539539	Standard Error	23448.3012
Median	189	Median	1510.5	Median	8435
Mode	175	Mode	#N/A	Mode	#N/A
Standard Deviation	935.7404825	Standard Deviation	3859.684917	Standard Deviation	52431.99545
Sample Variance	875610.2506	Sample Variance	14897167.66	Sample Variance	2749114147
Kurtosis	9.136259623	Kurtosis	2.657119731	Kurtosis	4.89453675
Skewness	2.832722016	Skewness	1.65889532	Skewness	2.205787161
Range	4488.2	Range	12135	Range	122818
Minimum	4.8	Minimum	110	Minimum	881
Maximum	4493	Maximum	12245	Maximum	123699
Sum	20151.8	Sum	31939	Sum	150791
Count	35	Count	10	Count	5
Largest(1)	4493	Largest(1)	12245	Largest(1)	123699
Smallest(1)	4.8	Smallest(1)	110	Smallest(1)	881
Confidence Level(95.0%)	321.4381022	Confidence Level(95.0%)	2761.05226	Confidence Level(95.0%)	65102.9211

E.21 Average Functional Unit for Maintenance Interventions ER Scenarios for B Stages of ER EXP

E.21.1 Embankment Vegetation Intervention

Maintenance Embankment Case Study Name	ER A1-A5 kgCO ₂ e	Volumes	Life Span (years)	Functional Unit ER kg CO ₂ e per Volume/Per Year
Appley Locks	39	1	2	19.50
Bathpool Reservoir	176	6	2	14.67
Courteenhall	619	1	2	309.50
Dimbols farm foot crossing	746	3	2	124.33
Lime Chalk Embankment	34	1	2	17.00
NAJ2 South Ruislip	27	1	2	13.50
Old Hill	20	1	2	10.00
Stonebridge	1298	1	2	649.00
Average				144.69

E.21.2 Soil Cutting Vegetation Intervention

In calculating the maintenance stage for the soil cutting renewals, Bowling Green and Killicrankie, four maintenance case studies were identified as being maintenance de vegetation as such their average functional unit was used to calculate the B LC stages for the expansion scenario.

Soil Cutting Case Study Name	ER A1-A5 kgCO ₂ e	Volumes	Life Span (years)	Functional Unit ER kg CO ₂ e per Volume/Per Year
Dalton Junction Overhang	1,283	1	2	641.5
Hattersley No. 2	218	4	2	27.25
Postwick interchange	125	6	2	10.42
Ipswich southern tunnel portal	21	1	2	10.5
Average				172.42

E.21.3 Scour Refurbishment Intervention

In calculating the B maintenance LC stage for the scour protection renewal, Cove LX, only one case study pertained to scour maintenance, Claydon, as such the functional unit for this maintenance intervention was used to calculate the B LC stages.

Soil Cutting Case Study Name	ER A1-A5 kgCO ₂ e	Volumes	Life Span (years)	Functional Unit ER kg CO ₂ e per Volume/Per Year
Claydon Embankment	110	1	20	5.5

E.22 Aldercar & Station Plantation Recalculation C1-4 Based on ER Scenario

Aldercar				BAU	ER EF	ER
C1	end of life deconstruction	plant and equipment transport	colmar t10000	qty kg each kg total sub total		qty kg each kg total sub total
			jcb telescopic	3 2141 6423		3 557 1671
			14 t & 9t excava	1 43 43		1 11 11
				1 1589 1589 8055		1 413 413 2095
		worker travel to from	transit type van	66864.4 0.26 17384.74	0.07951	66864.4 5316.388 5316.388
			car travel	9888 0.23 2274.24 19658.98	0.07469	9888 738.5347 738.5347 6054.923
		fossil fue use for plant and kit	colmar	1200 119 142800	ER reduced vlaues from case stu	36972
			jcb	700 58 40600		10468.64
			14t	50 58 2900		747.76
			9t	50 41 2050		534.04 48722.44
		Proportional emobided carbon	colmar for all 3	1 1018 1018		1 1018 1018
			jcb telescopic	1 197 197		1 197 197
			14t	1 319 319		1 319 319
			9t	1 205 205 1739		1 205 205 1739
C2	end of life transportation of deconstructed materials			t km		
			h piles	1 2246 105.631 187.2		
			armco barrier	1 104 6.16 148.6		
			keeklampt spars	1 387 8.212 414.4		712 for all from calcs for ER HGV 712
C4	END of Lifedisposal of deconstructed materials			t kg		
	closed loop recycling 1.0192kg per tonne		metals - steel	112.6 112581.9	closed loop recycling factor same as used for BAU	
	closed loop recycling 1.0192kg per tonne		metals - galvanised steel	7.4 7421.14	1.0192kgco2/tonne	122.304
				220660		
						59445.67 / C life cycle stages

Appendix E

Station Plantation			BAU				ER EF	ER				
C1	end of life deconstruction	plant and equipment transport	colmar t10000	qty	kg each	kg total	sub total		qty	kg each	kg total	sub total
			colmar t10001	1		1226			1	557	557	
			small generator	1		138	3325		1	11	11	
									1	413	413	981
		worker travel to from	transit type van	14771	0.26	3789		0.07951	14771	1174.442	1174.442	
			car travel	1486.8	0.23	337	4126	0.07469	1486.8	111.0491	111.0491	1285.491
		fossil fue use for plant and kit	colmar	48	119	5712						
			jcb	15	58	870		ER reduced	viaues from case stu	1478.88		
			small generator	216	4.3	928.8	7510.8				224.328	
										239.5786	1942.787	
		Proportional emobided carbon	colmar t10000	1	202	202			1	202	202	
			colmar t10001	1	202	202			1	202	202	
			telescopic handler	1	56	56			1	56	56	
			small generator	1	4.7	4.7	464.7		1	4.7	4.7	464.7
C2	end of life transportation of deconstructed materials						t	km				
			h piles	1		103	10.95	83				
			armco barrier	1		20	1.4	123				
			keeklampt spans	1		31	0.69897	387.2	40 for all from calcs for ER HGVs			40
C4	END of Lifedisposal of deconstructed materials					t	kg		closed loop recycling factor same as used for BAU			
	closed loop recycling 1.0192kg per tonne	metals - steel			12.4		12417.62		1.0192kgco2/tonne			
	closed loop recycling 1.0192kg per tonne	metals - galvanised steel			6.3		631.35		1.0192			19.05904
												4733.037 / C life cycle stages

E.23 Expansion of 5 Renewals ER to Include A0 Stage

Renewal Case Study Name	A0	A1-A5	B	C1-4
Aldercar	Based on the higher limit for A0 ER scenario as per Appendix E.14 multiplied by 3 volumes.	Values taken from ER scenarios	Re-calculated using ER values for maintenance studies. See Appendix E.21.	Re-calculated using ER scenario figures. See Appendix E.22.
Bowling Green	Based on the higher limit for A0 ER scenario as per Appendix E.14, for one volume.	Values taken from ER scenarios	Re-calculated using ER values for SC. See Appendix E.21.	N/A
Cove LX	Based on the higher limit for A0 ER scenario as per Appendix E.14, for one volume.	Values taken from ER scenarios	Use Claydon Embankment ER scenario functional unit here multiplied by 120 years	N/A
Killiecrankie	Based on the higher limit for A0 ER scenario as per Appendix E.14, for one volume.	Values taken from ER scenarios	Re-calculated using ER values for SC. See Appendix E.21.	N/A
Station Plantation	Based on the higher limit for A0 ER scenario as per Appendix E.14, for one volume.	Values taken from ER scenarios	Re-calculated using ER values for maintenance studies. See Appendix E.21.	Re-calculated using ER scenario figures. See Appendix E.22.

E.24 ER new EXP Scenario (A0-C4) Totals for 5 Renewals kgCO₂e per LC**Stage**

Renewal Case Study Name	A0	A1-A5	B	C1-4	A0-C4 total
Aldercar	6,474.00	123,699.00	52,088.40	59,445.67	241,707.07
Bowling Green	2,158.00	6,370.00	20,690.40	-	29,218.40
Cove LX	2,158.00	881.00	660.00	-	3,699.00
Killiecrankie	2,158.00	8,435.00	20,690.40	-	31,283.40
Station Plantation	2,158.00	11,406.00	17,362.80	4,733.04	35,659.84

Figures in above as per explanation given in Appendix E.23.

E.25 ER EXP Scenario Totals for Renewals Percentage Contribution per**Stage**

Renewal Case Study Name	A0	A1-A5	B	C1-4	A0-C4 total
Aldercar	2.7%	51.2%	21.6%	24.6%	100.0%
Bowling Green	7.4%	21.8%	70.8%	0.0%	100.0%
Cove LX	58.3%	23.8%	17.8%	0.0%	100.0%
Killiecrankie	6.9%	27.0%	66.1%	0.0%	100.0%
Station Plantation	6.1%	32.0%	48.7%	13.3%	100.0%

E.26 Data Used for BAU to ER EXP Comparison

ER					
Data for graphs ER					
	kgCO ₂ e per LC Stage				
Renewal Case Study Name	A0	A1-A5	B	C1-4	A0-C4 total
Aldercar	6,474.00	123,699.00	52,088.40	59,445.67	241,707.07
Bowling Green	2,158.00	6,370.00	20,690.40	-	29,218.40
Cove LX	2,158.00	881.00	660.00	-	3,699.00
Killiecrankie	2,158.00	8,435.00	20,690.40	-	31,283.40
Station Plantation	2,158.00	11,406.00	17,362.80	4,733.04	35,659.84
	Percentage Contribution				
Renewal Case Study Name	A0	A1-A5	B	C1-4	A0-C4 total
Aldercar	2.7%	51.2%	21.6%	24.6%	100.0%
Bowling Green	7.4%	21.8%	70.8%	0.0%	100.0%
Cove LX	58.3%	23.8%	17.8%	0.0%	100.0%
Killiecrankie	6.9%	27.0%	66.1%	0.0%	100.0%
Station Plantation	6.1%	32.0%	48.7%	13.3%	100.0%

BAU					
Data for graphs BAU					
	kgCO ₂ e per LC Stage				
Renewal Case Study Name	A0	A1-A5	B	C1-4	A0-C4 total
Aldercar	18,189.00	406,121.00	129,736.80	219,441.00	773,487.80
Bowling Green	6,063.00	15,378.00	70,244.00	-	91,685.00
Cove LX	6,063.00	2,522.00	2,137.20	-	10,722.20
Killiecrankie	6,063.00	22,761.00	70,244.00	-	99,068.00
Station Plantation	6,063.00	35,572.00	43,245.60	15,556.00	100,436.60
	Percentage Contribution				
Renewal Case Study Name	A0	A1-A5	B	C1-4	A0-C4 total
Aldercar	2.4%	52.5%	16.8%	28.4%	100.0%
Bowling Green	6.6%	16.8%	76.6%	0.0%	100.0%
Cove LX	56.5%	23.5%	19.9%	0.0%	100.0%
Killiecrankie	6.1%	23.0%	70.9%	0.0%	100.0%
Station Plantation	6.0%	35.4%	43.1%	15.5%	100.0%

	Percentage difference BAU to ER
Renewal Case Study Name	A0-C4 Total
Aldercar	-69%
Bowling Green	-68%
Cove LX	-66%
Killiecrankie	-68%
Station Plantation	-64%

E.27 Extrapolation of Asset Data for Maintenance Interventions

Maintenance Intervention Type	Percentage Contribution to Maintenance	Actual Number of Anticipated Jobs	Average BAU Carbon from Case Studies (kgCO ₂ e)	Total BAU Carbon for Intervention (kgCO ₂ e)
Vegetation Management	26.2	384	1,074.5	412,706.85
Vermin Eradication	16.9	248	1,333.8	330,454.29
Surveys	15	220	98.9	21,748.11
Drainage Maintenance	17	249	4,567	1,138,187.74
Total	75.1% OF ALL MAINTENANCE	1101 OF 1466 FOR ALL NR FOR WHOLE CP		1,903,096.99

Vegetation Management	Raw BAU	Vermin Eradication	Raw BAU	Surveys	Raw BAU	Drainage Maintenance	Raw BAU
Dalton Junction Overhang	4338.487748	Heron Close - Badger Mitigation	2023.72	OWW Evaluations - Survey only	15.3924	Fearn Station	16419.78
Hattersley No. 2	791.85668	Kindallachan	286.7831025	CDM2 Badger Env. Man. Survey Only	224.98558	Kirkham Tip	412.90122
Ipswich Southern Tunnel Portal	68.27383	Stonebridge	1690.86664	DCL Fenny Compton - Survey only	56.1768	Capelrig Road	735.227976
Postwick Interchange	469.416	Average BAU	1333.789914	Average BAU	98.85159333	Maybole	700.10638
Airbles Station	80.55574					Average BAU	4567.003894
FHR6 Jumps Lane Down	140.28902						
Hayfield Rock	2292.92818						
Mossley Cutting	682.26884						
Appley Locks	133.93674						
Bathpool Reservoir + Survey	635.74538						
Courteenhall	2666.13366						
Dimbols Farm	2947.7865						
Lime Chalk Embankment	86.84841						
NAJ2 South Ruislip	87.73668						
Old Hill	78.90012						
Stonebridge	1690.86664						
Average BAU	1074.501886						

Appendix F Appendices Relating to Chapter 6

F.1 Benefits of NETs amended from (McGeever *et al.*, 2019, p.3) including performance of NETS from (Rueda *et al.*, 2021)

	OF	SCS	Biochar	EW	Afforestation	BECCS	DACCS
Carbon removal /Mitigation Effect	Low*	Medium	Medium	Medium/High*	Medium	High/Medium*	Very High
Readiness /Technical Feasibility	Low*	Very High	Very High/Medium*	Medium/Low*	Very High	Medium/High*	Very Low/Medium*
Cost/ Economic Feasibility	High*	Medium	Medium/High*	Medium/High*	Low/Medium*	Medium/High*	Very High
Vulnerability to re-release / Inverse of Permanence	High*	High	High	Medium/Low*	Medium/ High	Low	Low
Vulnerability to future climate change		Very High	High	Medium	High	Medium	Very Low
Biodiversity Risk /Environmental Side Impact	Low*	Low/Medium*	Low/Medium*	Medium	High	High/Low*	Low
Energy Penalty		Low	Medium	High	Low	Very Low	Very High
Land Pressure		Low	Medium	Low	High	High	Very Low

- where green indicates a positive rating, through yellow for a medium rating and red for a negative rating.
- where * indicates data from (Rueda *et al.*, 2021)

F.2 Positive and Negative Issues of Differing CO₂ Sequestration

Routes (amended from (Yadav and Mehra, 2021) and (Rueda *et al.*, 2021, p.6) and (McGeever *et al.*, 2019, p.2) and (Nagireddi, Agarwal and Vedapuri, 2023, p.28) *

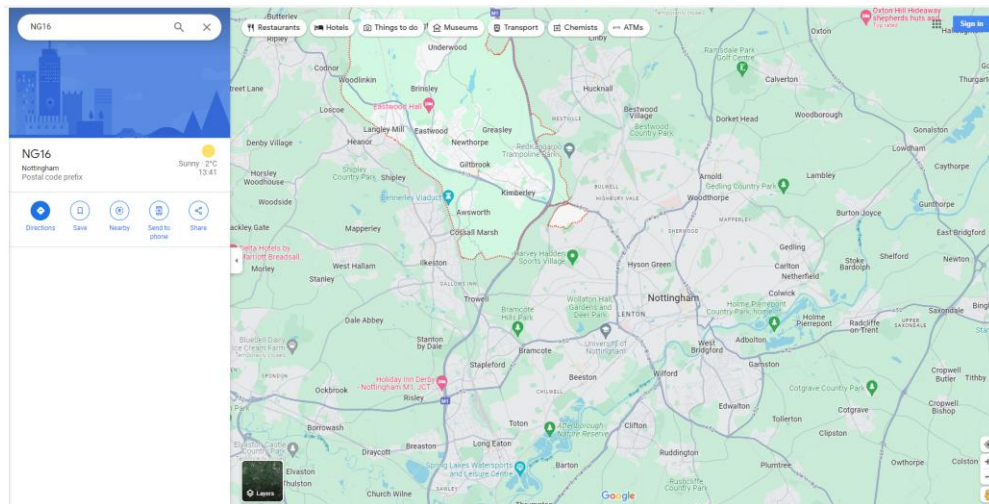
CO ₂ Sequestration Route by low to high storage potential	Examples in Route	Positive	Negative
Biological 100 Gt	AR BC SCS	Low cost Less environmental issues High potential	Monoculture plantation can imbalance ecosystem Insufficient capacity Risk of impact to food chain
Ocean >1,000 Gt	Biological Chemical (via EW) Electrochemical Deep Ocean via sediment *	High potential Abundance No monitoring required	High environmental risk More expensive than geological Negative perception
Geological 1,800 Gt	EW (via technological removal) BECCS (via Biological) DACCS (via technological removal)	Developed technology Economical Public acceptance	Leakage threat Constant monitoring required Shortage of suitable sites
Mineral 10,000-10,000,000 Gt	Direct Carbonation Indirect Carbonation	Environmentally safe Exothermic reaction Abundance of feedstock Permanence Utilization of industrial waste	High cost Energy intensive Slow reaction kinetics Pre-treatment Environmental issues from mining of feedstock Unsecure future potential Poor recovery of additives

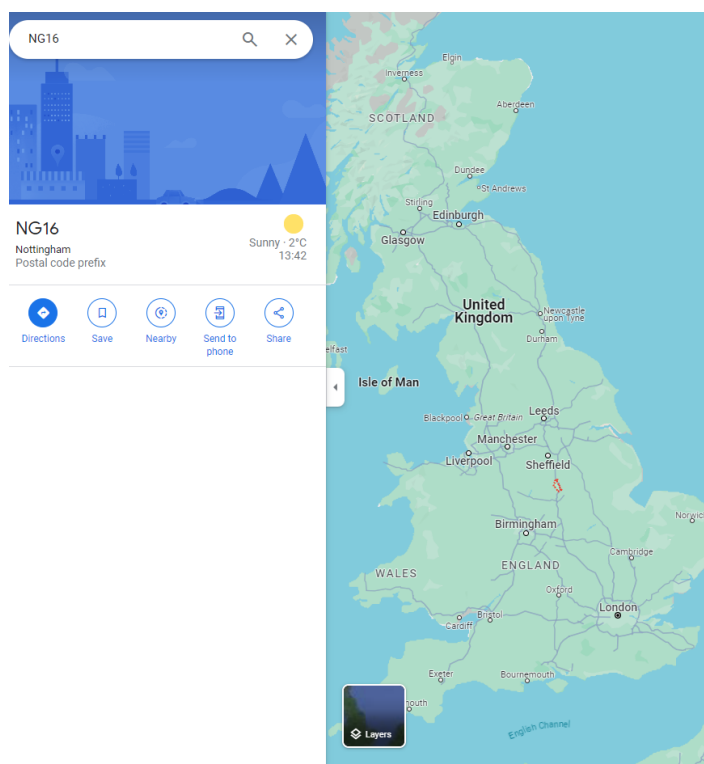
F.3 Peatlands and Grasslands

Given the importance of peatlands and grasslands in LUC they are addressed in the application of LUC to the NR estate. It is important to appreciate the large quantities of carbon that can be sequestered and stored in peatland (Ostle *et al.*, 2009, p.S275; Brown, 2020, p.1), compared to the “humble contribution” to emissions reduction provided via sequestration by SOC (Sommer and Bossio, 2014, p.87), and that it is the draining of peatlands that is causing these peatlands to become sources rather than sinks of carbon (Brown, 2020, p.4). A mixed picture emerges for grasslands’ sink potential with some indicating a sink (Wang, VandenBygaart and McConkey, 2014, p.333), and others no sink (Smith, 2014, p.2708). Availability of peatlands and grasslands in the NR estate to contribute towards offsetting is reviewed in Section 6.5.1, with peatland restoration potentially making a positive contribution.

F.4 Country Assignment Using Postcode

The first half of the postcode for each renewal site was inserted into Google Maps and the subsequent area of the country identified on the map, and from this location the country could be identified as either England or Scotland. The example screen shots below are for partial postcode NG16 = Nottingham = England.





For the other renewal sites the area and country identified are given below:

SK14 = Hyde = England

DG11 = Lockerbie = Scotland

PH16 = Pitlochry = Scotland

LE12 = Loughborough = England

F.5 Assumptions in WCC Small Project Carbon Calculator

Full details on how to use the Carbon Calculation Tool are provided in the Woodland carbon Code document using the WCC carbon calculation spreadsheet version 2 .4 (link to document) and assumptions inherent in the small project carbon calculation sheet are given below.

DESCRIPTION OF THIS SMALL PROJECT CARBON CALCULATOR

This calculator is designed to be used for projects following the Small Project Process, and can be used for any species mix of woodland.

Assumptions in planting density: This calculator can be used for planting densities of at least 816 stems/ha - or 3.5m spacing (over the net planted area). NOT for less dense planting.

Assumptions in management: This calculator can only be used for minimum intervention, thinned or CCF woodlands. It CANNOT be used where clearfell is involved.

Assumptions in emissions from establishment: Seedlings for whole net area at 2.5m spacing, ground prep using vehicle, fenced area allows for additional 15% open ground, herbicide is applied twice.

Assumptions in soil carbon: Establishment technique / soil carbon loss tables have been simplified compared with the 'standard' method.

Buffer Contribution: This calculator assumes all projects contribute 20% to the risk buffer.

This small woods calculator is based on WCC Carbon Lookup Table V2.0 March 2018

F.6 Cove LX Differing Broadleaf Planting Scenarios to Offset Carbon Using WCC

Screen shots of Cove LX differing broadleaf planting scenarios to offset carbon of 4tCO₂e using WCC carbon calculator Excel sheet are now given.

A range of differing scenarios were trialled with the aim being to find the worst case options for a pessimistic scenario and the best case options for an optimistic scenario using broadleaf minimum intervention with no thinning.

The net area was kept consistent at 0.1 hectares (amended as necessary to gauge it's effect).

The Soil type, previous landuse and site preparation technique were manipulated to find the best and worst case options.

F.6.1 Differing Parameters to Investigate Options for Broadleaf Planting Regime

Example Screen Shot below	Area of Broadleaf Planting per ha, no thinning	Soil Type	Previous Landuse	Site Preparation Technique (level of disturbance)	tCO2e sequestered by yr 25 (2050 NZ deadline)
A	5	Organomineral	Semi Natural	Medium	550
B***	0.1	Organomineral	Semi Natural	Medium	11
C	0.1	Mineral	Semi Natural	Medium	14
D	0.1	Organomineral	Pasture	Medium	12
E	0.1	Organomineral	Arable	Medium	13
F	0.1	Organomineral	Semi Natural	Very High	-2
G*	0.1	Organomineral	Semi Natural	High	6
H**	0.1	Mineral	Arable	Negligible	15
I	0.1	Mineral	Arable	Low	15
J	0.1	Organomineral	Semi Natural	Low	13

(*)Worst case option that meets NZ by 2050 sequestration target for this site to be offset

(**) Best case option exceeds NZ by 2050 sequestration target

(***) Mid Case option meets NZ by 2050 sequestration target)

For soil type, it was found that the worst case choice is organomineral and the best case choice is mineral.

For previous landuse the order found from worst case to best case is semi natural, pasture, arable.

For site preparation technique the order found from worst case to best case is very high, high, medium, low, negligible)

Appendix F

A - Below using area of 5ha for planting gives 205tCO₂e sequestration by yr 20

Project Name:			Small mixed native woodland
Calculation Completed by:			Tracey Navaei
Date calculation completed:			15-Jan-24
Project Start Date (date planting was completed)			01-Jan-25
Country			Scotland
If in England, applying for Woodland Carbon Guarantee?			Please select
If in the Guarantee, 10-yearly or 5-yearly verifications?			Please select
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)			5.00
Net area Broadleaf thinned (ha)			0.00
Net area Conifer minimum intervention / no thinning (ha)			0.00
Net area Conifer thinned (ha)			0.00
Total net planting area (ha)			5.00
Total Emissions from establishment		tCO ₂ e/ha	tCO ₂ e
		-2.23	-11.15
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Seminatural	
Site Preparation Technique		Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost		10	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e
Total soil carbon emissions	5.00	-53.2	-265.8

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-267	-53	-214	-43
10	-230	-46	-184	-37
15	-105	-21	-84	-17
20	256	51	205	41
25	688	138	550	110
30	1000	200	800	160
35	1227	245	982	196
40	1410	282	1128	226
45	1565	313	1252	250
50	1743	349	1394	279
55	1829	366	1463	293
60	1888	378	1510	302
65	1938	388	1550	310
70	1962	392	1570	314
75	1991	398	1593	319
80	2019	404	1615	323
85	2042	408	1634	327
90	2065	413	1652	330
95	2140	428	1712	342
100	2148	430	1718	344

B - Below using area of 0.1ha for planting gives 4t CO2 sequestration by yr 20

Project Name:				Small mixed native woodland	
Calculation Completed by:				Tracey Navaei	
Date calculation completed:				15-Jan-24	
Project Start Date (date planting was completed)				01-Jan-25	
Country				Scotland	
If in England, applying for Woodland Carbon Guarantee?				Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?				Please select	
Project Basics					
Management & Species					
Net area Broadleaf minimum intervention / no thinning (ha)				0.10	
Net area Broadleaf thinned (ha)				0.00	
Net area Conifer minimum intervention / no thinning (ha)				0.00	
Net area Conifer thinned (ha)				0.00	
Total net planting area (ha)				0.10	
Total Emissions from establishment			tCO₂e/ha	tCO₂e	
			-2.23	-0.22	
Soil type, previous landuse and establishment technique					
Soil Type				Organomineral	
Previous Landuse				Seminatural	
Site Preparation Technique				Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost				10	
Soil C emissions from site prep		Area (ha)	tCO₂e/ha	tCO₂e	
Total soil carbon emissions		0.10	-53.2	-5.3	

Sectr No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Woody Shrubs	Specify Species here		0.00%	0.0
Total Area				0.0%	0.0

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-5	-1	-4	-40
10	-5	-1	-4	-40
15	-2	0	-2	-20
20	5	1	4	40
25	14	3	11	110
30	20	4	16	160
35	25	5	20	200
40	28	6	22	220
45	31	6	25	250
50	35	7	28	280
55	37	7	30	300
60	38	8	30	300
65	39	8	31	310
70	39	8	31	310
75	40	8	32	320
80	40	8	32	320
85	41	8	33	330
90	41	8	33	330
95	43	9	34	340
100	43	9	34	340

Appendix F

C - With above changed to mineral soil gives greater sequestration at yr 20, 7tCO₂e, yr 25 14t

Project Name:				Small mixed native woodland	
Calculation Completed by:				Tracey Navaei	
Date calculation completed:				15-Jan-24	
Project Start Date (date planting was completed)				01-Jan-25	
Country				Scotland	
If in England, applying for Woodland Carbon Guarantee?				Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?				Please select	
Project Basics					
Management & Species					
Net area Broadleaf minimum intervention / no thinning (ha)				0.10	
Net area Broadleaf thinned (ha)				0.00	
Net area Conifer minimum intervention / no thinning (ha)				0.00	
Net area Conifer thinned (ha)				0.00	
Total net planting area (ha)				0.10	
Total Emissions from establishment			tCO ₂ e/ha	tCO ₂ e	
			-2.23	-0.22	
Soil type, preivous landuse and establishment technique					
Soil Type				Mineral	
Previous Landuse				Seminatural	
Site Preparation Technique				Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost				02	
Soil C emissions from site prep		Area (ha)	tCO ₂ e/ha	tCO ₂ e	
Total soil carbon emissions		0.10	-10.6	-1.1	

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-1	0	-1	-10
10	0	0	0	0
15	2	0	2	20
20	9	2	7	70
25	18	4	14	140
30	24	5	19	190
35	29	6	23	230
40	32	6	26	260
45	36	7	29	290
50	39	8	31	310
55	41	8	33	330
60	42	8	34	340
65	43	9	34	340
70	43	9	34	340
75	44	9	35	350
80	45	9	36	360
85	45	9	36	360
90	46	9	37	370
95	47	9	38	380
100	47	9	38	380

D - With organomineral soil (worst case) and pasture increased sequestration rate at yr 20 of 5tCO₂e

Project Name:				Small mixed native woodland	
Calculation Completed by:				Tracey Navaei	
Date calculation completed:				15-Jan-24	
Project Start Date (date planting was completed)				01-Jan-25	
Country				Scotland	
If in England, applying for Woodland Carbon Guarantee?				Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?				Please select	
Project Basics					
Management & Species					
Net area Broadleaf minimum intervention / no thinning (ha)				0.10	
Net area Broadleaf thinned (ha)				0.00	
Net area Conifer minimum intervention / no thinning (ha)				0.00	
Net area Conifer thinned (ha)				0.00	
Total net planting area (ha)				0.10	
Total Emissions from establishment			tCO₂e/ha	tCO₂e	
			-2.23	-0.22	
Soil type, previous landuse and establishment technique					
Soil Type				Organomineral	
Previous Landuse				Pasture	
Site Preparation Technique				Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost				10	
Soil C emissions from site prep		Area (ha)	tCO₂e/ha	tCO₂e	
Total soil carbon emissions		0.10	-42.2	-4.2	

[illegible]

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-4	-1	-3	-30
10	-3	-1	-2	-20
15	-1	0	-1	-10
20	6	1	5	50
25	15	3	12	120
30	21	4	17	170
35	26	5	21	210
40	29	6	23	230
45	32	6	26	260
50	36	7	29	290
55	38	8	30	300
60	39	8	31	310
65	40	8	32	320
70	40	8	32	320
75	41	8	33	330
80	41	8	33	330
85	42	8	34	340
90	42	8	34	340
95	44	9	35	350
100	44	9	35	350

E - With organomineral soil (worst case) and arable increased sequestration rate at yr 20 of 6tCO₂e

[illegible]

Sequestern to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-3	-1	-2	-20
10	-3	-1	-2	-20
15	0	0	0	0
20	7	1	6	60
25	16	3	13	130
30	22	4	18	180
35	27	5	22	220
40	30	6	24	240
45	33	7	26	260
50	37	7	30	300
55	39	8	31	310
60	40	8	32	320
65	41	8	33	330
70	41	8	33	330
75	42	8	34	340
80	42	8	34	340
85	43	9	34	340
90	43	9	34	340
95	45	9	36	360
100	45	9	36	360

F - With Organomineral soil (worst case) and semi natural previous landuse (worse case) and very high disturbance during site preparation (worst case) 3t CO₂e achieved in yr 30, which is outside NZ commitment (2025+30= 2055) - using this scenario NZ can not be achieved by 2050 as the losses from disturbance will not be balanced out in the time frame – different sizes up to

Project Name:				Small mixed native woodland
Calculation Completed by:				Tracey Navaei
Date calculation completed:				15-Jan-24
Project Start Date (date planting was completed)				01-Jan-25
Country				Scotland
If in England, applying for Woodland Carbon Guarantee?				Please select
If in the Guarantee, 10-yearly or 5-yearly verifications?				Please select
Project Basics				
Management & Species				
Net area Broadleaf minimum intervention / no thinning (ha)			0.10	
Net area Broadleaf thinned (ha)			0.00	
Net area Conifer minimum intervention / no thinning (ha)			0.00	
Net area Conifer thinned (ha)			0.00	
Total net planting area (ha)			0.10	
Total Emissions from establishment		tCO ₂ e/ha	tCO ₂ e	
		-2.23	-0.22	
Soil type, previous landuse and establishment technique				
Soil Type			Organomineral	
Previous Landuse			Seminatural	
Site Preparation Technique			Very High Disturbance: Agricultural ploughing	
% Topsoil Carbon Lost			40	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e	
Total soil carbon emissions	0.10	-212.7	-21.3	

[illegible]

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-21	-4	-17	-170
10	-21	-4	-17	-170
15	-18	-4	-14	-140
20	-11	-2	-9	-90
25	-2	0	-2	-20
30	4	1	3	30
35	9	2	7	70
40	12	2	10	100
45	15	3	12	120
50	19	4	15	150
55	21	4	17	170
60	22	4	18	180
65	23	5	18	180
70	23	5	18	180
75	24	5	19	190
80	24	5	19	190
85	25	5	20	200
90	25	5	20	200
95	27	5	22	220
100	27	5	22	220

G - With Organomineral soil (worst case) and semi natural previous land use (worse case) and high disturbance during site preparation (second worst case) 6t CO₂e achieved in yr 25 meeting NZ guidance

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	<i>Specify Species here</i>		0.00%	0.00
Total Area				0.0%	0.00

Sequestm to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-11	-2	-9	-90
10	-10	-2	-8	-80
15	-7	-1	-6	-60
20	0	0	0	0
25	8	2	6	60
30	15	3	12	120
35	19	4	15	150
40	23	5	18	180
45	26	5	21	210
50	30	6	24	240
55	31	6	25	250
60	32	6	26	260
65	33	7	26	260
70	34	7	27	270
75	34	7	27	270
80	35	7	28	280
85	36	7	29	290
90	36	7	29	290
95	37	7	30	300
100	38	8	30	300

H – Best case option using mineral, arable and negligible site prep technique

Project Name:			Small mixed native woodland
Calculation Completed by:			Tracey Navaei
Date calculation completed:			15-Jan-24
Project Start Date (date planting was completed)			01-Jan-25
Country			Scotland
If in England, applying for Woodland Carbon Guarantee?			Please select
If in the Guarantee, 10-yearly or 5-yearly verifications?			Please select
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.10	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.00	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.10	
Total Emissions from establishment		tCO ₂ e/ha	tCO ₂ e
		-2.23	-0.22
Soil type, previous landuse and establishment technique			
Soil Type		Mineral	
Previous Landuse		Arable	
Site Preparation Technique		Negligible Disturbance: Hand screening only	
% Topsoil Carbon Lost		00	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e
Total soil carbon emissions	0.10	0.0	0.0

[illegible]

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestern to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	0	0	0	0
10	1	0	1	10
15	3	1	2	20
20	10	2	8	80
25	19	4	15	150
30	25	5	20	200
35	30	6	24	240
40	34	7	27	270
45	37	7	30	300
50	40	8	32	320
55	42	8	34	340
60	43	9	34	340
65	44	9	35	350
70	45	9	36	360
75	45	9	36	360
80	46	9	37	370
85	46	9	37	370
90	47	9	38	380
95	48	10	38	380
100	48	10	38	380

Appendix F

I - Secondary best case scenario trialled, Mineral arable low disturbance, also 15 tCO₂e by 2025

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		Scotland	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.10	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.00	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.10	
Total Emissions from establishment	tCO₂e/ha	tCO₂e	
	-2.23	-0.22	
Soil type, previous landuse and establishment technique			
Soil Type		Mineral	
Previous Landuse		Arable	
Site Preparation Technique		Low disturbance: Hand turfing, inverted, hinge & trench mounding, patch scarification, subsoiling, drains	
% Topsoil Carbon Lost		00	
Soil C emissions from site prep	Area (ha)	tCO₂e/ha	tCO₂e
Total soil carbon emissions	0.10	0.0	0.0

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestm to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	0	0	0	0
10	1	0	1	10
15	3	1	2	20
20	10	2	8	80
25	19	4	15	150
30	25	5	20	200
35	30	6	24	240
40	34	7	27	270
45	37	7	30	300
50	40	8	32	320
55	42	8	34	340
60	43	9	34	340
65	44	9	35	350
70	45	9	36	360
75	45	9	36	360
80	46	9	37	370
85	46	9	37	370
90	47	9	38	380
95	48	10	38	380
100	48	10	38	380

J – organomineral, semi natural, low disturbance =13 tCO₂e by 2025

Project Name:				Small mixed native woodland
Calculation Completed by:				Tracey Navaei
Date calculation completed:				15-Jan-24
Project Start Date (date planting was completed)				01-Jan-25
Country				Scotland
If in England, applying for Woodland Carbon Guarantee?				Please select
If in the Guarantee, 10-yearly or 5-yearly verifications?				Please select
Project Basics				
Management & Species				
Net area Broadleaf minimum intervention / no thinning (ha)			0.10	
Net area Broadleaf thinned (ha)			0.00	
Net area Conifer minimum intervention / no thinning (ha)			0.00	
Net area Conifer thinned (ha)			0.00	
Total net planting area (ha)			0.10	
Total Emissions from establishment		tCO ₂ e/ha	tCO ₂ e	
		-2.23	-0.22	
Soil type, previous landuse and establishment technique				
Soil Type			Organomineral	
Previous Landuse			Seminatural	
Site Preparation Technique			Low disturbance: Hand turving, inverted, hinge & trench mounding, patch scarification, subsoiling, drains	
% Topsoil Carbon Lost			05	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e	
Total soil carbon emissions	0.10	-26.6	-2.7	

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Select Species	0.0	Select Mgmt Regime	0.00%	0.0
	Woody Shrubs	<i>Specify Species here</i>		0.00%	0.0
Total Area				0.0%	0.0

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-3	-1	-2	-20
10	-2	0	-2	-20
15	1	0	1	10
20	8	2	6	60
25	16	3	13	130
30	23	5	18	180
35	27	5	22	220
40	31	6	25	250
45	34	7	27	270
50	38	8	30	300
55	39	8	31	310
60	40	8	32	320
65	41	8	33	330
70	42	8	34	340
75	42	8	34	340
80	43	9	34	340
85	44	9	35	350
90	44	9	35	350
95	45	9	36	360
100	46	9	37	370

F.7 Cove LX Differing Conifer Planting Scenarios to Offset Carbon Using WCC

Screen shots of Cove LX differing conifer planting scenarios to offset carbon of 4tCO₂e using WCC carbon calculator Excel sheet are now given.

Appendix F

A range of differing scenarios were trailed with the aim being to find the worst case options for a pessimistic scenario and the best case options for an optimistic scenario using conifer minimum intervention with no thinning.

The net area was kept consistent at 0.1 hectares (amended as necessary to gauge its effect).

The Soil type, previous landuse and site preparation technique were manipulated to find the best and worst case options.

Following change to conifer planting the scenarios used for broadleaf were redone for conifers with results in table below and screen shots after that.

F.7.1 Differing Parameters to Investigate Options for Conifer Planting Regime

Example Screen Shot below	Area of Conifer Planting per ha, no thinning	Soil Type	Previous Landuse	Site Preparation Technique (level of disturbance)	tCO2e sequestered by yr 25 (2050 NZ deadline)
A	5	Organomineral	Semi Natural	Medium	494
B***	0.1	Organomineral	Semi Natural	Medium	10
C**	0.1	Mineral	Semi Natural	Medium	14
D	0.1	Organomineral	Pasture	Medium	10
E	0.1	Organomineral	Arable	Medium	11
F	0.1	Organomineral	Semi Natural	Very High	-3
G*	0.1	Organomineral	Semi Natural	High	6
H**	0.1	Mineral	Arable	Negligible	14
I	0.1	Mineral	Arable	Low	14
J	0.1	Organomineral	Semi Natural	Low	12

(*)Worst case option that meets NZ by 2050 sequestration target for this site to be offset

(**) Best case options both exceeds NZ by 2050 sequestration target

(**) Mid Case option meets NZ by 2050 sequestration target)

For soil type, it was found that the worst case choice is organomineral and the best case choice is mineral.

For previous landuse the order found from worst case to best case is semi natural, pasture, arable.

For site preparation technique the order found from worst case to best case is very high, high, medium, low, negligible)

Appendix F

A - orgnomineral, semi natural, medium 5ha

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		Scotland	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.00	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		5.00	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		5.00	
Total Emissions from establishment		tCO₂e/ha	tCO₂e
		-2.23	-11.15
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Seminatural	
Site Preparation Technique		Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost		10	
Soil C emissions from site prep	Area (ha)	tCO₂e/ha	tCO₂e
Total soil carbon emissions	5.00	-53.2	-265.8

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-265	-53	-212	-42
10	-233	-47	-186	-37
15	-146	-29	-117	-23
20	110	22	88	18
25	618	124	494	99
30	984	197	787	157
35	1340	268	1072	214
40	1699	340	1359	272
45	2039	408	1631	326
50	2416	483	1933	387
55	2678	536	2142	428
60	2868	574	2294	459
65	3015	603	2412	482
70	3135	627	2508	502
	3235	647	2588	518
75				
80	3322	664	2658	532
	3394	679	2715	543
85				
90	3456	691	2765	553
	3510	702	2808	562
95				
100	3561	712	2849	570

B - Conifer 0.1ha oragnomineral, semi natural, medium

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		Scotland	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.00	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.10	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.10	
Total Emissions from establishment	tCO ₂ e/ha	tCO₂e	
	-2.23	-0.22	
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Seminatural	
Site Preparation Technique		Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost		10	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO₂e
Total soil carbon emissions	0.10	-53.2	-5.3

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime		

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestm to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-5	-1	-4	-40
10	-5	-1	-4	-40
15	-3	-1	-2	-20
20	2	0	2	20
25	12	2	10	100
30	20	4	16	160
35	27	5	22	220
40	34	7	27	270
45	41	8	33	330
50	48	10	38	380
55	54	11	43	430
60	57	11	46	460
65	60	12	48	480
70	63	13	50	500
75	65	13	52	520
80	66	13	53	530
85	68	14	54	540
90	69	14	55	550
95	70	14	56	560
100	71	14	57	570

Appendix F

C – Mineral Semi natural medium

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		Scotland	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.00	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.10	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.10	
Total Emissions from establishment	tCO ₂ e/ha	tCO₂e	
	-2.23	-0.22	
Soil type, previous landuse and establishment technique			
Soil Type		Mineral	
Previous Landuse		Seminatural	
Site Preparation Technique		Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost		02	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO₂e
Total soil carbon emissions	0.10	-10.6	-1.1

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestern to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-1	0	-1	-10
10	0	0	0	0
15	1	0	1	10
20	6	1	5	50
25	17	3	14	140
30	24	5	19	190
35	31	6	25	250
40	38	8	30	300
45	45	9	36	360
50	53	11	42	420
55	58	12	46	460
60	62	12	50	500
65	65	13	52	520
70	67	13	54	540
	69	14	55	550
75				
80	71	14	57	570
	72	14	58	580
85				
90	73	15	58	580
	74	15	59	590
95				
100	75	15	60	600

D -organomineral, pasture, medium

Project Name:			Small mixed native woodland
Calculation Completed by:			Tracey Navaei
Date calculation completed:			15-Jan-24
Project Start Date (date planting was completed)			01-Jan-25
Country			Scotland
If in England, applying for Woodland Carbon Guarantee?			Please select
If in the Guarantee, 10-yearly or 5-yearly verifications?			Please select
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)			0.00
Net area Broadleaf thinned (ha)			0.00
Net area Conifer minimum intervention / no thinning (ha)			0.10
Net area Conifer thinned (ha)			0.00
Total net planting area (ha)			0.10
Total Emissions from establishment	tCO ₂ e/ha	tCO₂e	
	-2.23	-0.22	
Soil type, previous landuse and establishment technique			
Soil Type			Organomineral
Previous Landuse			Pasture
Site Preparation Technique			Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding
% Topsoil Carbon Lost			10
Soil C emissions from site prep	Area (ha)	tCO₂e/ha	tCO₂e
Total soil carbon emissions	0.10	-42.2	-4.2

[illegible]

**** NOTE** The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-4	-1	-3	-30
10	-4	-1	-3	-30
15	-2	0	-2	-20
20	3	1	2	20
25	13	3	10	100
30	21	4	17	170
35	28	6	22	220
40	35	7	28	280
45	42	8	34	340
50	49	10	39	390
55	55	11	44	440
60	58	12	46	460
65	61	12	49	490
70	64	13	51	510
75	66	13	53	530
80	68	14	54	540
85	69	14	55	550
90	70	14	56	560
95	71	14	57	570
100	72	14	58	580

Appendix F

E – organomineral, arable, medium

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		Scotland	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.00	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.10	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.10	
Total Emissions from establishment	tCO ₂ e/ha	tCO ₂ e	
	-2.23	-0.22	
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Arable	
Site Preparation Technique		Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost		10	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e
Total soil carbon emissions	0.10	-33.0	-3.3

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-3	-1	-2	-20
10	-3	-1	-2	-20
15	-1	0	-1	-10
20	4	1	3	30
25	14	3	11	110
30	22	4	18	180
35	29	6	23	230
40	36	7	29	290
45	43	9	34	340
50	50	10	40	400
55	56	11	45	450
60	59	12	47	470
65	62	12	50	500
70	65	13	52	520
75	67	13	54	540
80	68	14	54	540
85	70	14	56	560
90	71	14	57	570
95	72	14	58	580
100	73	15	58	580

F – organomineral, seminatural, very high

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		Scotland	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.00	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.10	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.10	
Total Emissions from establishment	tCO ₂ e/ha	tCO ₂ e	
	-2.23	-0.22	
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Seminatural	
Site Preparation Technique		Very High Disturbance: Agricultural ploughing	
% Topsoil Carbon Lost		40	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e
Total soil carbon emissions	0.10	-212.7	-21.3

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-21	-4	-17	-170
10	-21	-4	-17	-170
15	-19	-4	-15	-150
20	-14	-3	-11	-110
25	-4	-1	-3	-30
30	4	1	3	30
35	11	2	9	90
40	18	4	14	140
45	25	5	20	200
50	32	6	26	260
55	38	8	30	300
60	41	8	33	330
65	44	9	35	350
70	47	9	38	380
	49	10	39	390
75				
80	50	10	40	400
	52	10	42	420
85				
90	53	11	42	420
	54	11	43	430
95				
100	55	11	44	440

Appendix F

G -organomineral, seminatural, high

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		Scotland	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.00	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.10	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.10	
Total Emissions from establishment	tCO ₂ e/ha	tCO₂e	
	-2.23	-0.22	
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Seminatural	
Site Preparation Technique		High Disturbance: Deep (>30cm) plough, with or without tine	
% Topsoil Carbon Lost		20	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO₂e
Total soil carbon emissions	0.10	-106.3	-10.6

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestm to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-11	-2	-9	-90
10	-10	-2	-8	-80
15	-8	-2	-6	-60
20	-3	-1	-2	-20
25	7	1	6	60
30	14	3	11	110
35	21	4	17	170
40	29	6	23	230
45	35	7	28	280
50	43	9	34	340
55	48	10	38	380
60	52	10	42	420
65	55	11	44	440
70	57	11	46	460
75	59	12	47	470
80	61	12	49	490
85	63	13	50	500
90	64	13	51	510
95	65	13	52	520
100	66	13	53	530

H - mineral, arable, negligible

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		Scotland	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.00	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.10	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.10	
Total Emissions from establishment	tCO ₂ e/ha	tCO ₂ e	
	-2.23	-0.22	
Soil type, previous landuse and establishment technique			
Soil Type		Mineral	
Previous Landuse		Arable	
Site Preparation Technique		Negligible Disturbance: Hand screefing only	
% Topsoil Carbon Lost		00	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e
Total soil carbon emissions	0.10	0.0	0.0

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestm to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	0	0	0	0
10	1	0	1	10
15	2	0	2	20
20	8	2	6	60
25	18	4	14	140
30	25	5	20	200
35	32	6	26	260
40	39	8	31	310
45	46	9	37	370
50	54	11	43	430
55	59	12	47	470
60	63	13	50	500
65	66	13	53	530
70	68	14	54	540
75	70	14	56	560
80	72	14	58	580
85	73	15	58	580
90	74	15	59	590
95	76	15	61	610
100	77	15	62	620

I - Mineral, arable, low

[illegible]

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	0	0	0	0
10	1	0	1	10
15	2	0	2	20
20	8	2	6	60
25	18	4	14	140
30	25	5	20	200
35	32	6	26	260
40	39	8	31	310
45	46	9	37	370
50	54	11	43	430
55	59	12	47	470
60	63	13	50	500
65	66	13	53	530
70	68	14	54	540
75	70	14	56	560
80	72	14	58	580
85	73	15	58	580
90	74	15	59	590
95	76	15	61	610
100	77	15	62	620

J - organomineral, semi natural, low

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		Scotland	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.00	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.10	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.10	
Total Emissions from establishment	tCO ₂ e/ha	tCO₂e	
	-2.23	-0.22	
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Seminatural	
Site Preparation Technique		Low disturbance: Hand turfing, inverted, hinge & trench mounding, patch scarification, subsoiling, drains	
% Topsoil Carbon Lost		05	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO₂e
Total soil carbon emissions	0.10	-26.6	-2.7

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

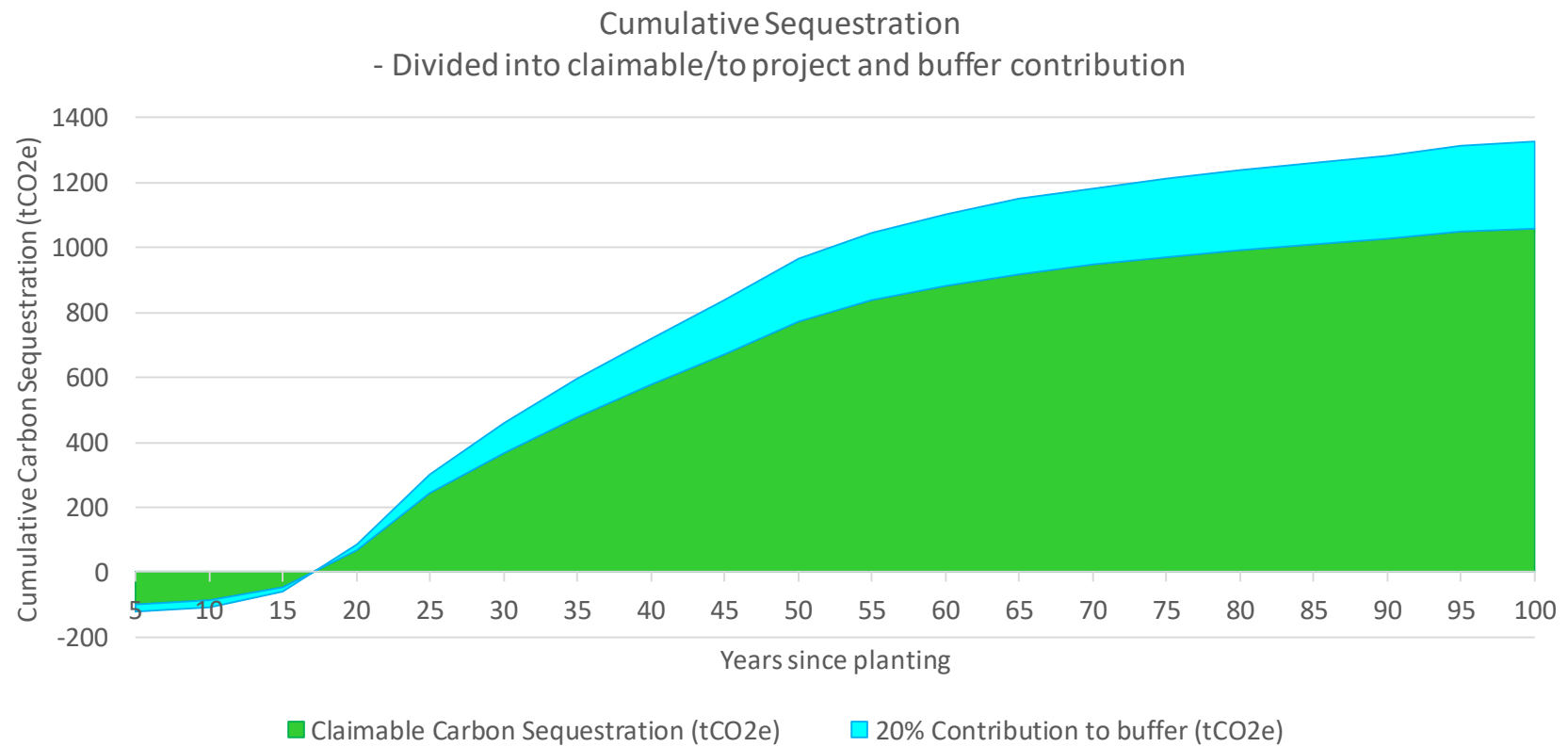
** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestm to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-3	-1	-2	-20
10	-2	0	-2	-20
15	0	0	0	0
20	5	1	4	40
25	15	3	12	120
30	22	4	18	180
35	29	6	23	230
40	37	7	30	300
45	43	9	34	340
50	51	10	41	410
55	56	11	45	450
60	60	12	48	480
65	63	13	50	500
70	65	13	52	520
75	67	13	54	540
80	69	14	55	550
85	71	14	57	570
90	72	14	58	580
95	73	15	58	580
100	74	15	59	590

Project Name:				Small mixed native woodland
Calculation Completed by:				Tracey Navael
Date calculation completed:				15-Jan-24
Project Start Date (date planting was completed)				01-Jan-25
Country				England
If in England, applying for Woodland Carbon Guarantee?				Please select
If in the Guarantee, 10-yearly or 5-yearly verifications?				Please select
Project Basics				
Management & Species				
Net area Broadleaf minimum intervention / no thinning (ha)			1.16	
Net area Broadleaf thinned (ha)			0.00	
Net area Conifer minimum intervention / no thinning (ha)			1.16	
Net area Conifer thinned (ha)			0.00	
Total net planting area (ha)			2.32	
Total Emissions from establishment		tCO ₂ e/ha	tCO ₂ e	
		-2.23	-5.17	
Soil type, previous landuse and establishment technique				
Soil Type			Organomineral	
Previous Landuse			Seminatural	
Site Preparation Technique			Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost			10	
Soil C emissions from site prep		Area (ha)	tCO ₂ e/ha	tCO ₂ e
Total soil carbon emissions		2.32	-53.2	-123.9

[illegible]

Sequestrn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-123	-25	-98	-42
10	-107	-21	-86	-37
15	-58	-12	-46	-20
20	85	17	68	29
25	303	61	242	104
30	460	92	368	159
35	596	119	477	206
40	721	144	577	249
45	836	167	669	288
50	965	193	772	333
55	1046	209	837	361
60	1103	221	882	380
65	1149	230	919	396
70	1183	237	946	408
75	1212	242	970	418
80	1239	248	991	427
85	1261	252	1009	435
90	1281	256	1025	442
95	1311	262	1049	452
100	1324	265	1059	456



Appendix F

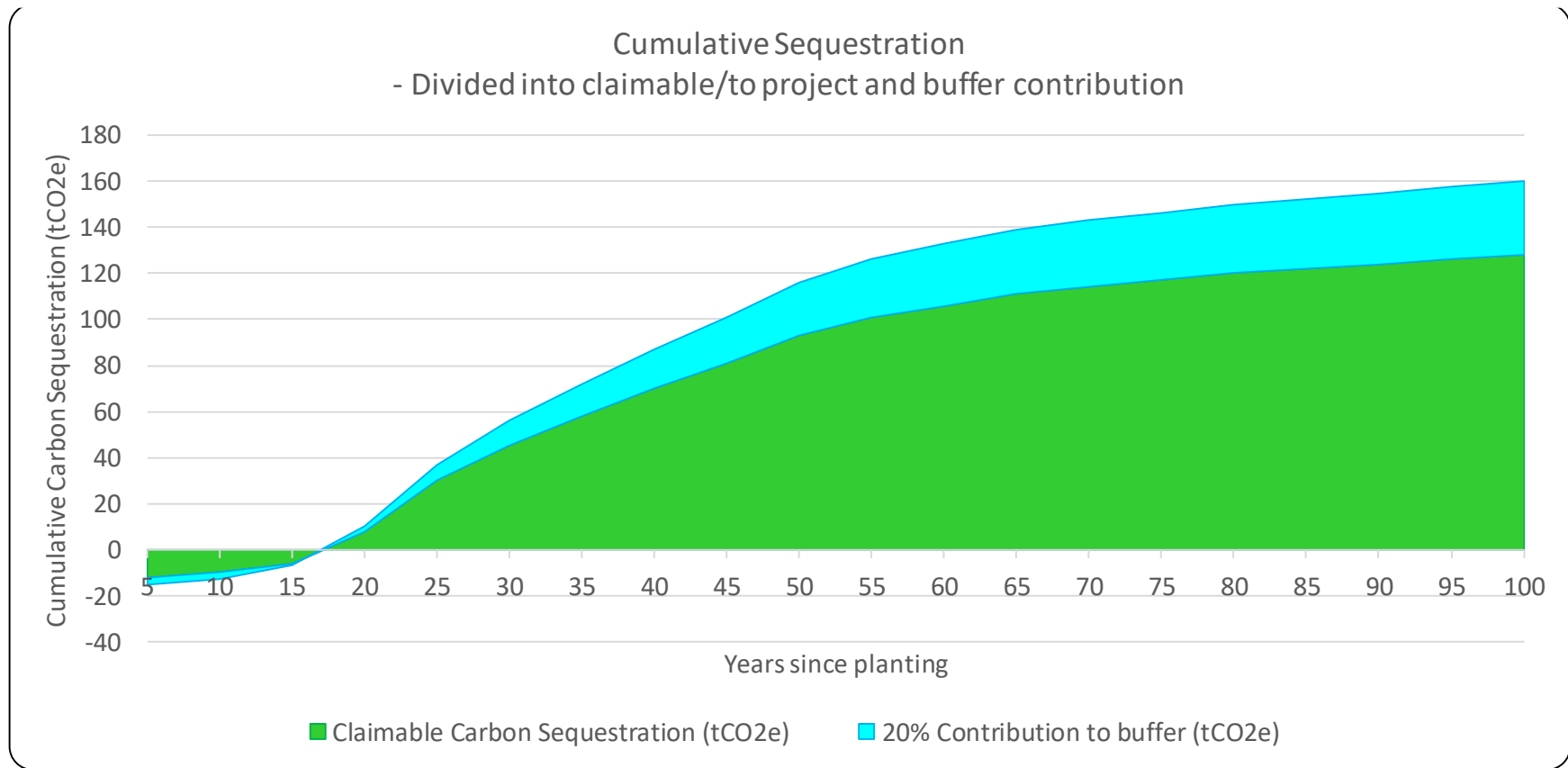
Bowling Green

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		England	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.14	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.14	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.28	
Total Emissions from establishment	tCO ₂ e/ha	tCO ₂ e	
	-2.23	-0.62	
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Seminatural	
Site Preparation Technique		Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost		10	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e
Total soil carbon emissions	0.28	-53.2	-14.9

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestm to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-15	-3	-12	-43
10	-13	-3	-10	-36
15	-7	-1	-6	-21
20	10	2	8	29
25	37	7	30	107
30	56	11	45	161
35	72	14	58	207
40	87	17	70	250
45	101	20	81	289
50	116	23	93	332
55	126	25	101	361
60	133	27	106	379
65	139	28	111	396
70	143	29	114	407
75	146	29	117	418
80	150	30	120	429
85	152	30	122	436
90	155	31	124	443
95	158	32	126	450
100	160	32	128	457



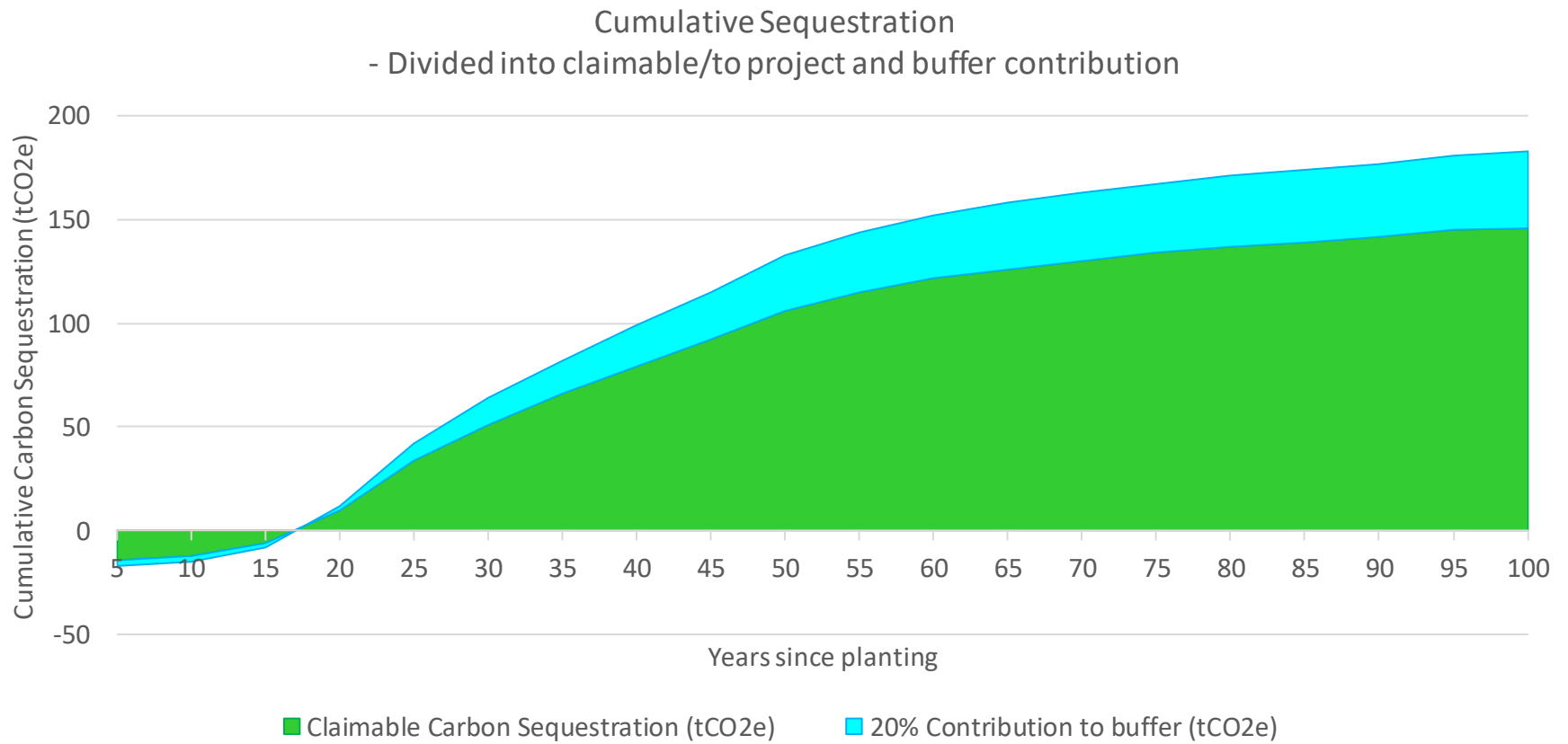
Killiecrankie

Project Name:			Small mixed native woodland	
Calculation Completed by:			Tracey Navaei	
Date calculation completed:			15-Jan-24	
Project Start Date (date planting was completed)			01-Jan-25	
Country			Scotland	
If in England, applying for Woodland Carbon Guarantee?			Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?			Please select	
Project Basics				
Management & Species				
Net area Broadleaf minimum intervention / no thinning (ha)			0.16	
Net area Broadleaf thinned (ha)			0.00	
Net area Conifer minimum intervention / no thinning (ha)			0.16	
Net area Conifer thinned (ha)			0.00	
Total net planting area (ha)			0.32	
Total Emissions from establishment		tCO ₂ e/ha	tCO ₂ e	
		-2.23	-0.71	
Soil type, previous landuse and establishment technique				
Soil Type			Organomineral	
Previous Landuse			Seminatural	
Site Preparation Technique			Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost			10	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e	
Total soil carbon emissions	0.32	-53.2	-17.0	

[illegible]

**** NOTE** The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestern to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-17	-3	-14	-44
10	-15	-3	-12	-38
15	-8	-2	-6	-19
20	12	2	10	31
25	42	8	34	106
30	64	13	51	159
35	82	16	66	206
40	99	20	79	247
45	115	23	92	288
50	133	27	106	331
55	144	29	115	359
60	152	30	122	381
65	158	32	126	394
70	163	33	130	406
75	167	33	134	419
80	171	34	137	428
85	174	35	139	434
90	177	35	142	444
95	181	36	145	453
100	183	37	146	456



Appendix F

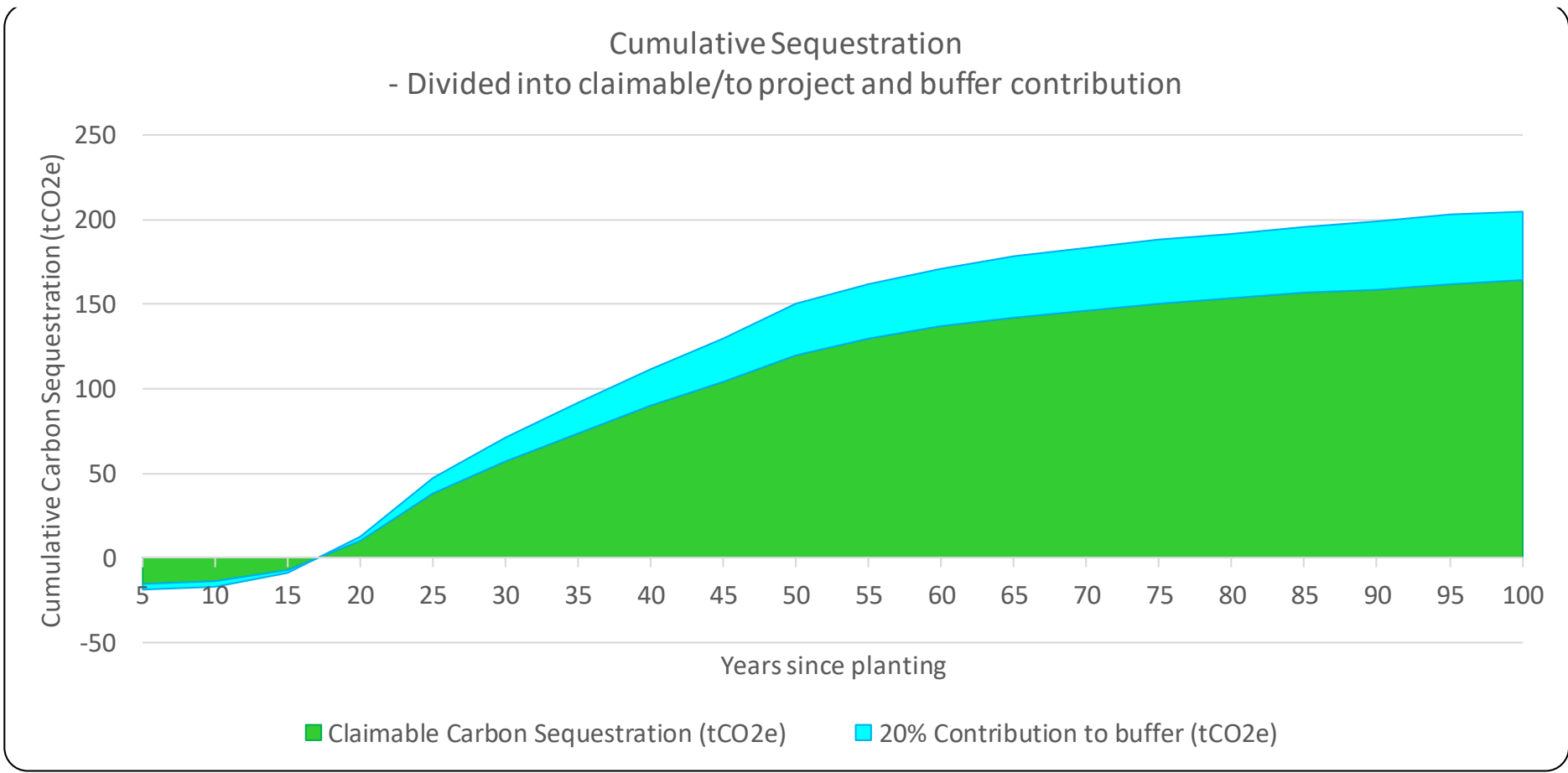
Station Plantation

Project Name:		Small mixed native woodland	
Calculation Completed by:		Tracey Navaei	
Date calculation completed:		15-Jan-24	
Project Start Date (date planting was completed)		01-Jan-25	
Country		England	
If in England, applying for Woodland Carbon Guarantee?		Please select	
If in the Guarantee, 10-yearly or 5-yearly verifications?		Please select	
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)		0.18	
Net area Broadleaf thinned (ha)		0.00	
Net area Conifer minimum intervention / no thinning (ha)		0.18	
Net area Conifer thinned (ha)		0.00	
Total net planting area (ha)		0.36	
Total Emissions from establishment	tCO ₂ e/ha	tCO₂e	
	-2.23	-0.80	
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Seminatural	
Site Preparation Technique		Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost		10	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO₂e
Total soil carbon emissions	0.36	-53.2	-19.1

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestern to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-19	-4	-15	-42
10	-17	-3	-14	-39
15	-9	-2	-7	-19
20	13	3	10	28
25	47	9	38	106
30	71	14	57	158
35	92	18	74	206
40	112	22	90	250
45	130	26	104	289
50	150	30	120	333
55	162	32	130	361
60	171	34	137	381
65	178	36	142	394
70	183	37	146	406
	188	38	150	417
75				
80	192	38	154	428
	196	39	157	436
85				
90	199	40	159	442
	203	41	162	450
95				
100	205	41	164	456



F.9 EW Carbon Storage Potential

This table presents the EW carbon storage potential using differing percentages of the theoretical 1m wide strip adjacent to track

Percentage use of 1m strip adjacent to track	Using Lower Value 18 tCO ₂ ha ⁻¹ yr ⁻¹	Using Mid Value 85 tCO ₂ ha ⁻¹ yr ⁻¹	Using Higher Value 120 tCO ₂ ha ⁻¹ yr ⁻¹
100%	1,426,140.00	6,734,550.00	9,507,600.00
90%	1,283,526.00	6,061,095.00	8,556,840.00
80%	1,140,912.00	5,387,640.00	7,606,080.00
70%	998,298.00	4,714,185.00	6,655,320.00
60%	855,684.00	4,040,730.00	5,704,560.00
50%	713,070.00	3,367,275.00	4,753,800.00
40%	570,456.00	2,693,820.00	3,803,040.00
30%	427,842.00	2,020,365.00	2,852,280.00
20%	285,228.00	1,346,910.00	1,901,520.00
10%	142,614.00	673,455.00	950,760.00

F.10 NR Pixel Data

The tables illustrate the raw NR pixel data for their land assets and with percentages of total added.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	
PIREL COUNT	DECIDUOUS WOODLAND	CONIFEROUS WOODLAND	ARABLE	IMPROVED GRASSLAND	NEUTRAL GRASSLAND	CALCAREOUS GRASSLAND	ACID GRASSLAND	FEN, MARSH, SWAMP	DWARF SHRUB AND HEATH	HEATHER GRASSLAND	BOG	INLAND ROCK	SALTWATER	FRESHWATER	SUPRALITTORAL ROCK	SUPRALITTORAL SEDIMENT	LITTORAL ROCK	LITTORAL SEDIMENT	SALT MARSH	URBAN	BUILT UP AREAS AND GARDENS	SUM			
ANGLIA	48500	2167	77494	34913	5701	7	294	13592	2041	0	0	315	0	423	0	205	0	1	5457	90551	77001	346751			
LNE AND EAST MIDLAND	234112	1332	346251	78106	16217	162	820	4537	596	5022	1477	2275	1	43794	0	402	400	199	4132	224099	258509	1223995			
LNW	234199	3170	170646	17802	40374	3902	10916	148	3974	5299	913	17416	0	10744	14	4055	560	47	10017	107345	246429	1097229			
SCOTLAND	229025	9873	101101	72470	237	0	15990	623	18143	31143	21615	12411	162	922	232	315	61	4731	65971	158163	724097				
SOUTHEAST	135910	3543	34201	52423	134	9324	140	4345	1596	1251	0	2190	0	4870	0	502	0	430	5317	103194	133556	442248			
VALES	110147	740	24244	31019	2593	23	1624	14591	63	921	20	11953	179	0	11953	0	4642	117	47	49041	27055	42723	409473		
WESSER	52185	6477	14775	50357	416	1933	87	124	27965	2451	0	180	0	1733	0	2	0	1	2973	50594	104102	324360			
WESTERN	13402	1753	15413	73143	1346	1039	3	611	4719	1312	0	4043	0	12443	432	140	97	164	10310	64579	124037	517016			
TOTAL	1133770	31955	554550	403216	61997	15390	32278	31404	52942	54451	23433	50951	333	57960	1491	12025	1559	1000	100975	82160	12376500	512045			
METER SQUARE	DECIDUOUS WOODLAND	CONIFEROUS WOODLAND	ARABLE	IMPROVED GRASSLAND	NEUTRAL GRASSLAND	CALCAREOUS GRASSLAND	ACID GRASSLAND	FEN, MARSH, SWAMP	DWARF SHRUB AND HEATH	HEATHER GRASSLAND	BOG	INLAND ROCK	SALTWATER	FRESHWATER	SUPRALITTORAL ROCK	SUPRALITTORAL SEDIMENT	LITTORAL ROCK	LITTORAL SEDIMENT	SALT MARSH	URBAN	BUILT UP AREAS AND GARDENS	SUM			
ANGLIA	4850000	216700	7749400	3491300	570100	700	29400	1355200	204100	0	0	31500	0	423000	0	20500	0	100	545700	9055000	7700100	34675100			
LNE AND EAST MIDLAND	23411200	133200	34625100	7810600	1621700	16200	82000	453700	59600	502200	147700	227500	100	4379400	0	402000	40000	19900	413200	22409900	25850900	12269900			
LNW	23411900	317000	17064600	1780200	4037400	3902000	1091600	14800	397400	529900	91300	1741600	0	1074400	1400	405500	56000	4700	1001700	10734500	24642900	11007500			
SCOTLAND	22902500	987300	10110100	7247000	237000	0	1599000	623000	1814300	3114300	2161500	1241100	162000	922000	232000	315000	61000	473100	6597100	15816300	72409700				
SOUTHEAST	13591000	354300	3420100	5242300	134000	924000	140000	435000	159600	125100	0	219000	0	487000	0	502000	0	430000	531700	10319400	13355600	44224800			
SOUTHEAST	13591000	354300	3420100	5242300	134000	924000	140000	435000	159600	125100	0	219000	0	487000	0	502000	0	430000	531700	10319400	13355600	44224800			
VALES	11014700	74000	2404400	3100900	259300	2300	162400	1459100	63000	92100	2000	1195200	17900	0	1195200	0	464200	11700	4700	490400	2705500	4272300	40947300		
WESSER	5218500	647700	1457500	5035700	416000	193300	87000	124000	2796500	245000	0	180000	0	173200	0	20000	0	100	297200	5059400	10410200	32436000			
WESTERN	1340200	175300	1541300	7314300	134600	103900	3000	61000	471900	131200	0	404300	0	1244300	43200	14000	97000	164000	1031000	6457900	12403700	51701600			
TOTAL	113377000	3195500	55455000	40321600	6199700	1539000	3227800	3140400	5294200	5445100	2343300	5095100	333000	5796000	1491000	1202500	1559000	1000000	10097500	8216000	123765000	51204500			
HECTARES	DECIDUOUS WOODLAND	CONIFEROUS WOODLAND	ARABLE	IMPROVED GRASSLAND	NEUTRAL GRASSLAND	CALCAREOUS GRASSLAND	ACID GRASSLAND	FEN, MARSH, SWAMP	DWARF SHRUB AND HEATH	HEATHER GRASSLAND	BOG	INLAND ROCK	SALTWATER	FRESHWATER	SUPRALITTORAL ROCK	SUPRALITTORAL SEDIMENT	LITTORAL ROCK	LITTORAL SEDIMENT	SALT MARSH	URBAN	BUILT UP AREAS AND GARDENS	SUM			
ANGLIA	451	21.67	774.94	349.13	57.01	0.07	2.94	135.92	204.1	0	0	3.15	0	42.3	0	2.05	0	0.01	54.57	905.5	770.01	3467.51			
LNE AND EAST MIDLAND	2341.12	13.32	3462.51	781.06	162.17	1.62	8.2	45.37	5.96	50.22	14.77	22.75	0.01	437.94	0	4.02	4	1.99	41.32	2240.99	2585.09	12239.95			
LNW	2341.19	31.7	1706.46	178.02	403.74	39.02	110.16	1.41	39.74	52.99	9.13	174.16	0	107.44	0.14	40.55	5.6	4.7	100.17	1073.45	2464.29	10972.29			
SCOTLAND	2290.25	98.73	1011.01	724.7	2.37	0	159.9	6.23	181.43	311.43	216.15	124.11	1.62	9.22	2.32	3.15	0.61	47.31	659.71	1581.63	7240.97				
SOUTHEAST	1359.1	35.43	342.01	524.21	1.34	92.4	1.4	43.45	15.96	12.51	0	21.9	0	48.7	0	5.02	0	4.3	53.17	1031.94	1335.56	4422.48			
VALES	1101.47	7.4	242.44	310.19	25.93	2.3	16.24	145.91	6.3	9.21	0.21	119.53	1.7	11.9	0	46.42	1.17	4.7	499.41	270.55	427.23	4094.73			
WESSER	521.85	64.77	147.75	503.57	41.6	19.33	0.87	1.24	279.65	24.51	0	1.8	0	17.33	0	0.02	0	0.01	29.73	505.94	1041.02	3243.6			
WESTERN	134.02	17.53	154.13	731.43	13.46	10.39	0.03	1.11	47.19	13.12	0	40.43	0	124.43	4.32	1.4	0.97	1.64	103.1	64.579	124.037	5170.16			
TOTAL	11337.7	319.55	5545.5	4032.16	619.97	153.9	322.78	314.04	529.42	544.51	234.33	509.51	3.33	579.6	14.91	120.25	15.59	10.0	1009.75	8216.0	12376.5	51204.5			
PERCENTAGE OF GRAND TOTAL	DECIDUOUS WOODLAND	CONIFEROUS WOODLAND	ARABLE	IMPROVED GRASSLAND	NEUTRAL GRASSLAND	CALCAREOUS GRASSLAND	ACID GRASSLAND	FEN, MARSH, SWAMP	DWARF SHRUB AND HEATH	HEATHER GRASSLAND	BOG	INLAND ROCK	SALTWATER	FRESHWATER	SUPRALITTORAL ROCK	SUPRALITTORAL SEDIMENT	LITTORAL ROCK	LITTORAL SEDIMENT	SALT MARSH	URBAN	BUILT UP AREAS AND GARDENS	SUM			
ANGLIA	0.395952591	0.00248932	1.516433504	0.632446599	0.111412527	0.000912799	0.008714626	0.24846206	0.040271452	0	0	0.007523922	0	0.037701991	0	0.004004244	0	0.000000000	1.95427E-05	0.106446258	1.749743749	1.520433399	7.056032		
LNE AND EAST MIDLAND	5.595370775	0.024200916	5.191850354	1.540971463	0.239103262	0.002165991	0.010621811	0.035145926	0.017617422	0.091422323	0.023014501	0.044489554	1.95427E-05	0.355619117	0	0.007356147	0.0071717942	0.0021031915	0.00175025	4.410574746	5.051662194	24.17113			
LNW	4.14029249	0.075430075	3.342453377	1.702204337	0.001557707	0.05164705	0.215210157	0.002755554	0.077642511	0.234465512	0.010025332	0.340315794	0	0.209964215	0.000273597	0.094817959	0.019942317	0.000915505	0.215064003	3.679617554	5.754191717	21.44277			
SCOTLAND	4.475756555	0.192446123	1.971114155	1.491412547	0.004313694	0.262529756	0.015170704	0.221022191	0.100714617	0.422416417	0.246455422	0.00316591	0.010103231	0.004532396	0.010913174	0.007523922	0.001192102	0.002593099	1.239248491	2.963197611	14.2462				
SOUTHEAST	1.632091717	0.064225927	0.643373243	1.84412497	0.002139776	0.002739712	0.005391999	0.027052174	0.029702739	0	0.042791414	0	0.009727299	0	0.015722099	0	0.003304474	0.003901294	2.016147337	2.190313127	1.642091				
VALES	2.322859495	0.016615945	0.571721462	0.746234155	0.001495245	0.000449451	0.031771257	0.203331044	0.000211017	0.010146132	0.000547194	0.231629099	0.002551335	0.005181375	0.007170104	0.002224491	0	0.000915505	0.455319742	0.724511700	1.152249023	1.8002217			
WESSER	1.033593203	0.169571617	0.201742727	0.914091476	0.000181202	0.035821637	0.007700211	0.002462375	0.040519346	0.052331553	0	0.003571576	0	0.076646066	0	0.00053E-05	0	1.95427E-05	0.05190313	0.457621232	2.03424894	1.374205			
WESTERN	1.629194591	0.024259274	2.259474231	1.424001403	0.163102299	0.020304819	5.8423E-05	0.011940059	0.042221719	0.025339943	0	0.070910954	0	0.258103231	0.000442427	0.002135972	0.001958433	0.002204995	0.357823243	1.306993222	2.439464419	10.12017			
TOTAL	22.1017593	0.24407593	16.70210917	5.544259491	1.345314555	0.30076144	0.370171117	0.752104119	1.034621279	1.064702335	0.995711713	1.71779372	0.004591704	0.029102199	0.029102199	0.029102199	0.029102199	0.029102199	0.029102199	1.972319514	15.11444514	24.11444514	100.0		
ROUNDED TO 2 DP	22.1	0.24	16.7	5.54	1.35	0.30	0.37	0.75	1.03	1.06	0.46	1.72	0.01	0.03	0.03	0.03	0.03	0.03	1.97	15.1	24.1	100.0			
	WOODLAND TOTAL	ARABLE	GRASSLAND TOTAL					FEN	SHRUB		BOG														
	5117,612.00		5170.12					0.75	1.03		0.46														
PIRELS	5117,612.00		5170.12																						
1HECTARE = 10000																									

Appendix F

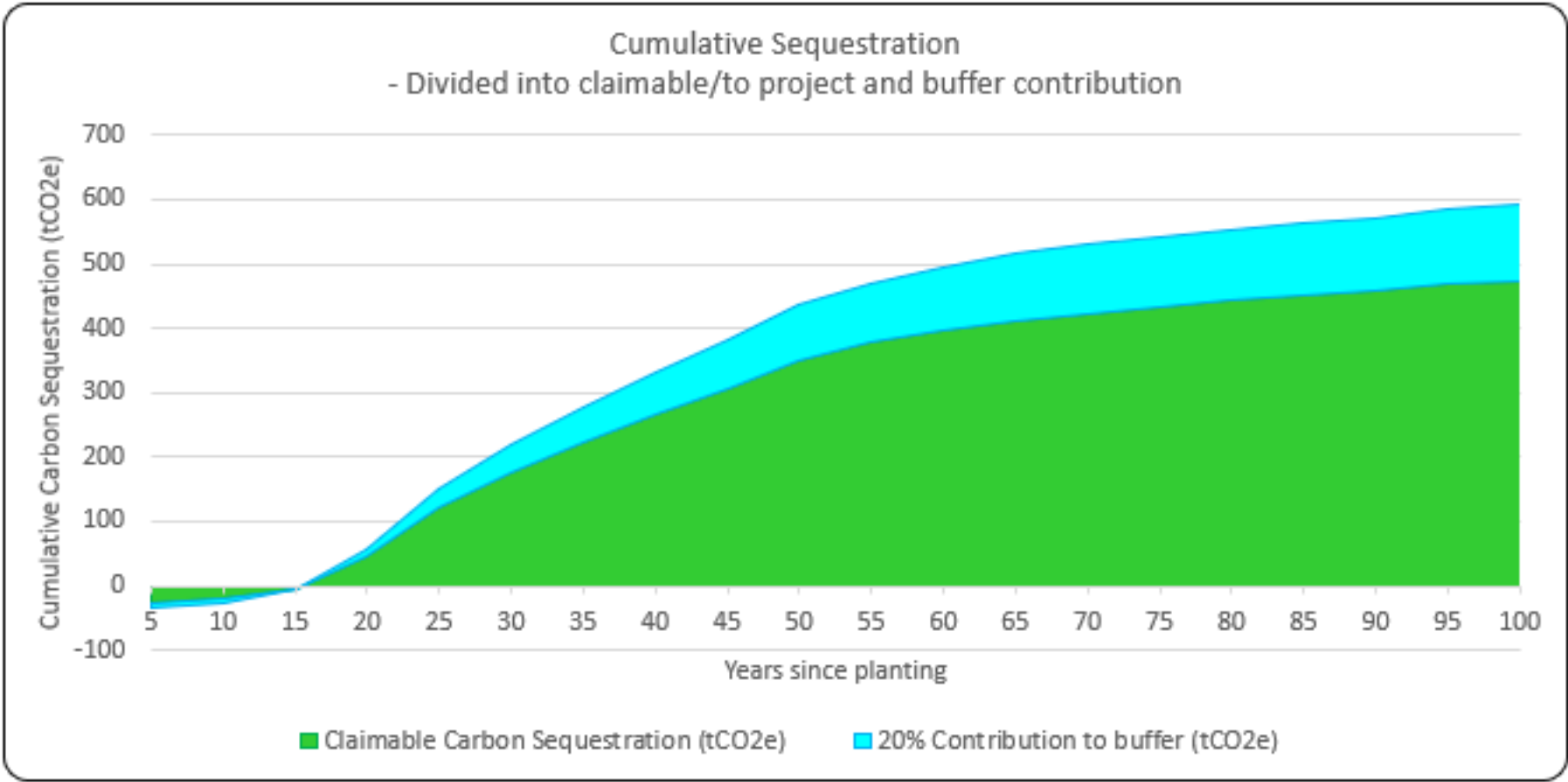
A	B	C	D	E	F	G	H	I	J	K	L
PIXEL COUNT											
	DECIDUOUS WOODLAND	CONIFEROUS WOODLAND	ARABLE	IMPROVED GRASSLAND	NEUTRAL GRASSLAND	CALCAREOUS GRASSLAND	ACID GRASSLAND	FEN, MARSH, SWAMP	DWARF SHRUB AND HEATH	HEATHER GRASSLAND	BOG
ENGLAND	45800	2167	77494	34983	5701	7	296	13552	2061	0	0
ENGLAND AND EAST MIDLAND	284182	1332	306261	78806	10287	162	520	4537	596	5022	1477
ENGLAND AND NORTH WALES	236119	3870	171044	87102	41374	3002	11016	141	3974	12099	513
SCOTLAND	229025	9873	101118	72478	237	0	18590	623	11668	31148	21615
SOUTH EAST	83510	3543	34201	53428	134	9324	140	4395	1896	1288	0
WALES	118847	740	34344	38089	2503	23	1626	14501	63	931	28
WESSEX	52885	8677	14775	50357	415	1833	87	126	27965	2681	0
WESTERN	83402	1753	115413	73143	8346	1039	3	611	4719	1312	0
TOTAL	1133770	31955	854650	488386	68997	15390	32278	38486	52942	54481	23633
METER SQUARE											
	DECIDUOUS WOODLAND	CONIFEROUS WOODLAND	ARABLE	IMPROVED GRASSLAND	NEUTRAL GRASSLAND	CALCAREOUS GRASSLAND	ACID GRASSLAND	FEN, MARSH, SWAMP	DWARF SHRUB AND HEATH	HEATHER GRASSLAND	BOG
ENGLAND	4580000	216700	7749400	3498300	570100	700	29600	1355200	206100	0	0
ENGLAND AND EAST MIDLAND	28418200	133200	30626100	7880600	1028700	16200	52000	453700	59600	502200	147700
ENGLAND AND NORTH WALES	23611900	387000	17104400	8710200	4137400	300200	1101600	14100	397400	1209900	51300
SCOTLAND	22902500	987300	10111800	7247800	23700	0	1859000	62300	1166800	3114800	2161500
SOUTH EAST	8351000	354300	3420100	5342800	13400	932400	14000	439500	189600	128800	0
WALES	11884700	74000	3434400	3808900	250300	2300	162600	1450100	6300	93100	2800
WESSEX	5288500	867700	1477500	5035700	41500	183300	8700	12600	2796500	268100	0
WESTERN	8340200	175300	11541300	7314300	834600	103900	300	61100	471900	131200	0
TOTAL	113377000	3195500	85465000	48838600	6899700	1539000	3227800	3848600	5294200	5448100	2363300
HECTARES											
	DECIDUOUS WOODLAND	CONIFEROUS WOODLAND	ARABLE	IMPROVED GRASSLAND	NEUTRAL GRASSLAND	CALCAREOUS GRASSLAND	ACID GRASSLAND	FEN, MARSH, SWAMP	DWARF SHRUB AND HEATH	HEATHER GRASSLAND	BOG
ENGLAND	458	21.67	774.94	349.83	57.01	0.07	2.96	135.52	20.61	0	0
ENGLAND AND EAST MIDLAND	2841.82	13.32	3062.61	788.06	102.87	1.62	5.2	45.37	5.96	50.22	14.77
ENGLAND AND NORTH WALES	2361.19	38.7	1710.44	871.02	413.74	30.02	110.16	1.41	39.74	120.99	5.13
SCOTLAND	2290.25	98.73	1011.18	724.78	2.37	0	185.9	6.23	116.68	311.48	216.15
SOUTH EAST	835.1	35.43	342.01	534.28	1.34	93.24	1.4	43.95	18.96	12.88	0
WALES	1188.47	7.4	343.44	380.89	25.03	0.23	16.26	145.01	0.63	9.31	0.28
WESSEX	528.85	86.77	147.75	503.57	4.15	18.33	0.87	1.26	279.65	26.81	0
WESTERN	834.02	17.53	1154.13	731.43	83.46	10.39	0.03	6.11	47.19	13.12	0
TOTAL	11337.70	319.55	8546.50	4883.86	689.97	153.90	322.78	384.86	529.42	544.81	236.33
PERCENTAGE OF GRAND TOTAL											
	DECIDUOUS WOODLAND	CONIFEROUS WOODLAND	ARABLE	IMPROVED GRASSLAND	NEUTRAL GRASSLAND	CALCAREOUS GRASSLAND	ACID GRASSLAND	FEN, MARSH, SWAMP	DWARF SHRUB AND HEATH	HEATHER GRASSLAND	BOG
ENGLAND	0.89503598	0.04234893	1.514438504	0.883660699	0.111412676	0.000136799	0.005784626	0.26484206	0.040277412	0	0
ENGLAND AND EAST MIDLAND	5.553670775	0.026030816	5.985153054	1.540078468	0.201035242	0.00316591	0.010162181	0.088665026	0.011647422	0.098143213	0.028864501
ENGLAND AND NORTH WALES	4.614392149	0.075630075	3.342653877	1.702204233	0.808557807	0.05866705	0.215281887	0.002755514	0.077662511	0.236446582	0.010025382
SCOTLAND	4.475756555	0.192944633	1.976114185	1.416412547	0.004631609	0	0.363297956	0.012175074	0.228023698	0.608714617	0.422414487
SOUTH EAST	1.632007117	0.069239627	0.668378343	1.04412497	0.002618716	0.182215715	0.002735972	0.085889969	0.037052874	0.02517094	0
WALES	2.322585915	0.014461565	0.671172942	0.744360185	0.048915265	0.000449481	0.031776357	0.28338804	0.001231187	0.018194212	0.000547194
WESSEX	1.033513308	0.169571617	0.288742727	0.984109476	0.008110202	0.035821637	0.001700211	0.002462375	0.546510346	0.052393858	0
WESTERN	1.62899651	0.034258274	2.255476438	1.429408413	0.163102998	0.020304819	5.8628E-05	0.011940562	0.092221789	0.025639963	0
TOTAL	22.15687593	0.62448554	16.70213007	9.544359091	1.348384565	0.30076146	0.630797817	0.752118619	1.034627239	1.064703385	0.461851565
ROUNDED TO 2 DP	22.16	0.62	16.70	9.54	1.35	0.30	0.63	0.75	1.03	1.06	0.46
	WOODLAND TOTAL	ARABLE	GRASSLAND TOTAL				FEN	SHRUB		BOG	
	22.78		16.70	12.89				0.75	1.03		0.46
10X10M PIXELS	5,117,012.00	511,701,200.00	51,170.12								
PIXELS	BY 100 - M2	DIVIDE BY 10000 - HECTARES									
1 HECTARE - 10000M2											

M	N	O	P	Q	R	S	T	U	V	W	X	Y
INLAND ROCK	SALTWATER	FRESHWATER	SUPRALITTORAL ROCK	SUPRALITTORAL SEDIMENT	LITTORAL ROCK	LITTORAL SEDIMENT	SALT MARSH	URBAN	BUILT UP AREAS AND GARDENS	SUM		
385	0	4283	0	205	0	1	5457	90558	77801	360751		
2275	1	43796	0	402	400	199	4132	226099	258509	1228995		
17414	0	10744	14	4855	560	47	11007	187895	294439	1097229		
12611	162	922	232	977	385	61	4738	65971	151663	734097		
2190	0	4870	0	802	0	480	5317	103194	133556	442268		
11853	170	1309	813	4642	117	47	49041	37058	92733	409478		
180	0	8733	0	2	0	1	2973	50506	104112	326308		
4043	0	13243	432	140	97	164	18310	66879	124837	517886		
50951	333	87900	1491	12025	1559	1000	100975	828160	1237650	5117012		
INLAND ROCK	SALTWATER	FRESHWATER	SUPRALITTORAL ROCK	SUPRALITTORAL SEDIMENT	LITTORAL ROCK	LITTORAL SEDIMENT	SALT MARSH	URBAN	BUILT UP AREAS AND GARDENS	SUM		
38500	0	428300	0	20500	0	100	545700	9055800	7780100	36075100		
227500	100	4379600	0	40200	40000	19900	413200	22609900	25850900	1.23E+08		
1741400	0	1074400	1400	485500	56000	4700	1100700	18789500	29443900	1.1E+08		
1261100	16200	92200	23200	97700	38500	6100	473800	6597100	15166300	73409700		
219000	0	487000	0	80200	0	48000	531700	10319400	13355600	44226800		
1185300	17000	130900	81300	464200	11700	4700	4904100	3705800	9273300	40947800		
18000	0	873300	0	200	0	100	297300	5050600	10411200	32630800		
404300	0	1324300	43200	14000	9700	16400	1831000	6687900	12483700	51788600		
5095100	33300	8790000	149100	1202500	155900	100000	10097500	82816000	123765000	5.12E+08		
INLAND ROCK	SALTWATER	FRESHWATER	SUPRALITTORAL ROCK	SUPRALITTORAL SEDIMENT	LITTORAL ROCK	LITTORAL SEDIMENT	SALT MARSH	URBAN	BUILT UP AREAS AND GARDENS	SUM		
3.85	0	42.83	0	2.05	0	0.01	54.57	905.58	778.01	3607.51		
22.75	0.01	437.96	0	4.02	4	1.99	413.2	2260.99	2585.09	12289.95		
174.14	0	107.44	0.14	48.55	5.6	0.47	110.07	1878.95	2944.39	10972.29		
126.11	1.62	9.22	2.32	9.77	3.85	0.61	47.38	659.71	1516.63	7340.97		
21.9	0	48.7	0	8.02	0	4.8	53.17	1031.94	1335.56	4422.68		
118.53	1.7	13.09	8.13	46.42	1.17	0.47	490.41	370.58	927.33	4094.78		
1.8	0	87.33	0	0.02	0	0.01	29.73	505.06	1041.12	3263.08		
40.43	0	132.43	4.32	1.4	0.97	1.64	183.1	668.79	1248.37	5178.86		
509.51	3.33	879.00	14.91	120.25	15.59	10.00	1009.75	8281.60	12,376.50	*****		
INLAND ROCK	SALTWATER	FRESHWATER	SUPRALITTORAL ROCK	SUPRALITTORAL SEDIMENT	LITTORAL ROCK	LITTORAL SEDIMENT	SALT MARSH	URBAN	BUILT UP AREAS AND GARDENS	SUM		
0.007523922	0	0.083701191	0	0.004006244	0	1.95427E-05	0.106644268	1.769743749	1.520438099	7.050032		
0.04445954	1.95427E-05	0.85890117	0	0.007356147	0.007817062	0.003889988	0.08075025	4.418574746	5.051952194	24.01793		
0.340315794	0	0.209966285	0.000273597	0.09487959	0.010943887	0.000918505	0.215106003	3.671967156	5.754119787	21.44277		
0.246452422	0.00316591	0.018018328	0.004533896	0.019093174	0.007523922	0.001192102	0.092593099	1.289248491	2.962897681	14.2462		
0.042798414	0	0.09517273	0	0.015673209	0	0.009380474	0.103908296	2.016684737	2.610038827	8.643091		
0.231639089	0.003322251	0.025581335	0.015888178	0.090717004	0.002286491	0.000918505	0.958391342	0.724211708	1.812249023	8.002287		
0.003517678	0	0.170666006	0	3.90853E-05	0	1.95427E-05	0.058100313	0.987021332	2.034624894	6.376925		
0.079010954	0	0.25880338	0.008442427	0.002735972	0.001895638	0.003204995	0.357826013	1.306993222	2.439646419	10.12087		
0.995717813	0.006507704	1.717799372	0.029138099	0.235000426	0.030466999	0.019542655	1.973319586	16.18444514	24.18696693	100		
1.00	0.01	1.72	0.03	0.24	0.03	0.02	1.97	16.18	24.19	100.00		

Project Name:			Small mixed native woodland
Calculation Completed by:			Tracey Navaei
Date calculation completed:			15-Jan-24
Project Start Date (date planting was completed)			01-Jan-25
Country			England
If in England, applying for Woodland Carbon Guarantee?			Please select
If in the Guarantee, 10-yearly or 5-yearly verifications?			Please select
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)			0.50
Net area Broadleaf thinned (ha)			0.00
Net area Conifer minimum intervention / no thinning (ha)			0.50
Net area Conifer thinned (ha)			0.00
Total net planting area (ha)			1.00
Total Emissions from establishment		tCO₂e/ha	tCO₂e
		-2.23	-2.23
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Arable	
Site Preparation Technique		Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost		10	
Soil C emissions from site prep	Area (ha)	tCO₂e/ha	tCO₂e
Total soil carbon emissions	1.00	-33.0	-33.0

**** NOTE** The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

494



Appendix F

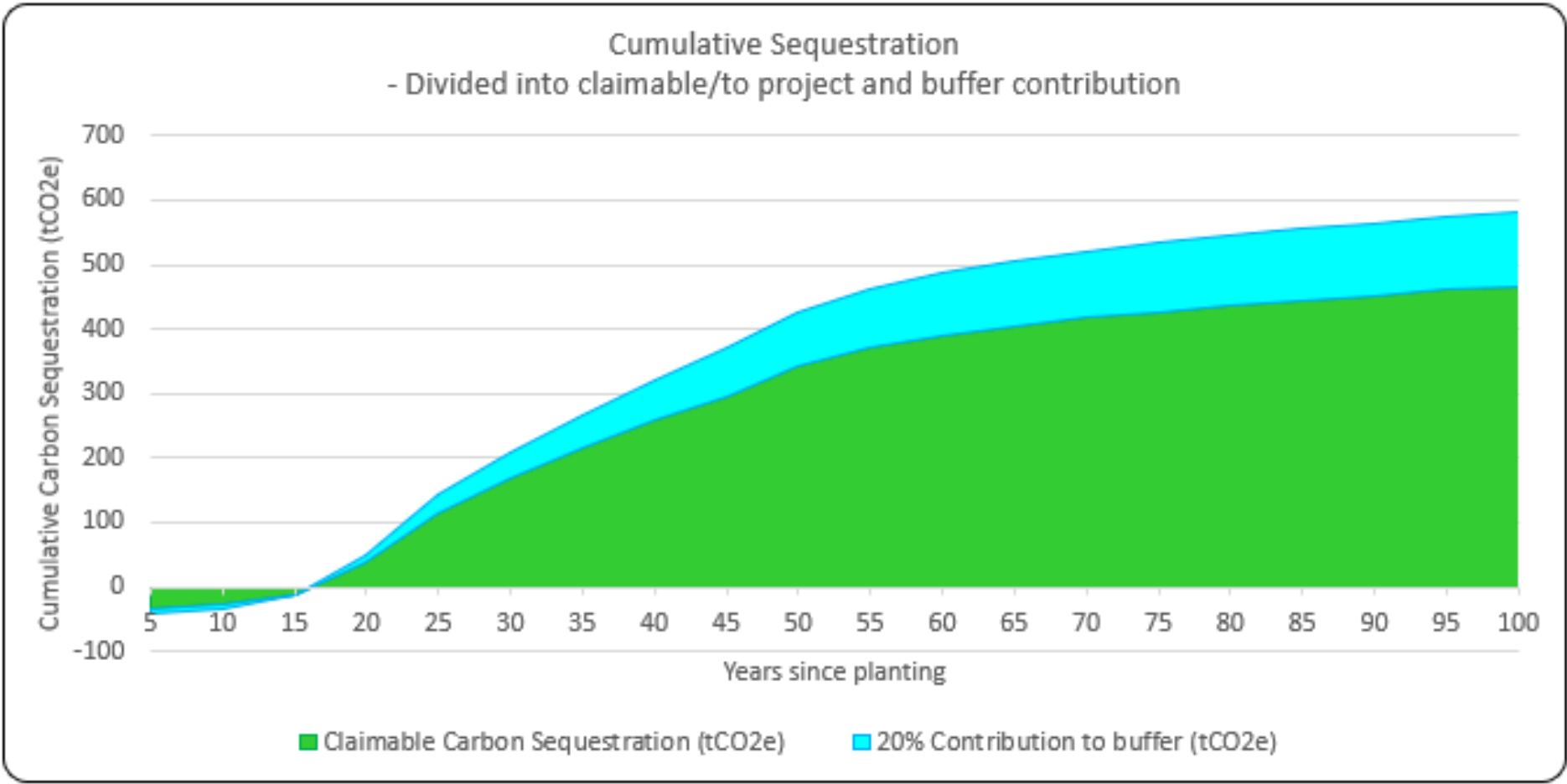
Grassland offset 1ha

Project Name:			Small mixed native woodland
Calculation Completed by:			Tracey Navaei
Date calculation completed:			15-Jan-24
Project Start Date (date planting was completed)			01-Jan-25
Country			England
If in England, applying for Woodland Carbon Guarantee?			Please select
If in the Guarantee, 10-yearly or 5-yearly verifications?			Please select
Project Basics			
Management & Species			
Net area Broadleaf minimum intervention / no thinning (ha)			0.50
Net area Broadleaf thinned (ha)			0.00
Net area Conifer minimum intervention / no thinning (ha)			0.50
Net area Conifer thinned (ha)			0.00
Total net planting area (ha)			1.00
Total Emissions from establishment	tCO ₂ e/ha	tCO ₂ e	
	-2.23	-2.23	
Soil type, previous landuse and establishment technique			
Soil Type		Organomineral	
Previous Landuse		Pasture	
Site Preparation Technique		Medium Disturbance: Shallow/rotary (<30cm) plough, Disc/line scarification/continuous mounding	
% Topsoil Carbon Lost		10	
Soil C emissions from site prep	Area (ha)	tCO ₂ e/ha	tCO ₂ e
Total soil carbon emissions	1.00	-42.2	-42.2

Sectn No:	Actual Species	Actual Spacing (m)	Management Regime	% of Area if mixture	Area (ha)
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Select Species	0.0	Select Mgmt Regime	0.00%	0.00
	Woody Shrubs	Specify Species here		0.00%	0.00
Total Area				0.0%	0.00

** NOTE The species mix table is not required to complete a small woods calculation, but it is required as a record of the species mix of the project to complete validation.

Sequestn to year	Total project carbon sequestration (tCO ₂ e)	20% risk buffer (tCO ₂ e)	Total claimable carbon sequestration (tCO ₂ e)	Average total claimable sequestration per hectare by year x (tCO ₂ e/ha)
5	-42	-8	-34	-34
10	-35	-7	-28	-28
15	-14	-3	-11	-11
20	48	10	38	38
25	142	28	114	114
30	209	42	167	167
35	268	54	214	214
40	322	64	258	258
45	371	74	297	297
50	427	85	342	342
55	462	92	370	370
60	487	97	390	390
65	506	101	405	405
70	521	104	417	417
75	534	107	427	427
80	545	109	436	436
85	555	111	444	444
90	563	113	450	450
95	576	115	461	461
100	582	116	466	466



F.12 Calculation of 25 Year NR Carbon Footprint

The below table was used to calculate the 25 year NR Carbon Footprint based on NR Scope 3 Reduction Routemap

Control Period	Year	Reduction from Baseline	tCO ₂ e
CP5	2019-2024	Baseline	8,071,000
CP6	2024	25% reduction	6,053,250
	2025	25% reduction	6,053,250
	2026	25% reduction	6,053,250
	2027	25% reduction	6,053,250
	2028	25% reduction	6,053,250
CP7	2029	46% reduction	4,358,340
	2030	46% reduction	4,358,340
	2031	46% reduction	4,358,340
	2032	46% reduction	4,358,340
	2033	46% reduction	4,358,340
CP8	2034	65% reduction	2,824,850
	2035	65% reduction	2,824,850
	2036	65% reduction	2,824,850
	2037	65% reduction	2,824,850
	2038	65% reduction	2,824,850
CP9	2039	79% reduction	1,694,910
	2040	79% reduction	1,694,910
	2041	79% reduction	1,694,910
	2042	79% reduction	1,694,910
	2043	79% reduction	1,694,910
CP10	2044	90% reduction	807,100
	2045	90% reduction	807,100
	2046	90% reduction	807,100
	2047	90% reduction	807,100
	2048	90% reduction	807,100
CP11	2049	98% reduction	161,420
	2050	100% reduction	0
		Total carbon over 25 years	86,924,670

F.13 Climate Change Adaptation

Independent assessment of the CCRA3 outlines the highest priorities for adaption over the next two years, with biodiversity, soil, land management, and green finance all being inextricably interwoven issues. The risks to carbon stores and sequestration rates from multiple hazards could lead to carbon stores which have accrued over many decades being lost in a relatively short period of time (Climate Change Committee, 2021, p.12). Action now on the adaption risks will be cheaper in the long run

then dealing with the consequences of inaction (Climate Change Committee, 2021, p.11). NR are acting in line with this advice as part of their WRACCA strategy and repairs on the network are better-for-like rather than like-for-like (Network Rail, 2017c, p.1). Better choice of species in tree planting, using the right trees in the right place, is pivotal to increasing the sequestration ability of nature. Other factors in line with this include; peatland maintenance and restoration, where viable and practicable, and soil carbon monitoring. Current and forthcoming government policies providing guidance to combat both climate change and the Net Zero by 2050 commitment, include:

- “England – Net Zero Strategy, Environmental Land Management Scheme, Soil Health Action Plan, Green Finance Strategy and funding measures (e.g. Sovereign Green Bond), England Trees Action Plan, England Peat Action Plan.
- Northern Ireland – Sustainable Agricultural Land Management Strategy.
- Scotland – Soil and Nutrient Network, Farm Advisory Strategy.
- Wales – Sustainable Farming and Our Land Strategy.”

(Climate Change Committee, 2021, p.17)

Trees, wetlands and peatbogs need to be revived and maintained. Without additional assistance these natural resources will not be able to sequester carbon to aid in meeting climate goals, especially in the face of a rapidly changing climatic conditions (Climate Change Committee, 2021, p.5). Peatlands are of particular interest, with estimates of storage levels the equivalent of 25 times that of UK total current annual emissions (some 11,700 MtCO₂ ± 1,100) and an order of magnitude larger than the carbon stored in trees (Climate Change Committee, 2021, p.17). NR land assets include bogs which account for 0.46% and fen, marsh and swamp which account for 0.75%. These small percentages, due to their vast carbon storage potential, may prove to be significant.

F.14 Proctor Lecture Payback Times

The below table illustrates payback times for differing embankment types and was constructed for W Powrie for the Proctor lecture.

Modal Shift Travel Types to Rail		19.02.24						
Travel Type	Scopes	EF in g	Emission Factor per passenger km or km	Carbon Saving between Travel Type and National Rail	Carbon Saving per day/m for Historic Embankment 144 trains x 400 passengers	Carbon Saving per day/m for Highly Engineered Embankment 288 trains x 600 passengers	Carbon Payback Time days	OPTION B
					144	288	Highly Engineered Embankment Include Berms	Payback time Highly Engineered inc Berms
					400	600	44,534 kgCO ₂ e/m	years
					1000	1000	44534	
National Rail	WTT & Upstream Scope 3	44.433	0.044433	0	0	0	0	
Domestic Air with RF	WTT & Scope 3 impact of flight fuel	306.08	0.30608	0.261647	15.0708672	45.2126016	984.9908748	2.698605136
Domestic Air without RF	WTT & Scope 3 impact of flight fuel	194.49	0.19449	0.150057	8.6432832	25.9298496	1717.480074	4.705424859
Diesel Car	Scope 1&3	211.28	0.21128	0.166847	9.6103872	28.8311616	1544.648135	4.231912699
Petrol Car	Scope 1&3	209.42	0.20942	0.164987	9.5032512	28.5097536	1562.061904	4.279621656
PHEV	All Scopes	117.84	0.11784	0.073407	4.2282432	12.6847296	3510.83558	9.618727616
BEV	All Scopes	66.95	0.06695	0.022517	1.2969792	3.8909376	11445.57034	31.35772697
Original train seat		12	0.012	0				
Original Car seat		20	0.02	0.008	0.4608	1.3824	32214.98843	88.26024226

F.14.1 Assumptions for Proctor Lecture Payback Times

Proctor Lecture William Powrie Carbon Calcs:

Assumptions for RSSB RCT based on below (18.05.21 and revised payback times 09.10.23, new option D highly engineered Including Berms Excluding Piles)

Assumptions: Historic Embankment – OPTION A

<i>Material/Process Description</i>	<i>Convert to kg/hrs work</i>	<i>Material/Plant Choice in RSSB Tool</i>
Historic Embankment Initial Construction: Materials only		
90m3 of general soil per m run of embankment	Assumed sandy soil at 1800kg/m3 = 162,000kg = 162 tonnes	Waste construction soils
Historic Embankment Initial Construction: Processes only		
Excavation of 90m3 of soil	1 hour assumed	Large Excavator 16-25t: Diesel Engine 38kW/51.7hp
Transport of 90m3 of soil 1km	6 hours assumed	Articulated Dump Truck 20-30t: Diesel Fuel
Compaction of 90m3 of soil	6 hours assumed	COM-2 Compactor: Diesel Engine 41kW/55.7hp
Historic Embankment First Lifetime Major Maintenance: Materials only		

Appendix F

+ 20% of material at first lifetime compaction = 18m ³	18m ³ x 1800kg/m ³ = 32,400kg = 32.4t	Waste construction soils

Historic Embankment First Lifetime Major Maintenance: Processes only		
Excavation of 18m ³ of soil	1 hour assumed	Large Excavator 16-25t Diesel Engine 38kW/51.7hp
Transport of 18m ³ of soil 1km	1 hour assumed	Articulated Dump Truck 20-30t Diesel Fuel
Compaction of 18m ³ of soil at first lifetime compaction	1 hour assumed	COM-2 Compactor Diesel Engine 41kW/55.7hp
Historic Embankment Second Lifetime Major Maintenance: Materials only		
+ 20% of material at first lifetime compaction = 18m ³	18m ³ x 1800kg/m ³ = 32,400kg = 32.4t	Waste construction soils
Historic Embankment Second Lifetime Major Maintenance: Processes only		
Excavation of 18m ³ of soil	1 hour assumed	Large Excavator 16-25t: Diesel Engine 38kW/51.7hp
Transport of 18m ³ of soil 1km	1 hour assumed	Articulated Dump Truck 20-30t: Diesel Fuel
Compaction of 18m ³ of soil at first lifetime	1 hour assumed	COM-2 Compactor: Diesel Engine 41kW/55.7hp

Soil Density: Sandy Soil 1800kg/m³, Clay soil 1900kg/m³, Gravel soil 2000kg/m³, Sandstone 2000kg/m³

Assumptions: Modern Embankment Excluding Berms - OPTION B

<i>Material/Process Description</i>	<i>Convert to kg/hrs work</i>	<i>Material/Plant Choice in RSSB Tool</i>
Modern Embankment excluding berms: Materials only		
97.5m ³ of high grade fill per m run of embankment	Assumed limestone at 2,711 kg/m ³ = 264,322.5kg = 264.32 tonnes	Assumed limestone (general limestone chosen – however there is an option for ground limestone should you wish)
50m ³ of general soil per m run of embankment	Assumed rammed soil at 1600kg/m ³ = 80,000 kg = 80 tonnes	Assumed rammed soil – (however a couple of other choices here – GGBS stabilised soil or fly ash stabilised soil)
6.5087m ³ reinforced concrete per m run of embankment [Reinforced concrete piles – 0.36m diameter, length 6m (vol = $3.14 \times 0.18 \times 0.18 \times 6$) = 0.610m ³ , 10.67 rigid inclusions per m length of embankment = $0.610 \times 10.67 = 6.5087\text{m}^3$]	Assumed reinforced concrete at 2,400kg/m ³ = 15,620.88kg	Assumed reinforced concrete – precast beams and column, steel reinforced
16.8 m ³ Load transfer platform 0.6 m thick, material class 6C SHW, [so 28 m x 0.6 m = 16.8 m ³ per m run of the embankment]	Assumed aggregates general at 2,200kg/m ³ = 36,960 kg	Assumed aggregates and sand – typical UK mix

18 m2 per m run of the embankment of geogrid reinforcement: [Tr> 520 kN/m for longitudinal direction and Tr> 984 kN/m for transversal direction across the width, so 18 m2 per m run of the embankment]	Struggling to find geo grids with these tensile strengths to pull a conversion factor off for the grid weight therefore plastic density of 920kg/m3 used here, Convert m2 of material into m3 from tensar geogrids weight per m2 assumed 1kg = 18kg here	Assumed plastics general as worst case carbon factor compared to polypropylene or polyethylene
Modern Embankment excluding berms: Processes only		
Transport of 97.5m3 of high grade fill to site	Assumed 30km travel to site on rigid hgv for 264 tonnes	Road freight HGV >17t average load
Transport of 50m3 of soil to site	Assumed 30km travel to site on rigid hgv for 80 tonnes	Road freight HGV >17t average load
Transport of 6.5087m3 of reinforced concrete to site	Assumed 30km travel to site on rigid hgv for 15.62 tonnes	Road freight HGV >17t average load
Transport of 16.8m3 of load transfer platform to site	Assumed 30km travel to site on rigid hgv for 36.96 tonnes	Road freight HGV >17t average load
Transport of 18m2 of geogrid to site	Assumed 30km travel to site on rigid hgv for 0.018 tonnes	Road freight HGV >17t average load
Compaction of 97.5m3 of high grade fill	6 hours assumed	COM-2 Compactor

		Diesel Engine 41kW/55.7hp
Compaction of 50m ³ of soil	2 hours assumed	COM-2 Compactor Diesel Engine 41kW/55.7hp
Installation of reinforced concrete - Drilling of hole for piling -	10.67 rigid inclusions per m length of embankment, each 6m length = 10.67 x 6m depth of holes to be drilled = 64.02m of drilling per m length of embankment	Pile Rig – Driller Diesel Engine 38kW/51.7hp (engine size as recommended by carbon tool for Pile Rig - Driller)
Installation of load transfer platform Compaction of 16.8 m ³ of fill	1 hour assumed	COM-2 Compactor Diesel Engine 41kW/55.7hp
Installation of geogrid – compactor assumed appropriate machinery for this process	Assumed 15 min for 1m ² of geogrid and 18m ² of grid on 1m section of embankment	Assumed compacting machinery after fill laid on top of grid COM-2 Compactor Diesel Engine 41kW/55.7hp

Assumptions: Modern Embankment Including Berms – OPTION C

Material/Process Description	Convert to kg/hrs work	Material/Plant Choice in RSSB Tool
Modern Embankment including berms: Materials only		
97.5m ³ of high grade fill per m run of embankment	Assumed limestone at 2,711 kg/m ³ = 264,322.5kg = 264.32 tonnes	Assumed limestone (general limestone chosen – however there is an option for ground limestone should you wish)
242m ³ of general soil per m run of embankment [50m ³ of general soil per m run of embankment + berms = 192m ³ of general soil per m run of embankment]	Assumed rammed soil at 1600kg/m ³ = 387,200 kg= 387.2 tonnes	Assumed rammed soil – (however a couple of other choices here – GGBS stabilised soil or fly ash stabilised soil)
6.5087m ³ reinforced concrete per m ³ run of embankment: [Reinforced concrete piles – 0.36m diameter, length 6m (vol = 3.14 x 0.18x0.18 x 6) =0.610m ³ 10.67 rigid inclusion per m length of embankment = 0.610 x 10.67 = 6.5087m ³]	Assumed reinforced concrete at 2,400kg/m ³ = 15,620.88kg	Assumed reinforced concrete – precast beams and column, steel reinforced
16.8 m ³ Load transfer platform 0.6 m thick, material class 6C SHW, [so 28 m x 0.6 m = 16.8 m ³ per m run of the embankment]	Assumed aggregates general at 2,200kg/m ³ = 36,960 kg	Assumed aggregates and sand – typical UK mix

18 m2 per m run of the embankment of geogrid reinforcement: [Tr> 520 kN/m for longitudinal direction and Tr> 984 kN/m for transversal direction across the width, so 18 m2 per m run of the embankment]	Struggling to find geo grids with these tensile strengths to pull a conversion factor off for the grid weight therefore plastic density of 920kg/m3 used here: Convert m2 of material into m3 from tensar geogrids weight per m2 assumed 1kg = 18kg here	Assumed plastics general as worst case carbon factor compared to polypropylene or polyethylene
Modern Embankment including berms: Processes only		
Transport of 97.5m3 of high grade fill to site	Assumed 30km travel to site on rigid hgv for 264 tonnes	Road freight HGV >17t average load
Transport of 242m3 of soil to site	Assumed 30km travel to site on rigid hgv for 387.2 tonnes	Road freight HGV >17t average load
Transport of 6.5087m3 of reinforced concrete to site	Assumed 30km travel to site on rigid hgv for 15.62 tonnes	Road freight HGV >17t average load
Transport of 16.8m3 of load transfer platform to site	Assumed 30km travel to site on rigid hgv for 36.96 tonnes	Road freight HGV >17t average load
Transport of 18m2 of geogrid to site	Assumed 30km travel to site on rigid hgv for 0.018 tonnes	Road freight HGV >17t average load
Compaction of 97.5m3 of high grade fill	6 hours assumed	COM-2 Compactor

Appendix F

		Diesel Engine 41kW/55.7hp
Compaction of 242m ³ of soil	10 hours assumed	COM-2 Compactor Diesel Engine 41kW/55.7hp
Installation of reinforced concrete - Drilling of hole for piling -	10.67 rigid inclusions per m length of embankment, each 6m length = 10.67 x 6m depth of holes to be drilled = 64.02m of drilling per m length of embankment	Pile Rig – Driller Diesel Engine 38kW/51.7hp (engine size as recommended by carbon tool for Pile Rig - Driller)
Installation of load transfer platform Compaction of 16.8 m ³ of fill	1 hour assumed	COM-2 Compactor Diesel Engine 41kW/55.7hp
Installation of geogrid – compactor assumed appropriate machinery for this process	Assumed 15 min for 1m ² of geogrid and 18m ² of grid on 1m section of embankment	Assumed compacting machinery after fill laid on top of grid COM-2 Compactor Diesel Engine 41kW/55.7hp

Assumptions: Modern Embankment Including Berms Excluding Piles– OPTION D

Material/Process Description	Convert to kg/hrs work	Material/Plant Choice in RSSB Tool
Modern Embankment including berms excluding piles: Materials only		
97.5m ³ of high grade fill per m run of embankment	Assumed limestone at 2,711 kg/m ³ = 264,322.5kg = 264.32 tonnes	Assumed limestone (general limestone chosen – however there is an option for ground limestone should you wish)
242m ³ of general soil per m run of embankment [50m ³ of general soil per m run of embankment + berms = 192m ³ of general soil per m run of embankment]	Assumed rammed soil at 1600kg/m ³ = 387,200 kg= 387.2 tonnes	Assumed rammed soil – (however a couple of other choices here – GGBS stabilised soil or fly ash stabilised soil)
16.8 m ³ Load transfer platform 0.6 m thick, material class 6C SHW, [so 28 m x 0.6 m = 16.8 m ³ per m run of the embankment]	Assumed aggregates general at 2,200kg/m ³ = 36,960 kg	Assumed aggregates and sand – typical UK mix
18 m ² per m run of the embankment of geogrid reinforcement: [Tr> 520 kN/m for longitudinal direction and Tr> 984 KN/m for transversal direction across the width, so 18 m ² per m run of the embankment]	Struggling to find geo grids with these tensile strengths to pull a conversion factor off for the grid weight therefore plastic density of 920kg/m ³ used here: Convert m ² of material into m ³ from tensar geogrids weight per m ² assumed 1kg = 18kg here	Assumed plastics general as worst case carbon factor compared to polypropylene or polyethylene

Modern Embankment including berms excluding piles: Processes only		
Transport of 97.5m3 of high grade fill to site	Assumed 30km travel to site on rigid hgv for 264 tonnes	Road freight HGV >17t average load
Transport of 242m3 of soil to site	Assumed 30km travel to site on rigid hgv for 387.2 tonnes	Road freight HGV >17t average load
Transport of 16.8m3 of load transfer platform to site	Assumed 30km travel to site on rigid hgv for 36.96 tonnes	Road freight HGV >17t average load
Transport of 18m2 of geogrid to site	Assumed 30km travel to site on rigid hgv for 0.018 tonnes	Road freight HGV >17t average load
Compaction of 97.5m3 of high grade fill	6 hours assumed	COM-2 Compactor Diesel Engine 41kW/55.7hp
Compaction of 242m3 of soil	10 hours assumed	COM-2 Compactor Diesel Engine 41kW/55.7hp
Installation of load transfer platform Compaction of 16.8 m3 of fill	1 hour assumed	COM-2 Compactor Diesel Engine 41kW/55.7hp
Installation of geogrid – compactor assumed appropriate machinery for this process	Assumed 15 min for 1m2 of geogrid and 18m2 of grid on 1m section of embankment	Assumed compacting machinery after fill laid on top of grid COM-2 Compactor

		Diesel Engine 41kW/55.7hp

General Assumptions for all Footprints

All figures based on 1m run of embankment.

All footprints **exclude** transport of staff to site, transport of plant to site, transport of waste from site, and embodied carbon in plant.

Results for 4 Differing Embankments

OPTION A Carbon Footprint for Historic Embankment inc 2 lifetime maintenance 1,122 kgCO₂e

OPTION B Carbon Footprint for New style embankment excluding Berms 34,926 kgCO₂e

OPTION C Carbon Footprint for New style embankment including Berms 44,534 kgCO₂e

OPTION D Carbon Footprint for New style embankment including Berms Excluding Piles 38,546 kgCO₂e

Appendix F

Original Payback time calculations 2021

Obviously one could play all sorts of tunes - arguably this is a best case scenario in assuming all seats are occupied (although this is the same for the cars also) and that no new journeys are created.

A very heavily trafficked railway could have say 12 trains per hour for 12 hours a day. In both directions so that would be 288 trains per day. And maybe 600 passengers on each

So the daily saving would be

$288 \times 600 \times 0.008 = 1382 \text{ kg per day (for a 1 km run). } 1.3824 \text{ kg per day per metre.}$

I think your total was 44534 kg per metre – so the payback time would be 32200 days or 88 years.

Using your figs 12g train seat, 20g car seat does give you a large payback figure, 88 years! The difference in these two figures, 8g CO₂e, being used to calculate the payback period.

However, as the parameters of all of this data are slightly ambiguous (ie does it include embedded carbon for the cars' or trains' manufacture etc), I would use them with caution, as from the below calculations you can see that this difference does vary widely and can give greatly varying results.

See below for how the payback period looks using RSSB figures and DEFRA 2020 figures for comparison, FYI.

50g rail passenger journey, 230g car journey gives 180g difference CO₂e = 4 years payback figure.
(RSSB tool)

36.94g rail passenger journey, 174.3g car journey gives 137.36g difference CO₂e = 5 years payback figure. (DEFRA 2020 figures)

Payback Times calculated using RSSB tool and DEFRA

Using RSSB tool figs to calculate payback period - based on DEFRA Cars all scope 2018

0.05 CO₂e kg /km for rail journey via national rail

0.23 CO₂e kg /km for a petrol car

$0.23 - 0.05 = 0.18$ Co₂e kg/ km

$288 \times 600 \times 0.18 = 31,104$ kg Co₂e per day (for a 1 km run)

= 31.104 kg Co₂e per day per m

Embankment with Berms 44,534 CO₂e kg per m / 31.104 = 1,431 days = 4 years payback period

See also the attached download I found online regarding transport CO₂ figures FYI, which appear to be more in line with the RSSB figures, ***Grams_CO2_transportmodesUK.pdf***

Using DEFRA conversion factors 2020 to calculate payback period

Business Travel Land – National 0.03694 kg CO₂e passenger km

Passenger vehicles – avg car petrol 0.1743 kg CO₂e km

$288 \times 600 \times 0.14 = 24,192$ kg Co₂e per day (for a 1 km run)

= 24.192 kg Co₂e per day per m

Embankment with Berms 44,534 CO₂e kg per m / 24.192 = 1,840 days = 5 years payback period

See also the attached DEFRA 2020 figures where I obtained this information,

Conversion_Factors_2020_-_Condensed_set_for_most_users_.xlsx

Revised Payback/modal shift figures 2023

1km domestic air with RF 0.27258 kgCO₂ per passenger.km (includes for indirect effects on non-CO₂ emissions eg water vapour, contrails NO_x) (70% increase) + WTT business travel air (scope 3 impact of the flight fuel) = 0.03350 = 0.27258+0.03350 = xxxx0.30608

Appendix F

1km (business travel air(domestic air without RF 0.16099 kg co2e per passenger km + WTT business travel air 0.03350=0.19449

1km Petrol scope 1 and 3 =0.20942

1km Diesel scope 1 and 3 = 0.21128

1km BEV all scopes 0.06695

1km PHEV all scopes 0.11784

0.044433 co2 kg/km rail national rail

0.20942 kg/km petrol car

See “carbon payback figs table for proctor lecture for WP 190224.Xls” for calculations of payback times for each embankment type.

F.15 Overview of NETs, CDR and NbS

UN Secretary-General António Guterres (2020) specifically discusses AR, and its potential implications for climate mitigation, in the 2030 UN Agenda. UN Secretary-General António Guterres (2020) states that NbS “could provide one third of the net reductions in GHGs required to meet the goals of the Paris Agreement” (UN Secretary-General António Guterres, 2020), indicating the importance of embracing these solutions to contribute towards climate mitigation. This advocacy of use of NbS to drive down carbon emissions is highlighted again in “The Ten Point Plan for a Green Industrial Revolution,” (HM Government, 2021e), making specific reference to NbS to achieve net zero carbon emissions by 2050 for the UK.

Positive and negative benefits of the six major offsets, presented using RAG ratings, are given in Appendix F.1, amended from McGeever *et al.* (2019, p.3) for Ireland, considered a suitable UK comparator, and from the performance of NETs amended from Rueda *et al.* (2021) to rationalise the choice of offsetting used, AR and EW.

Appendix F.1 highlights the very high readiness level of AR, meaning quick implementation will be possible. Furthermore, it shows the medium carbon removal, readiness, costs and vulnerability to re-release for EW compared to the high vulnerability found in SCS to re-release and high biodiversity risk in BECCS.

From the wide variety of offsets available and compared in terms of low to high vulnerabilities and penalties, in-depth analysis conducted in several prominent reviews, including Rueda *et al.* (2021),

concludes that inexpensive options tend to offer more positive environmental impacts (Rueda *et al.*, 2021, p.6). Low-cost measures such as AR alone being implemented in the 2020s provides a good mid-point solution, providing steady negative emissions from the 2040s through to the 2070s, then tailing off, highlighting the transient nature of AR, once stocks are built, they will need replenishing to remain into perpetuity.

An effective NET such as EW alone, which requires technological support today for future deployment at the end of the 2030s, shows a steep climb in negative emissions up to the 2050s and then a steady upward trajectory past 2100 (Rueda *et al.*, 2021, p.7), indicating that timely NET deployment is essential (Rueda *et al.*, 2021, p.5). A portfolio preference for sustainability favours use of natural solutions such as AR, Soil Organic Carbon (SOC) and biochar with DACCS. Portfolios to enhance climate change effectiveness favour the engineered solutions of EW, BECCS and DACCS to meet the same negative emissions need. The higher negative emissions needs are only fulfilled by a diverse portfolio encompassing all available natural and engineered solutions (Rueda *et al.*, 2021, p.10).

CO₂ sequestration can be classified by storage location, divided by ocean, geological (stored deep in the earth), biological (via trees, plants and other vegetation) and mineral sequestration routes (Yadav and Mehra, 2021). The NETs sit within these groups. Using these groupings a comparison of the positive and negative issues including examples surrounding different CO₂ sequestration routes is presented in Appendix F.2.

Appendix F.2 indicates the scale of storage available via the differing routes along with details of a variety of positive and negative issues aligned to these differing storage locations. The far greater mitigation potential of AR (biological storage) and avoided forest loss compared to other natural solutions (European Academies Science Advisory Council, 2019) highlights this as a suitable choice for carbon sequestration in the case studies. This is in addition to the AR choice being feasible owing to it being currently technically ready for large-scale deployment (with AR currently being the “conventional” CDR deployed on land (Smith *et al.*, 2023, p.8)), however their permanence is classified as reversible (Minx *et al.*, 2018, p.12), see Section 6.2.2.

Alongside AR, an alternative approach of mineral carbonation via EW is provided as a viable alternative owing to the abundance of feedstock and permanence alongside examples in the literature pointing towards carbon offset use adjacent to trackside (Kolosz *et al.*, 2017). EW is chosen as an alternative offset method as, although EW is a more novel method of CDR (or a “more speculative option” (Climate Change Committee, 2020b)) and only accounts for a tiny fraction of current CDR deployment (Smith *et al.*, 2023, p.8). Application of EW in ballast could have great potential given its ubiquitous use throughout the NR network (in addition to EW in the offset area

adjacent to trackside). There is limited evidence of ballast being tested for this purpose found in the literature (Delatares, 2021). In a feasibility report on use of olivine as ballast for railways dunite/olivine has been used by the Spanish railway (ADIF) for new HSR routes and for maintenance, and in the Netherlands it has been used for inspection paths along the railway line (Delatares, 2021). Delatares (2021) concluded using their modelling “One ton (1000 kg) of olivine as ballast material, applied to the track bed, will have captured approximately 40 kg of CO₂ over a period of 2 to 3 decades” (Delatares, 2021, p.15). Use of EW in footpaths, pavements and soil amendments has also been advocated in Vink and Knops (2023).

EW is classified as having stable permanence, with the technical readiness limitation being that of limited mineral production (Minx *et al.*, 2018, p.12). This mineral carbonation route has the highest storage potential of the four sequestration routes, see Appendix F.2, with permanence further discussed in Section 6.2.2. For net zero purposes, use of AR and EW is applied in this thesis to “offset” residual emissions in the case studies following mitigation via materials, transport and construction areas, with SCS including LULUC being aligned to AR implementation, see below and Section 6.2.1.

SCS is aligned with AR as it intrinsically linked with the above ground carbon stocks and will be overviewed later along with LULUC which again aligns with AR principles such as changing scrub land to forested land. DACCS and OF are specifically excluded from further exploration here as their deployment by NR would include additional infrastructure, and hence further carbon emissions. BECCS and BC are similarly excluded due to the large land quantities potentially required for their implementation, and the possibility of this large land requirement impinging on agricultural land or land required to meet biodiversity targets.

F.15.1 Afforestation and Reforestation (AR)

Here forest area and diversity of planting are discussed, followed by LULUC. See Appendix F.3 for further details of peatlands and grasslands.

The UK has great potential to adopt AR and utilise carbon sequestration to offset residual carbon emissions owing to its relatively low percentage of forest area as a total of land area, 13% compared to the European and world percentages of 46% and 31% respectively (Forestry Research, 2020, p.206). Ancient and long established woodlands make a greater percentage contribution to the carbon stocks in GB, 36% versus 25%, than the percentage of woodland they account for (Reid *et al.*, 2021, p.13). Older trees, of larger diameter, store and sequester more carbon than smaller diameter trees (Chaparro and Terradas, 2009, p.46) highlighting the link between tree age and sequestration

rates. Speed of growth also affects sequestration rate, with fast growing species sequestering carbon at a greater rate than slow growing species (Hirons and Sjöman, 2019, p.39).

A clear understanding of sequestration rate versus storage potential is needed, (see Figure 6.2 (Gregg *et al.*, 2021)). The early peak in carbon sequestration rate can be seen in this figure along with the increasing cumulative carbon storage amount at a decreasing sequestration rate.

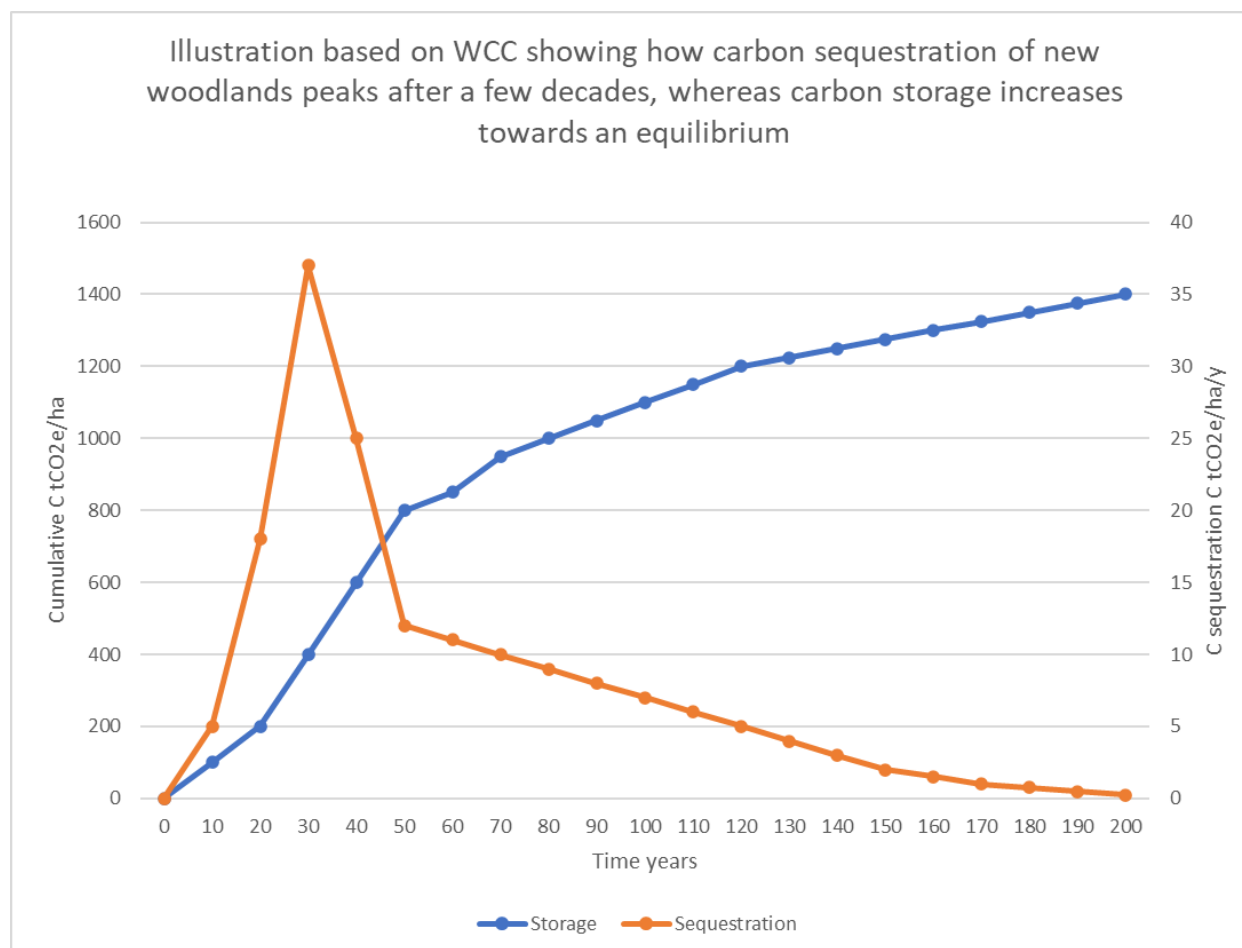


Figure 7.2 Carbon Sequestration Rate vs Cumulative Storage amended from (Gregg *et al.*, 2021)

When choosing vegetation, trees with long life expectancy and requiring minimal maintenance should be chosen to maximise sustainability via reduced maintenance emissions over the trees' lifetime, alongside recycling of wood once the tree dies (Chaparro and Terradas, 2009, p.64). When replacing ancient woodland (AW), the sequestration rate, along with store of carbon, will not be directly replaced by planting of new woodland, as it could take many decades for the new planting to reach the previous woodlands sequestration rate and storage amount (Razzaque and Lester, 2021, p.147). HS2 in their carbon footprint allow for "carbon sequestration – from planting 2 million trees" (HS2 Limited, 2013a, p.34) illustrating that inclusion of tree planting in carbon footprints is an acceptable offset to use in comparable linear infrastructure. Additional benefits from larger trees are their large leaf area to enable trapping of pollutants from the air and to cast shade, along with their

ability to “intercept or slow rainfall run-off” (Brack, 2002, p.196), indicating some of the potential benefits of increasing existing forest area and allowing forest planting to mature.

Four of the main AR strategies are: expansion of forested land via reforestation, increasing carbon density of existing forests, increased use of forest products that sustainably replace fossil-fuel CO₂ emissions, and reduced emissions from deforestation and degradation (Canadell and Raupach, 2008, p.1456). The positive co-benefit of biodiversity increases is given by AR (Nemet *et al.*, 2018) and (IPCC, 2018, p.329), tempered by the negative biodiversity impacts of monocultures in AF (IPCC, 2018, p.343).

Current research shows uncertainty as to which planting regime will sequester the greatest levels of carbon (Hulvey *et al.*, 2013, p.869). Specific research on diversity of planting, and effect on carbon storage potential find that adding diversity in specific carbon plantings “may maximize aboveground C storage in planted forests when compared with the average productivity of monocultures” (Hulvey *et al.*, 2013, p.871). A diverse mixture of trees and shrubs can potentially provide equal productivity to that of productive monoculture trees (Standish and Prober, 2020, p.165). Implementation of diverse planting could achieve even greater carbon storage levels, particularly in the SOC pool (Standish and Prober, 2020, p.165), alongside theoretically contributing to other ecosystem service goals (Hulvey *et al.*, 2013, p.869), including ecological resilience (Standish and Prober, 2020, p.165). While aboveground biomass levels have been shown to provide a steady carbon sequestration and storage level when moving from monoculture to high diversity plantings, soil carbon levels, root biomass, woody debris and litter carbon sequestration, and storage pools, all gain carbon (at decreasing levels respectively) as the tree species move from monoculture to greater diversity. This shows that increased diversity increases the total carbon sequestration rate and the carbon storage pool (Hulvey *et al.*, 2013, p.873).

AR is therefore an area that NR can potentially add to via its land assets, fulfilling the temperate region criteria to harness improved forest management. As this technology is at a suitable stage of technological readiness for deployment, it could be implemented in the short term.

Changes in LULUC can affect SOC stocks and should be included in carbon footprints (Williams *et al.*, 2012, p.65). The relative proportion of carbon stored in soil accounts for around ¾ of all carbon in UK forests, compared to less than a quarter in above ground biomass. The remainder being attributed in below ground biomass (BGB), dead wood and litter. As such, changes in the soil carbon stocks will have greater impact to carbon storage than that of above ground biomass (Gregg *et al.*, 2021, p.17), although it is evident that the two are inextricably linked, as climate change and biodiversity loss are also linked (Gregg *et al.*, 2021, p.iv). Therefore LULUC impacts should be included in transport infrastructure LCA calculations for carbon as creation and maintenance of transport infrastructure

can affect changes in land use (Saxe and Kasraian, 2020, p.1039). Some interventions will therefore be starting with a negative carbon balance due to vegetation removals, which need accounting for in the carbon footprint. Gains in soil carbon occur slowly, at the decadal timescale, and can be found in changes of croplands to grasslands, or forest and land use changes to peatlands, grasslands and forests can all result in a rapid loss of this slowly built up carbon stock (Ostle *et al.*, 2009, p.S275). Not all of the literature agrees with SOC playing a significant contribution towards carbon stores, some ascertain it provides only a “humble contribution” to the climate change problem as its percentage contributing globally is relatively small, and owing to its dynamic nature will reach a saturation point, when a new SOC equilibrium is reached (Sommer and Bossio, 2014, pp.86-87).

Use of the UK Woodland Carbon Code (WCC) tool (UK Woodland Carbon Code, 2021b) will include for soil conditions and land use changes. It is therefore considered a more comprehensive tool than simply utilising differing tree sequestration rates which may not take account of the soil and LUC. There are a great variety of LULUC options to be considered. The three afforestation options reviewed in the literature are cropland to trees, cropland to shrubs and grassland to trees, with the latter showing the greatest carbon accumulation. The cropland to shrubs option however showed a stronger ability than cropland to trees to enhance the deep SOC stores (Shi *et al.*, 2013, p.57).

When LUC is made, the before use land factor is of critical importance with values for changes in this ranging from 2.50 tCO₂/ha as the lower forest land value and 165.00 tCO₂/ha the higher value, grassland values range from 3.12 – 15.58 and crops 18.33 tCO₂/ha (from IPCC cited in Hill 2011 p.73). Using the IPCC factors as a basis for land use change for infrastructure construction of twin tracks for conventional speed rail over the five LUC factors outlined above, these result in the LUC proportion of lifecycle emissions/ha being between 0.13% for the grassland low figure, to 6.56% for the forest land high figure (Hill *et al.*, 2011, p.76).

Land will always have competing uses including abatement, agriculture, water and biodiversity and leisure spaces (such as golf courses (Fitzpatrick, White and Matthews, 2021)), and this will affect its value in both monetary and carbon terms (Bryan *et al.*, 2015, p.4112). NR needs to view its land assets differently, see Section 6.5.1, and explore ways of improving and expanding existing assets, to improve not only biodiversity but also the dual benefit of additional sequestration.

The simplicity and scalability of EW (with 10,000-10,000,000 Gt CO₂ sequestration potential) make it a serious contender for implementation in the race to net zero (Tan and Aviso, 2021, p.1). An example of its simplicity is application of a mineral such as olivine on land with high acidity giving the dual benefit of improving soil quality via increased soil pH alongside CO₂ capture from ambient atmosphere over 30 years (Saran, Arora and Yadav, 2018). Other potential benefits of application of minerals are its potential “to act as a nutrient source for nutrient-demanding AR and BG” and its

“potential for water retention management of top soils” (Garcia *et al.*, 2020, p.2126). These benefits outline factors that could become more important to NR management as part of their biodiversity strategy, considering the nutrient source that could be provided, and for addressing climate change resilience in geotechnical solutions via the potential for water retention. It is worth noting that the application of minerals for EW in this form should be used with caution as the science is emerging (Saran, Arora and Yadav, 2018), and there is also uncertainty surrounding mineral dissolution rates in EW (Renforth, Pogge von Strandmann and Henderson, 2015). Upscaling of this form of sequestration is currently being undertaken in the UK via the GGR-D projects (UKRI, 2021) to measure and capture data on the environmental impacts of this intervention. Large scale implementation of EW could cause the unintended consequence of extensive mobilization of materials at regional and or global scale (Fuss *et al.*, 2018), hence increasing the transport carbon for use of these materials.

EW is concerned with speeding up an otherwise natural geological process of storing CO₂ in minerals. This mineral situation can be divided into two discrete methods of in situ or ex situ. In situ sequestration is the injecting of CO₂ into underground geological storage chambers where it will react with existing minerals to form carbonates. Ex situ sequestration is concerned with the carbonation process taking place above ground. Here the minerals used for carbonation require mining and grinding, and then spreading before the carbonation process takes place (Ibrahim *et al.*, 2019, p.4). In EW the minerals (silicate or carbonate) react with atmospheric CO₂ in the presence of water and form soluble bicarbonates which are transported to the ocean deep carbon store via run-off water (European Academies Science Advisory Council, 2018). Storage times here can be considered permanent as carbon can be sequestered indefinitely in the ocean. Via carbonation the EW reaction may also form solid carbonates, also considered a permanent sequestration of the carbon in the form of CaCO₃ for example (Tan and Aviso, 2021).

Particle size is crucial for all types of minerals utilised for EW, owing to the high energy requirements, and hence additional carbon for grinding the materials to sufficiently small size (Fuss *et al.*, 2018, p.33). Two main classes of feedstocks are available for ex situ carbonation, natural minerals (including Basalt, Brines, Brucite, Olivine, Serpentine and Wollastonite) and industrial by products (including cement wastes, fuel combustion ashes, iron and steel slags, and mine tailings), with the latter having potential circularity co benefits of re use of these waste materials for sequestration purposes (Yadav and Mehra, 2021).

Use of EW alongside AR, via application of rock powder, will give additional benefits to the soil in the form of increased phosphorus (Garcia *et al.*, 2020), and also use of crushed olivine in forests, in addition to fixing CO₂ in the soil, would also make the forest healthier. However, spreading of olivine is impossible to do in a standing forest, therefore its application will be limited to new forests where

the ground can be dosed with olivine prior to planting (Schuiling and Krijgsman, 2006, p.352). Use of the ball mill rolling process ex situ mineral carbonation of waste materials from mafic rock quarries can also provide a methodology for permanent storage of CO₂ (Rigopoulos *et al.*, 2016, p.369).

Additional milling and rolling of rock materials can create nanomaterials with enhanced CO₂ adsorption capacity, however this comes with an increased carbon footprint of the production of EW materials (Rigopoulos *et al.*, 2016, p.361). The cost of comminution and material transport can account for around 77-94% of total energy requirements, meaning that from an energy (and cost perspective) it may not always be viable to grind down and transport minerals to final locations (Renforth, 2012, p.1). As such, the travel distance emissions for the rocks to use in EW may outweigh any positive (sequestration) benefit of their application (Lefebvre *et al.*, 2019). NR could utilise its own infrastructure network using trains (especially if using application of such offsets trackside, see Figure 6.3) to reduce transport emissions away from HGVs, and reduce them further still via use of local materials (see Directory of Mines and Quarries (Cameron *et al.*, 2020)). For a summary of side effects of EW see Table 6.1.

Table 7.1 Positive and Negative Side Effects of EW, amended from (Hartmann *et al.*, 2013, p.136) and (Fuss *et al.*, 2018)* and (Birkinshaw and Jarvis, 2021)** and (Garcia *et al.*, 2020)***.

Positive Side Effects of EW	Negative Side Effects of EW
Increasing pH of ocean water, counteracting CO ₂ induced acidification.	Change in pH of soils and surface waters, affecting terrestrial and aquatic ecosystems.
Supply of Si to coastal oceans: Ocean fertilization to enhance sequestration of atmospheric CO ₂ via the organic carbon biological pump.	Change in Si concentration of surface waters, altered nutrient ratios affecting ecosystems.
Supply of Si and other nutrients to terrestrial ecosystem: Increase in terrestrial productivity and lead to greater sequestration of CO ₂ in terrestrial biomass; increase in crop production; additional income for farmers via CO ₂ certificate trading.	Release of trace metals associated with target minerals.
Increased phosphorus. ***	Generation of dust.
Making forests healthier. ***	Socioeconomic and sociopolitical consequences for agricultural communities.
Recycling of quarry waste to recycle CO ₂ and put it back into the circular economy. **	Environmental costs of increased magnitude in olivine mining.
	Local air pollution. *
	Heavy metal pollution in soils. *

Table 6.1 illustrates that EW could be a cost-effective solution for use on land unsuited to plantings. It could also be used along with those parts of the NR estate which do not have engineering constraints on them, such as non-load bearing access footpaths and be used to increase

sequestration for the estate as a whole (see Figure 6.3), as long as the transport carbon costs can be kept to a minimum.

F.15.2 Permanence of Storage, Saturation and Leakage

Permanence of carbon storage, saturation, and leakage using AR and EW, cannot be ignored. The carbon stored in trees is not a permanent carbon sink in geological timescales. The carbon will be released when the tree dies or is destroyed (Davies *et al.*, 2011, p.1131). This indicates that AR activities will always be inherently at risk of leakage, and the implementation of robust forestry management practices is required to reduce this risk from forests that can occur due to natural or human disturbance from drought, forest fires and pests, or reversals in land use (Fuss *et al.*, 2018, p.16). If harvested wood products (HWP) are used in short-lived products like paper it will release carbon back into the atmosphere quickly compared to HWP used to manufacture long-lived products such as furniture, which act as sinks until the wood decays (Sedjo and Sohngen, 2012, p.129; Johnston and Radeloff, 2019, p.14526). It should be noted that this carbon pool in HWP is very small in relation to total carbon emissions (Buchanan and Levine, 1999). A novel method to increase the permanence of wood products and other biomass, is burial and dry bio-landfill (Zeng, 2008; Yablonovitch and Deckman, 2023), with Yablonovitch and Deckman (2023) citing storage times of hundreds to thousands of years for the dry bio-landfill. In comparison, storage in geological underground storage would be considered permanent due to its time scale of storage of many thousands of years. Using EW the carbon can be considered permanently locked away in the deep ocean store (Tan and Aviso, 2021) and not subject to leakage.

There is a point where natural carbon sinks including trees, land, and oceans will reach saturation level. This is usually within decades to centuries for forests, compared to geological underground storage which reaches maximum capacity within centuries (but up to thousands of years in some instances (Fuss *et al.*, 2018)). Trees reach maturity at the point where net removal of GHGs reverts to zero (Fajardy *et al.*, 2019, p.52).

F.15.3 Sequestration Rates

For AR a variety of carbon sequestration rates can be found by extensive research reports published in the literature by tree species (Mutch *et al.*, 2017, pp.39-41) and by habitat (Gregg *et al.*, 2021, p.12) giving rates of flux of between -1.99 to -14.5 tCO₂e ha⁻¹ yr⁻¹ for hedgerows and mixed native broadleaf woodland respectively, with sequestration rates of 0.6, 0.4 and 0.6 tCh⁻¹ yr⁻¹ for grassland, arable land, and forested land in Ireland (McGeever *et al.*, 2019, p.7). Converted to CO₂e these figures for grassland, arable and forested land are respectively 2.2, 1.5 and 0.7 tCO₂ha⁻¹ yr⁻¹ using

conversion rate of 1kg C = 3.67kg CO₂ (Hendriks *et al.*, 2023, p.6). With the creation of multi-layered plantings being a strategy to further increase C storage (Jo, 2002, p.123). A comprehensive overview of sequestration rates has been found in the literature, covering the range of vegetation overviewed herein, see Table 6.2.

Table 7.2 Habitat Sequestration Rates, amended from (Trewick and Anderson, 2023) and (Qubaja, Moinester and Kronfeld, 2022)

Habitat	Carbon Sequestration Rate (tCO ₂ eha ⁻¹ yr ⁻¹)	Cited Author's Reference
Mixed broadleaved woodland	7-14.5	Gregg et al. 2021
Natural woodland generation on former arable soils	7.3-14.3	Poulton et al. 2003; Anderson 2021
Conifer plantation (Sitka spruce)	11-20.5	Dewar and Cannell 1992; Anderson 2021
Old growth forest and ancient broadleaved woodland	4.77-17-97	Anderson, 2021
Hedgerows	0.47-23.36	Gregg et al. 2021
Heathlands	3.34-12.65	Alonso et al. 2012; Quin et al. 2015; Anderson 2021
Improved grassland	0.18-1.78	Janssens et al. 2005
Reversion of arable land to low input grassland	1.59	Warner et al. 2020; Gregg et al. 2021
Peatlands	0.18-3.70	Artz et al. 2013; Anderson 2021
Restored peatlands	3.23-25.41* *mostly reduction in carbon lost rather than sequestration	Artz et al. 2013; Anderson 2021
Planted Pine forest growing at semi-arid timberline	550g CO ₂ m ⁻² yr ⁻¹ converted to tonne.ha = 5.5tCO ₂ haYr ⁻¹	Qubaja, Moinester and Kronfeld (2022)

Owing to the wide range of sequestration rates in the literature for differing habitats, the rates given in the WCC (used extensively in the Nature England Report (Gregg *et al.*, 2021)), which also includes for initial soil conditions, have been used to calculate this value for case studies offsets, see Section 6.4.

For EW it is predicted that 85 tCO₂ha⁻¹yr⁻¹ is possible to achieve, using crushed concrete from demolition in transport-based sequestration projects (track side and roadside verge offset projects), however the demonstrated value found is much lower for a single application of dolerite in soil, 18 tCO₂ha⁻¹yr⁻¹ over 7 years.

Other EW sequestration values found for differing minerals give potential carbon removal on cropland areas of potentially 95 GtCO₂a⁻¹ for dunite and 4.9 GtCO₂a⁻¹ for basalt (Strefler *et al.*, 2018). These values, given as “weathering rates” and assumed annual values, are, when converted to hectares, 120 tCO₂ha⁻¹ for dunite and 6.2 tCO₂ha⁻¹ for basalt. The lower value for basalt appears

much lower than the demonstrated value from Kolosz *et al.* (2017, p.80) for crushed concrete and the higher value for dunite is around two times higher than that for crushed concrete.

Therefore, both the demonstrated value and the two values for crushed concrete and dunite will be used in the EW exercise to give a demonstrated lower bound and a theoretical mid bound (crushed concrete) and upper bound (dunite) value. Using these values, the area of land in hectares that would be required to have minerals applied to it to sequester the lifetime carbon A0-C4 for each renewal ER scenarios over the 25 year time period from a 2025 application year, to enable net zero by 2050, are calculated, see Section 6.4.2.

In addition to the above values from the literature, application of dunite consisting of approximately 90% olivine has been found in Delatares (2021) giving a value of 40kg carbon capture over 20-30 years per 1,000kg of olivine used as ballast. This figure has been derived from laboratory and modelling methods, however as this is an emerging area with concurrent research in the GGR-Ds also, the adjacent land strip theoretical exercise has been deemed a potentially more feasible for potential EW use for immediate deployment, but use of olivine as ballast, could have additional sequestration potential for NR in the future.

In this thesis the focus has been offset via AR owing to the potential co benefits for biodiversity. EW has been overviewed in depth as an alternative strategy to sequestration in those areas of trackside where plantings are not feasible. The amount of trackside available to NR (15,846 km (ORR, 2023)) which has the potential to be utilised as a carbon offset “zone”, see Figure 6.3, is a unique beneficial asset for NR to galvanise and utilise in its trajectory to net zero, discussed further in the next section.

F.16 Rail Corridor Vegetation, Hedgerows and Other Linear Forest Formations

In this section specific literature on rail corridor vegetation, hedgerows and linear forest formation is reviewed. This is followed by a discussion on line-side vegetation and its management along with the potential for EW zones trackside.

Managing over 16,000 miles of lineside vegetation England and Wales, NR is a major caretaker of lineside vegetation assets and changes here could have great potential (Varley, 2018, p.7). However, few long-term carbon studies have been found investigating carbon sequestration in rail corridors. One example found looked at measures to bind sand dunes along railway on the edge of the desert in China (Li *et al.*, 2016). In this study changes in SOC following afforestation were measured over a period of nearly 60 years, finding an increase in total SOC from 14.9 to 58.5%. Very little increase

occurred in the first 14 years leading to the conclusion that afforestation with shrubs produced a “substantial and steady gain” in the SOC content (Li *et al.*, 2016, p.191). A second example for carbon capture in soil in transport infrastructure found that 30,000 ha of railway land provided potential for carbon sequestration (Kolosz *et al.*, 2017, p.74). There are constraints to plantings as well as other interventions trackside, due to needing to keep the lines clear of leaf debris and not impinge on the soil area which is taking the overburden pressure from the track construction. Suitable areas at trackside for potential CO₂ “capture areas” would therefore be located outside of the ballast shoulder on the sub-soil layer (Kolosz *et al.*, 2017, p.78), see Figure 6.3. These carbon capture areas are where additional sequestration measures such as crushed concrete for mineral carbonation could be located with projections of around 85 tCO₂ha⁻¹yr⁻¹ (mid value) sequestration achieved using crushed concrete from demolition (Kolosz *et al.*, 2017, p.80), see Section 6.2.3.

Line side vegetation and its management requires exploration due to the interrelations between these and the rail corridor in terms of biodiversity, ecosystem services, and additional benefits such as “increased stability and resilience of embankments and cuttings” (Hoerbinger *et al.*, 2020, p.1). In this relationship not all benefits are positive, with adhesion-related paybacks caused by leaf fall being a negative relationship (Network Rail, 2021d, p.82). Rail corridor vegetation management is often not highly prioritised in railway infrastructure construction and maintenance activities (Sydney Trains, 2019, p.2). Vegetating the rail corridor with trees and bushes could increase carbon sequestration and storage potential by 40% (Blair *et al.*, 2016, p.1723). In one study a three-fold increase in sequestration potential converting bare ground to trees was found (Ghosh and Khan, 2019, p.263). This strengthens the assertion that lineside vegetation, as a very specialised part of the landscape, has a high capacity in terms of delivery of environmental services (Hoerbinger *et al.*, 2020, p.1).

Earthwork sustainability is affected by vegetation in several ways including habitats and biodiversity, the location of vegetation (crucial to avoid tree fall and leaves on the line), vegetation maintenance involving cutting and replanting, visual and acoustic screening provided by the vegetation for neighbouring areas, and engineering performance in terms of both slope failure and excessive seasonal movements (Glendinning *et al.*, 2009, p.102). The question that needs to be addressed is what types of vegetation to plant considering the ongoing changes in climate, with 2023 being reported to be the hottest on record (NASA, 2024). Many infrastructure operations, including earthworks, construction and vehicle movement along with excessive tree removal and vegetation clearance activities, have the potential to disturb stable vegetation habitats in the rail corridor (Sydney Trains, 2019, p.4). Careful planning of construction and maintenance works and liaison with ecologists is required to minimise ecological and hence biodiversity impacts of earthworks on the rail corridor. NR is undertaking such liaison via completion of environmental appraisals, examples of these include National Vegetation Classification (NVC) Surveys (QTS Rail, 2015), Habitat Surveys, Bat,

Bird, Badger & Otter Surveys, alongside detailed design summaries before works commence, such as Environmental Impact Assessments (EIA), Environmental Appraisal (QTS, 2015), and Environment and Social Management Plans (ESMP) (Network Rail, 2021f).

Detrimental effects resulting from the presence of trees on slopes impact the rail tracks with serviceability problems due to trees' transpiration causing soil volume change resulting in movement and deformation of the railway track. This problem presents a dichotomy for earthworks managers with respect to keeping or removing trees, due to the limited available guidance (Briggs, 2011). Further guidance documents on tree species selection for transport infrastructure are available for NR on Safety Central (Hirons and Sjöman, 2019) where classification of water demand for various tree species and minimum tree planting distances from the rail can be found. Use of native plants to stabilise slopes (Pallewattha, Indraratna and Rujikiatkamjorn, 2016) and transport corridors (Fatahi *et al.*, 2015) has shown potentially beneficial results in terms of properly selected vegetation reducing soil moisture by root water uptake (Fatahi *et al.*, 2015, p.593), pointing towards increased slope stability via increased soil stability as a co-benefit of increased vegetation plantings on the lineside with careful choices of plantings. Planting choices support good root systems (not overly shallow) and evergreen (not deciduous in behaviour) as being the most appropriate for lineside sub grade improvement (Pallewattha, Indraratna and Rujikiatkamjorn, 2016, p.10).

The Varley Report (Varley, 2018), discussed utilising rail corridor vegetation as an “operational asset” which is contrary to how vegetation is currently viewed, as a maintenance intervention. The Varley Report specifically references the NR lineside vegetation management manual (Network Rail, 2020c) which NR introduced primarily to address the issue of planned maintenance. This manual facilitates the achievement of a compliant profile to maintain the earthwork sustainability aspects of tree fall and leaf fall, despite the management of vegetation for stability and security of earthworks falling outside the manual's scope. In addition, a tree species selection guide for specifiers was introduced alongside this manual, overviewing use of trees for carbon storage and sequestration where by the greater carbon storage advantages of healthy, fast growing and long-lived tree species are highlighted (Hirons and Sjöman, 2019, p.39). This tree guide specifically details trees suited to the transport corridor noting these have no size or environmental tolerance imposed and also that many have the co benefit of a tolerance to air pollution (Hirons and Sjöman, 2019, p.9). The additional benefit for increased sequestration of planting vegetation is also noted in the rail industry strategy route map for sustainable rail (RSSB, 2022, p.12).

When discussing any CDR, NET or NbS these cannot always be strictly divided into discrete areas. An alternative CDR method is mineral carbonation which could be located in suitable land adjacent to the rail corridor (not suited to tree plantings or other vegetation) to enable additional sequestration

to be utilised, see Figure 6.3 (Kolosz *et al.*, 2017, p.78-79). Use of this method of sequestration could be beneficial on lands which are not suited to biodiversity enhancements or have other constraints such as access. In these cases additional sequestration benefits from using this method of carbon capture could be realised alongside CE benefits such as being potentially able to reuse crushed concrete from demolition of near-by infrastructure (Kolosz *et al.*, 2017, p.79).

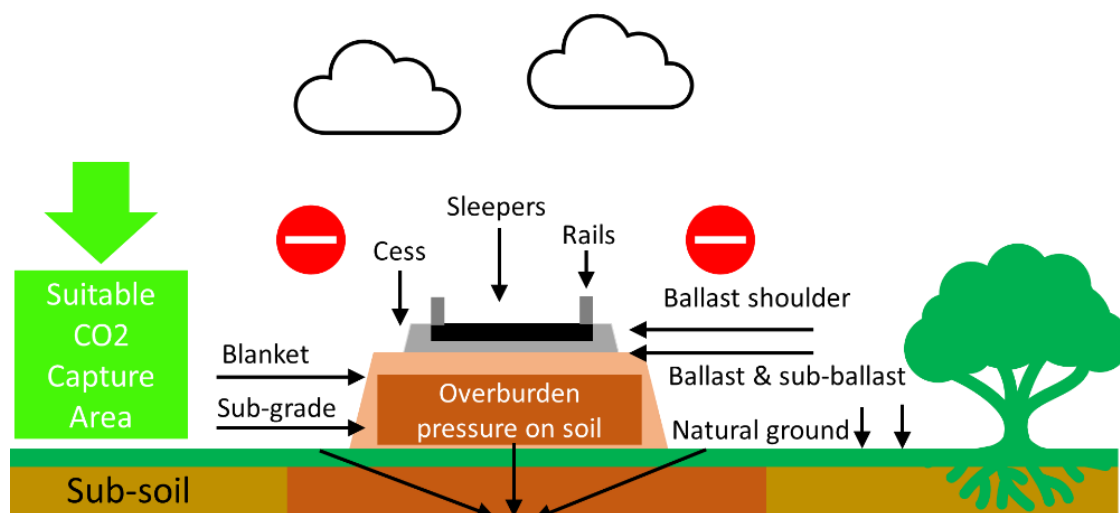


Figure 7.3 Carbon Capture Placement Guidance for Rail Track infrastructure, amended from (Kolosz *et al.*, 2017, p.78)

Reviewing the above cited rail corridor vegetation reports, identifies a gap in explicitly linking this area of research with carbon offsetting and biodiversity principles and the multitude of additional potential societal and economic benefits which come from this increased biodiversity. Increased sequestration was also clearly demonstrated in many of these studies as a beneficial outcome of increased vegetation.

Figure 6.4 illustrates the gap identified between rail corridor vegetation, increased vegetation and sequestration benefits, and linear forest formations, discussed next.

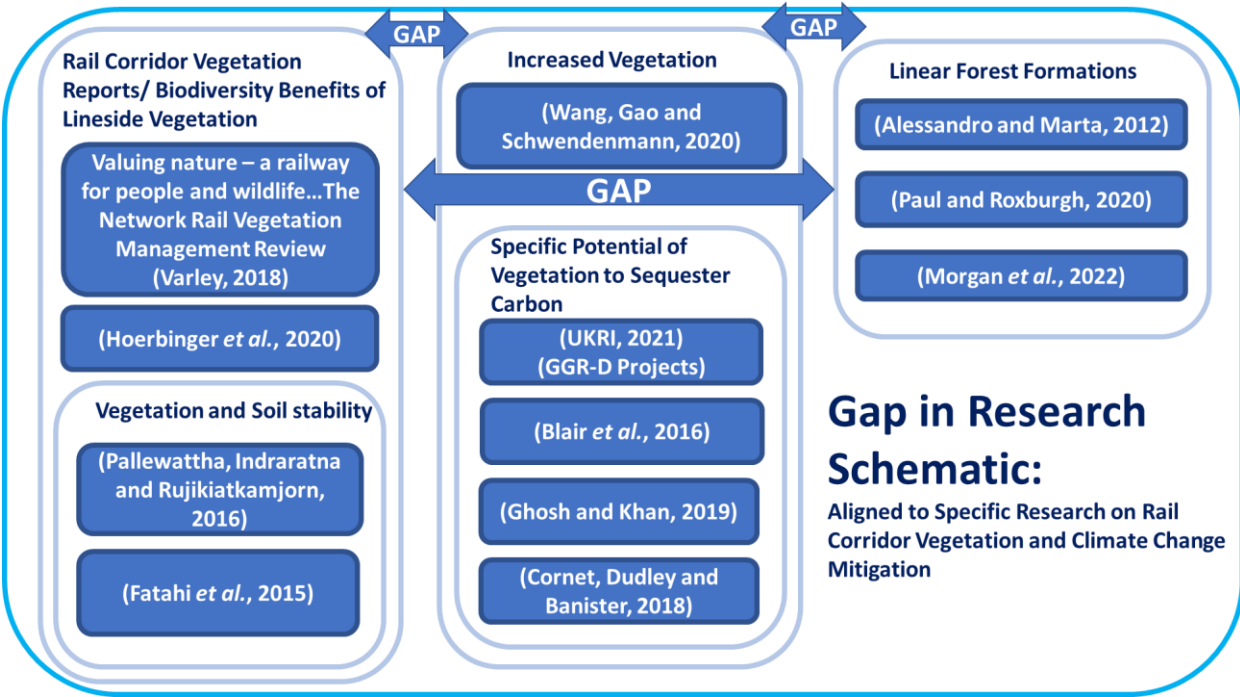


Figure 7.4 Gap in Research Schematic

F.16.1 Linear Forest Formations (LFFs) and Other Linear Vegetation

Research into LFFs, with a specific focus on hedgerows, could be applied to railway corridors due to the linear nature of railway routes (Alessandro and Marta, 2012). Investigating the biodiversity conservation function of these LFFs finds that they have an important role to play in carbon storage and soil protection along with ecosystem connectivity (Alessandro and Marta, 2012). Both of these issues contribute towards increased biodiversity as a positive side effect of increasing sequestration via planting of new vegetation. The railway can also assist the biodiversity of an area in terms of forming a green or wildlife corridor for nature to transit along, alleviating some of the fragmentation effects of the rail route (Varley, 2018). Dense strands of woody biomass configured in belts (or LFFs) have carbon sequestration benefits due to benefits this configuration gives to above ground biomass (AGB) as this has a higher rate of accumulation in such a configuration compared to that of natural regeneration (Paul and Roxburgh, 2020). In a linear configuration of tree stands carbon sequestration can be maximised by tree planting of high wood density stands configured with <40m width with >40m of non planted land to either side, allowing trees at the periphery to use resources such as water, nutrients and light from adjacent areas. In contrast biodiversity is maximised in configurations of >40m width (Paul and Roxburgh, 2020, p.2).

LFFs can also be found in road verges, which share many common features with the rail corridor including earthworks and bridges. Research has been conducted on this grey infrastructure to include roads, rail, and landfill sites and alludes to their potential to provide positive ecosystem services

(Ghosh and Khan, 2019). Road verges are also found to deliver a parallel ecosystem provision providing biodiversity services and storing carbon in orders of magnitude of gigatonnes (Phillips *et al.*, 2020). Road verges are able to offset between 4 and 7% (per km of road) of the carbon emitted during the construction phase of a road via grass assets adjacent to highways (Winston, Bouchard and Hunt, 2013, p.356). These grass assets also provide stormwater control, suggesting that conversion of barren or derelict land adjacent to linear infrastructure would give positive environmental benefits alongside additional sequestration benefits. Services and disservices provided by grass verges adjacent to linear infrastructure are presented in Figure 6.5.

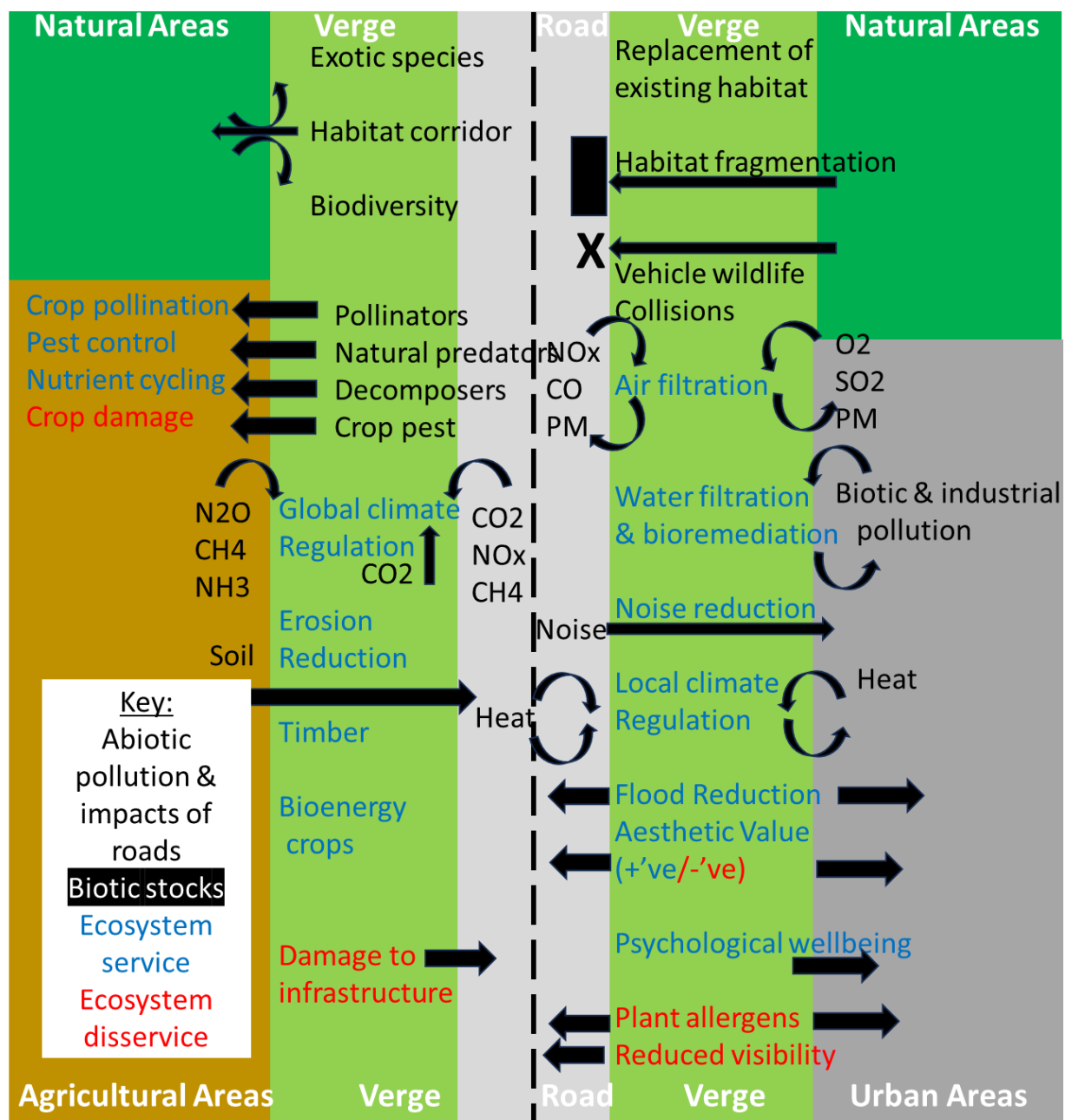


Figure 7.5 Ecosystem Services & Disservices of Verges Adjacent to Linear Infrastructure, amended from Phillips *et al.* (2020)

The three management actions being cited as methods of boosting ecosystem services at little or no extra cost (win-wins) are: reduced cutting frequency of verges, trees planted far back on wide roads, and use of verge cuttings for biogas generation. All three actions could potentially be implemented as part of a wider biodiversity initiative for NR trackside. Reduced cutting frequency gives immediate cost savings in terms of carbon emissions of machinery and staff travel to site, and their associated fiscal costs for lineside vegetation maintenance. Trees planted farther back would also potentially give rise to reduced maintenance visits as these only need cutting back when they impinge on the railway intervention zone (Varley, 2018). See Chapter 4 for the carbon costs of vegetation management, and particularly the extrapolation exercise demonstrating the large impact this intervention type has on earthwork assets for NR.

The Varley Report, which gives rise to the intervention zones from the new standard, sets out guidance that work should “encourage the establishment of desirable lineside conditions that add value not only to the lineside but also to the surrounding environment” (Varley, 2018, p.19). The Report goes on to list these as: including providing biodiversity and improving resilience of the vegetation. Use of verge cuttings for biogas generation is an initiative that also could be investigated further by NR and their contractors to ensure zero waste to landfill of this product, and even potential gain if it can be sold on to others for biogas generation. As this is outside of the AR and EW offsets identified for exploration in this thesis, this avenue has not been explored further.

F.16.2 Sequestration via Hedgerows

Research carried out on hedgerows’ sequestration potential by Axe, Grange and Conway (2017) found that “High concentrations of stems per unit area were found in the hedgerows, leading to an efficient use of space for AGB C storage, when compared to other woody vegetation” (Axe, Grange and Conway, 2017, p.87). Hedges can be formed from tree species and are managed into their distinctive boundary shape or can be formed from shrubs or a mixture of shrub and tree species such as hawthorn, blackthorn, hazel, ash and oak (Woodland Trust, 2024). The increased above ground carbon storage offered by hedgerows suggests encouraging NR to increase their own and neighbouring hedgerows, rather than individual trees, which have their own specific issues for the railway in terms of intervention zones from the NEW standard for vegetation management, NR/L2/OTK/5201/02 (Varley, 2018, p.19).

Research into sequestration via hedgerows by Axe, Grange and Conway (2017) (increased AGB via changes to management practices to taller/wider), Baah-Acheamfour *et al.* (2015), Ford *et al.* (2021)

and Lenka *et al.* (2012) (finding that grass filter strips (GFS) with hedgerows were most beneficial for the GFS and hedgerow and to maintain better soil quality in sloping agricultural lands), all showing that they have manifold benefits to adjacent landowners, including reduced run off and increased carbon storage. Lenka *et al.* (2012) finds that with the hedgerows there was increased soil moisture storage, decreased runoff and reduced SOC loss via runoff (Axe, Grange and Conway, 2017). They found that actively managed hedges showed increased carbon storage with increased width and height. In their study they reported some of the first empirically derived values for AGB and BGB carbon stocks for English hawthorn and blackthorn flailed laid hedges, which may be of interest to NR when considering their plant options adjacent to trackside.

The three differing agroforestry systems of hedgerows, shelterbelts (both include trees between fields and shelterstrips (Woodland Trust, 2022, p.11)) and silvopastures (individual, wood grazing or orchard trees in grazing fields (Woodland Trust, 2022, p.11)) can affect the SOC in adjacent soils, affecting the relative amounts of carbon in the differing pools of active, intermediate and passive. However, for all the differing soil pools over all the three agroforestry system, the areas that were treed “consistently stored more C and N in all soil density fractions than the adjacent hermland without trees,” adding further weight to the argument that planting trees is a justified pathway to sequester optimal amounts of carbon (Baah-Acheamfour *et al.*, 2015, p.112).

The above indicates hedgerow plantings would be beneficial for NR in terms of reduced drainage requirements trackside, resulting in lower carbon accounts for drainage works and increased SOC storage due to reduced runoff. The increased SOC could also give a win for farmers of adjacent land via increased crop yields. The situation with hedgerows is win-win-win with reduced drainage and thus reduced embodied carbon for NR carbon accounts, increased SOC and thus increased crops for farmers, and increased biodiversity for the public. These are recommended to be considered further by NR as part of their offsetting carbon strategy. Specific use of hedgerows has not been explored further as part of this thesis as the AR strategy of tree planting has been utilised via use of the WCC tool.

Use of biochar or BECCS as part of the solution sits both within this vegetation section and within NETS, as a dual approach solution, however, its use is outside the scope of this thesis as it they are both not direct sequestration paths.

F.16.3 Choice of Vegetation

The semi-natural grasslands which form corridors along linear infrastructure such as railways and highways are become increasingly important habitats as these can be rich in species diversity (Glendinning *et al.*, 2009). There are two conflicting sets of issues regarding maintenance of

vegetation in these areas, the engineering performance of the slope, versus the maintenance of biodiversity on the slope (Glendinning *et al.*, 2009). These corridors, owing to their location adjacent to track and highway are not suitable for grazing. As a result, manual cutting and raking along with removal of cuttings can be utilised to maintain the species richness and diversity, albeit with an associated carbon vegetation maintenance cost.

Choice of vegetation to plant adjacent to trackside for HS1 has included incorporation of species such as low maintenance oxeye daisy grass seed, to meet the requirements of the Environmental Statement and other strategic landscape management principles. These principles include healthy habitats with no net loss of biodiversity, alongside other strategies such as low-nutrient soils which will encourage slow growing grass species and hence require little or no maintenance in the form of mowing. As such the embodied carbon of maintaining the grassed area will be reduced while increasing biodiversity benefits (Stroud, Brintrup and Fancourt, 2023, p.4-5). This low nutrient soil strategy is also advocated for other linear infrastructure, such as land adjacent to highways, to again reduce the maintenance requirement and hence carbon, as lower levels of soil nutrients result in reduced vegetation growth (Sterling *et al.*, 2023, p.159). Other strategies used in highways to reduce maintenance and hence carbon include cut and collect management to reduce the frequency of grass mows, with use of bare mineral soil potentially leading to no maintenance requirements for decades (Sterling *et al.*, 2023, p.159). Reduced mowing of grassland is also advocated alongside increased planting of trees along highways (Phillips *et al.*, 2021, p.1) with additional positive ecosystem services being provided by these verges adjacent roads, such as mitigation of traffic pollution and additional carbon sequestration potential (Phillips *et al.*, 2020).

The choice of planting is crucial if fuel use, both in use of fossil fuel in hand-held tools and transport for site for maintenance of track side, is to be minimised. Use of fossil fuel in hand-held tools and vehicles has been shown in Chapter 4 to be major contributors to the carbon footprint of these types of vegetation management. A key consequence of using stress-tolerant plants is reduced burden of maintenance, and hence lower carbon, owing to the fact that these plants will not grow tall and require cutting back (Sterling *et al.*, 2023, p.167).

F.17 Assessing Net Zero Potential of Combined CO₂e Reduction & Offsetting

In this section the combination of ER with offsetting to reach Net Zero will be explored at the macro scale, for all NR emissions. In Section 6.4 the offsetting values have been applied to the case studies via AR and EW, and Net Zero has been demonstrated to be achievable at an individual case study

level. Exploration of attaining Net Zero at a NR whole business emissions level will now be demonstrated, with EW able to potentially offset around one fifth of the residual carbon. This application of mitigation combined with offsetting, meeting Objective 5, see Section 1.2.

F.17.1 Applying Emission Offsets to NR Land Assets

Here, emission offsets via AR and EW were applied to NR land assets to give a macro scale view of these strategies in comparison to the project level exploration of offsetting provided in Section 6.4.1 and 6.4.2.

NR holds land assets of around 52,000 hectares, including 16,000 miles of lineside vegetation and 6.3 million trees (Varley, 2018). Of this land holding, around 23% is classified as deciduous or coniferous woodland, and around 17% and 13% are classified as arable and grassland respectively (Dr Neil Strong, 2021). The background raw data and calculated percentages of total are given in Appendix F.10. The arable and grasslands are of most interest as they have the potential for their land use to be changed via afforestation to woodland, thereby theoretically increasing the carbon sequestration potential of NR land holdings.

Land use change is an area of carbon sequestration that is not unique to NR and their holdings. In response to increasing ecological and environmental concerns the Ecosystem Approach (EcAp) approach is applied in the UK to woodland management (Razzaque and Lester, 2021). Razzaque and Lester (2021, p.137) examine “special characteristics” of AW and the challenges of applying EcAp to its management. It is argued that the decline of AW in the UK can be addressed through an approach which weighs up economic and social values of woodland. This is reiterated in the Woodland Trust’s report on the State of the UK’s Woods and Trees 2021 where the large contribution of AW and their contribution to society as whole is discussed, with AW holding 36% of carbon in all UK woodland (Reid *et al.*, 2021).

When calculating sequestration potential of NR land holdings, care must be taken to avoid double counting of assets which have already been included in national inventories such as those estimated for National Highways which are counted in national accounts (Marsden, Lokesh and Densley-Tingley, 2022, p.10). This may not be as problematic as seems at first glance as a national inventory will look at national emissions vs national offsets and both project and offset should therefore be included at this larger scale.

7.6.1.1 Applying AR to NR

From the pixel data for NR 2019-20 from NR via personal correspondence (Dr Neil Strong, 2021), around 17% equates to arable and 13% to grasslands, which when taken as a percentage of the

Appendix F

entire circa. 52,000 ha land assets equate to 8,546.50 ha arable and 6,595.32 ha grassland. The WCC tool is used with the optimum set up as found for the case studies in Section 6.4.1, except for the starting conditions, which are amended from semi natural to pasture and arable as applicable, as the starting conditions are known in this scenario for this land use change to NR land assets. To maintain consistency a mixture of broadleaf (50%) and coniferous (50%) plantings, with a planting date of 1 January 2025, are input as per the case studies, and the full details are provided below as the final choice for sequestration in Appendix F.11.

The 6,595.32 ha pasture (grassland) converted to small mixed native woodland with 50% coniferous/50% broadleaf equates to cumulative sequestration of 2,255,599.44 tCO₂ by 2050. The 8,546.50 ha arable land converted to small mixed native woodland with 50% coniferous/50% broadleaf equates to cumulative sequestration of 2,982,728.50 tCO₂ by 2050. Figures used are based on 1 ha woodland plots multiplied up to total number of hectares as the WCC Small Projects tool used is for use with small projects up to 5 ha only. It is anticipated that this method of implementing additional land use change would be via small parcels of land use change (less than 5 ha) throughout the NR land holdings.

For both grassland and arable conversion, a number of implementation strategies, from 100% of the land holding down to 10%, in 10% increments, have been calculated. The potential amounts of carbon that could be sequestered by 2050 using these differing percentages of the given land types are shown in Figure 6.10 with the data behind this graph being given in Appendix F.11.

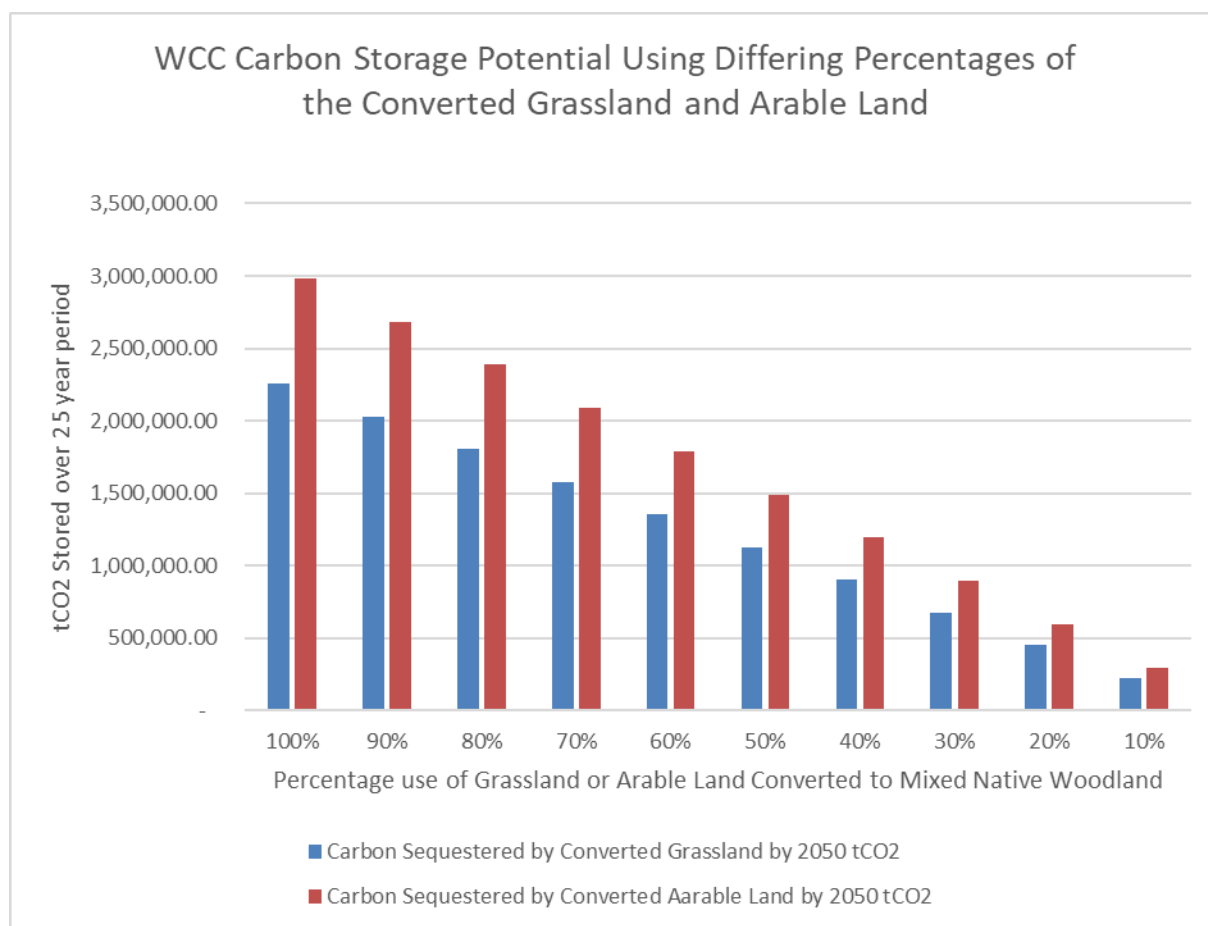


Figure 7.6 WCC Carbon Storage Potential of Converted Grassland & Arable Land

Figure 6.10 illustrates the range of potential carbon storage available up to 2050 using differing percentages of each land type of grassland and arable land.

To contextualize these, the storage for converting grassland to small mixed native woodland using 100% of the available grassland is 1 ha plots is equivalent to over 9,000 earthworks similar to Aldercar renewal with A0-C4 ER carbon of 242 tCO₂, and for converting 100% of the arable land to small mixed native woodland equivalent to over 12,000 renewals similar to Aldercar. Both of these equivalent figures are based on whole lifetime (A0-C4 carbon expenditure).

7.6.1.2 Applying EW to NR

The route length open for traffic for NR for 2022-23 is 15,846 km (ORR, 2023) (with route length being used to encompass any areas of double track where there will nevertheless only be one UP and one DOWN side of trackside land area, for potential EW application). To enable an estimation using the low, mid and upper boundaries for EW, as applied to case studies, this figure can be doubled to allow for application on both sides of the track (UP and DOWN). If an arbitrary width of sequestration area is used of 1m, then the uppermost potential for application (100%) can be calculated for the three EW values of 18, 85 and 120 tCO₂ha⁻¹yr⁻¹ based on a 25 year application in the year 2025 to

allow for use of sequestered value of CO₂ in net zero by 2050 calculations, and is illustrated in Table 6.7.

Table 7.3 Application of EW Low, Mid and Upper Values to Track Side 1m Strip

Application to whole of NR Track Assets	Values	Units
NR track from ORR 2023	15,846.00	km
Assumed UP and DOWN land	31,692.00	km
Convert to m ² for 1m width either side	31,692,000.00	m ²
Convert to hectares to apply EW rates	3,169.20	ha
Storage potential in 100% of this area using lower value	1,426,140.00	tCO ₂
Storage potential in 100% of this area using mid value	6,734,550.00	tCO ₂
Storage potential in 100% of this area using upper value	9,507,600.00	tCO ₂

Using the above method, the storage potential at differing percentage storage potentials of the hypothetical 1m strip adjacent to track side for the three differing EW rates were calculated and are illustrated in Figure 6.11 with the background data behind this being given in Appendix F.9.

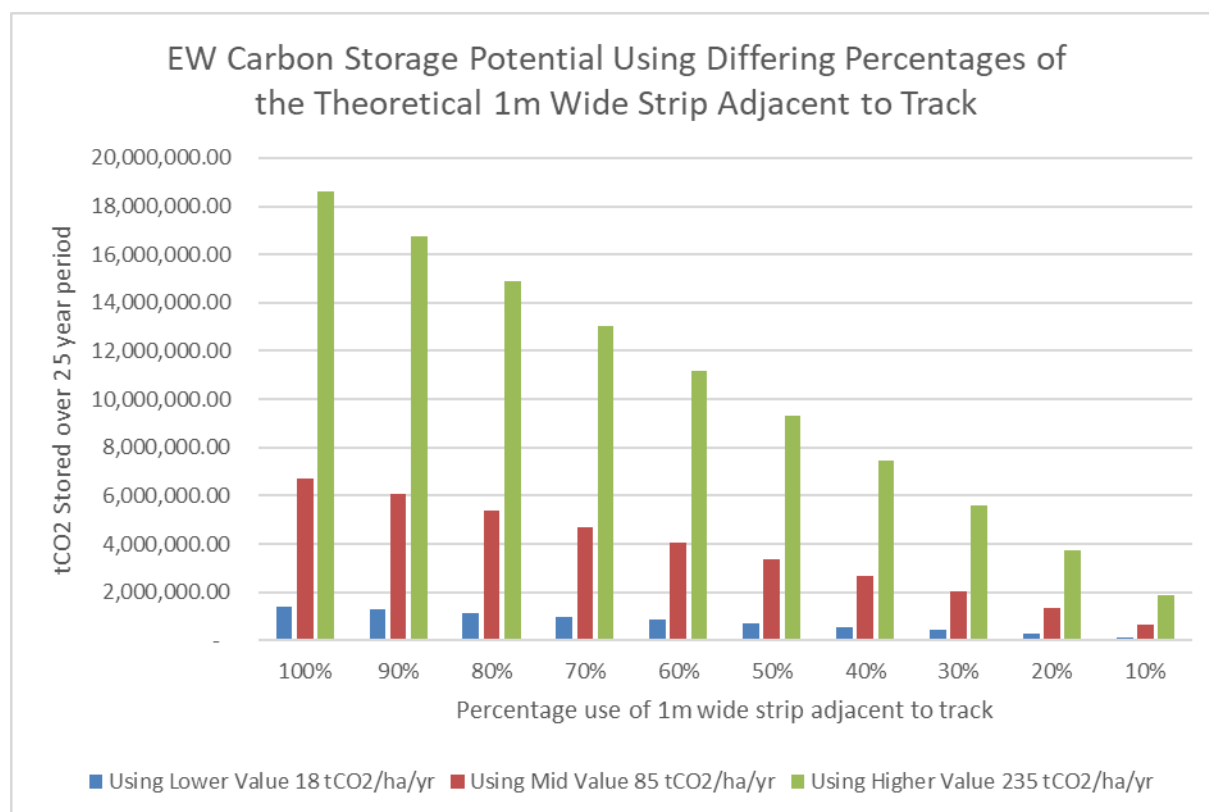


Figure 7.7 EW Carbon Storage Potential of 1m Strip Adjacent to Track

Figure 6.11 illustrates the wide range of theoretical carbon storage using EW trackside from 143,000 tonnes in the lower boundary to 1.8 million tonnes for 10% of line side offset area all the way up to 1.4 million and 18 million tonnes, in the 100% scenario, for lower and upper boundaries respectively. This indicates that, even via the demonstrated lower boundary, there is great potential for use of EW to assist NR in meeting their net zero by 2050 goals.

To contextualise this carbon storage in terms of the case studies, the lower boundary value at 10% use of the theoretical 1m strip adjacent to track, is equivalent to nearly 600 earthworks similar to Aldercar renewal with A0-C4 ER carbon of 242 tCO₂, or at 50% use of the theoretical 1 m strip adjacent to track, at the lower EW boundary value, is equivalent to nearly 3,000 renewals similar to Aldercar. Both of these equivalent figures are based on whole lifetime (A0-C4 carbon expenditure).

7.6.1.3 WCC Sequestration Rate Validation Exercise

Following application of the sequestration rates for AR from the WCC tool these rates have been compared to those found in the literature to assess their accuracy. Carbon sequestration rates found in the literature for woodland give values of low and high respectively for broadleaved of 7 and 14.5 tCO₂eha⁻¹yr⁻¹ and 11 and 20.5 tCO₂eha⁻¹yr⁻¹ for coniferous, giving an average value for the mid points of the two with a 50%/50% usage of 13.25 tCO₂ (Trewick and Anderson, 2023). Multiplying this value by 25 to align with the 25 years to Net Zero, a value of 331.25 tCO₂ha⁻¹ if found, which is within 3% of that of 342 tCO₂ha⁻¹ given for grassland to woodland conversion in the WCC tool. This gives confidence in use of the WCC figures as the value found aligns well with that found in the literature.

The ability of land assets of businesses to offset their carbon has been challenged in the literature by Fox *et al.* (2020) where they show that small scale plantings are not sufficient to offset small business carbon emissions. The totals of carbon that can be offset by the NR estate changing arable and/or grassland to woodland and/or EW rates trackside at differing percentages have been assessed alongside the total NR carbon footprint multiplied over 25 years to enable comparison to see which strategy could offset the total NR global footprint of 8,071 kt = 8,071,000 t (Expedition, 2020, p.4), multiplied by 25 years = 201,775,000 tCO₂e.

- Arable to woodland sequestration potential over whole estate, if 100% of the total arable land is converted to woodland, after 25 years 2,982,728.50 tCO₂ can be sequestered and stored in these woodlands accounting for less than 1.5% of the total NR carbon footprint during that time period. This percentage is in line with that found in the literature by Fox *et al.* (2020, p.462) who found live trees at a university could only potentially offset 0.11% of the University of Georgia's carbon emissions.
- Grass land to woodland sequestration potential over whole estate, 2,255,599.44 tCO₂ accounting for around 1.1% of the total NR footprint.
- EW sequestration applied to 100% of trackside in 1m width using higher theoretical value 9,507,600 t would be able to offset around 9.2% of total NR footprint over the 25-year period, using lower value this would fall to around 0.7%.

The above illustration is made with very simplistic figures, but illustrates the point that use of offsetting, when confined to land within NR's estates alone, is not sufficient for NR to reach Net Zero, and that mitigation to lower carbon in earthworks will help to reduce the residual emissions to a level where offsetting may be able to make a difference. Assuming that the whole NR footprint could be reduced by the average reduction figure found in the case studies using the three differing emission reduction strategies covering materials, transport and construction of around 2/3, then the new residual figure for NR emissions over 25 years would be 67,258,333 tCO₂. The arable and, grassland to woodland and EW sequestration figures above would then represent 4.4%, 3.4%, and 14% of this figure respectively and illustrate here the potential for EW in particular to be able to offset nearly 1/7 of the residual carbon emissions. As outlined in FES2020 in their leading the way, consumer transformation and system transformation trajectories for electricity production and heavy industries showing a steady decrease year on year to Net Zero, the figures mentioned above are in reality likely to fall thereby leading to additional incremental reductions in the carbon footprint year on year of NR.

Looking in more depth at NR scope 3 reductions (Expedition, 2020) and the NR path to Net Zero (Network Rail, 2019) if these are applied to the baseline figure for all scopes in five year CPs then the total over 25 years for offset is estimated to be 86,924,670 tCO₂e, a reduction of 55.4% on the previous annual figure, based on 2019-20, multiplied by 25 years. See Appendix F.12 for reduction data calculation.

Using this revised figure over the 25 years to 2050 the following is found with the sequestration and EW for the whole NR estate.

- Arable to woodland sequestration potential over whole estate, if 100% of the total arable land is converted to woodland, after 25 years 2,982,728.50 tCO₂ can be sequestered and stored in these woodlands accounting for 3.3% of the total NR carbon footprint during that time period.
- Grass land to woodland sequestration potential over whole estate, 2,255,599.44 tCO₂ accounting for around 2.5% of the total NR footprint.
- EW sequestration applied to 100% of trackside in 1m width using higher theoretical value 9,507,600 t would be able to offset 10.9% of total NR footprint over the 25-year period, using lower value this would fall to 1.6%.

The above has demonstrated the potential of EW to assist NR in meeting its Net Zero by 2050 targets. ER plus EW will not be able to fully offset all estimated residual emissions without further actions such as Climate Change Adaption, an appreciation of payback times and understanding of ethics of use of NETs, all of which will now be outlined.

F.17.2 Climate Change Adaption

Climate change adaption is vital and an area that requires attention alongside that of ER and offsetting. Without action in this area, government, and societal goals, including Net Zero will not be able to be met. Further discussion on these is provided in Appendix F.13.

F.17.3 Pay Back Time

Modal shift from cars to rail has the potential to enable pay back of the carbon from construction and maintenance of rail. As the national grid decarbonises in the UK it will become increasingly more difficult to pay back the carbon expended on infrastructure by taking cars off the road (Lokesh, Densley-Tingley and Marsden, 2022b, p.9). See Section 2.3.2 where offsetting carbon payback times have been discussed against differing infrastructure projects.

A detailed understanding of the “pay back” periods for rail infrastructure also needs to be contended with to ensure that the modal shift portion of this is understood and applied consistently across projects to enable for just and fair comparison between them. With HS2 for example using a theoretical motorway comparator to the new HSR, calculating theoretical modal shift from conventional rail and car trips against a baseline of 162.9 million km of road trips removed from a theoretical 2027 baseline via phase one (HS2 Limited, 2017a, p.116). HS2 also allow for carbon offset via carbon sequestration using 2 million trees (HS2 Limited, 2017a).

Carbon calculations have been made using the RSSB RCT for Powrie (2024) illustrating pay back times for traditional and highly engineered embankments (See Appendix F.14 for calculations and assumptions). These highly engineered embankments give a payback time against air travel with radiative forcing (RF) of 3 years and without RF of 5 years. The payback time against petrol or diesel cars is 4 years; however, against BEV (as one of the lowest carbon forms of road transport) would be 31 years. These figures illustrate the increasing difficulty of achieving payback for infrastructure by modal shift from cars as these vehicles themselves decarbonise.

F.17.4 Ethics of NETs

The ethics of using NETs must also be considered when employing offset technology. It should not be employed before carbon has been reduced to its lowest possible level thereby following the Oxford Offsetting taxonomy (Axelsson *et al.*, 2024), to aid in avoiding the appeal to not reduce carbon first and just to rely on NETs to achieve Net Zero. This is particularly pertinent as some of the newer and more speculative NETs are unproven at large scale deployment, although work in the GGR-Ds is advancing to allow for large scale implementation. These NETs should not be thought of as a remedy

to solve the carbon problem at some future point in time, which would draw people’s attention away from making the deep decarbonisation efforts that are required right now (McLaren *et al.*, 2019, p.4).

The case for separate measuring of reduced emissions and negative emissions while sound, needs to be used in a two-stage process. First the most carbon effective solutions are to be found and only when this path is exhausted, can negative carbon measures be utilised to ensure carbon neutrality. During this process there is a need to be ever watchful of the issue of using negative carbon to justify use of carbon intensive materials when lesser carbon producing ones are available. All carbon needs to be locked away indefinitely and assurances need to be made that it will not be subject to rerelease at a later date and thus pushing the problem onto the next generation (McLaren *et al.*, 2019, p.4).

Recent guidance released on emissions offsetting ensuring adherence with the Net Zero by 2050 pathway and as such the SBTs is illustrated in Figure 6.12. This clearly illustrates the results of this thesis in that ER should always come before offset, with the additional clarification alluded to earlier, that avoided deforestation and habitat loss (Section 6.5.2) are part of the ER strategy rather than an offset strategy.

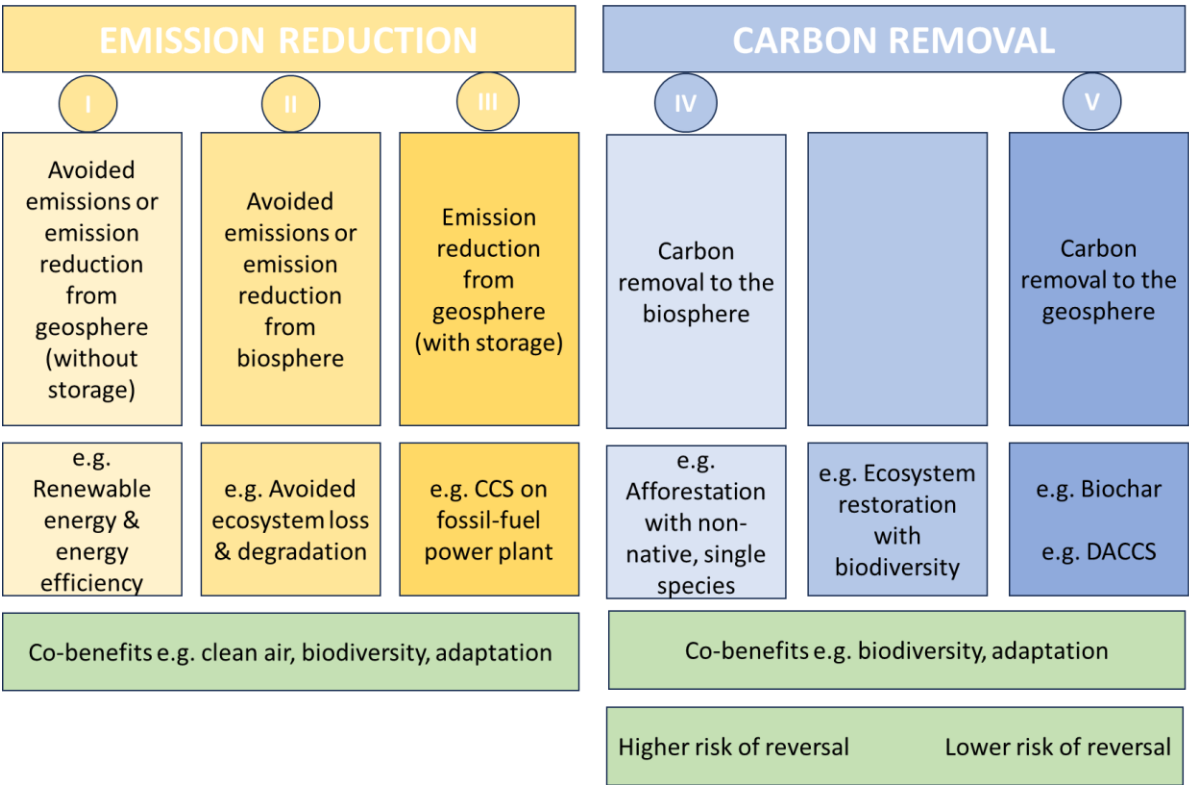


Figure 7.8 Taxonomy of ER and Carbon Removal, amended from (Axelsson *et al.*, 2024,, p.12)

Further clarification of timings of differing interventions and how their input to the global ER and offset changes over times is given by Figure 6.13.

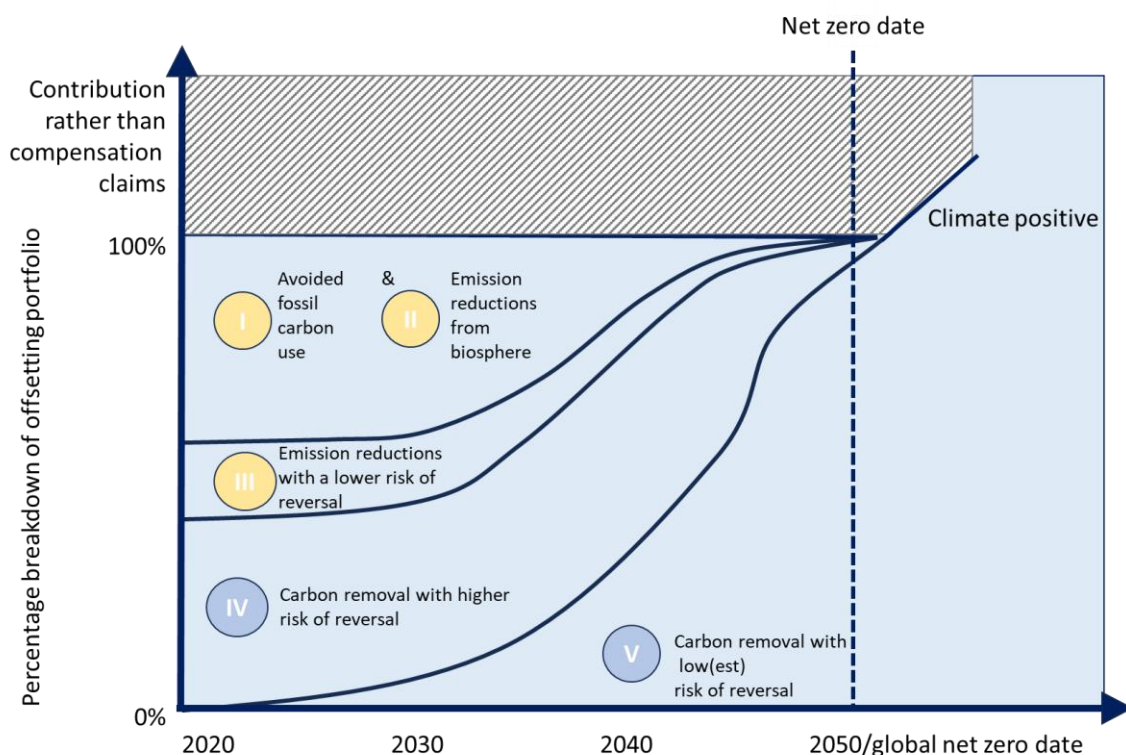


Figure 7.9 Example of Net Zero Aligned Portfolio of Offsetting Interventions, amended from (Axelsson *et al.*, 2024, p.19)

Figure 6.13 illustrates, in line with the actions advocated for NR, that emissions reductions must be used in greater proportions now, reducing as the path to net zero grows closer. Carbon removal with the highest risk of reversal, such as AR should be used in greater quantities now than in the future, with the lowest risk of reversal strategies, such as EW, gradually scaling up its inception date to 2050.

F.18 Assessing Potential Sustainability Co-Benefits

In this section the potential sustainability co-benefits of offsetting via the two methods outlined of AR and EW will be explored, fulfilling Objective 6. Specifically, biodiversity and social co-benefits for AR and EW will be outlined followed by alignment of co-benefits with UNSDGs. An exploration of disbenefits and then impacts of implementing the circular economy will be followed by concluding remarks.

F.18.1 Increased Vegetation Co-Benefits

The benefits of “careful plant selection” (Blair *et al.*, 2016, p.1723) to green the rail corridor to offset CO₂ and increase carbon sequestration have been introduced in Section 2.6.2. Here the potential sustainability benefits of increasing vegetation at the lineside are explored.

Increased vegetation has the potential to lead to increased sequestration (Blair *et al.*, 2016; Ghosh and Khan, 2019; Wang, Gao and Schwendenmann, 2020). In this section the reverse is explored, offsetting using NbS for sequestration, and use of land in a sustainable manner to improve biodiversity (HM Government, 2018, p.4), which may be able to fulfil a dual purpose; the potential to aid infrastructure owners in meeting the now mandatory 10% biodiversity net gain (BNG) for those works which fall under the Environment Act's new mandate (HM Government, 2020b). This is in addition to the duty placed on public authorities, such as NR, by the Natural Environment and Rural Communities Act 2006 as cited in Varley (2018) to conserve biodiversity, which, if NR were not to adequately manage its vegetation as a an asset, whole life costs may be increased and natural capital destroyed (Varley, 2018, p.7). Adding this additional natural capital as sites are remediated gives benefits to the locality and community such as mitigating flood impacts, pollution control and other services and benefits to people, such as recreational access, vital for health and wellbeing (Reid *et al.*, 2021, p.14). This reduction of air pollution and storm water is also found by Blair *et al.* (2016, p.1723) and Lorenz and Lal (2012, p.153). Maintenance of high levels of biodiversity has also been shown to have the ability to enhance soil carbon sequestration (Chen *et al.*, 2018, p.4027). Biodiversity offsetting is advocated by the UK government, whereby unavoidable biodiversity loss is offset elsewhere, (Cornet, Dudley and Banister, 2018, p.382) which aligns with the Environment Act and NBS of 10% mandated in 2024 (HM Government, 2020b) and biodiversity gain is found in a HSR project in France (Aubrat and Lemer, 2018).

F.18.2 Biodiversity Co-Benefits

The literature points to a rebuilding and rewilding strategy for biodiversity, rather than new forest in woodlands plantings, as the optimum pathway to amassing greater carbon stocks alongside larger areas for biodiversity and other ecosystem services such as reduced water run off (Anderson, 2021, p.33). Planted forest, in comparison to natural forest, is found to be an excellent source of both biodiversity and carbon sink potential (Gogoi, Ahirwal and Sahoo, 2021, p.1). Both strategies having metrics that point towards the linking up of NBS with working practices in NR to increase not only biodiversity but also carbon sequestration.

The time lag between implementation of planting for AR offsetting, and sequestration benefits being realised has been explored in the case studies offset examples with inception dates of 2025, using the carbon sequestered in the first 25 years as the Net Zero by 2050 value, and is an important concept. AR needs to be used at scale now and then gradually ramped down in use up to 2050. This offsetting option may help plug the gap in emissions to avoid overshoot while waiting for other NETs to advance and/or upscale, but they are not permanent solutions (Minx *et al.*, 2018) see Figure 6.13, as they are a CDR strategy with high risk of reversal.

A further co-benefit of planting more trees and creating new habitats for wildlife, is that this can assist in stopping the decline in native species (HM Government, 2018, p.4). Global biodiversity decline between 1970 and 2020 is highlighted in the infographic given in **Error! Reference source not found..**

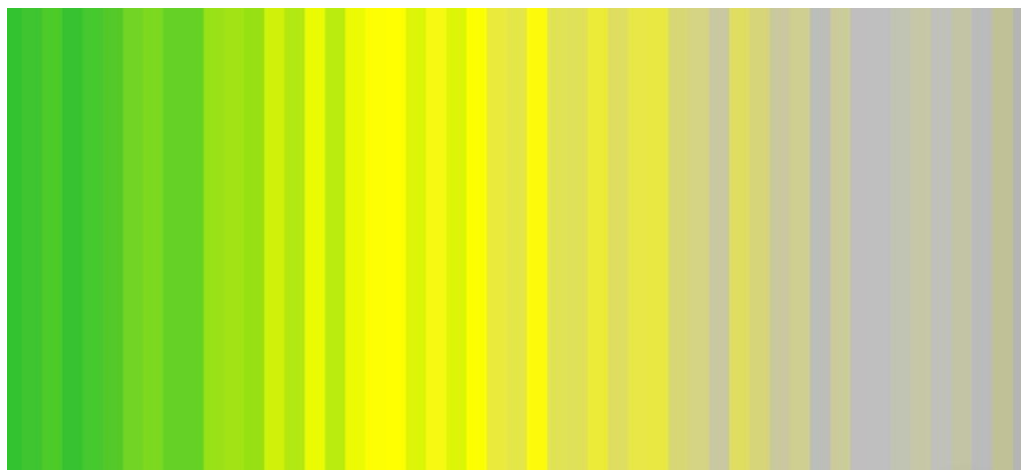


Figure 7.10 Biodiversity Stripes, from (Richardson, 2021)

Other co-benefits of AR include being a potential source of local wood fuel, amenities and recreation for local people (UK National Ecosystem Assessment, 2014) indicating that the forest sector can contribute to atmospheric GHG reduction, while also providing other environmental, economic, and social benefits (Alig *et al.*, 2010).

The use of AR to mitigate climate change has three interwoven actions, each with its own discrete co-benefits:

- 1) Increasing the rate of sequestration and size of carbon store via increase of forested land and general age of forests is a strategy for increasing existing forested land and the co-benefits of biodiversity and recreation which come with this.
- 2) Increased use of wood-based products in firstly building materials (as materials with long life spans thereby locking up the carbon in the wood for longer) and secondly as a substitute for fossil fuels (to give net benefit to global carbon budget), is a further strategy which works with the managed forestry sector. There are substitution co-benefits for use of wood products instead of materials such as plastics, metals, concrete to reduce the embodied carbon in PAS2080 stage A1-3.
- 3) Decreasing carbon and other GHG emissions from wood production methods, can be achieved via use of strategies set out here for reducing carbon in both construction processes and transport and applied to the wood production industry giving the co-benefit of reduced carbon in the PAS2080 stages of A4 and A5 (European Academies Sciences Advisory Council, 2017). A4 transport carbon has been shown to account a significant amount of the A1-5 lifecycle stages for timber transport. Via

refinement of the transport emissions factors used a reduction of around ¼ can be made (Skinner, Morton and Dowdall, 2024, p.35).

Urban forests, as a particular subset of AR, can provide additional benefits in addition to those already identified from AR of sequestration, mitigating pollutants, and improved air and water quality. These additions include improvement of urban climate extremes and mitigating the urban heat island effect, reduced noise pollution, cooling benefits to parked cars and buildings. A secondary effect of reduced heating and cooling requirements is reduced energy and therefore further carbon savings (Brack, 2002, p.5196). These multi-faceted co-benefits give small yet incremental improvements to the carbon footprints of other buildings, for example in their operational PAS2080 B stages via reduced heating and cooling requirements.

The benefits of urban trees also have monetary values attached to them as outlined in a research project on the value of trees in Southampton. This project found significant monetary values for the removal of around 90 tonnes of airborne pollutants and aiding in alleviating flooding of around 95 million litres of water via interception and drainage by tree roots (Mutch *et al.*, 2017).

A further positive benefit of AR is via harvested wood products (HWP). HWPs have a substitution effect, replacing for example, plastic, metals, and concrete in construction and thus reducing the embodied carbon in any construction projects utilising these HWPs (Malmsheimer *et al.*, 2011). Sustainably managed forests deliver a range of other benefits in the environmental arena, including timber and biomass, and wildlife habitat, and benefits in the social sphere, in the form of recreation spaces (Malmsheimer *et al.*, 2011).

AR and land based EW (along with SC management and biochar) all have the potential to impact soil quality, the retention of nutrients, and water cycling (including storm water runoff (Lorenz and Lal, 2012)) resulting in enhanced crop yields leading to socio-economic benefits for locals and regional livelihoods (Fuss *et al.*, 2018). Flood control is also a co-benefit of some NETs (Nemet *et al.*, 2018). A co-benefit of EW with croplands is the delivering of “resource-efficient sustainable food security” (Beerling, 2017, p.3).

The large potential of AR on a global scale such as biodiversity and increased soil quality will diminish over time as the forests saturate, therefore this offset should be used as a short term intermediary to bridge the gap, preventing climate boundaries overshooting, as other novel and new offsets scale up (IPCC, 2018).

Even though the benefits of reduced deforestation are far greater than that of AR in the near term, when discussing co-benefits of offsetting careful definition of what is included in AR is required, as slowing or ending deforestation is classed as a CO₂ mitigation strategy and not CDR (National

Research Council, 2015), see Figure 6.12. Due to the significant quantities of carbon being sequestered in forests, improved forest management will involve less additional CO₂ uptake when compared to newly formed forests (National Academies of Sciences Engineering and Medicine, 2019).

Co-benefits or indirect sequestration benefits from EW include replacement benefits via direct replacing of cement with carbonated materials made from waste, replacing of virgin quarried stone, replacement of hydraulic cement by carbonate-able binders. Reduction benefits of using waste include reducing transport concerned with landfilling of waste, reduced transport and materials handling owing to “solid waste and point-source CO₂ ... located close to the market” (Hills, Tripathi and Carey, 2020, p.11).

EW has both positive and negative benefits. Positive benefits are concerned with sequestration potential and increased productivity of the soil (Fajardy *et al.*, 2019) due to increased nutrients and hence fertility of the soil, along with increased pH due to products of EW chemical reactions which can improve the soil fertility via reduced acidity. Negative benefits include impacts on local flora and fauna and increased carbon footprint of the production process of the minerals for weathering associated with grinding and transportation emissions (Tan and Aviso, 2021).

The scale of these positive and negative benefits is still uncertain, with the demonstrated value of 18 tCO₂ha⁻¹yr⁻¹ and hypothetical sequestration values used in the EW application to both case studies and NR assets explored in Section 6.4 covering a range from 85 and 120 tCO₂ha⁻¹yr⁻¹. Ongoing research is exploring the scaling up of this technology particularly in the UK context via the GGR-D projects. Negative effects include mineral deposition and heavy metal contamination of the soil from trace amounts in the minerals (Tan and Aviso, 2021, p.2).

Planetary scale sequestration potential of EW and benefits of enhanced crop yields and preventing soil erosion alongside abundant minerals such as Olivine for EW, “industrially reprocessed carbonates such as quicklime (CaO)” are also an option to be used for EW (Bach *et al.*, 2019). Unlike other NETS such as AR, EW is not competing against other UNSDGs like food or security.

Linear configuration of plantings, naturally advocated for NR owing to their linear construction, show benefits over block planting configurations on an area basis. This is owing the ability of the roots and canopies of the edge trees in the linear configuration being able to make use of the additional soil water, nutrients and light from the land running adjacent to the linear planting (Paul and Roxburgh, 2020). Hedgerows (another type of linear planting) have also been shown to provide additional co-benefits including provision of significant above-ground biodiversity benefits within farmed landscapes (Lenka *et al.*, 2012). Road verges, as a comparative linear infrastructure to rail, have lots

of potential to increase nature benefits, see Figure 6.5, including reduced run off (Phillips *et al.*, 2021).

Increased AR will provide ecosystem services and environmental benefits on top of enhanced biodiversity and sequestration. These are alongside helping wildlife thrive, and bring a wealth of additional co benefits including increased landscape aesthetics (ONS, 2019), greater public enjoyment, pollination, carbon capture, water quality improvement and flood management (UK National Ecosystem Assessment, 2014). Also physical and mental health benefits are found from the right place for the right tree (Bateman *et al.*, 2023). This public enjoyment could be also classified as a health benefit of recreation, which can also have a monetary value assigned to it. In 2020 the “estimated cultural service in the UK natural capital accounts, were 17.8% of the total asset value in 2020 (£62.4 billion)” (ONS, 2022, p.3).

In this thesis PAS2080: 2016 methodology has been used extensively, however in April 2023 PAS2080: 2023 was released (BSI, 2023) with some important revisions aligned with the conclusions of this thesis, with further guidance also being provided from ICE (ICE, 2023). One of the main revisions of the standard is the focus, infrastructure in 2016 version, and expanded to cover the built environment in 2023 version. The new version of PAS addresses the balance between capital carbon investment and operational, or user benefit, via a whole-life perspective for carbon. The new version also has a greater focus on NbS via carbon reduction and climate change resilience, which aligns with the hierarchy of carbon offsetting alongside being used in tandem with climate change resilience via the NR WRACCA.

The focus of this thesis has been carbon accounting in the PAS2080 stages and not a detailed appraisal of wider sustainability or environmental aspects, which lie outside the scope of PAS2080, however, a brief discussion of these is now provided.

F.18.3 Social Co-Benefits

Sustainability in this rail context, cannot be looked at in isolation, especially given its interrelation to the “triple bottom line,” via the three key elements of economic, environmental and social aspects (Pritchard, 2015). The social aspects as co-benefits of mitigation and adaptation are an integral part of any actions taken on the route to net zero and need careful consideration and understanding of their interrelationship with mitigation and adaptation despite these co-benefits being “overlooked and underutilised in policymaking” (Chastin *et al.*, 2021, p.2), and despite their apparent role in attainment of environmental and development goals such as net zero and the UNSDGs.

A novel approach to increase biodiversity while maximising carbon sequestration rates is found in sharing vs sparing methods. This is where the biodiversity and sequestration costs and benefits of sharing farmland versus sparing it with nature are weighed up. Sparing farmland gives greater sequestration benefits and maintenance of sensitive species at potentially a lower cost. This philosophy may tie in with how NR could utilise its trackside assets which are adjacent to farmland (Collas and Balmford, 2021).

Tree planting specifically along the rail corridor can help to improve the microclimate of surrounding neighbourhoods (Ghosh and Khan, 2019, p.265), alongside air pollution benefits in terms of removing specific pollutants from the air such as CO, NO₂, O₃, PM 2.5, SO₂, PM10. Revegetation of bare land also has additional benefits if trees are planted including rainfall interception and prevention of soil erosion. Vegetation planted along the rail corridor could also join up wildlife areas creating, maintaining, and potentially extending wildlife corridors via protection of biodiversity (Ghosh and Khan, 2019, p.265). Specific ecosystem services associated with rail corridor vegetation are “carbon storage and sequestration and air pollution and storm water reduction” (Blair *et al.*, 2016). Storm water reduction may be beneficial for earthworks. Further information in this area for NR is available via [The Rail Social Value Tool \(rssb.co.uk\)](https://www.rssb.co.uk/the-rail-social-value-tool).

F.18.4 UNSDG Co-Benefits

Use of UNSDGs is advocated to assess co benefits of sustainability (and Niall Mac Dowell) with the 17 UNSDGs (UN General Assembly, 2015a), interconnected global goals adopted by the UN in 2015 with a goal of achievement of 2030, being critical for companies to align with in meeting their full ESG portfolio and their SBTs on the journey to Net Zero (Economist Impact, 2022). Specific sectors have their own roadmaps on the route to attainment of these goals such as the Forest Sector roadmap (WBCSD, 2019), steel (Expedition, 2020), and concrete (ICE, 2022). In particular the EFFC in their carbon reduction guidance refer back to SDG 7, affordable and clean energy which can be attained via supply of green energy and reduced energy use, and 13, climate action attained via reduced carbon emissions and adaptation to climate change (EFFC, 2022), aligning with two of the five SDGs identified as aligning with this thesis, SDGs 7, 9, 11, 12, and 13, with actions towards their attainment detailed further in Chapter 7.

The above sections, demonstrate movement away from siloed thinking into integrated solutions for NR to incorporate in its earthworks, providing dual or potentially triple benefits of biodiversity, carbon and climate resilience, see Figure 2.4.

F.18.5 Disbenefits

The focus of this section is the potential disbenefits of offsetting using AR and EW.

For material choices, such as use of lower carbon cements, for example Belite, care needs to be taken that additional material, of Portland cement for example, to meet the strength characteristics required does not negate the reduced CO₂ and energy claimed for the product (Quillin, 2001). Use of concrete made from recycled aggregate (RA), requires the maximum transport distance to be no more than twice that of natural aggregate (NA). This is to avoid negating the carbon reduction benefits of using RA (Hafez et al., 2020). Although concrete recycling has been shown to make important contributions towards the CE in the construction industry, it does not per se reduce GHG emissions and resource consumption together (Gallego-Schmid et al., 2020).

Use of fly ash, a pulverised coal by product and thus contributing to the CE by diverting this from landfill, for specific railway construction applications such as stabilization of soft subsoil and construction of embankments, is not recommended, as the geotechnical properties of fly ash are not suitable for this application (Vilotijevic *et al.*, 2018).

Use of AR in the UK as a temperate zone forest area could have “uncertain or net neutral benefits for global temperature reduction” (Fuss *et al.*, 2018, p.16) which is why plantings should be undertaken with care and in line with the latest science (IPCC, 2021) and government policy (HM Government, 2021d).

F.18.6 Circular Economy Co-Benefits

The CE (BS8001) and its interlinkage with carbon mitigation and offsets are a theme of this thesis, with many CE principles having dual carbon benefits, such as reuse of materials at EOL. The manifold benefits of moving from take-make-use-dispose to circularity via use of recycled aggregates detailed in Figure 2.18 via movement from linear to circularity, and is discussed in Chapter 5 where materials' carbon reduction is overviewed, including steel. A benefit of increased circularity via use of source-segregated recycled materials is that this can avoid the often substantial GHGs from (avoided) primary material production (Turner, 2016). Figure 2.19 illustrates the circular framework of LCA stages for transport infrastructure outlining the specific areas for transport infrastructure to adopt these important CE principles, in particular aligning CE with the build clever principles, see Figure 2.3. section

Appendix G Appendices Relating to Chapter 7

G.1 FU Comparison of Means from BAU to ER

Descriptive Statistic Type for Functional Unit	50 Case Studies	35 Maintenance Interventions	15 Refurbishment Interventions	5 Renewal Interventions
Mean BAU	551	577	558	353
Mean ER	152	175	98	114
Largest BAU	4105	4105	2400	1128
Largest ER	749	749	318	344
Smallest BAU	8	8	18	21
Smallest ER	2	2	6	7

G.2 Five Major Impacts

This thesis has produced five major impacts:

- 1) Identification of gap in data collection and creation of a novel carbon calculation data form to ensure this vital first step captures all required data to enable accurate and consistent carbon footprinting via use of the PAS2080 template in the RSSB RCT. This form's use could also be recommended as part of the NR Digital Sustainability Guidance as part of the toolkit to use with the RSSB Rail Carbon Tool ([RSSB Rail Carbon Tool - Railway Sustainability Design Guide \(planengage.com\)](https://planengage.com/rssb-rail-carbon-tool)). This form's use could also potentially be encouraged as part of carbon design standards, and discussions have taken place with relevant NR stakeholders to discuss this. The form aligns with other innovations in linear infrastructure, notably, the Highways Sector Council (HSC) launch of PAS2080 alignment toolkit (Highways Sector Council, 2024).
- 2) New insights into the A0 carbon emissions have been found in renewals earthworks to enable whole LCA of renewals earthworks covering PAS2080 stages A0-C4. This A0 stage (with lower and upper estimates per volume of 4,077 – 6,063 kgCO₂e) has been found to equate to 3.6-5.4% of the total of the expanded A0-C4 LCA footprints.
- 3) Indication of the potential percentage emission reductions from BAU that are possible via implementation of ER strategies have been presented (68%, 74% and 65% of mean values for maintenance, refurbishment and renewals see Table 5.5). A subsequent hierarchy of interventions falling under transport, construction and materials areas has been given with application of ER by stage for differing intervention types, see Table 5.6.

4) Extrapolation of most common maintenance intervention types to whole cost and volume data show the NR-wide impact over a complete CP of the application of the ER measures detailed under materials, transport, and construction activities to be around 1.8 million kgCO₂e. This figure accounts for 0.02% of NRs annual global footprint of 8,071,000 tCO₂e, however if compared to the more simplistic extrapolation of all earthwork volumes detailed in Section 7.2 of 1,200 million kgCO₂e, this percentage could increase to 15% of NR's annual global footprint (Expedition, 2020, p.4).

5) Demonstration of the potential of AR and EW for offsetting, including calculation of the areas required to offset project level emissions using these two strategies has been presented.

Extrapolation exercises based on NR reduction of scope 3 emissions to 2050, using the average ER reduction percentage of the case studies, suggest the percentage impact these measures could have (4.4%, 3.4% and 27.7% respectively for arable to woodland, grassland to woodland and EW) on the total NR footprint using all the land assets available to NR.

The above impacts have been discussed in the two substantive sections in Chapter 6 where the potential for offsetting and ER to meet net zero by 2050 goals and potential sustainability co-benefits have been discussed. The main points arising from these discussions are summarised in Sections 7.4.1 and 7.4.2.

Glossary of Terms

This glossary is an amalgamation of selected terms from several excellent glossaries found in the literature which can be accessed in full via the citations below. The references for each term are as per the asterix number given here, or individual reference given in the glossary.

Route kilometres are the total extent of routes available for trains to operate. Sidings and depots are excluded. From ORR 2019-20. Track kilometres take into account multiple track routes (e.g. for each route kilometre where there is double track, there are two track kilometres). Sidings and depots are excluded. From ORR 2019-20.

NR and carbon related terminology^{*1} Carbon Assessment NR NW&C Works Delivery Team Nov 2021 (Mott MacDonald, 2021)

Energy related terminology ^{*2} Future Energy Scenarios (UK National Grid, 2020)

Railway infrastructure carbon specific terminology^{*3} Measuring Railway Infrastructure Carbon: A 'critical' in transport's journey to net-zero (Lokesh, Densley-Tingley and Marsden, 2022a)

HS2 related terminology ^{*4} (0644) HS2 Environmental Sustainability Progress Report April 2020-March 2021 (HS2 Limited, 2022e)

Concrete and cement specific terminology ^{*5} Low Carbon Concrete Routemap (ICE, 2022)

NR specific vegetation and lineside terminology ^{*6} NR Lineside vegetation management manual (Network Rail, 2020c)

NR capital carbon related terminology ^{*7} Managing whole life carbon in infrastructure (Network Rail, 2022c)

NR Costs and volumes terminology^{*8} NR Cost and Volume Handbook (Network Rail, 2021a)

EPA Glossary of Climate Change Terms^{*9}

https://19january2017snapshot.epa.gov/climatechange/glossary-climate-change-terms_.html

Carbon neutrality lexicon (Malmsheimer *et al.*, 2011)^{*10}

Further lexicon from SBTi (SBTi, 2021c) Corporate net-zero standard^{*11}

BS8001 2017 ^{*12}

Glossary of Terms

Abatement.....	Measures that companies take to prevent, reduce or eliminate sources of GHG emissions within their value chain. Examples include reducing energy use, switching to renewable energy and retiring high-emitting assets. *11
Adaptation.....	Adjustment or preparation of natural or human systems to a new or changing environment which moderates harm or exploits beneficial opportunities. *9
Activity.....	Activity data is a key input for calculation of emissions and refers to the data associated with an activity that generates emissions. It is collected in physical units (e.g., litres) or energy units (e.g., kWhs) and then combined with a UK Government (2020) Greenhouse gas conversion factor and the relevant emissions Global Warming Potential (GWP) value to calculate the tCO ₂ e. *1
Adaptive Capacity.....	The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. *9
Aerosols.....	Small particles or liquid droplets in the atmosphere that can absorb or reflect sunlight depending on their composition. *9
Afforestation	Planting of new forests on lands that historically have not contained forests. *9
Anthropogenic.....	Made by people or resulting from human activities. Usually used in the context of emissions that are produced as a result of human activities. *9
Arisings	Material resulting from management and maintenance operations which requires control or removal. *6
Atmosphere.....	The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium, radiatively active greenhouse gases such as carbon dioxide (0.035% volume mixing ratio), and ozone. In addition, the atmosphere contains water vapor, whose amount is highly variable but typically 1% volume mixing ratio. The atmosphere also contains clouds and aerosols. *9

Baseline	The scenario, and associated carbon emissions, that would occur if normal conventional practices were followed and planned measures to reduce carbon were not applied. This marks a defined starting point from where a comparison is made. Note: For Network Rail the reference baseline would be the design solution and delivery method that most closely represents the conventional rail infrastructure solution before any new, innovative carbon reduction measures were applied. *7
Bioenergy.....	Energy generated from the combustion of biomass. In certain cases, bioenergy is considered “carbon neutral” because combustion-related CO ₂ emissions are balanced by CO ₂ that is sequestered during the growth of bioenergy feedstock. *11
Biofuels.....	Gas or liquid fuel made from plant material. Includes wood, wood waste, wood liquors, peat, railroad ties, wood sludge, spent sulfite liquors, agricultural waste, straw, tires, fish oils, tall oil, sludge waste, waste alcohol, municipal solid waste, landfill gases, other waste, and ethanol blended into motor gasoline. *9
Biomass	Materials that are biological in origin, including organic material (both living and dead) from above and below ground, for example, trees, crops, grasses, tree litter, roots, and animals and animal waste. *9
Biosphere.....	The part of the Earth system comprising all ecosystems and living organisms, in the atmosphere, on land (terrestrial biosphere) or in the oceans (marine biosphere), including derived dead organic matter, such as litter, soil organic matter and oceanic detritus. *9
Borehole	Any exploratory hole drilled into the Earth or ice to gather geophysical data. Climate researchers often take ice core samples, a type of borehole, to predict atmospheric composition in earlier years. *9
Carbon cycle	All parts (reservoirs) and fluxes of carbon. The cycle is usually thought of as four main reservoirs of carbon interconnected by pathways of exchange. The reservoirs are the atmosphere, terrestrial biosphere (usually includes freshwater systems), oceans, and sediments (includes fossil fuels). The annual movements of carbon, the carbon exchanges between reservoirs, occur because of various chemical, physical, geological, and biological processes. The ocean contains the largest pool

of carbon near the surface of the Earth, but most of that pool is not involved with rapid exchange with the atmosphere. *9

Carbon-cycle neutrality (carbon neutral) If uptake of carbon (in CO₂) by plants over a given area and time is equal to emissions of biogenic carbon attributable to that area, biomass removed from that area is carbon-cycle neutral. *10

Carbon Dioxide A naturally occurring gas, and also a by-product of burning fossil fuels and biomass, as well as land-use changes and other industrial processes. It is the principal human caused greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1. *9

Carbon Dioxide Equivalent .. A metric measure used to compare the emissions from various greenhouse gases based upon their global warming potential (GWP). Carbon dioxide equivalents are commonly expressed as "million metric tons of carbon dioxide equivalents (MMTCO₂Eq)." The carbon dioxide equivalent for a gas is derived by multiplying the tons of the gas by the associated GWP.
MMTCO₂Eq = (million metric tons of a gas) * (GWP of the gas) *9

Carbon Footprint Also listed as Carbon Account, Carbon Inventory or Carbon Account Inventory

Carbon Literacy Project Education scheme run by the Carbon Literacy Trust, which aims to raise awareness of carbon emissions and climate change-related issues. *4

Carbon Sequestration..... Terrestrial, or biologic, carbon sequestration is the process by which trees and plants absorb carbon dioxide, release the oxygen, and store the carbon. Geologic sequestration is one step in the process of carbon capture and sequestration (CCS), and involves injecting carbon dioxide deep underground where it stays permanently. *9

Carbon Capture and Sequestration

Carbon capture and sequestration (CCS) is a set of technologies that can greatly reduce carbon dioxide emissions from new and existing coal- and gas-fired power plants, industrial processes, and other stationary sources of carbon dioxide. It is a three-step process that includes capture of carbon dioxide from power plants or industrial sources; transport of the captured and compressed carbon dioxide (usually in

pipelines); and underground injection and geologic sequestration, or permanent storage, of that carbon dioxide in rock formations that contain tiny openings or pores that trap and hold the carbon dioxide. *9

Cess..... The ground from the outer edge of the ballasted area to 3 metres from the running rail. *6

Cess Strip The ground area 3 to 5 metres from the running rail. *6

Climate Climate in a narrow sense is usually defined as the "average weather," or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands of years. The classical period is 3 decades, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. *9

Climate Change Climate change refers to any significant change in the measures of climate lasting for an extended period of time. In other words, climate change includes major changes in temperature, precipitation, or wind patterns, among others, that occur over several decades or longer. *9

Climate Change Mitigation.. According to the IPCC, "a human intervention to reduce emissions or enhance the sinks of greenhouse gases." *11

Climate Model A quantitative way of representing the interactions of the atmosphere, oceans, land surface, and ice. Models can range from relatively simple to quite comprehensive. *9

Climate Sensitivity In IPCC reports, equilibrium climate sensitivity refers to the equilibrium change in global mean surface temperature following a doubling of the atmospheric (equivalent) CO₂ concentration. More generally, equilibrium climate sensitivity refers to the equilibrium change in surface air temperature following a unit change in radiative forcing (degrees Celsius, per watts per square meter, (C/Wm⁻²). One method of evaluating the equilibrium climate sensitivity requires very long simulations with Coupled General Circulation Models (Climate model). The effective climate sensitivity is a related measure that circumvents this requirement. It is evaluated from model output for evolving non-equilibrium conditions. It is a measure of the strengths of the feedbacks

at a particular time and may vary with forcing history and climate state. *9

Conference of the Parties.... The supreme body of the UN Framework Convention on Climate Change (UNFCCC). It comprises more than 180 nations that have ratified the Convention. Its first session was held in Berlin, Germany, in 1995 and it is expected to continue meeting on a yearly basis. The COP's role is to promote and review the implementation of the Convention. It will periodically review existing commitments in light of the Convention's objective, new scientific findings, and the effectiveness of national climate change programs. *9

Consumer Transformation Pathway Scenario from FES2020, the second fastest route to decarbonisation where there are significant societal changes, higher levels of energy efficiency, and lower levels of energy demand. *3

Cutting slope angle..... Steepness of the slope measured from the horizontal. *6

Deforestation Those practices or processes that result in the conversion of forested lands for non-forest uses. Deforestation contributes to increasing carbon dioxide concentrations for two reasons: 1) the burning or decomposition of the wood releases carbon dioxide; and 2) trees that once removed carbon dioxide from the atmosphere in the process of photosynthesis are no longer present. *9

Downcycling process of converting secondary raw materials/by-products into new materials, components or products, typically of lesser quality, reduced functionality and/or lower value compared to their original intended purpose. *12

Embankment "A construction (formed of earth) that allows railway lines to pass at an acceptable level and gradient over low-lying ground or ground that is susceptible to flooding and appears in the Network Rail Earthworks asset register as an 'Embankment'." *8

Emissions The release of a substance (usually a gas when referring to the subject of climate change) into the atmosphere. *9

Emissions Factor A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., grams of carbon dioxide emitted per barrel of fossil fuel consumed, or per pound of product produced). *9

- FLAG emissions..... GHG emissions from Forestry, Land use and Agriculture. Examples of key sources of FLAG emissions include deforestation, forest & grassland fires enteric fermentation, fertilizers, manure management and rice cultivation Reducing FLAG emissions, as well as enhancing land-related carbon sinks through activities such as reforestation, is an important climate change mitigation opportunity. *11
- Fossil Fuel A general term for organic materials formed from decayed plants and animals that have been converted to crude oil, coal, natural gas, or heavy oils by exposure to heat and pressure in the earth's crust over hundreds of millions of years. *9
- Fuel Switching..... In general, this is substituting one type of fuel for another. In the climate-change discussion it is implicit that the substituted fuel produces lower carbon emissions per unit energy produced than the original fuel, e.g., natural gas for coal. *9
- Functional Unit (FU) A quantified description of a product and/or its functionality, which in comparative LCA, creates a level playing field (a standard unit) for the comparison of environmental performance of two or more products. *3
- Global Emissions Budget A cumulative emissions threshold that must not be exceeded to limit global temperature rise by a specified amount and probability. Emissions budgets can be determined for CO₂ only or all greenhouse gases (GHGs). *11
- Global Reporting Initiative .. The world's most widely used framework for sustainability reporting. *4
- GRIP Governance for Railway Investment Projects
- High risk leaf fall species Sycamore (*Acer pseudoplatanus*), ash (*Fraxinus excelsior*), sweet chestnut (*Castanea sativa*), horse chestnut (*Aesculus hippocastanum*, lime (*Tilia species*).), poplar (*Populus*) species – except aspen (*P. tremula*). *6
- HS2 Green Corridor Network of climate-resilient habitats and green spaces that runs alongside the HS2 line. *4
- ICE..... Inventory of Carbon and Energy. *3
- Indirect Emissions..... Indirect emissions from a building, home or business are those emissions of greenhouse gases that occur as a result of the generation of electricity used in that building. These emissions are called "indirect"

because the actual emissions occur at the power plant which generates the electricity, not at the building using the electricity. *9

Inherent carbon neutrality.. Biomass carbon was only recently removed from the atmosphere; returning it to the atmosphere merely closes the cycle. *10

Insetting..... Insetting is used to describe projects that are wholly contained within a Scope 3 supply chain boundary of a company, a project partially within their Scope 3 supply chain boundary (spanning their supply chain and other companies' supply chains) and a project adjacent to a supply chain boundary. *11

Intensity convergence Method used to calculate emissions intensity targets based on the principle of converging to a sector-wide physical emissions intensity in a future year of a mitigation pathway. *11

IPCC..... United Nations body for assessing the science related to climate change. *11

Intergovernmental Panel on climate Change (IPCC)

The IPCC was established jointly by the United Nations Environment Programme and the World Meteorological Organization in 1988. The purpose of the IPCC is to assess information in the scientific and technical literature related to all significant components of the issue of climate change. The IPCC draws upon hundreds of the world's expert scientists as authors and thousands as expert reviewers. Leading experts on climate change and environmental, social, and economic sciences from some 60 nations have helped the IPCC to prepare periodic assessments of the scientific underpinnings for understanding global climate change and its consequences. With its capacity for reporting on climate change, its consequences, and the viability of adaptation and mitigation measures, the IPCC is also looked to as the official advisory body to the world's governments on the state of the science of the climate change issue. For example, the IPCC organized the development of internationally accepted methods for conducting national greenhouse gas emission inventories. *9

Kyoto Basket of Gases Carbon dioxide (CO₂), Methane (CH₄), Nitrous oxide (N₂O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulphur hexafluoride (SF₆), Nitrogen trifluoride (NF₃) (7 gases included in Kyoto basket as amended by Doha Agreement)

Landfill	Land waste disposal site in which waste is generally spread in thin layers, compacted, and covered with a fresh layer of soil each day. *9
Life-cycle neutrality	If emissions of all greenhouse gases from the lifecycle of a product system are equal to transfers of CO ₂ from the atmosphere into that product system, the product system is life-cycle neutral. *10
Lineside.....	The area between the ballasted area and the boundary measure. *6
Lineside estate.....	The extensive area of land that falls within the ownership boundary. *6
Lineside assets.....	Infrastructure assets on the lineside that require vegetation management. NOTE: These include but are not limited to the following: cess paths, walking routes, troughing/cable routes, access steps, access roadways, location cabinets/rooms, lineside buildings, equipment housing, signalling gantries, and overhead line equipment stanchions. *6
Material Footprint	A consumption-based indicator of resource use. It is defined as a global allocation of used raw material extraction to the final demand of an economy (Wiedmann <i>et al.</i> , 2015).
Mitigation	A human intervention to reduce emissions or enhance the sinks of greenhouse gases (IPCC). *11
Mitigation Strategy.....	A set of measures planned by a company to mitigate GHG emissions that may include abatement, insetting, compensation and neutralisation. *11
NbS	The WWF defines Nature Based Solutions as “Ecosystem conservation, management and/or restoration interventions intentionally planned to deliver measurable positive climate adaptation and /or mitigation benefits that have human development and biodiversity co-benefits managing anticipated climate risks to nature that can undermine their long-term effectiveness.” *11
Neutralization.....	Measures that companies take to remove carbon from the atmosphere and permanently store it to counterbalance the impact of emissions that remain unabated. *11
Offset neutrality	If emissions of greenhouse gases are compensated for by using offsets representing removals that occur outside of a product system, that product or product system is offset neutral. *10

Glossary of Terms

Other cements.....	A term used to designate potential alternatives to existing general purpose cements whose suitability is not yet established in the UK concrete standard BS 8500. *5
PACE	Project Acceleration in a Controlled Environment
Physical emissions intensity	A metric describing the emissions per physical unit of an activity (e.g., cement production). The intensity convergence method is based on the principle that all companies in a sector will converge to the same physical emissions intensity in a future year of mitigation pathways. *11
Portland cement (CEM I)	A mixture of compounds formed from the oxides of calcium (CaO), silicon (SiO ₂), aluminium (Al ₂ O ₃) and iron (Fe ₂ O ₃), predominantly comprising hydraulic calcium silicates, which react and harden in contact with water. It is produced by grinding Portland cement clinker with a source of calcium sulphate to yield a fine powder. It is classified as the common cement type CEM I according to BS EN 197-1. *5
Radiative Forcing	A measure of the influence of a particular factor (e.g. greenhouse gas (GHG), aerosol, or land use change) on the net change in the Earth's energy balance. *9
Recycling.....	Collecting and reprocessing a resource so it can be used again. An example is collecting aluminium cans, melting them down, and using the aluminium to make new cans or other aluminium products. *9
Recycled aggregates	Aggregates that arise from reprocessing inorganic or mineral materials that have previously been used in construction (see also: BS EN 12620). *5
Recycling Closed Loop	e.g. milk bottle return for reuse. *12
Recycling Open Loop	e.g. glass return for aggregates. *12
Reforestation.....	Planting of forests on lands that have previously contained forests but that have been converted to some other use. *9
Removals	Measures that companies take to remove carbon from the atmosphere and permanently store it within or beyond the value chain. *11
Renewable Energy	Energy resources that are naturally replenishing such as biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action.*9

Resilience.....	A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment. *9
Reuse	operation by which a product, component or material can be used again without requiring any reprocessing or treatment. *12
Reverse logistics	Process of reclaiming products and materials from the end user with the objective of capturing value. *12
Rock Cutting	“An excavation (through rock) that allows railway lines to pass at an acceptable level and gradient through the surrounding ground and appears in the Network Rail Earthworks asset register as an Earthwork asset of the asset type 'Rock Cutting’.” *8
Scenarios	A plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships. *9
Science-based targets	Business carbon reduction targets are described as ‘science-based targets’ if they have been independently verified and endorsed by the science-based targets initiative (SBTi). To receive endorsement the targets must fit into a plan to keep the business’s proportion of GHG emissions within the limits of 1.5°C temperature increase above pre-industrial levels, or no more than 2°C above pre-industrial levels. *7 The Environmental Commitments of Network Rail can be found here: https://networkrail.sharepoint.com/sites/myconnect/technicalauthority/Documents/Forms/AllItems.aspx?id=/sites/myconnect/technicalauthority/Documents/NR%20Environmental%20Strategy%20FINAL%20published%2023%20Sept%202020.pdf&parent=/sites/myconnect/technicalauthority/Documents
Secondary aggregates	Aggregates that are usually by-products of other industrial processes that have not previously been used in construction. *5
Sector-specific pathways.....	Absolute emissions or emissions intensity pathways for a specific sector that may be used for calculating near-term and long-term intensity targets, as well as long-term absolute targets, in most cases. *11
Sink	Any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere. *9

Glossary of Terms

- Soil Carbon A major component of the terrestrial biosphere pool in the carbon cycle. The amount of carbon in the soil is a function of the historical vegetative cover and productivity, which in turn is dependent in part upon climatic variables. *9
- Soil Cutting “An excavation (through soil) that allows railway lines to pass at an acceptable level and gradient through the surrounding ground and appears in the Network Rail Earthworks asset register as an Earthwork asset of the asset type 'Soil Cutting’.” *8
- Solar Radiation Radiation emitted by the Sun. It is also referred to as short-wave radiation. Solar radiation has a distinctive range of wavelengths (spectrum) determined by the temperature of the Sun. *9
- SPEED..... Swift, Pragmatic, and Efficient Enhancement Delivery
- Substitution neutrality If emissions associated with the lifecycle of a product are equal to (or less than) those associated with likely substitute products, that product or product system is (at least) substitution neutral. *10
- Terawatt Hour (TWh) 1,000,000,000,000 watt hours, a unit of energy. *2
- UNFCCC United Nations Framework Convention on Climate Change (UNFCCC)
The Convention on Climate Change sets an overall framework for intergovernmental efforts to tackle the challenge posed by climate change. It recognizes that the climate system is a shared resource whose stability can be affected by industrial and other emissions of carbon dioxide and other greenhouse gases. The Convention enjoys near universal membership, with 189 countries having ratified.
Under the Convention, governments: gather and share information on greenhouse gas emissions, national policies and best practices; launch national strategies for addressing greenhouse gas emissions and adapting to expected impacts, including the provision of financial and technological support to developing countries; cooperate in preparing for adaptation to the impacts of climate change. The Convention entered into force on 21 March 1994. *9
- Upcycling process of converting secondary raw materials/by-products into new materials, components or products of better quality, improved functionality and/or a higher value. *12

Value Chain..... Organisations and stakeholders involved in creating and managing infrastructure assets, including asset owners/managers, designers, contractors, and product/material manufacturers/suppliers. *7

Value Chain emissions..... A company's scope 1, 2, and 3 emissions as defined by the GHG Protocol accounting standard. *11

List of References

- AAA Automotive (2023) *How efficient is your cars engine*. Available at: <https://www.aaa.com/autorepair/articles/how-efficient-is-your-cars-engine> (Accessed: 2 November 2023).
- Acquaye, A.A. *et al.* (2011) 'Identification of 'carbon hot-spots' and quantification of GHG intensities in the biodiesel supply chain using hybrid LCA and structural path analysis', *Environmental science & technology*, 45(6), pp. 2471-2478. Available at: <https://doi.org/10.1021/es103410q>
- Adams, K.T. *et al.* (2017) 'Circular economy in construction: current awareness, challenges and enablers', *Proceedings of the Institution of Civil Engineers-Waste and Resource Management*, 170(1), pp. 15-24. Available at: <http://dx.doi.org/10.1680/jwarm.16.00011>.
- Akan, M.Ö.A., Dhavale, D.G. and Sarkis, J. (2017) 'Greenhouse gas emissions in the construction industry: An analysis and evaluation of a concrete supply chain', *Journal of Cleaner Production*, 167, pp. 1195-1207. Available at: <http://dx.doi.org/10.1016/j.jclepro.2017.07.225>.
- Akponeware, A. *et al.* (2022) 'An integrated empirical analysis of UK rail industry's carbon assessment: An industry perspective', *Case Studies on Transport Policy*, 10(1), pp. 315-330. Available at: <http://dx.doi.org/10.1016/j.cstp.2021.12.012>.
- Alduán, A.S., Pindado, P.V. and Arribas, M.M. (2016) *Las cuentas ecológicas del transporte en España*. Libros en acción.
- Alessandro, P. and Marta, C. (2012) 'Heterogeneity of linear forest formations: differing potential for biodiversity conservation. A case study in Italy', *Agroforestry Systems*, 86(1), pp. 83-93. Available at: <http://dx.doi.org/10.1007/s10457-012-9511-y>.
- Alig, R. *et al.* (2010) 'Mitigating greenhouse gases: The importance of land base interactions between forests, agriculture, and residential development in the face of changes in bioenergy and carbon prices', *Forest Policy & Economics*, 12(1), pp. 67-75. Available at: <https://doi.org/10.1016/j.forpol.2009.09.012>.
- Aljuneidi, T. and Bulgak, A.A. (2020) 'Carbon footprint for designing reverse logistics network with hybrid manufacturing-remanufacturing systems', *Journal of Remanufacturing*, 10(2), pp. 107-126. Available at: <https://doi.org/10.1007/s13243-019-00076-5>.
- Allwood, J.M. *et al.* (2022) 'Construction Sector Innovation within Absolute Zero: Business growth in a transformative journey to zero emissions'. Available at: <https://api.repository.cam.ac.uk/server/api/core/bitstreams/16ce22f7-5712-4ecf-b412-727de442b795/content> (Accessed: 29 April 2024).
- Almeida, M. *et al.* (2010) 'Life Cycle Assessment (Cradle to gate) of a Portuguese Brick', *Portugal SB10- Sustainable Building Affordable to All* pp. 477-482. Available at: https://www.researchgate.net/profile/Antonio-Dias-21/publication/255179506_Life_cycle_assessment_cradle_to_gate_of_a_Portuguese_brick/links/541bdcd50cf203f155b33477/Life-cycle-assessment-cradle-to-gate-of-a-Portuguese-brick.pdf (Accessed: 10 October 2023).
- Ambrose, H. *et al.* (2020) 'Trends in life cycle greenhouse gas emissions of future light duty electric vehicles', *Transportation Research Part D-Transport and Environment*, 81, p. 14. Available at: <https://doi.org/10.1016/j.trd.2020.102287>.

- Anand, C.K. and Amor, B. (2017) 'Recent developments, future challenges and new research directions in LCA of buildings: A critical review', *Renewable and Sustainable Energy Reviews*, 67, pp. 408-416. Available at: <https://doi.org/10.1016/j.rser.2016.09.058>.
- and, M.B. and Niall Mac Dowell, E. (2022) *Greenhouse Gas Removal Technologies*. Royal Society of Chemistry. Energy and Environment, 31.
- Anderson, P. (2021) 'Carbon and ecosystems: restoration and creation to capture carbon. '. Available at: <https://cieem.net/wp-content/uploads/2021/05/Carbon-and-habitats-paper-v3.pdf> (Accessed 14 March 2023).
- Antonias, N. *et al.* (2022) 'Carbon footprint and LCA methodologies to quantify, account and minimize GHG emissions along the entire life cycle of rail infrastructure', *Proceedings of the World Congress on Railway Research 2022: OP.12 Reducing carbon footprint*. Birmingham, UK, 6-10 June Available at: <https://crowdcomms.com/wcrr2022/modules/132783/document> (Accessed: 16 June 2022).
- Araujo, J.F. *et al.* (2019) 'Method to assess the atmospheric pollutant emissions generated by railway track maintenance', *Production*, 30. Available at: <https://doi.org/10.1590/0103-6513.20190037>.
- Arias, P.A., N. Bellouin, E. Coppola, R. G. Jones, G. Krinner, J. Marotzke, V. Naik, M. D. Palmer, G-K. *et al.* (2021) 'Technical Summary. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change', in [Masson-Delmotte, V. *et al.* (eds.)]. Available at: <https://www.ipcc.ch/report/ar6/wg1/>.
- Arora, V.K. and Montenegro, A. (2011) 'Small temperature benefits provided by realistic afforestation efforts', *Nature Geoscience*, 4(8), pp. 514-518. Available at: <http://dx.doi.org/10.1038/NGEO1182>.
- asknumbers.com (2023) *UK MPG to KM/L Conversion*. Available at: <https://www.asknumbers.com/imperial-mpg-to-kml.aspx> (Accessed: 29 October 2023).
- Aubrat, M. and Lemer, J. (2018) 'Advancing environmental mitigation on the Bretagne-Pays de la Loire railway, France', *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, 171(8), pp. 402-10. Available at: <https://doi.org/10.1680/jensu.16.00014>.
- Axe, M.S., Grange, I.D. and Conway, J.S. (2017) 'Carbon storage in hedge biomass—A case study of actively managed hedges in England', *Agriculture, Ecosystems and Environment*, 250, pp. 81-88. Available at: <http://dx.doi.org/10.1016/j.agee.2017.08.008>.
- Axelsson, K. *et al.* (2024) 'The Oxford Principles for Net Zero Aligned Carbon Offsetting. Smith School of Enterprise and the Environment, University of Oxford Revised 2024'. Oxford, UK, September. Available at: <https://www.smithschool.ox.ac.uk/sites/default/files/2024-02/Oxford-Principles-for-Net-Zero-Aligned-Carbon-Offsetting-revised-2024.pdf> (Accessed: 14 September 2024).
- Baah-Acheamfour, M. *et al.* (2015) 'Carbon pool size and stability are affected by trees and grassland cover types within agroforestry systems of western Canada', *Agriculture, Ecosystems and Environment*, 213, pp. 105-113. Available at: <http://dx.doi.org/10.1016/j.agee.2015.07.016>.
- Bach, C. (2019) *Record efficiency for a gas engine*. Available at: <https://phys.org/news/2019-06-efficiency-gas.html> (Accessed: 2 November 2023).
- Bach, L.T. *et al.* (2019) *CO2 removal with enhanced weathering and ocean alkalinity enhancement: Potential risks and co-benefits for marine pelagic ecosystems*. Available at: <http://dx.doi.org/10.3389/fclim.2019.00007>.
- Baker-Brown, D., Gowler, P. and Arnold, W. (2023) *Circular economy and reuse: guidance for designers*. United Kingdom: The Institution of Structural Engineers.

List of References

- Banar, M. and Ozdemir, A. (2015) 'An evaluation of railway passenger transport in Turkey using life cycle assessment and life cycle cost methods', *Transportation Research Part D-Transport and Environment*, 41, pp. 88-105. Available at: <http://dx.doi.org/10.1016/j.trd.2015.09.017>.
- Baron, T., Martinetti, G. and P  pion, D. (2011) *UIC Report Carbon Footprint of High Speed Rail - High Speed Rail and Sustainability. Background Report: Methodology and results of carbon footprint analysis*. Paris, France: International Union of Railways. Available at: https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/15009/Carbon%20Footprint%20of%20High-Speed%20Rail%20UIC%202011.pdf (Accessed 30 April 2022).
- Basilisk (2022) *Basilisk Self-Healing Concrete*. Available at: <https://basiliskconcrete.com/en/> (Accessed: 25 May 2022).
- Bateman, I.J. et al. (2023) 'A review of planting principles to identify the right place for the right tree for 'net zero plus' woodlands: Applying a place-based natural capital framework for sustainable, efficient and equitable (SEE) decisions', *People and Nature*, 5(2), pp. 271-301. Available at: <https://besjournals.onlinelibrary.wiley.com/doi/abs/10.1002/pan3.10331>.
- BBC News (2024) *UK needs big emissions cut, climate watchdog says*. Available at: <https://click.e.bbcmail.co.uk/?qs=44301c1e6ba9e9fc04804d8d5aecab92414d3207cf25237af3f69e58f365a8412f3c78c3c1ef94a1a9c0c859d33209e5b9f3be1acbe7fcef> (Accessed: 9 November 2024).
- Beerling, D.J. (2017) 'Enhanced rock weathering: biological climate change mitigation with co-benefits for food security?', *Biol. Lett.*, 13. Available at: <http://dx.doi.org/10.1098/rsbl.2017.0149>.
- BEIS (2021) *2019 UK Greenhouse Gas Emissions, Final Figures*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/957887/2019_Final_greenhouse_gas_emissions_statistical_release.pdf (Accessed: 19 January 2022).
- Bergman, R. et al. (2014) 'The carbon impacts of wood products', *Forest Products Journal*, 64(7-8), pp. 220-231. Available at: <https://doi.org/10.13073/FPJ-D-14-00047>.
- Beuttler, C., Charles, L. and Wurzbacher, J. (2019) 'The role of direct air capture in mitigation of anthropogenic greenhouse gas emissions', *Frontiers in Climate*, 1:10. Available at: <https://www.frontiersin.org/articles/10.3389/fclim.2019.00010/full> (Accessed: 30 April 2022).
- Bevans, R. (2023) *Choosing the Right Statistical Test | Types & Examples*. Scribbr. Available at: <https://www.scribbr.com/statistics/statistical-tests/> (Accessed: 23 September 2024).
- Low Carbon Concrete [Webinar]* (2021) Retrieved from Institute of Civil Engineers website: <https://www.ice.org.uk/eventarchive/low-carbon-concrete-webinar>.
- Blair, J. et al. (2016) 'Greening rail infrastructure for carbon benefits', *International High-Performance Built Environment Conference - a Sustainable Built Environment Conference 2016 Series*. Amsterdam. Elsevier Science Bv, pp. 1716-1724. Available at: <http://dx.doi.org/10.1016/j.proeng.2017.04.334>
- Brack, C.L. (2002) 'Pollution mitigation and carbon sequestration by an urban forest', *Environmental Pollution*, 116, pp. S195-S200. Available at: [https://doi.org/10.1016/S0269-7491\(01\)00251-2](https://doi.org/10.1016/S0269-7491(01)00251-2).
- Brander, M. et al. (2021) 'Carbon accounting for negative emissions technologies', *Climate Policy*, 21(5), pp. 699-717. Available at: <https://doi.org/10.1080/14693062.2021.1878009>.
- BRE (2021) *BRE Environmental & Sustainability Standard BES 6001: ISSUE 3.2 Framework Standard for Responsible Sourcing*. BRE Global. Available at: https://www.greenbooklive.com/filelibrary/responsible_sourcing/BES-6001-3.2.pdf (Accessed 22 March 2022).

- BRE (2022) *BRE Environmental & Sustainability Standard BES 6001: ISSUE 4.0 Framework Standard for Responsible Sourcing DRAFT*. Available at: https://www.greenbooklive.com/filelibrary/responsible_sourcing/BES-6001-V4.0-Draft.pdf (Accessed: 6 August 2022).
- Briggs, K., Loveridge, F. and Glendinning, S. (2017) 'Failures in transport infrastructure embankments', *Engineering Geology*, 219, pp. 107-117. Available at: <http://dx.doi.org/10.1016/j.enggeo.2016.07.016>.
- Briggs, K.M. (2011) *Impacts of climate and vegetation on railway embankment hydrology*. EngD thesis. University of Southampton.
- British Ports Association (2021) *A Guide to Alternative Fuels For Non-Road Mobile Machinery Used in Ports*. Available at: https://www.britishports.org.uk/content/uploads/2021/12/NRMM_Fuels1.pdf (Accessed: 27 November 2023).
- British Railways Board (1963) *The reshaping of British railways. Part 1 : report*. HM Stationary Office.
- Brown, I. (2020) 'Challenges in delivering climate change policy through land use targets for afforestation and peatland restoration', *Environmental Science and Policy*, 107, pp. 36-45. Available at: <http://dx.doi.org/10.1016/j.envsci.2020.02.013>.
- Bryan, B.A. et al. (2015) 'Land use efficiency: anticipating future demand for land-sector greenhouse gas emissions abatement and managing trade-offs with agriculture, water, and biodiversity', *Global Change Biology*, 21(11), pp. 4098-4114. Available at: <https://doi.org/10.1111/gcb.13020> (Accessed: Nov).
- BSI (2011) *BS EN 15978:2011: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*. BSI. Available at: <https://bsol-bsigroup-com.soton.idm.oclc.org/> (Accessed: 21 April 2021).
- BSI (2016) *PAS 2080:2016: Carbon Management in Infrastructure*. Available at: <https://bsol-bsigroup-com.soton.idm.oclc.org/> (Accessed: 5 August 2021).
- BSI (2017) *BS8001:2017: Framework for implementing the principles of the circular economy in organisations - Guide*. Available at: <https://bsol-bsigroup-com.soton.idm.oclc.org/> (Accessed: 2 February 2022).
- BSI (2018) *BS EN ISO 14044:2006+A1:2018 Incorporating corrigendum May 2018: Environmental management - Life cycle assessment - Requirements and guidelines*. Available at: <https://bsol-bsigroup-com.soton.idm.oclc.org/> (Accessed: 21 January 2021).
- BSI (2020) *BS EN ISO 14040:2006+A1:2020 Incorporating corrigendum August 2006: Environmental management - Life cycle assessment - Principles and framework*. Available at: <https://bsol-bsigroup-com.soton.idm.oclc.org/> (Accessed: 21 January 2021).
- BSI (2022) *A Guide to the PD ISO IWA 42 Net Zero Guidelines*. Available at: <https://pages.bsigroup.com/pdisoiwa42guide> (Accessed: 8 May 2024).
- BSI (2023) *PAS 2080:2023 Carbon Management in Buildings and Infrastructure*. Available at: https://www.bsigroup.com/siteassets/pdf/en/insights-and-media/insights/brochures/pas_2080.pdf (Accessed: 12 April 2024).
- Buchanan, A.H. and Levine, S.B. (1999) 'Wood-based building materials and atmospheric carbon emissions', *Environmental Science & Policy*, 2(6), pp. 427-437. Available at: [https://doi.org/10.1016/S1462-9011\(99\)00038-6](https://doi.org/10.1016/S1462-9011(99)00038-6).

List of References

- Burchart-Korol, D. and Folega, P. (2020) 'Environmental footprints of current and future electric battery charging and electric vehicles in Poland', *Transport Problems*, 15(1), pp. 61-70. Available at: <http://dx.doi.org/10.21307/tp-2020-006>.
- Burmeister, E. and Aitken, L.M. (2012) 'Sample size: How many is enough?'. Available at: <https://doi.org/10.1016/j.aucc.2012.07.002>.
- Cabinet Office (2021) *Procurement Policy Note - Taking Account of Carbon Reduction Plans in the procurement of major government contracts (Action Note PPN 06/21)*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1054374/PPN-0621-Taking-account-of-Carbon-Reduction-Plans-Jan22_1_.pdf (Accessed: 1 November 2021).
- Cameron, D.G. et al. (2020) *Directory of Mines and Quarries 2020*. 11th Edition edn. Available at: https://www2.bgs.ac.uk/mineralsuk/download/dmq/Directory_of_Mines_and_Quarries_2020.pdf (Downloaded: 5 May 2021).
- Canadell, J.G. and Raupach, M.R. (2008) 'Managing forests for climate change mitigation', *Science*, 320(5882), pp. 1456-1457. Available at: <https://science.sciencemag.org/content/sci/320/5882/1456.full.pdf> (Accessed: 30 April 2021).
- Carbon Literacy Project (2023) *The Carbon Literacy Project*. Available at: <https://carbonliteracy.com/> (Accessed: 12 September 2023).
- Carbon Trust (2021) *Product Carbon Footprint Label*. Available at: <https://www.carbontrust.com/what-we-do/assurance-and-certification/product-carbon-footprint-label> (Accessed 27 August 2021).
- Carbon Trust (2022a) *Carbon Neutral Certification*. Available at: <https://www.carbontrust.com/what-we-do/assurance-and-certification/carbon-neutral-certification> (Accessed: 23 June 2022).
- Carbon Trust (2022b) *A Guide to Net Zero for Business*. Available at: <https://www.carbontrust.com/resources/a-guide-to-net-zero-for-businesses> (Accessed: 26 May 2022).
- CENTS (2023) *Circular Economy Network + in Transportation Systems*. Available at: <https://warwick.ac.uk/fac/sci/wmg/research/materials/smam/cents/> (Accessed: 10 October 2023).
- Chang, B. and Kendall, A. (2011) 'Life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system', *Transportation Research Part D-Transport and Environment*, 16(6), pp. 429-434. Available at: <https://doi.org/10.1016/j.trd.2011.04.004>.
- Chaparro, L. and Terradas, J. (2009) *Ecological services of urban forest in Barcelona*. Àrea de Medi Ambient, Institut Municipal de Parcs i Jardins, Ajuntament de Barcelona. Available at: https://www.researchgate.net/profile/Jaume-Terradas-3/publication/286449350_Ecosystem_services_of_urban_forest/links/5669d0e908ae430ab4f743de/Ecosystem-services-of-urban-forest.pdf (Accessed: 22 March 2021).
- Chastin, S. et al. (2021) 'Co-benefits of climate change mitigation and adaptation actions', *COP26 Universities Network Briefing*.
- Chen, S.P. et al. (2018) 'Plant diversity enhances productivity and soil carbon storage', *Proceedings of the National Academy of Sciences of the United States of America*, 115(16), pp. 4027-4032. Available at: www.pnas.org/cgi/doi/10.1073/pnas.1700298114.

- Chen, W. *et al.* (2022) 'Embodied energy and carbon emissions of building materials in China', *Building and Environment*, 207, p. 108434. Available at: <https://doi.org/10.1016/j.buildenv.2021.108434>.
- Cheng, S. *et al.* (2020) 'Carbon, water, land and material footprints of China's high-speed railway construction', *Transportation Research Part D: Transport and Environment*, 82, p. 102314. Available at: <https://doi.org/10.1016/j.trd.2020.102314>.
- Chester, M.V. and Ryerson, M.S. (2014) 'Grand challenges for high-speed rail environmental assessment in the United States', *Transportation Research Part A-Policy and Practice*, 61, pp. 15-26. Available at: <http://dx.doi.org/10.1016/j.tra.2013.12.007>.
- Chiquier, S. *et al.* (2022) 'A comparative analysis of the efficiency, timing, and permanence of CO₂ removal pathways', *Energy & Environmental Science*, 15(10), pp. 4389-4403. Available at: <https://pubs.rsc.org/en/content/articlehtml/2022/ee/d2ee01021f>.
- Circular Ecology (2021) *Environmental Glossary of Terms and Definitions*. Available at: <https://circularecology.com/glossary-of-terms-and-definitions.html#YW7eUBrMKUk> (Accessed: 19 October 2021).
- Circular Ecology (2023) *The Carbon Emissions of Homeworking and Office Working*. Available at: <https://circularecology.com/news/the-carbon-emissions-of-homeworking-and-office-working> (Accessed: 7 December 2023).
- Climate Change Committee (2020a) *Advice to the Secretary of State, BEIS, on the UK's 2030 NDC*. Available at: <https://www.theccc.org.uk/publication/letter-advice-on-the-uks-2030-nationally-determined-contribution-ndc/> (Accessed: 9 March 2022).
- Climate Change Committee (2020b) *The Sixth Carbon Budget: The UK's Path to Net Zero*. Available at: <https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf> (Accessed: 28 May 2021).
- Climate Change Committee (2021) *Independent Assessment of UK Climate Risk: Advice to Government for the UK's third Climate Change Risk Assessment (CCRA3)*. Available at: <https://www.theccc.org.uk/wp-content/uploads/2021/07/Independent-Assessment-of-UK-Climate-Risk-Advice-to-Govt-for-CCRA3-CCC.pdf> (Accessed: 7 April 2022).
- Climate Change Committee (2024) *Letter: Advice on the UK's 2035 Nationally Determined Contribution (NDC)*. Available at: <https://www.theccc.org.uk/publication/letter-advice-on-the-uks-2035-nationally-determined-contribution-ndc/>.
- Colangelo, F. *et al.* (2020) 'Comparative LCA of concrete with recycled aggregates: a circular economy mindset in Europe', *The International Journal of Life Cycle Assessment*, 25(9), pp. 1790-1804. Available at: <https://doi.org/10.1007/s11367-020-01798-6>.
- Coles, D. (2022) Email to Tracey Navaei re Shared Digital Carbon Architecture, 20 January 2022.
- Collas, L. and Balmford, A. (2021) 'ONLINE POSTER: Should UK agricultural policy adopt a land-sharing or land-sparing approach to deliver biodiversity and carbon sequestration?', *Climate Expo 2021*.
- Conant, R.T. (2011) 'Sequestration through forestry and agriculture', *Wiley Interdisciplinary Reviews-Climate Change*, 2(2), pp. 238-254. Available at: <http://dx.doi.org/10.1002/wcc.101>.
- Construction Leadership Council (2023) *Zero diesel sites route map*. Available at: <https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2023/06/Zero-Diesel-Route-Map-June-2023.pdf> (Accessed: 27 September 2023).

List of References

- Cornet, Y., Dudley, G. and Banister, D. (2018) 'High Speed Rail: Implications for carbon emissions and biodiversity', *Case Studies on Transport Policy*, 6(3), pp. 376-390. Available at: <http://dx.doi.org/10.1016/j.cstp.2017.08.007>.
- Crishna, N., Banfill, P. and Goodsir, S. (2011) 'Embodied energy and CO₂ in UK dimension stone', *Resources, Conservation and Recycling*, 55(12), pp. 1265-1273. Available at: <https://doi.org/10.1016/j.resconrec.2011.06.014>.
- Cuenot, F. and Hernandez, G.C. (2016) *UIC Report: Carbon footprint of Railway Infrastructure: Comparing existing methodologies on typical corridors; Recommendations for harmonized approach*. Paris. Available at: https://uic.org/IMG/pdf/carbon_footprint_of_railway_infrastructure.pdf (Accessed: 26 July 2021).
- Dalkic, G. et al. (2017) 'An assessment of the CO₂ emissions reduction in high speed rail lines: Two case studies from Turkey', *Journal of Cleaner Production*, 165, pp. 746-761. doi: 10.1016/j.jclepro.2017.07.045. Available at: <http://dx.doi.org/10.1016/j.jclepro.2017.07.045>.
- Davidson, A. et al. (2023a) 'Reducing emissions in construction: non-road mobile machinery retrofit', in *High Speed Two (HS2): Infrastructure Design and Construction (Volume 4)*. ICE Publishing, pp. 217-227.
- Davidson, A. et al. (2023b) 'Clean Air Gas Engine (CAGE): reducing emissions by replacing diesel power in construction', in *High Speed Two (HS2): Infrastructure Design and Construction (Volume 4)*. ICE Publishing, pp. 229-235.
- Davidson, A. et al. (2023c) 'Alternative fuels and additives in construction', in *High Speed Two (HS2): Infrastructure Design and Construction (Volume 4)*. ICE Publishing, pp. 255-260.
- Davies, Z.G. et al. (2011) 'Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale', *Journal of applied ecology*, 48(5), pp. 1125-1134. Available at: <http://dx.doi.org/10.1111/j.1365-2664.2011.02021.x>.
- de Andrade, C.E.S. and D'Agosto, M.D. (2016) 'Energy use and carbon dioxide emissions assessment in the lifecycle of passenger rail systems: the case of the Rio de Janeiro Metro', *Journal of Cleaner Production*, 126, pp. 526-536. Available at: <http://dx.doi.org/10.1016/j.jclepro.2016.03.094>.
- de Bortoli, A., Bouhaya, L. and Feraille, A. (2020) 'A life cycle model for high-speed rail infrastructure: environmental inventories and assessment of the Tours-Bordeaux railway in France', *The International Journal of Life Cycle Assessment*, 25, pp. 814-830. Available at: <https://doi.org/10.1007/s11367-019-01727-2>.
- DeCicco, J.M. (2015) 'The liquid carbon challenge: evolving views on transportation fuels and climate', *Wiley Interdisciplinary Reviews-Energy and Environment*, 4(1), pp. 98-114. Available at: <http://dx.doi.org/10.1002/wene.133>.
- DEFRA (2023) *Carbon footprint for the UK and England to 2020*. Available at: <https://www.gov.uk/government/statistics/uks-carbon-footprint/carbon-footprint-for-the-uk-and-england-to-2019> (Accessed: 8 September 2023).
- Delatares (2021) *Suitability of olivine as ballast material*. Available at: https://publications.deltares.nl/11207232_002.pdf (Accessed: 30 July 2024).
- Deschamps, J. et al. (2018) 'Is open-loop recycling the lowest preference in a circular economy? Answering through LCA of glass powder in concrete', *Journal of Cleaner Production*, 185, pp. 14-22. Available at: <https://doi.org/10.1016/j.jclepro.2018.03.021>.

- Desouza, C.D. *et al.* (2020) 'Real-world emissions from non-road mobile machinery in London', *Atmospheric Environment*, 223, p. 117301. Available at: <https://doi.org/10.1016/j.atmosenv.2020.117301>.
- DfT (2017) *Freight Carbon Review*. Available at: <https://assets.publishing.service.gov.uk/media/5a755d04e5274a59fa717927/freight-carbon-review-2017.pdf> (Accessed: 29 April 2024).
- DfT (2019) *Enhancing Biodiversity and Wildlife on the Lineside*. Available at: <https://www.nsar.co.uk/wp-content/uploads/2019/07/Enhancing-biodiversity-and-wildlife-on-the-lineside.pdf> (Accessed: 2 August 2021).
- DfT (2020) 'Decarbonising Transport: Setting the Challenge'. DfT London. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/932122/decarbonising-transport-setting-the-challenge.pdf (Accessed: 6 August 2021).
- DfT (2021a) *Decarbonising Transport: A Better, Greener Britain*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1009448/decarbonising-transport-a-better-greener-britain.pdf (Accessed: 1 August 2021).
- DfT (2021b) *Great British Railways The Williams-Shapps Plan for Rail*. Available at: <https://assets.publishing.service.gov.uk/media/60cb29dde90e0743ae8c29c1/gbr-williams-shapps-plan-for-rail.pdf> (Accessed: 31 October 2023).
- DfT (2021c) *Integrated Rail Plan for the North and Midlands*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1062157/integrated-rail-plan-for-the-north-and-midlands-web-version.pdf (Accessed: 7 April 2022).
- DfT (2021d) *Rail Environment Policy Statement: On Track for a Cleaner, Greener Railway*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1002166/rail-environment-policy-statement.pdf (Accessed: 4 August 2021).
- DfT (2023) *Renewable Fuel Statistics, 2023 (first provisional)*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1176827/2023-first-provisional-rf-01-rtfo-tables.ods (Accessed: 27 September 2023).
- DfT & ORR & NR (2021) *Better Value Rail Toolkit - BETA*. Available at: <https://www.bettervaluerail.uk/> (Accessed: 27 September 2021).
- Di Ruocco, G. *et al.* (2017) 'Sustainable Reuse of Disused Railway', *Procedia Engineering*, 180, pp. 1643-1652.
- Dixon, N., Fowmes, G. and Frost, M. (2017) 'Global challenges, geosynthetic solutions and counting carbon', *Geosynthetics International*, 24(5), pp. 451-464. Available at: <http://dx.doi.org/10.1680/jgein.17.00014>.
- Dovetail Partners, I. (2015) *Understanding Steel Recovery and Recycling Rates and Limitations to Recycling*. Available at: https://www.researchgate.net/publication/312136926_Understanding_Steel_Recovery_and_Recycling_Rates_and_Limits_to_Recycling (Accessed: 19 October 2023).
- Dr Neil Strong (2021) Register of Land Use - Geo-RINM, 05.05.21.
- Economist Impact (2022) *Sustainability Week US 2022: The CSO's data-driven road to net zero*.

List of References

EFFC (2022) *EFFC Sustainability Guides for Foundation Contractors Guide No. 1 Carbon Reduction*. Available at: https://www.effc.org/content/uploads/2022/05/EFFC-Carbon-Reduction-Guide_FINAL.pdf (Accessed: 11 April 2024).

EFFC (2023a) 'EFFC DFI Carbon Calculator Tool v4.0'. Available at: <http://geotechnicalcarboncalculator.com/cs/index/login> (Accessed 18 January 2023).

EFFC (2023b) *EFFC DFI User Guide v2.1*. Available at: <http://geotechnicalcarboncalculator.com/cs/userguide/downloaduserguide> (Accessed: 3 November 2023).

Ellen MacArthur Foundation (2019) *Circular economy systems diagram (based on Braungart & McDonough, Cradle to Cradle (C2C))*. Available at: <https://ellenmacarthurfoundation.org/circular-economy-diagram> (Accessed: 24 January 2021).

Ellis, T., Manidaki, M. and Pantelidou, H. (2020) *Infrastructure Carbon Report: Good progress but not fast enough*. Green Construction Board. Available at: https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2021/04/Infrastructure-Carbon-Review-seven-years-on_March-2021.pdf (Accessed: 14 September 2024).

EPA (2017) *Glossary of Climate Change Terms*. Available at: https://19january2017snapshot.epa.gov/climatechange/glossary-climate-change-terms_.html (Accessed: 13.06.2022).

Eshton, B. and Katima, J.H. (2015) 'Carbon footprints of production and use of liquid biofuels in Tanzania', *Renewable and Sustainable Energy Reviews*, 42, pp. 672-680. Available at: https://www.sciencedirect.com/science/article/pii/S136403211400865X?casa_token=sj5QtLeGLVEA AAAA:dTt8co77gfr9RcGbkp1yLxYtTDIcqAlONSGMIrKkYkkLu-jHfpOuqclshj79UZJRtsGHHY5XOD0.

eTool (2023) *HS2 LCA modelling and reporting*. Available at: <https://support.etoold.com/index.php/knowledgebase/hs2-lca-modelling-and-reporting/> (Accessed: 2 September 2024).

EUROFER (2019) *LOW CARBON ROADMAP PATHWAYS TO A CO₂-NEUTRAL EUROPEAN STEEL INDUSTRY*. Available at: <https://www.eurofer.eu/assets/Uploads/EUROFER-Low-Carbon-Roadmap-Pathways-to-a-CO2-neutral-European-Steel-Industry.pdf> (Accessed: 11 October 2023).

EUROFER (2023) *Annual Report 2023*. Available at: https://www.eurofer.eu/assets/publications/reports-or-studies/annual-report-2023/FINAL_EUROFER_Annual-Report_2023.pdf (Accessed: 11 October 2023).

European Academies Science Advisory Council (2018) *Negative Emission Technologies: What role in meeting Paris Agreement targets?* (EASAC policy report 35). Germany: German National Academy of Sciences Leopoldina. Available at: https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Report_on_Negative_Emission_Technologies.pdf (Accessed: 20 August 2021).

European Academies Science Advisory Council (2019) *Forest Bioenergy, Carbon Capture And Storage, And Carbon Dioxide Removal: An Update*. European Academies Science Advisory Council Brussels, Belgium. Available at: https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Commentary_Forest_Bioenergy_Feb_2019_FINAL.pdf (Accessed: 23 May 2022).

European Academies Sciences Advisory Council (2017) *Multi-functionality and sustainability in the European Union's forests*. Available at: <https://easac.eu/publications/details/multi-functionality-and-sustainability-in-the-european-unions-forests/> (Downloaded: 17 June 2021).

- European Union (1998) *Directive 98/70/EC of the European Parliament and of the Council of 13 October 1998 relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC*. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31998L0070&qid=1704805607503> (Accessed: 9 January 2024).
- European Union Agency for Railways (2020) *Report Fostering the Railway Sector Through the European Green Deal Part 2 Freight* (ERA1234). European Union Agency for Railways,. Available at: https://www.era.europa.eu/content/era-report-fostering-railway-sector-through-european-green-deal-part-2-freight_en (Accessed: 28 April 2022).
- Everett, B., Peake, S. and Warren, J. (2021) *Energy Systems & Sustainability*. 3rd edn.
- Expedition (2020) *Route Map to Low CO₂e Steel* (EXP-REP-1395-001 Rev 00). Unpublished.
- Fairley, P. (2011) 'Introduction: Next generation biofuels', *Nature*, 474(7352), pp. S2-S5. Available at: <https://www.nature.com/articles/474S02a>.
- Fajardy, M. et al. (2019) *Negative emissions: priorities for research and policy design*. Available at: <https://www.frontiersin.org/articles/10.3389/fclim.2019.00006>.
- Fang, K., Heijungs, R. and de Snoo, G. (2013) 'The footprint family: comparison and interaction of the ecological, energy, carbon and water footprints', *Revue De Metallurgie-Cahiers D Informations Techniques*, 110(1), pp. 77-86. Available at: <http://dx.doi.org/10.1051/metal/2013051>.
- Fatahi, B. et al. (2015) 'The Role of Native Vegetation in Stabilizing Formation Soil for Transport Corridors: An Australian Experience', in, pp. 591-628. Available at: <http://dx.doi.org/10.1016/B978-0-08-100191-2.00020-4>.
- Fenner, R., Sykes, J. and Ainger, C. (2023) *Sustainable Infrastructure: Principles into Practice*. Second edn.: ICE publishing.
- Fernandez-Dacosta, C. et al. (2019) 'Potential and challenges of low-carbon energy options: Comparative assessment of alternative fuels for the transport sector', *Applied Energy*, 236, pp. 590-606. Available at: <http://dx.doi.org/10.1016/j.apenergy.2018.11.055>.
- Fitzpatrick, R., White, R. and Matthews, I. (2021) 'It's all fun and games!' Supporting nature-based solutions through golf', *Climate Expo 2021*.
- Fletcher, T.I. et al. (2021) 'The carbon sequestration potential of Scottish native woodland', *Environmental Research Communications*, 3(4). doi: 10.1088/2515-7620/abf467. Available at: <https://iopscience.iop.org/article/10.1088/2515-7620/abf467/pdf> (Accessed: Apr 1).
- Ford, H. et al. (2021) 'Hedgerow effects on CO₂ emissions are regulated by soil type and season: Implications for carbon flux dynamics in livestock-grazed pasture', *Geoderma*, 382, p. 114697. Available at: <https://doi.org/10.1016/j.geoderma.2020.114697>.
- Forestry Research (2020) *Forestry Statistics 2020: A compendium of statistics about woodland, forestry and primary wood processing in the United Kingdom*. Available at: <https://cdn.forestryresearch.gov.uk/2022/02/completestfs2020.pdf> (Accessed: 2 April 2021).
- Forster, P.M. et al. (2024) 'Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence', *Earth Syst. Sci. Data*, 16, 2625–2658,. Available at: <https://doi.org/10.5194/essd-16-2625-2024>.
- Fox, W. et al. (2020) 'Estimating Carbon Stock of Live Trees Located on the Main Campus of the University of Georgia', *Journal of Forestry*, 118(5), pp. 457-465. Available at: <http://dx.doi.org/10.1093/jofore/fvaa025>.

List of References

- Frontier Economics and BMG Research (2022) *Transforming Construction Challenge Evaluation-Phase 2: Impact Evaluation*. Available at: <https://www.ukri.org/publications/transforming-construction-challenge-evaluation/>.
- Fuss, S. *et al.* (2018) 'Negative emissions—Part 2: Costs, potentials and side effects', *Environmental Research Letters*, 13(6), p. 063002. Available at: <https://doi.org/10.1088/1748-9326/aabf9f>.
- Gallego-Schmid, A. *et al.* (2020) 'Links between circular economy and climate change mitigation in the built environment', *Journal of Cleaner Production*. Available at: <https://doi.org/10.1016/j.jclepro.2020.121115>.
- Gao, C.-k. *et al.* (2020) 'Technologies-based potential analysis on saving energy and water of China's iron and steel industry', *Science of the total environment*, 699, p. 134225. Available at: <https://doi.org/10.1016/j.scitotenv.2019.134225>.
- Garcia, W.d.O. *et al.* (2020) 'Impacts of enhanced weathering on biomass production for negative emission technologies and soil hydrology', *Biogeosciences*, 17(7), pp. 2107-2133. Available at: <https://doi.org/10.5194/bg-17-2107-2020>.
- GHG Protocol (2024) *Life Cycle Databases*. Available at: <https://ghgprotocol.org/life-cycle-databases> (Accessed: 3 June 2024).
- Ghosh, A. (2020) 'Possibilities and Challenges for the Inclusion of the Electric Vehicle (EV) to Reduce the Carbon Footprint in the Transport Sector: A Review', *Energies*, 13(10), p. 22. doi: 10.3390/en13102602. Available at: <https://doi.org/10.3390/en13102602>.
- Ghosh, S. and Khan, F. (2019) 'Potential of trees to mitigate climate change impacts in a railway corridor case study in Sydney', *Smart and Sustainable Built Environments 6th CIB International Conference*. Sydney, Australia, 4-7 December 2018. Available at: https://docs.wixstatic.com/ugd/6e13f1_682d42481a4d4e08b9a046cfade9616a.pdf (Accessed: 21 May 2021).
- Glendinning, S. *et al.* (2009) *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*. Thomas Telford Ltd.
- Gogoi, A., Ahirwal, J. and Sahoo, U.K. (2021) 'Plant biodiversity and carbon sequestration potential of the planted forest in Brahmaputra flood plains', *Journal of Environmental Management*, 280, p. 8. Available at: <https://doi.org/10.1016/j.jenvman.2020.111671>.
- Gov.Scot (2018) *Scottish Government Urban Rural Classification 2016 - Output Area Lookup*. Available at: <https://www.gov.scot/binaries/content/documents/govscot/publications/advice-and-guidance/2018/03/scottish-government-urban-rural-classification-2016/documents/scottish-government-urban-rural-classification-2016-output-area-lookup/scottish-government-urban-rural-classification-2016-output-area-lookup/govscot%3Adocument/00544929.csv> (Accessed: 11 January 2024).
- Greenhouse Gas Protocol (2011) *Corporate value chain (scope 3) accounting and reporting standard*. Available at: <https://ghgprotocol.org/standards/scope-3-standard> (Accessed: 27 August 2021).
- Gregg, R. *et al.* (2021) *NERR094 Carbon storage and sequestration by habitat: a review of the evidence*. Available at: <https://publications.naturalengland.org.uk/file/6257983284838400> (Accessed: 29 February 2024).
- Grid Reference Finder (2023) *UK Grid Reference Finder*. Available at: <https://gridreferencefinder.com/> (Accessed: 11 January 2024).

- Grossrieder, C. (2011) *Life-cycle assessment of future high-speed rail in Norway*. Institutt for energi- og prosesssteknikk.
- Groundtrax (2022) 'Groundtrax Terram T1000 Geotextile Membrane Product Data Sheet'. Available at: https://www.groundtrax.com/downloads/site/Terram_T1000_Spec_Sheet.pdf (Accessed: 30 September 2024).
- Gursel, A.P. *et al.* (2014) 'Life-cycle inventory analysis of concrete production: A critical review', *Cement and Concrete Composites*, 51, pp. 38-48. Available at: <http://dx.doi.org/10.1016/j.cemconcomp.2014.03.005>.
- Gustavsson, L. and Sathre, R. (2006) 'Variability in energy and carbon dioxide balances of wood and concrete building materials', *Building and Environment*, 41(7), pp. 940-951. Available at: <https://doi.org/10.1016/j.buildenv.2005.04.008>.
- Halliwell, E. (2024) 'Build Clever', *The Structural Engineer*. Available at: <https://www.istructe.org/sitefiles/handlers/DownloadFile.ashx?productId=10495>.
- Hamad, H.M.A. (2019) *Modification and performance of activated carbon for CO₂ sequestration in pervious concrete*. PhD. University of Cambridge.
- Hamilton, J.L. *et al.* (2021) 'Carbon accounting of mined landscapes, and deployment of a geochemical treatment system for enhanced weathering at Woodsreef Chrysotile Mine, NSW, Australia', *Journal of Geochemical Exploration*, 220, p. 14. Available at: <https://doi.org/10.1016/j.gexplo.2020.106655>.
- Hammond, G.P. and Jones, C.I. (2008) 'Embodied energy and carbon in construction materials', *Proceedings of the Institution of Civil Engineers-Energy*, 161(2), pp. 87-98. Available at: <http://dx.doi.org/10.1680/ener.2008.161.2.87>.
- Hammond, G.P. and Seth, S.M. (2013) 'Carbon and environmental footprinting of global biofuel production', *Applied Energy*, 112, pp. 547-559. Available at: https://www.sciencedirect.com/science/article/pii/S0306261913000172?casa_token=YnD53y_x68oAAAAA:rUAFmj56jw5Z18Ptjt8762VpArtXRNnU92aJBvQRv0_9dLduz47w2bJ5J7FLuAOTi7jk3r0Ylg0.
- Hanson (2019) *EPD Hanson Multicem CEM II*.
- Hartmann, J. *et al.* (2013) 'Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification', *Reviews of Geophysics*, 51(2), pp. 113-149. Available at: <http://dx.doi.org/10.1002/rog.20004>.
- Harvey, J. *et al.* (2016) *Pavement life cycle assessment framework* United States. Federal Highway Administration. Available at: <https://www.fhwa.dot.gov/pavement/sustainability/hif16014.pdf> (Accessed: 7 July 2022).
- Heinen, R. and Johnson, E. (2008) 'Carbon footprints of biofuels & petrofuels', *Industrial Biotechnology*, 4(3), pp. 257-261. Available at: <https://www.liebertpub.com/doi/pdf/10.1089/ind.2008.4.257>.
- Hendriks, K. *et al.* (2023) 'Carbon stocks and sequestration in terrestrial and marine ecosystems: a lever for nature restoration?'. Available at: https://www.researchgate.net/profile/Gorm-Dige/publication/360219317_Carbon_stocks_and_sequestration_in_terrestrial_and_marine_ecosystems_a_lever_for_nature_restoration_A_quick_scan_for_terrestrial_and_marine_EUNIS_habitat_types/links/62692d401b747d19c2acd43d/Carbon-stocks-and-sequestration-in-terrestrial-and-marine-ecosystems-a-lever-for-nature-restoration-A-quick-scan-for-terrestrial-and-marine-EUNIS-habitat-types.pdf (Accessed: 11 August 2024).

List of References

- Hertwich, E.G. and Wood, R. (2018) 'The growing importance of scope 3 greenhouse gas emissions from industry', *Environmental Research Letters*, 13(10), p. 104013. Available at: <https://iopscience.iop.org/article/10.1088/1748-9326/aae19a>
- Highina, B., Bugaje, I. and Umar, B. (2014) 'A review on second generation biofuel: A comparison of its carbon footprints', *European Journal of Engineering and Technology Vol*, 2(2). Available at: <https://www.idpublications.org/wp-content/uploads/2016/02/Full-Paper-A-REVIEW.pdf>.
- Highways Sector Council (2024) *HSC PAS 2080 Toolkit: About this tool kit*. Available at: <https://www.hscpas2080toolkit.com/about> (Accessed: 29 April 2024).
- Hill, N. *et al.* (2011) 'The role of GHG emissions from infrastructure construction, vehicle manufacturing, and ELVs in overall transport sector emissions. Task 2 paper produced as part of a contract between European Commission Directorate-General Climate Action and AEA Technology plc;'. Available at: <https://www.idpublications.org/wp-content/uploads/2016/02/Full-Paper-A-REVIEW.pdf>.
- Hills, C.D., Tripathi, N. and Carey, P.J. (2020) 'Mineralization Technology for Carbon Capture, Utilization, and Storage', *Frontiers in Energy Research*, 8, p. 14. Available at: <http://dx.doi.org/10.3389/fenrg.2020.00142>.
- Hirons, A. and Sjöman, H. (2019) *Tree species selection for green infrastructure: a guide for specifiers*. Available at: <https://safety.networkrail.co.uk/wp-content/uploads/2021/03/Tree-Species-Selection-for-Green-Infrastructure-A-Guide-for-Specifiers.pdf> (Accessed: 22 August 2021).
- HM Government (2011a) *The Carbon Plan: Delivering our low carbon future*. London. Available at: <https://assets.publishing.service.gov.uk/media/5a79744ced915d07d35b5a17/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf> (Accessed: 24 September 2024).
- HM Government (2011b) *Rural Urban Classification 2011 Lookup Tables for Small Area Geographies*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011667/Rural_Urban_Classification_2011_lookup_tables_for_small_area_geographies.ods (Accessed: 11 January 2024).
- HM Government (2013) *Construction 2025: Industrial Strategy: government and industry in partnership*. London. Available at: <https://assets.publishing.service.gov.uk/media/5a7b7ea140f0b62826a03f2c/bis-13-955-construction-2025-industrial-strategy.pdf> (Accessed: 14 September 2024).
- HM Government (2017a) *Average heavy goods vehicle fuel consumption, Great Britain: 2003 to 2016: Table ENV0104*. Available at: <https://assets.publishing.service.gov.uk/media/5bc75808e5274a1219d54a18/env0104.ods> (Accessed: 29 October 2023).
- HM Government (2017b) *The Clean Growth Strategy: Leading the way to a low carbon future*. London. Available at: <https://assets.publishing.service.gov.uk/media/5ad5f11ded915d32a3a70c03/clean-growth-strategy-correction-april-2018.pdf> (Accessed: 14 September 2024).
- HM Government (2018) *A Green Future: Our 25 Year Plan to Improve the Environment*. Available at: <https://assets.publishing.service.gov.uk/media/5ab3a67840f0b65bb584297e/25-year-environment-plan.pdf> (Accessed: 14 September 2024).
- HM Government (2019a) *The Climate Change Act 2008 (2050 Target Amendment) Order 2019*. Available at: <https://www.legislation.gov.uk/ukdsi/2019/9780111187654> (Accessed: 7 March 2023).

- HM Government (2019b) *Environmental Reporting Guidelines: Including streamlined energy and carbon reporting guidance*. Available at: https://assets.publishing.service.gov.uk/media/5de6acc4e5274a65dc12a33a/Env-reporting-guidance_inc_SECR_31March.pdf (Accessed: 14 September 2024).
- HM Government (2020a) *The Construction Playbook*. Available at: https://assets.publishing.service.gov.uk/media/6312222de90e075880923330/14.116_CO_Construction_Playbook_Web.pdf (Accessed: 14 September 2024).
- HM Government (2020b) *Environment Bill: Environmental Targets*. Available at: <https://www.gov.uk/government/publications/environment-bill-2020/august-2020-environment-bill-environmental-targets> (Accessed 12 July 2022).
- HM Government (2021a) *Average new car and light goods vehicle (LGV) fuel consumption: Great Britain, 1997-2020: Table ENV0103*. Available at: <https://assets.publishing.service.gov.uk/media/61b7e040e90e070441bcf977/env0103.ods> (Accessed: 29 October 2023).
- HM Government (2021b) *E10 petrol explained*. Available at: <https://www.gov.uk/guidance/e10-petrol-explained> (Accessed: 9 January 2024).
- HM Government (2021c) *The England Trees Action Plan 2021-2024*. UK: APS Group on behalf of the Controiller of Her Majesty's Stationery Office. Available at: <https://assets.publishing.service.gov.uk/media/60a3ddd1d3bf7f2886e2a05d/england-trees-action-plan.pdf> (Accessed: 24 September 2024).
- HM Government (2021d) *Net Zero Strategy: Build Back Greener*. Available at: <https://assets.publishing.service.gov.uk/media/6194dfa4d3bf7f0555071b1b/net-zero-strategy-beis.pdf> (Accessed: 14 September 2024).
- HM Government (2021e) *The Ten Point Plan for a Green Industrial Revolution*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf.
- HM Government (2022a) *Mission Zero: Independent Review of Net Zero - final report*. Available at: <https://www.gov.uk/government/publications/review-of-net-zero> (Accessed: 17 January 2024).
- HM Government (2022b) *United Kingdom of Great Britain and Northern Ireland's Nationally Determined Contribution*. Available at: <https://assets.publishing.service.gov.uk/media/633d937d8fa8f52a5803e63f/uk-nationally-determined-contribution.pdf> (Accessed: 17 January 2024).
- HM Government (2023a) *2023 Government Greenhouse Gas Conversion Factors for Company Reportin: Methodology Paper for Conversion Factors Final Report*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1161317/2023-ghg-cf-methodology-paper.pdf (Accessed: 29 October 2023).
- HM Government (2023b) *Final UK greenhouse gas emissions national statistics 1990-2021*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1146751/final-greenhouse-gas-emissions-tables-2021.xlsx (Accessed: 22 September 2023).
- HM Government (2023c) *GHG Conversion Factors 2023* Available at: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fgovernment%2Fuploads%2Fsystem%2Fuploads%2Fattachment_data%2Ffile%2F1166237%2Fghg-conversion-factors-2023-full-file-update.xlsx&wdOrigin=BROWSELINK (Accessed: 27 September 2023).

List of References

- HM Treasury (2013) *Infrastructure Carbon Review*. Available at: https://assets.publishing.service.gov.uk/media/5a7c9803ed915d12ab4bbd33/infrastructure_carbon_review_251113.pdf (Accessed: 14 September 2024).
- Hoerbinger, S. *et al.* (2020) 'Assessment of safety-relevant woody vegetation structures along railway corridors', *Ecological Engineering*, 158, p. 9. Available at: <http://dx.doi.org/10.1016/j.ecoleng.2020.106048>.
- HS2 Limited (2013a) *London-West Midlands Environmental Statement Volume 3 Route-wide effects*. Available at: <https://www.gov.uk/government/publications/hs2-phase-one-environmental-statement-volume-3-route-wide-effects> (Accessed: 23 March 2023).
- HS2 Limited (2013b) *London-West Midlands Environmental Statement Volume 5 Technical Appendices*. Available at: <https://www.gov.uk/government/publications/hs2-phase-one-environmental-statement-volume-5-climate> (Accessed: 23 March 2023).
- HS2 Limited (2017a) *High Speed Rail Phase 2a (West Midlands - Crewe) Environmental Statement Volume 3: Route-wide effects*. Available at: <https://www.gov.uk/government/publications/hs2-phase-2a-environmental-statement-volume-3-route-wide-effects> (Accessed: 23 March 2023).
- HS2 Limited (2017b) *High Speed Two Phase One Information Paper E10: Carbon*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/672382/E10_-_Carbon_v1.7.pdf (Accessed: 14 February 2023).
- HS2 Limited (2020) *Establishing best practice whole-life carbon baselines for Phase One of HS2*. Available at: <https://learninglegacy.hs2.org.uk/document/establishing-best-practice-whole-life-carbon-baselines-for-phase-one-of-high-speed-two/> (Accessed: 12 January 2022).
- HS2 Limited (2021) FOI HS2-22-71464-E.
- HS2 Limited (2022a) 'Asset attributes - cuttings and embankments'. 18 January 2022.
- HS2 Limited (2022b) 'Asset_Data_N1_BBV_Sept21'. 15 January 2022.
- HS2 Limited (2022c) 'Asset_Data_N2_BBV_Sept21'. 15 January 2022.
- HS2 Limited (2022d) Email to Tracey Navaei, 18 January 2022.
- HS2 Limited (2022e) *HS2 Environmental Sustainability Progress Report April 2020 - March 2021*. Available at: https://assets.hs2.org.uk/wp-content/uploads/2022/01/25091_HS2_EnvironmentalSustainabilityProgressReport20-21_CS1547_Final_InteractiveWeb_Accessible.pdf (Accessed: 14 September 2024).
- HS2 Limited (2022f) *Major green milestone for HS2 as project announces first diesel-free construction site*. Available at: <https://mediacentre.hs2.org.uk/news/major-green-milestone-for-hs2-as-project-announces-first-diesel-free-construction-site> (Accessed: 23 January 2024).
- HS2 Limited (2022g) 'Material Efficiency Metric'. 18 January 2022.
- HS2 Limited (2022h) *Net Zero Carbon Plan: A Cleaner, Greener Future*. Available at: https://assets.hs2.org.uk/wp-content/uploads/2022/01/25357_HS2_NetZeroCarbonPlan_CS1656_Final_InteractiveWeb_Accessible.pdf (Accessed: 5 September 2022).
- HS2 Limited (2022i) 'Phase One cuttings and embankments LCA S2, S2 and C1'. 15 January 2022.
- HS2 Limited (2023) FOI-23-5199-RESPONSE, September 2023.

- Hulvey, K.B. *et al.* (2013) 'Benefits of tree mixes in carbon plantings', *Nature Climate Change*, 3(10), pp. 869-874. Available at: <http://dx.doi.org/10.1038/NCLIMATE1862>.
- Ibrahim, M.H. *et al.* (2019) 'Carbon Mineralization by Reaction with Steel-Making Waste: A Review', *Processes*, 7(2), p. 21. Available at: <http://dx.doi.org/10.3390/pr7020115>.
- ICE (2022) *Low Carbon Concrete Routemap*. ICE. Available at: <https://www.ice.org.uk/media/q12jkljj/low-carbon-concrete-routemap.pdf> (Accessed: 14 September 2024).
- ICE (2023) *Guidance Document for PAS 2080*. Available at: https://www.ice.org.uk/media/vm0nwehp/2023-03-29-pas_2080_guidance_document_april_2023.pdf (Accessed: 12 April 2024).
- ICE Workstream 1 of The Carbon Project (2020) *Meaningful measurement for whole life carbon in infrastructure. A methodology for measuring carbon impacts from infrastructure*. Available at: <https://www.ice.org.uk/media/ftnjlf1/2022-04-13-meaningful-measurement-for-whole-life-carbon-in-infrastructure.pdf> (Accessed: 14 February 2023).
- ICWG (2021) 'Infrastructure Carbon Working Group Minutes of meeting 01 held on 21/06/2021 '. RSSB, via Teams. Unpublished.
- INECO (2012) *Huella de carbono de la construcción de una línea ferroviaria de alta velocidad*. Available at: https://ecodes.org/documentos/Informe_Huella_Carbono.pdf (Accessed: 1 December 2024).
- Institute of Civil Engineers (2019) *Carbon Capture and Storage*. Available at: <https://www.ice.org.uk/knowledge-and-resources/briefing-sheet/carbon-capture-and-storage> (Accessed: 04.08.21).
- Institution of Civil Engineers (2021) *State of the Nation 2021 Six ways for civil engineers to act on climate change*. Available at: <https://www.ice.org.uk/media/3wypvqnx/ice-state-of-the-nation-2021.pdf> (Accessed: 14 September 2024).
- Institution of Structural Engineers (2020) *How to calculate embodied carbon*. <https://www.istructe.org/IStructE/media/Public/Resources/istructe-how-to-calculate-embodied-carbon.pdf> Accessed: 15 September 2022.
- interchange25 (2024) *Logistics operators unite to give HGV fleet decarbonisation a JOLT*. Available at: <https://www.interchange-uk.com/news/logistics-operators-unite-to-give-hgv-fleet-decarbonisation-a-jolt> (Accessed: 27 August 2024).
- IPCC (2018) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Available at: <https://www.ipcc.ch/sr15/download/#chapter> (Accessed: 7 March 2023).
- IPCC (2019) *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Available at: https://www.ipcc.ch/site/assets/uploads/sites/4/2022/11/SRCCL_Full_Report.pdf (Accessed: 30 September 2024).
- IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Press, C.U. Available at: https://report.ipcc.ch/ar6/wg1/IPCC_AR6_WGI_FullReport.pdf (Accessed: 7 March 2023).

List of References

- IPCC (2022) *Summary for Policymakers Headline Statements*. Available at: <https://www.ipcc.ch/report/ar6/wg3/resources/spm-headline-statements/> (Accessed: 29 July 2024).
- ISO (2022) *ISO IWA 42 Net Zero Guidelines*. Available at: <https://www.iso.org/obp/ui/en/#iso:std:iso:iwa:42:ed-1:v1:en> (Accessed: 17 May 2024).
- Jo, H.K. (2002) 'Impacts of urban greenspace on offsetting carbon emissions for middle Korea', *Journal of Environmental Management*, 64(2), pp. 115-126. Available at: <http://dx.doi.org/10.1006/jema.2001.0491>.
- Johnson, T. (2023) *Inside Network Rail's four-night OLE renewal programme that produced zero carbon emissions*. Available at: https://www.newcivilengineer.com/latest/inside-network-rails-four-night-ole-renewal-programme-that-produced-zero-carbon-emissions-23-10-2023/?eea=ZkxiWkVQYkw1KzNUVW43UER4L1BUbXA3WTN6d2owbjF5QU1JTzBuaUhUUT0%3D&utm_source=acs&utm_medium=email&utm_campaign=CONE_NCE_MAR_WYMHM-23%2F10%2F27_A%2FB%20test%20on%20subject&deliveryName=DM185636 (Accessed: 31 October 2023).
- Johnston, C.M.T. and Radeloff, V.C. (2019) 'Global mitigation potential of carbon stored in harvested wood products', *Proceedings of the National Academy of Sciences of the United States of America*, 116(29), pp. 14526-14531. doi: 10.1073/pnas.1904231116. Available at: <https://doi.org/10.1073/pnas.1904231116> (Accessed: Jul).
- Johrens, J. and Helms, H. (2014) *2014 IEEE International Electric Vehicle Conference (IEVC)*. Florence, ITALY, Dec 17-19. NEW YORK: IEEE,. Available at: <https://doi.org/10.1109/IEVC.2014.7056154>.
- Jones, C. (2021) Email to Tracey Navaei 18 November.
- Jones, H., Moura, F. and Domingos, T. (2017) 'Life cycle assessment of high-speed rail: a case study in Portugal', *The International Journal of Life Cycle Assessment*, 22(3), pp. 410-422. Available at: <https://doi.org/10.1007/s11367-016-1177-7>.
- Jursova, S., Burchart-Korol, D. and Pustejovska, P. (2019) 'Carbon Footprint and Water Footprint of Electric Vehicles and Batteries Charging in View of Various Sources of Power Supply in the Czech Republic', *Environments*, 6(3), p. 11. Available at: <http://dx.doi.org/10.3390/environments6030038>.
- Kadefors, A. et al. (2021) 'Designing and implementing procurement requirements for carbon reduction in infrastructure construction – international overview and experiences', *Journal of Environmental Planning and Management*, 64(4), pp. 611-634. Available at: <https://doi.org/10.1080/09640568.2020.1778453>.
- Kaewunruen, S., Sresakoolchai, J. and Peng, J. (2020) 'Life cycle cost, energy and carbon assessments of Beijing-Shanghai high-speed railway', *Sustainability*, 12(1), p. 206. Available at: <http://dx.doi.org/10.3390/su12010206>.
- Karlsson, I., Rootzén, J. and Johnsson, F. (2020) 'Reaching net-zero carbon emissions in construction supply chains—Analysis of a Swedish road construction project', *Renewable and Sustainable Energy Reviews*, 120, p. 109651. Available at: <https://www.sciencedirect.com/science/article/pii/S1364032119308573>.
- Kennedy, K. (2019) *Data, Technology and Engineering Geology - What does the future hold?* Available at: <https://www.ags.org.uk/2019/03/data-technology-and-engineering-geology-what-does-the-future-hold/> (Accessed: 27 September 2022).
- KENOTEQ (2024) *It all starts with a better brick...* Available at: <https://www.kenoteq.com/> (Accessed: 3 May 2024).

- Kiani, M., Parry, T. and Ceney, H. (2008) 'Environmental life-cycle assessment of railway track beds', *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, 161(2), pp. 135-142. Available at: <http://dx.doi.org/10.1680/ensu.2008.161.2.135>.
- Kittipongvises, S. (2017) 'Assessment of environmental impacts of limestone quarrying operations in Thailand', *Environmental and Climate Technologies*, 20(1), pp. 67-83. Available at: <https://doi.org/10.1515/rtuct-2017-0011>.
- Kjerkol, H. and Kalager, A. (2011) *Life Cycle Assessment of the Follo Line - Infrastructure*. Available at: https://www.banenor.no/globalassets/documents/prosjekter/follobanen/lca-folloline_transportation_en.pdf (Accessed: 14 February 2023).
- Kolosz, B. et al. (2017) 'A sustainability framework for engineering carbon capture soil in transport infrastructure', *International Journal of Transport Development and integration*, 1(1), pp. 74-83. Available at: <https://doi.org/10.2495/TDI-V1-N1-74-83>.
- Kortazar, A., Bueno, G. and Hoyos, D. (2021) 'Environmental balance of the high speed rail network in Spain: A Life Cycle Assessment approach', *Research in Transportation Economics*. Available at: <https://doi.org/10.1016/j.retrec.2021.101035>.
- Krezo, S. et al. (2016) 'Field investigation and parametric study of greenhouse gas emissions from railway plain-line renewals', *Transportation Research Part D-Transport and Environment*, 42, pp. 77-90. Available at: <https://dx.doi.org/10.1016/j.trd.2015.10.021>
- Krezo, S. et al. (2018) 'Evaluation of CO2 emissions from railway resurfacing maintenance activities', *Transportation Research Part D-Transport and Environment*, 65, pp. 458-465. Available at: <http://dx.doi.org/10.1016/j.trd.2018.09.019>.
- Landgraf, M. and Horvath, A. (2021) 'Embodied greenhouse gas assessment of railway infrastructure: the case of Austria', *Environmental Research: Infrastructure and Sustainability*, 1(2), p. 025008. Available at: <http://dx.doi.org/10.1088/2634-4505/ac1242>.
- Lasne, M., Large, M.E. and Bruni, L. (2015) *Carbon Management Technology Conference*. OnePetro. Available at: <http://onepetro.org/CMTCONF/proceedings-pdf/15CMTC/All-15CMTC/CMTC-439314-MS/1330529/cmtc-439314-ms.pdf/1>.
- Lee, H. et al. (2014) *Asset Management Conference 2014*. IET.
- Lee, H.Y. (2016) *Combined Economic and Environmental Assessment Tool for Maintenance of Railway Bridges*. University of Surrey (United Kingdom). Available at: <https://www.proquest.com/docview/1978486351/fulltextPDF/BAF4D9FF14B144CFPQ/1?accountid=13963> (Accessed: 14 September 2024).
- Lee, J.-Y., Lee, C.-K. and Chun, Y.-Y. (2020) 'Greenhouse gas emissions from high-speed rail infrastructure construction in Korea', *Transportation Research Part D: Transport and Environment*, 87, p. 102514. Available at: <https://doi.org/10.1016/j.trd.2020.102514>.
- Lefebvre, D. et al. (2019) 'Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil', *Journal of Cleaner Production*, 233, pp. 468-481. Available at: <http://dx.doi.org/10.1016/j.jclepro.2019.06.099>.
- Lenka, N.K. et al. (2012) 'Soil carbon sequestration and erosion control potential of hedgerows and grass filter strips in sloping agricultural lands of eastern India', *Agriculture, ecosystems & environment*, 158, pp. 31-40. Available at: <http://dx.doi.org/10.1016/j.agee.2012.05.017>.

List of References

- Lesley, L. (2009) '2 - Fatigue in railway and tramway track', in Robinson, M. and Kapoor, A. (eds.) *Fatigue in Railway Infrastructure*, pp. 20-57. Available at: <https://doi.org/10.1533/9781845697020.20>.
- LETI (2023) 'Embodied Carbon one-pager'. Available at: <https://www.leti.uk/carbonalignment>.
- Li, X. *et al.* (2016) 'Changes in soil organic carbon fractions after afforestation with xerophytic shrubs in the Tengger Desert, northern China', *European Journal of Soil Science*, 67(2), pp. 184-195. Available at: <http://dx.doi.org/10.1111/ejss.12315>.
- Liew, K., Sojobi, A. and Zhang, L. (2017) 'Green concrete: Prospects and challenges', *Construction and building materials*, 156, pp. 1063-1095. Available at: <http://dx.doi.org/10.1016/j.conbuildmat.2017.09.008>.
- Lin, J. *et al.* (2020) 'Environmental footprints of high-speed railway construction in china: a case study of the Beijing–Tianjin Line', *International Journal of Environmental Research and Public Health*, 17(1), p. 105.
- Lin, J. *et al.* (2019) 'A Carbon Footprint of High-Speed Railways in China: A Case Study of the Beijing-Shanghai Line', *Journal of Industrial Ecology*, 23(4), pp. 869-878. Available at: <http://dx.doi.org/10.1111/jiec.12824>.
- Loffredo, F., Fedele, P. and Severini, M. (2011) *The climatic mark of railway infrastructure projects*.
- Lokesh, K., Densley-Tingley, D.a. and Marsden, G. (2022a) *Measuring Railway Infrastructure Carbon: A 'critical' in transport's journey to net-zero*. Leeds: DecarboN8 Research Network. . Available at: <https://DecarboN8.org.uk/EmbodiedEmissions> (Accessed: 25 February 2022).
- Lokesh, K., Densley-Tingley, D.a. and Marsden, G. (2022b) *Measuring Road Infrastructure Carbon: A 'critical' in road transports journey to net-zero*. Leeds: DecarboN8 Research Network. . Available at: <https://DecarboN8.org.uk/EmbodiedEmissions> (Accessed: 25 February 2022).
- Lorenz, K. and Lal, R. (2012) 'Carbon storage in some urban forest soils of Columbus, Ohio, USA', in *Carbon Sequestration in Urban Ecosystems*, pp. 139-158. Available at: https://doi.org/10.1007/978-94-007-2366-5_7.
- Malmsheimer, R.W. *et al.* (2011) 'Managing forests because carbon matters: Integrating energy, products, and land management policy', *Journal of Forestry*, 109(7 SUPPL.), pp. S7-S51. Available at: https://www.fs.fed.us/pnw/pubs/journals/pnw_2011_malmsheimer001.pdf (Accessed: 10 June 2021).
- Mann, M.E., Bradley, R.S. and Hughes, M.K. (1999) 'Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations', *Geophysical Research Letters*, 26(6), pp. 759-762. Available at: <https://doi.org/10.1029/1999GL900070>.
- Marlowe, J. and Clarke, A. (2022) 'Carbon Accounting: A Systematic Literature Review and Directions for Future Research', *Green Finance*, 4(1), pp. 71-87. Available at: <http://dx.doi.org/10.3934/GF.2022004>.
- Marsden, G., Lokesh, K.a. and Densley-Tingley, D. (2022) *Everything Counts: Why transport infrastructure emissions matter for decision makers*. Leeds: DecarboN8 Research Network. Available at: <https://DecarboN8.org.uk/EmbodiedEmissions> (Accessed: 25 February 2022).
- Marshalls Bricks & Masonry (2021) *Environmental Product Declaration Perforated Dense Facing Bricks*. Available at: <https://api.environdec.com/api/v1/EPDLibrary/Files/5d606594-ab43-4355-f532-08d93f6df637/Data> (Accessed: 24 September 2024).

- Matthews, K.B. *et al.* (2020) 'Not seeing the carbon for the trees? Why area-based targets for establishing new woodlands can limit or underplay their climate change mitigation benefits', *Land Use Policy*, 97, p. 13. Available at: <http://dx.doi.org/10.1016/j.landusepol.2020.104690>.
- Matustik, J. and Koci, V. (2021) 'What is a footprint? A conceptual analysis of environmental footprint indicators', *Journal of Cleaner Production*, 285, p. 10. Available at: <http://dx.doi.org/10.1016/j.jclepro.2020.124833>.
- McCann, E. and Behar, C. (2021) *Zero Carbon World Tiger Team Project Part 1 - Discovery Summary Presentation*
- McCann, E. *et al.* (2021) *Zero Carbon World Tiger Team Project - Part 1 Discovery Final Report*. Available at: <https://skipsolabs-i3p.s3.eu-west-1.amazonaws.com/uploads/content/d21622c3542039e6f011ab8ff9fc5930afcb0603.pdf> (Accessed: 14 February 2023).
- McGeever, A.H. *et al.* (2019) 'Assessing the terrestrial capacity for Negative Emission Technologies in Ireland', *Carbon Management*, 10(1), pp. 1-10. Available at: <https://doi.org/10.1080/17583004.2018.1537516>.
- McLaren, D.P. *et al.* (2019) 'Beyond “net-zero”: a case for separate targets for emissions reduction and negative emissions', *Frontiers in Climate*, 1, p. 4. Available at: <https://www.frontiersin.org/articles/10.3389/fclim.2019.00004/full>.
- Medina, E. and Fu, F. (2021) *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*. ICE Publishing. Available at: <https://doi.org/10.1680/jensu.20.00067>.
- Melin, H.E. (2019) 'Analysis of the climate impact of lithium-ion batteries and how to measure it', *Circular Energy Storage-Research and Consulting*, pp. 1-17. Available at: https://www.transportenvironment.org/wp-content/uploads/2021/07/2019_11_Analysis_CO2_footprint_lithium-ion_batteries-1.pdf (Accessed: 27 November 2023).
- Mi-ROG (2020) *The Circular Economy and Net Zero Carbon: Circular economy approaches to reaching net zero carbon infrastructure*. MI-ROG White Paper No. 4. Available at: <https://aecom.com/projects/circular-economy-action-major-infrastructure-resources-optimisation-group-mi-rog/> (Accessed: 3 February 2022).
- Milford, R.L. and Allwood, J.M. (2010) 'Assessing the CO2 impact of current and future rail track in the UK', *Transportation Research Part D-Transport and Environment*, 15(2), pp. 61-72. Available at: <http://dx.doi.org/10.1016/j.trd.2009.09.003>.
- Miller, S.A. (2018) 'Supplementary cementitious materials to mitigate greenhouse gas emissions from concrete: can there be too much of a good thing?', *Journal of Cleaner Production*, 178, pp. 587-598. Available at: <https://doi.org/10.1016/j.jclepro.2018.01.008>.
- Minx, J.C. *et al.* (2017) 'Fast growing research on negative emissions', *Environmental Research Letters*, 12(3), p. 035007. Available at: <https://iopscience.iop.org/article/10.1088/1748-9326/aa5ee5>.
- Minx, J.C. *et al.* (2018) 'Negative emissions—Part 1: Research landscape and synthesis', *Environmental Research Letters*, 13(6), p. 063001. Available at: <https://iopscience.iop.org/article/10.1088/1748-9326/aabf9b/pdf> (Accessed: 24 August 2021).
- Morita, Y. *et al.* (2011) 'A Study for the Measurement of Environmental Impact Resulting From Railway Construction', *2011 Joint Rail Conference*. Pueblo, Colorado, USA, 16-18 March 2011. pp. 453-459. Available at: <https://doi.org/10.1115/JRC2011-56006> (Accessed: 6 October 2021).

List of References

- Moro, A. and Helmers, E. (2017) 'A new hybrid method for reducing the gap between WTW and LCA in the carbon footprint assessment of electric vehicles', *International Journal of Life Cycle Assessment*, 22(1), pp. 4-14. Available at: <http://dx.doi.org/10.1007/s11367-015-0954-z>.
- Mostert, C. *et al.* (2021) 'Climate and resource footprint assessment and visualization of recycled concrete for circular economy', *Resources, Conservation and Recycling*, 174, p. 105767. Available at: <https://doi.org/10.1016/j.resconrec.2021.105767>.
- Mott MacDonald (2019) *Delivering net-zero infrastructure - Practical steps (Output from the 2019 Carbon Crunch summit hosted by Mott MacDonald at the Institution of Civil Engineers, London)* Available at: <https://www.mottmac.com/download/file?id=38243&isPreview=True> (Accessed: 23 January 2024).
- Mott MacDonald (2021) *Carbon Assessment: Network Rail North West and Central Works Delivery Team; Confidential*.
- MPA (2017) *EPD UK Average Portland Cement*.
- MPA (2020) *UK Concrete and Cement Industry Roadmap to Beyond Net Zero*. Available at: https://thisisukconcrete.co.uk/TIC/media/root/Perspectives/MPA-UKC-Roadmap-to-Beyond-Net-Zero_October-2020.pdf (Accessed: 24 September 2024).
- MPA (2021) *Decarbonising UK Concrete and Cement: Accelerating the Net Zero Journey*. Available at: https://www.thisisukconcrete.co.uk/TIC/media/root/Resources/MPA-UKC_Decarbonising-UK-concrete_Oct21.pdf (Accessed: 24 September 2024).
- MPA (2022) *Mineral Products Association Sustainable Development Report 2020/2021 Data and developments*. Available at: https://www.mineralproducts.org/MPA/media/root/Publications/2022/MPA_SD_Report_2022.pdf (Accessed: 16 October 2023).
- Muha, R. and Perosa, A. (2018) 'Energy Consumption and Carbon Footprint of an Electric Vehicle and a Vehicle with an Internal Combustion Engine', *Transport Problems*, 13(2), pp. 49-58. Available at: <http://dx.doi.org/10.20858/tp.2018.13.2.5>.
- Muller, S. *et al.* (2018) 'Effects of Distribution Choice on the Modeling of Life Cycle Inventory Uncertainty: An Assessment on the Ecoinvent v2.2 Database', *Journal of Industrial Ecology*, 22(2), pp. 300-313. Available at: <https://doi.org/10.1111/jiec.12574>.
- Mutch, E. *et al.* (2017) 'Understanding the value of Southampton's urban trees'. Available at: https://www.researchgate.net/publication/321329435_Understanding_the_value_of_Southampton_s_urban_trees.
- Nachmany, M. *et al.* (2014) 'The GLOBE climate legislation study: a review of climate change legislation in 66 countries'. Available at: <http://eprints.lse.ac.uk/63656/> (Accessed: 29 September 2024).
- Nagireddi, S., Agarwal, J.R. and Vedapuri, D. (2023) 'Carbon Dioxide Capture, Utilization, and Sequestration: Current Status, Challenges, and Future Prospects for Global Decarbonization', *ACS Engineering Au*. Available at: <https://doi.org/10.1021/acsengineeringau.3c00049>.
- Najafpour Navaei, T. (2022) 'Minutes of Meeting 19.10.22'. 19 October 2022.
- Najafpour Navaei, T. *et al.* (2024) 'Carbon footprinting of railway infrastructure: a standardized, consistent data collection method', *Carbon Management*, 15(1), p. 2368839. doi: 10.1080/17583004.2024.2368839. Available at: <https://doi.org/10.1080/17583004.2024.2368839> (Accessed: 2024/12/31).

- Najafpour Navaei, T.A. *et al.* (2022) 'Carbon accounting in mainline railway geotechnical solutions: Reducing embodied carbon in conjunction with offsetting to reach net zero'. Available at: <http://eprints.soton.ac.uk/id/eprint/468881> (Accessed: 29 September 2024).
- NASA (2024) *NASA Analysis Confirms 2023 as Warmest Year on Record*. Available at: <https://www.nasa.gov/news-release/nasa-analysis-confirms-2023-as-warmest-year-on-record/>.
- National Academies of Sciences Engineering and Medicine (2019) *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.
- National Research Council (2015) *Climate intervention: Carbon dioxide removal and reliable sequestration*. Washington, DC: The National Academies Press. Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration.
- Navaei, T. *et al.* (2022) 'Carbon Footprinting of Railway Embankments and Cuttings: A Circular Framework', *Energy Reports*, 8 (11), pp. 8-13. Available at: <https://doi.org/10.1016/j.egyr.2022.05.051>.
- Nemet, G.F. *et al.* (2018) 'Negative emissions-Part 3: Innovation and upscaling', *Environmental Research Letters*, 13(6). Available at: <http://dx.doi.org/10.1088/1748-9326/aabff4>.
- Neste Corporation (2020) *Neste Renewable Diesel Handbook*. Available at: https://www.neste.com/sites/default/files/attachments/neste_renewable_diesel_handbook.pdf (Accessed: 27 September 2023).
- Network Rail (2017a) *Environment Policy*. Available at: <https://www.networkrail.co.uk/wp-content/uploads/2016/11/Network-Rail-Environment-Policy.pdf> (Accessed: 29 September 2024).
- Network Rail (2017b) *NR/L2/CIV/086 Module 4 Earthworks Interventions*. London: Network Rail.
- Network Rail (2017c) 'Weather Resilience and Climate Change Adaptation Strategy 2017-2019'. <https://www.networkrail.co.uk/communities/environment/climate-change-and-weather-resilience/>, p. 32.
- Network Rail (2018a) *Capital Carbon Guidance Note Environment (NR/GN/ESD07)*. Available at: <https://safety.networkrail.co.uk/wp-content/uploads/2023/01/ESD07-Capital-carbon-Guidance-Note.pdf> (Accessed: 7 November 2023).
- Network Rail (2018b) *Earthworks Technical Strategy*. Available at: <https://www.networkrail.co.uk/wp-content/uploads/2018/07/Earthworks-Technical-Strategy.pdf> (Accessed: 14 September 2024).
- Network Rail (2018c) *Railway Sustainability Design Guide: Introduction & User Guide* Available at: <https://safety.networkrail.co.uk/wp-content/uploads/2021/07/1-Introduction-and-User-Guide.pdf> (Accessed: 23 June 2024).
- Network Rail (2018d) *Recycling recovered railway materials at our Whitemoor facility*. Available at: <https://www.networkrail.co.uk/stories/recycling-recovered-railway-materials-at-our-whitemoor-facility/> (Accessed: 19 October 2023).
- Network Rail (2019) *Our ambition for a low-emission railway 2020-2050* (15). Available at: <https://www.networkrail.co.uk/sustainability/a-low-emission-railway/> (Accessed: 9 February 2021).
- Network Rail (2020a) *Designing for Low Whole-Life Carbon - Decarbonisation Programme Workstream 13*. Available at: <https://safety.networkrail.co.uk/home-2/environment-and-sustainable-development/energy-and-carbon-management/designing-for-low-whole-life-carbon/>.

List of References

- Network Rail (2020b) *Environmental Sustainability Strategy 2020-2050*. Available at: <https://safety.networkrail.co.uk/environmental-sustainability-strategy/> (Accessed: 9 February 2021).
- Network Rail (2020c) *Level 2 Manual: Lineside vegetation management manual*. London.
- Network Rail (2020d) 'Network Rail Biodiversity Action Plan'. <https://www.networkrail.co.uk/campaigns/sustainability/>: 40.
- Network Rail (2020e) *Traction Decarbonisation Network Strategy: Interim Programme Business Case*. Available at: <https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf> (Accessed: 22 March 2023).
- Network Rail (2020f) *Traction Decarbonisation Network Strategy: Intermim Programme Business Case*
- Network Rail (2021a) *Cost & Volume Handbook*.
- Network Rail (2021b) 'M33 Earthwork Asset Figures 31.03.21'.
- Network Rail (2021c) *Network Rail joins leading railway organisations from across the globe in further commitment to tackling climate change*. Available at: <https://www.networkrailmediacentre.co.uk/news/network-rail-joins-leading-railway-organisations-from-across-the-globe-in-further-commitment-to-tackling-climate-change> (Accessed: 10 May 2024).
- Network Rail (2021d) *Network Rail Third Adaptation Report*. London, UK. Available at: <https://www.networkrail.co.uk/wp-content/uploads/2022/01/Network-Rail-Third-Adaptation-Report-December-2021.pdf> (Accessed: 10 March 2022).
- Network Rail (2021e) *A practitioner's introduction to the Rail Carbon Tool*.
- Network Rail (2021f) *PROJECT SPECIFIC ENVIRONMENT AND SOCIAL MANAGEMENT PLAN (ESMP) High Brooms*.
- Network Rail (2022a) *Carbon Communication: Improving Network Rail access to relevant projects in the RSSB Rail Carbon Tool*.
- . Available at: <https://safety.networkrail.co.uk/wp-content/uploads/2022/09/Carbon-Communication-Improving-Network-Rail-access-to-RCT-Projects.pdf> (Accessed: 28 September 2022).
- Network Rail (2022b) *Earthworks: cutting slopes and embankments*. Available at: <https://www.networkrail.co.uk/running-the-railway/looking-after-the-railway/earthworks-cutting-slopes-and-embankments/> (Accessed: 16.03.22).
- Network Rail (2022c) *Managing whole life carbon in infrastructure* (NR/GN/ESD07 Issue 2).
- Network Rail (2022d) *Our Regions*. Available at: <https://www.networkrail.co.uk/running-the-railway/our-regions/> Accessed: 12 September 2022.
- Network Rail (2022e) 'Railway Sustainability Design Guide: A Digital Design Guide'. Available at: <https://planengageuk.alytics.com/networkrail-digital-sdg/home> (Accessed: 12 July 2022).
- NR W&W Region (2022) 'Graphs Regional Waste Data Breakdown'.
- O'Leary, M.J., Osmani, M. and Goodier, C. (2024) 'Circular economy implementation strategies, barriers and enablers for UK rail infrastructure projects', *Resources, Conservation & Recycling Advances*, 21, p. 200195. doi: <https://doi.org/10.1016/j.rcradv.2023.200195>. Available at: <https://www.sciencedirect.com/science/article/pii/S2667378923000676> (Accessed: 2024/05/01/).

- Olugbenga, O., Kalyviotis, N. and Saxe, S. (2019) 'Embodied emissions in rail infrastructure: a critical literature review', *Environmental Research Letters*, 14(12), p. 123002. Available at: <https://iopscience.iop.org/article/10.1088/1748-9326/ab442f/pdf> (Accessed: 9 May 2022).
- Onat, N.C. *et al.* (2019) *Supply Chain Linked Sustainability Assessment of Electric Vehicles: the Case for Qatar in 6th IEEE International Conference on Industrial Engineering and Applications (ICIEA)*. Waseda Univ, Tokyo, JAPAN, Apr 12-15. NEW YORK: Ieee.
- Onat, N.C. and Kucukvar, M. (2020) 'Carbon footprint of construction industry: A global review and supply chain analysis', *Renewable & Sustainable Energy Reviews*, 124, p. 16.
- Onat, N.C., Kucukvar, M. and Tatari, O. (2014) 'Towards Life Cycle Sustainability Assessment of Alternative Passenger Vehicles', *Sustainability*, 6(12), pp. 9305-9342.
- ONS (2019) *Net zero and the different official measures of the UK's greenhouse gas emissions*. Available at: <https://www.ons.gov.uk/economy/environmentalaccounts/articles/netzeroandthedifferentofficialmeasuresoftheuksgreenhousegasemissions/2019-07-24> (Accessed: 11 April 2024).
- ONS (2022) *Woodland Natural Capital Accounts*. Available at: <https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/woodlandnaturalcapitalaccountsuk/2022> (Accessed: 30 September 2024).
- ONS (2023) *ONS Postcode Directory look-up*. Available at: <https://www.gov.uk/government/statistics/2011-rural-urban-classification-lookup-tables-for-all-geographies> (Accessed: 11 January 2024).
- ORR (2023) *Rail Infrastructure and Assets 2022-23*. Available at: <https://dataportal.orr.gov.uk/media/g3xjpk2p/infrastructure-and-assets-2022-23.pdf> (Accessed: 8 April 2024).
- ORR (2024) *The environment, sustainable development and rail: Network Rail in CP7*. Available at: <https://www.orr.gov.uk/monitoring-regulation/sustainable-development/rail> (Accessed: 16 November 2024).
- Ostle, N.J. *et al.* (2009) 'UK land use and soil carbon sequestration', *Land Use Policy*, 26, pp. S274-S283. Available at: <http://dx.doi.org/10.1016/j.landusepol.2009.08.006>.
- Ozcan-Deniz, G. and Zhu, Y. (2017) 'Multi-objective optimization of greenhouse gas emissions in highway construction projects', *Sustainable cities and society*, 28, pp. 162-171. Available at: <http://dx.doi.org/10.1016/j.scs.2016.09.009>.
- Pallewattha, M., Indraratna, B. and Rujikiatkamjorn, C. (2016) *6th Asia-Pacific Conference on Unsaturated Soil Mechanics from Theory to Practice, AP-UNSAT 2015, October 23, 2015 - October 26, 2015*. Guilin, China. CRC Press/Balkema. Available at: <http://dx.doi.org/10.1201/b19248-139>.
- Pang, K. *et al.* (2021) 'Quantification of emission variability for off-road equipment in China based on real-world measurements', *Frontiers of Environmental Science and Engineering*, 16(2). Available at: <https://doi.org/10.1007/s11783-021-1455-x>.
- Pang, S.-H. (2008) *Life Cycle Inventory Incorporating Fuel Cycle and Real-World In-Use Measurement Data for Construction Equipment and Vehicles*. Available at: <https://repository.lib.ncsu.edu/bitstream/handle/1840.16/3020/etd.pdf?sequence=1> (Accessed: 30 October 2023).

List of References

- Parente, M., Correia, A.G. and Cortez, P. (2016) *6th Transport Research Arena (TRA)*. Warsaw, POLAND, Apr 18-21. AMSTERDAM: Elsevier Science Bv. Available at: <https://doi.org/10.1016/j.trpro.2016.05.428>.
- Patrizio, P. et al. (2021) 'CO2 mitigation or removal: The optimal uses of biomass in energy system decarbonization', *Isience*, 24(7). Available at: [https://www.cell.com/isience/pdf/S2589-0042\(21\)00733-1.pdf](https://www.cell.com/isience/pdf/S2589-0042(21)00733-1.pdf) (Accessed: 22 February 2024).
- Paul, K.I. and Roxburgh, S.H. (2020) 'Predicting carbon sequestration of woody biomass following land restoration', *Forest Ecology and Management*, 460, p. 117838. Available at: <https://doi.org/10.1016/j.foreco.2019.117838>.
- Pell, R. and Lindsay, J., J., (2022) *Comparative Life Cycle Assessment Study of Solid State and Lithium-Ion Batteries for Electric Vehicle Application in Europe*. Available at: https://www.transportenvironment.org/wp-content/uploads/2022/07/2022_07_LCA_research_by_Minviro.pdf (Accessed: 1 February 2024).
- Peng, T.D. et al. (2017) 'Life Cycle Greenhouse Gas Analysis of Multiple Vehicle Fuel Pathways in China', *Sustainability*, 9(12), p. 24. Available at: <http://dx.doi.org/10.3390/su9122183>.
- Phillips, B.B. et al. (2020) 'Ecosystem service provision by road verges', *Journal of Applied Ecology*, 57(3), pp. 488-501. Available at: <https://doi.org/10.1111/1365-2664.13556>.
- Phillips, B.B. et al. (2021) 'Road verge extent and habitat composition across Great Britain', *Landscape and Urban Planning*, 214. Available at: <https://doi.org/10.1016/j.landurbplan.2021.104159>.
- Pipitone, E., Caltabellotta, S. and Occhipinti, L. (2021) 'A Life Cycle Environmental Impact Comparison between Traditional, Hybrid, and Electric Vehicles in the European Context', *Sustainability*, 13(19), p. 32. Available at: <http://dx.doi.org/10.3390/su131910992>.
- Plantinga, A.J., Mauldin, T. and Miller, D.J. (1999) 'An econometric analysis of the costs of sequestering carbon in forests', *American Journal of Agricultural Economics*, 81(4), pp. 812-824. Available at: <http://dx.doi.org/10.2307/1244326>.
- Pons, J.J. et al. (2020) 'Life cycle assessment of a railway tracks substructures: Comparison of ballast and ballastless rail tracks', *Environmental Impact Assessment Review*, 85, p. 11. Available at: <http://dx.doi.org/10.1016/j.eiar.2020.106444>.
- Power, C. et al. (2016) 'Development of an evidence-based geotechnical asset management policy for Network Rail, Great Britain', *Procedia Engineering*, 143, pp. 726-733. Available at: <http://dx.doi.org/10.1016/j.proeng.2016.06.112>.
- Powrie, W. (2024) 'Railway track substructure: Recent research and future directions', *Transportation Geotechnics*, 46, p. 101234. Available at: <https://doi.org/10.1016/j.trgeo.2024.101234>.
- Pritchard, J. (2015) *Investigating the environmental sustainability of rail travel in comparison with other modes*. University of Southampton.
- Pritchard, J.A. and Preston, J. (2018) 'Understanding the contribution of tunnels to the overall energy consumption of and carbon emissions from a railway', *Transportation Research Part D: Transport and Environment*, 65, pp. 551-563. Available at: <https://doi.org/10.1016/j.trd.2018.09.010>.
- Puricelli, S. et al. (2021) 'A review on biofuels for light-duty vehicles in Europe', *Renewable & Sustainable Energy Reviews*, 137, p. 19. Available at: <https://doi.org/10.1016/j.rser.2020.110398>.
- QTS (2015) *Environmental Appraisal Garrion Gill*.

- QTS Rail (2015) *National Vegetation Classification (NVC) Survey* Garrion Gill.
- Qubaja, R., Moinester, M. and Kronfeld, J. (2022) 'Potential Global Sequestration of Atmospheric Carbon Dioxide by Semi-Arid Forestation', *arXiv preprint arXiv:2205.10641*. Available at: <https://arxiv.org/ftp/arxiv/papers/2205/2205.10641.pdf> (Accessed: 5 April 2024).
- Quillin, K. (2001) *Low Energy Cements* (BR421).
- RailBusinessDaily (2022) 'Successful hydrogen generator trial results revealed by HS2'. Available at: <https://news.railbusinessdaily.com/hydrogen-generator-trial-results-revealed-by-hs2/> (Accessed: 27 September 2023).
- Railway Codes (2023) *Railway Codes and other data*. Available at: <http://www.railwaycodes.org.uk/index.shtml> (Accessed: 11 January 2024).
- Raja, J. *et al.* (2015) 'Obtaining reliable embodied carbon values for geosynthetics', *Geosynthetics International*, 22(5), pp. 393-401. Available at: <http://dx.doi.org/10.1680/gein.15.00020>.
- Razzaque, J. and Lester, C. (2021) 'Why Protect Ancient Woodland in the UK? Rethinking the Ecosystem Approach', *Transnational Environmental Law*, 10(1), pp. 135-158. Available at: <http://dx.doi.org/10.1017/S2047102520000333>.
- Reid, C. *et al.* (2021) *State of the UK's Woods and Trees 2021* Woodland Trust. Available at: <https://www.woodlandtrust.org.uk/state-of-uk-woods-and-trees/#:~:text=1.,this%20is%20non%2Dnative%20trees>. (Accessed: 27 July 2021).
- Rempelos, G. (2023) *A Whole Life Carbon Model for Railway Track System Interventions*. University of Southampton.
- Rempelos, G., Preston, J. and Blainey, S. (2020) 'A carbon footprint analysis of railway sleepers in the United Kingdom', *Transportation Research Part D-Transport and Environment*, 81, p. 24. Available at: <https://doi.org/10.1016/j.trd.2020.102285>.
- REN21 (2018) *REN21 Renewables 2018 Global Status Report: Energy Units and Conversion Factors*. Available at: <https://www.ren21.net/gsr-2018/pages/units/units/#:~:text=1%20l%20biodiesel%20%3D%20127%2C960%20Btu%20%2F,US%20gallon%20%3D%2032.1%20MJ%20%2F%20l> (Accessed: 27 September 2023).
- Renforth, P. (2012) 'The potential of enhanced weathering in the UK', *International Journal of Greenhouse Gas Control*, 10, pp. 229-243. Available at: <http://dx.doi.org/10.1016/j.ijggc.2012.06.011>.
- Renforth, P., Pogge von Strandmann, P.A.E. and Henderson, G.M. (2015) 'The dissolution of olivine added to soil: Implications for enhanced weathering', *Applied Geochemistry*, 61, pp. 109-118. Available at: <http://dx.doi.org/10.1016/j.apgeochem.2015.05.016>.
- Rethish, C. (2023) *Number of Assets*, 15 May 2023.
- RIA (2021) 'Learning from Major Rail Projects: A Supply Chain Perspective'. Available at: https://issuu.com/railindustry/docs/ria_major_projects_report_2021. (Accessed: 30 September 2024).
- Richardson, M. (2021) *Biodiversity Stripes: LPI 2022. Living Planet Index database; Department for Environment, Food and Rural Affairs, UK. 2021; & UK Biodiversity Indicators 2021*. Available at: <https://biodiversitystripes.info/global/> (Accessed: 20 November 2024).
- RICS (2012) *Methodology to Calculate Embodied Carbon of Materials: RICS Information Paper, IP 32/2012* (1842197959). Available at: https://www.igbc.ie/wp-content/uploads/2015/02/RICS-Methodology_embodied_carbon_materials_final-1st-edition.pdf (Accessed: 20 October 2021).

List of References

- Rigopoulos, I. et al. (2016) 'On the potential use of quarry waste material for CO₂ sequestration', *Journal of Co₂ Utilization*, 16, pp. 361-370. Available at: <http://dx.doi.org/10.1016/j.jcou.2016.09.005>.
- Rothwell, N., Lyons, H., Sarafi Baghsorkhi, M. (2022) 'Whole life carbon management in the rail industry', *The PWI Journal*,. Available at: https://www.thepwi.org/wp-content/uploads/2022/04/Journal-2022_04-Vol140-Pt2_Whole-life-carbon-management-in-the-rail-industry.pdf (Accessed: 8 November 2023).
- RSSB - Rail Industry Decarbonisation Taskforce (2019) *Final report to the minister for rail*. Available at: <https://www.rssb.co.uk/en/sustainability/decarbonisation/decarbonisation-our-final-report-to-the-rail-minister> (Accessed: 21 September 2021).
- RSSB (2021a) *DECARB: Carbon Measurements T1197*. Available at: <https://www.rssb.co.uk/research-catalogue/CatalogueItem/T1197> (Accessed: 29 September 2021).
- RSSB (2021b) *DECARB: Recommendations for Implementing and Managing Potential Rail Industry Decarbonisation Targets T1198*. Available at: <https://www.rssb.co.uk/research-catalogue/CatalogueItem/T1198> (Accessed: 10 March 2022).
- RSSB (2021c) *Infrastructure Carbon Working Group Remit*.
- RSSB (2022) *Sustainable Rail Strategy: Prototype*. Available at: <https://www.rssb.co.uk/sustainability/sustainable-rail-strategy> (Accessed: 14 June 2022).
- RSSB (2024a) *Carbon Literacy for Rail* Available at: <https://www.rssb.co.uk/services-and-resources/training/carbon-literacy-for-rail#msdynttrid=qwhi-shvry9380wf20YJnyVBTAMJPVP23TeaqsS6uOg> (Accessed: 22 July 2024).
- RSSB (2024b) *Report T1228 Enabling supply chain decarbonisation*. Available at: <https://www.rssb.co.uk/-/media/Project/RSSB/RssbWebsite/Documents/Registered/Research-Projects/2024/03/13/15/07/2024-03-T1228-Final-Report.pdf> (Accessed: 16 April 2024).
- RSSB (2024c) *Research Guidance Document Supply chain carbon data collection and reporting T1228*. Available at: <https://www.rssb.co.uk/-/media/Project/RSSB/RssbWebsite/Documents/Registered/Research-Projects/2024/02/19/13/38/2024-02-T1228-Supply-chain-carbon-data-collection-and-reporting.pdf> (Accessed: 16 April 2024).
- Rueda, O. et al. (2021) 'Negative-emissions technology portfolios to meet the 1.5° C target', *Global Environmental Change*, 67, p. 102238. Available at: <https://doi.org/10.1016/j.gloenvcha.2021.102238>.
- Rujikiatkamjorn, C. (2024) *Proceedings of the 5th International Conference on Transportation Geotechnics (ICTG) 2024, Volume 7: Sustainable Infrastructure and Numerical Modeling in Roads, Rails, and Harbours*. Springer Nature.
- Sang-lam, J., Smethurst, J. and Powrie, W. (2022) 'Assessment and remediation of old railway embankments for the next 175 years', *Proceedings of the World Congress on Railway Research: OP.18 Infrastructure Maintenance*. Birmingham, UK, 6-10 June. Available at: <https://crowdcomms.com/wcrr2022/modules/132783/document> (Accessed: 16 June 2022).
- Santana, M. and Toshie Oiko, O. (2019) 'Carbon Footprint: In search of a definition and method for Green Logistics [Abstract]', *Revista Gestão da Produção Operações e Sistemas*, 14(4), pp. 197-214.
- Saran, R.K., Arora, V. and Yadav, S. (2018) 'CO₂ sequestration by mineral carbonation: a review', *Global Nest Journal*, 20(3), pp. 497-503. Available at: <https://doi.org/10.30955/gnj.002597>.

- Saravanan, J., Venkateswara Rao, P., (2023) 'Past investigations on development of sustainable bricks – A comprehensive review', *Sustainable Chemistry for the Environment*, 3. Available at: <https://doi.org/10.1016/j.scenv.2023.100030>.
- Saxe, S. *et al.* (2015) 'Greenhouse gas considerations in rail infrastructure in the UK', *Proceedings of the Institution of Civil Engineers-Engineering Sustainability* Thomas Telford Ltd, pp. 171-180. Available at: <http://dx.doi.org/10.1680/jensu.15.00015>.
- Saxe, S. and Kasraian, D. (2020) 'Rethinking environmental LCA life stages for transport infrastructure to facilitate holistic assessment', *Journal of Industrial Ecology*, 24(5), pp. 1031-1046. Available at: <http://dx.doi.org/10.1111/jiec.13010>.
- SBTi (2020) *Foundations for Science-Based Net-Zero Target Setting in the Corporate Sector*. Available at: <https://sciencebasedtargets.org/resources/files/foundations-for-net-zero-full-paper.pdf> (Accessed: 23 September 2021).
- SBTi (2021a) *Companies Taking Action: Network Rail*. Available at: <https://sciencebasedtargets.org/companies-taking-action> (Accessed: 23 September 2021).
- SBTi (2021b) *Join the world's biggest companies by cutting your GHG emissions*. Available at: <https://sciencebasedtargets.org/> (Accessed: 27 October 2021).
- SBTi (2021c) *SBTi Corporate Net-Zero Standard V1.0*. Available at: <https://sciencebasedtargets.org/resources/files/Net-Zero-Standard.pdf> (Accessed: 4 August 2022).
- Schuiling, R.D. and Krijgsman, P. (2006) 'Enhanced weathering: An effective and cheap tool to sequester CO₂', *Climatic Change*, 74(1-3), pp. 349-354. Available at: <http://dx.doi.org/10.1007/s10584-005-3485-y>.
- Scrivener, K.L. *et al.* (2018) 'Eco-efficient cements: Potential economically viable solutions for a low-CO₂ cement-based materials industry', *Cement and Concrete Research*, 114, pp. 2-26. Available at: <https://doi.org/10.1016/j.cemconres.2018.03.015>.
- Sedjo, R. and Sohngen, B. (2012) 'Carbon Sequestration in Forests and Soils', in Rausser, G.C. (ed.) *Annual Review of Resource Economics*, Vol 4, pp. 126-143. Available at: <https://www.annualreviews.org/doi/pdf/10.1146/annurev-resource-083110-115941>.
- Sen, B. *et al.* (2019) 'Material footprint of electric vehicles: A multiregional life cycle assessment', *Journal of Cleaner Production*, 209, pp. 1033-1043. Available at: <https://doi.org/10.1016/j.jclepro.2018.10.309>.
- Sharma, R. *et al.* (2013) 'Conventional, hybrid and electric vehicles for Australian driving conditions. Part 2: Life cycle CO₂-e emissions', *Transportation Research Part C: Emerging Technologies*, 28, pp. 63-73. Available at: <https://doi.org/10.1016/j.trc.2012.12.011>.
- Sherriff, M. (2022) Teams conversation with Tracey Navaei 13 January.
- Shi, S. *et al.* (2013) 'A synthesis of change in deep soil organic carbon stores with afforestation of agricultural soils', *Forest Ecology and Management*, 296, pp. 53-63. Available at: <http://dx.doi.org/10.1016/j.foreco.2013.01.026>.
- Shillaber, C.M. (2016) *Toward Sustainable Development: Quantifying Environmental Impact via Embodied Energy and CO₂ Emissions for Geotechnical Construction*. PhD thesis. Virginia Tech. Available at: <https://vtechworks.lib.vt.edu/handle/10919/64935> (Accessed: 29 November 2021).

List of References

- Simpson, M. (2022) *Reaching Net Zero by 2050*. in The Field of Transport Net Zero: Collection of Essays on Net Zero Available at: <https://fieldconsulting.co.uk/wp-content/uploads/2022/03/Field-of-Transport-Report-Net-Zero.pdf> (Accessed: 8 March 2022).
- Skinner, J., Morton, J. and Dowdall, A. (2024) 'Transporting carbon: calculating A4 emissions for mass timber', *The Structural Engineer: journal of the Institution of Structural Engineer*, 102(9), pp. 34-36.
- Smith, P. (2014) 'Do grasslands act as a perpetual sink for carbon?', *Global Change Biology*, 20(9), pp. 2708-2711. Available at: <http://dx.doi.org/10.1111/gcb.12561>.
- Smith, S.M. et al. (2023) *The State of Carbon Dioxide Removal - 1st Edition*. Available at: Available at: <https://www.stateofcdr.org>.
- Sommer, R. and Bossio, D. (2014) 'Dynamics and climate change mitigation potential of soil organic carbon sequestration', *Journal of environmental management*, 144, pp. 83-87. Available at: <http://dx.doi.org/10.1016/j.jenvman.2014.05.017>.
- Standish, R.J. and Prober, S.M. (2020) 'Potential benefits of biodiversity to Australian vegetation projects registered with the Emissions Reduction Fund-is there a carbon-biodiversity trade-off?', *Ecological Management & Restoration*, 21(3), pp. 165-172. Available at: <http://dx.doi.org/10.1111/emr.12426>.
- Stechemesser, K. and Guenther, E. (2012) 'Carbon accounting: a systematic literature review', *Journal of Cleaner Production*, 36, pp. 17-38. Available at: <http://dx.doi.org/10.1016/j.jclepro.2012.02.021>.
- Steel, P. (2021) 'Making Concrete Greener', *Leeds Alumni Magazine*, Issue 22(22).
- Sterling, P. et al. (2023) 'Blue-green infrastructure on highways', in *ICE Manual of Blue-Green Infrastructure*. ICE Publishing, pp. 159-185.
- Stern, N. (2007) *The Economics of Climate Change: The Stern Review*. Cambridge: Cambridge University Press.
- Strefler, J. et al. (2018) 'Potential and costs of carbon dioxide removal by enhanced weathering of rocks', *Environmental Research Letters*, 13(3), p. 034010. Available at: <https://iopscience.iop.org/article/10.1088/1748-9326/aaa9c4>.
- Stripple, H. and Uppenberg, S. (2010) 'Life cycle assessment of railways and rail transports- Application in environmental product declarations (EPDs) for the Bothnia Line'. Available at: <https://www.diva-portal.org/smash/get/diva2:1552159/FULLTEXT01.pdf> Accessed: 22 September 2022.
- Stroud, T., Brintrup, C. and Fancourt, S. (2023) 'Designing with landscape maintenance in mind', in *High Speed Two (HS2): Infrastructure Design and Construction (Volume 4)*. ICE Publishing, pp. 3-24.
- Suer, J., Traverso, M. and Jäger, N. (2022) 'Review of life cycle assessments for steel and environmental analysis of future steel production scenarios', *Sustainability*, 14(21), p. 14131. Available at: <https://doi.org/10.3390/su142114131>.
- Sunak, R. (2023) *PM speech on Net Zero: 20 September 2023*. Available at: <https://www.gov.uk/government/speeches/pm-speech-on-net-zero-20-september-2023> (Accessed: 3 October 2023).
- Suthisripok, T. and Semsamran, P. (2018) 'The impact of biodiesel B100 on a small agricultural diesel engine', *Tribology International*, 128, pp. 397-409. doi: <https://doi.org/10.1016/j.triboint.2018.07.042>. Available at: <https://www.sciencedirect.com/science/article/pii/S0301679X18303803> (Accessed: 2018/12/01/).

- Sydney Trains (2019) *VEGETATION MANAGAEMENT IN THE CORRIDOR GUIDE*, *Environmental Management System*, EMS-06-GD-0067.
- Takano, A. *et al.* (2014) 'Comparison of life cycle assessment databases: A case study on building assessment', *Building and Environment*, 79, pp. 20-30. Available at: <http://dx.doi.org/10.1016/j.buildenv.2014.04.025>.
- Tan, R.R. and Aviso, K.B. (2021) 'On life-cycle sustainability optimization of enhanced weathering systems', *Journal of Cleaner Production*, 289. Available at: <https://doi.org/10.1016/j.jclepro.2021.125836>.
- The Concrete Centre (2020) *Specifying Sustainable Concrete*. London.
- Essential Tools for the Low Carbon Economy*, Carbon 101x, [MOOC], EdX (2021).
- Trevisan, L. and Bordignon, M. (2020) 'Screening Life Cycle Assessment to compare CO2 and Greenhouse Gases emissions of air, road, and rail transport: An exploratory study', *Procedia CIRP*, 90, pp. 303-309. Available at: <https://doi.org/10.1016/j.procir.2020.01.100>.
- Trewick, C. and Anderson, B. (2023) 'Options for carbon sequestration in the Solent Region'. Available at: https://eprints.soton.ac.uk/474758/1/Trewick_Anderson_2022_Options_for_carbon_sequestration_in_the_Solent_Region_v1.2.pdf (Accessed: 24 September 2024).
- Tuchs Schmid, M. *et al.* (2011) 'Carbon Footprint and environmental impact of Railway In-frastructure', *Carbon*, 2. Available at: https://uic.org/IMG/pdf/uic_rail_infrastructure_111104.pdf (Accessed: 28 April 2021).
- Turner, D.A. (2016) *Evaluating the life cycle climate impacts of solid waste management*. Doctoral Thesis. Available at: <https://eprints.soton.ac.uk/398127/> (Accessed: 11 April 2024).
- Turner, D.A., Kemp, S. and Williams, I. (2011) 'Carbon footprinting in the UK waste management sector', *Carbon Management*, 2(6), pp. 677-690. Available at: <https://doi.org/10.4155/cmt.11.67>.
- UIC (2021) 'UIC SUSTAINABILITY: Circular practices in the railway and ways forward: REUSE Project Final Report'. Available at: https://ertms.uic.org/IMG/pdf/reuse_project_final_report.pdf.
- UIC (2023) *Atlas High-Speed Rail 2023*. Available at: <https://uic.org/spip.php?action=telecharger&arg=3456> (Accessed: 13 June 2024).
- UK Government (2020) *United Kingdom of Great Britain and Northern Ireland's Nationally Determined Contribution*. London.
- UK Green Building Council (2019) *Net Zero Carbon Buildings: A Framework Definition*. Available at: <https://ukgbc.org/wp-content/uploads/2019/04/Net-Zero-Carbon-Buildings-A-framework-definition.pdf> (Accessed: 24 September 2024).
- UK National Ecosystem Assessment (2014) *UK National Ecosystem Assessment Follow on: Synthesis of the Key Findings*. Available at: <http://uknea.unep-wcmc.org/Resources/tabid/82/Default.aspx> (Downloaded: 16 September 2021).
- UK National Grid (2020) *Future Energy Scenarios* Available at: <https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2020-documents> (Accessed: 22 March 2022).
- UK Woodland Carbon Code (2021a) *Using the WCC Carbon Calculation Spreadsheet, Version 2.4*. Available at:

List of References

- https://woodlandcarboncode.org.uk/images/PDFs/WCC_CarbonCalculation_Guidance_V2.4_March2021.pdf.
- UK Woodland Carbon Code (2021b) *WCC Carbon Calculation Spreadsheet Version 2.4*. Available at: https://www.woodlandcarboncode.org.uk/images/Spreadsheets/WCC_CarbonCalculationSpreadsheet_Version2.4_March2021.xlsx.
- UK Woodland Carbon Code (2022) *UK Woodland Carbon Code Version 2.2*. Available at: https://www.woodlandcarboncode.org.uk/images/PDFs/Woodland_Carbon_Code_V2.2_April_2022.pdf.
- UK Woodland Carbon Code (2024) *UK Woodland Carbon Code Standards and Guidance*. Available at: Available at: <https://www.woodlandcarboncode.org.uk/standard-and-guidance> (Accessed: 16 September 2024).
- UKGBC (2022) *Insights on how circular economy principles can impact carbon and value*. Available at: <https://ukgbc.s3.eu-west-2.amazonaws.com/wp-content/uploads/2022/08/23174556/Whole-Life-Carbon-Circular-Economy-Report.pdf> (Accessed: 1 June 2024).
- UKRI (2021) *Greenhouse Gases Removal Demonstrator (GGR-D) Projects*. Available at: <https://www.ukri.org/news/uk-invests-over-30m-in-large-scale-greenhouse-gas-removal/> (Accessed: 8 September 2021).
- UN (2021) *UNSDG Communications materials*. Available at: <https://www.un.org/sustainabledevelopment/news/communications-material/>.
- UN General Assembly (2015a) *Resolution adopted by the General Assembly on 25 September 2015: 70/1 Transforming our world: the 2030 Agenda for Sustainable Development*. Available at: <https://documents.un.org/doc/undoc/gen/n15/291/89/pdf/n1529189.pdf> (Accessed: 24 September 2024).
- UN General Assembly (2015b) 'Transforming our world: The 2030 agenda for sustainable development (A/RES/70/1)', New York: UN General Assembly.
- UN Secretary-General António Guterres (2020) *UN Climate Change Speech*. Available at: <https://unfccc.int/news/un-secretary-general-making-peace-with-nature-is-the-defining-task-of-the-21st-century> (Accessed: 14 June 2021).
- UN Secretary-General António Guterres (2023) *Secretary-General's Opening Remarks at Press Conference on Climate*. Available at: <https://www.un.org/sg/en/content/sg/speeches/2023-07-27/secretary-generals-opening-remarks-press-conference-climate> (Accessed: 31 October 2023).
- UNFCCC (1992) *Forest Science*. Citeseer.
- Kyoto Protocol to the United Nations Framework Convention on Climate Change.
- UNFCCC (2013) *United Nations Framework Convention on Climate Change Amendment to the Kyoto Protocol Decision1 CMP.8 FCCC/KP/CMP/2012/13/Add.1*. Available at: https://treaties.un.org/doc/source/docs/Doha_Decision1_CMP.8-E.pdf.
- Varley, J. (2018) *Valuing nature - a railway for people and wildlife. The Network Rail Vegetation Management Review*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/955344/valuing-nature_a-railway-for-people-and-wildlife-the-network-rail-vegetation-management-review-document.pdf (Accessed: 14 June 2021).

- Velazquez Abad, A. (2016) *Selection of low carbon technologies for heavy goods vehicles*. University of Southampton.
- Vieira, D.R., Calmon, J.L. and Coelho, F.Z. (2016) 'Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review', *Construction and Building Materials*, 124, pp. 656-666. Available at: <http://dx.doi.org/10.1016/j.conbuildmat.2016.07.125>.
- Vilotijevic, M. *et al.* (2018) 'Sustainable Railway Infrastructure and Specific Environmental Issues in the Republic of Serbia', *Tehnicki Vjesnik-Technical Gazette*, 25, pp. 516-523. Available at: <https://doi.org/10.17559/TV-20171019124644> (Accessed: Sep).
- Vink, J.P. and Knops, P. (2023) 'Size-fractionated weathering of olivine, its CO₂-sequestration rate, and ecotoxicological risk assessment of nickel release', *Minerals*, 13(2), p. 235. Available at: <https://doi.org/10.3390/min13020235>.
- Vitta, S. (2021) 'Electric cars - Assessment of 'green' nature vis-a-vis conventional fuel driven cars', *Sustainable Materials and Technologies*, 30, p. 7. Available at: <https://doi.org/10.1016/j.susmat.2021.e00339>.
- Vogiatzis, D. *et al.* (2023) *Lifecycle Carbon Footprint Calculation of Hand-Held Tool Propulsion Concepts* (0148-7191). Available at: <https://doi.org/10.4271/2023-01-0553>.
- von Rozycki, C., Koeser, H. and Schwarz, H. (2003) 'Ecology profile of the German high-speed rail passenger transport system, ICE', *International Journal of Life Cycle Assessment*, 8(2), pp. 83-91. Available at: <https://link.springer.com/article/10.1007/BF02978431> (Accessed: 28 April 2021).
- Wang, V., Gao, J. and Schwendenmann, L. (2020) 'Assessing changes of urban vegetation cover and aboveground carbon stocks using LiDAR and Landsat imagery data in Auckland, New Zealand', *International Journal of Remote Sensing*, 41(6), pp. 2140-2158. Available at: <https://doi.org/10.1080/01431161.2019.1685716>.
- Wang, X., VandenBygaart, A.J. and McConkey, B.C. (2014) 'Land Management History of Canadian Grasslands and the Impact on Soil Carbon Storage', *Rangeland Ecology & Management*, 67(4), pp. 333-343. Available at: <http://dx.doi.org/10.2111/REM-D-14-00006.1>.
- Watt, R. (2021) 'The fantasy of carbon offsetting', *Environmental Politics*, pp. 1-20. Available at: <https://doi.org/10.1080/09644016.2021.1877063>.
- WBCSD (2019) *Forest Sector SDG Roadmap*. Available at: https://docs.wbcsd.org/2019/07/WBCSD_Forest_Sector_SDG_Roadmap.pdf (Accessed: 11 April 2024).
- Wei, T. and Chen, S. (2020) 'Dynamic energy and carbon footprints of urban transportation infrastructures: Differentiating between existing and newly-built assets', *Applied Energy*, 277, p. 115554. Available at: <https://doi.org/10.1016/j.apenergy.2020.115554>.
- Westin, J. and Kågeson, P. (2012) 'Can high speed rail offset its embedded emissions?', *Transportation Research Part D: Transport and Environment*, 17(1), pp. 1-7. Available at: <https://doi.org/10.1016/j.trd.2011.09.006>.
- White, H.P. (1963) 'The Reshaping of British Railways: A Review', *Geography*, 48(3), pp. 335-337.
- Wiedmann, T.O. *et al.* (2015) 'The material footprint of nations', *Proceedings of the national academy of sciences*, 112(20), pp. 6271-6276. Available at: www.pnas.org/cgi/doi/10.1073/pnas.1220362110.

List of References

- Wiik, M.K. *et al.* (2023) 'Electrification of Excavators: Electrical configurations, carbon footprint, and cost assessment of retrofit solutions', *IEEE Electrification Magazine*, 11(2), pp. 24-34. Available at: <https://ieeexplore.ieee.org/document/10143768> (Accessed: 27 November 2023).
- Wikipedia (2022) *Beeching cuts* (Accessed: 12 September 2022).
- Williams, I. *et al.* (2012) 'A beginner's guide to carbon footprinting', *Carbon Management*, 3(1), pp. 55-67. Available at: <https://doi.org/10.4155/cmt.11.80>.
- Winslow, P. (2020) *Low embodied carbon steel routemap - Progress update*.
- Winston, R.J., Bouchard, N.R. and Hunt, W.F. (2013) *2nd Green Streets, Highways, and Development Conference 2013: Advancing the Practice, November 3, 2013 - November 6, 2013*. Austin, TX, United states. American Society of Civil Engineers (ASCE). Available at: <http://dx.doi.org/10.1061/9780784413197.028>.
- Wise, C. and Winslow, P. (2019) *MaGIC for NR: Marginal Gains in Construction; Survey Response and Commentary*.
- Wong, E.Y.C. *et al.* (2021) 'Life Cycle Assessment of Electric Vehicles and Hydrogen Fuel Cell Vehicles Using the GREET Model-A Comparative Study', *Sustainability*, 13(9), p. 14. Available at: <https://doi.org/10.3390/su13094872>.
- Woodland Trust (2022) *Farming for the Future: How Agroforestry can Delivery for Nature and Climate*. Available at: <https://www.woodlandtrust.org.uk/media/51622/farming-for-the-future-how-agroforestry-can-deliver-for-nature-climate.pdf> (Accessed: 6 May 2024).
- Woodland Trust (2024) *Hedgerows*. Available at: <https://www.woodlandtrust.org.uk/trees-woods-and-wildlife/habitats/hedgerows/> (Accessed: 6 May 2024).
- World Business Council for Sustainable Development and the World Resources Institute (2004) *The Greenhouse Gas Protocol*. Available at: <https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf> (Accessed: 14 February 2023).
- Worldstainless (2023) *Stainless steel CO2 Emission Report*. Available at: https://www.worldstainless.org/files/issf/non-image-files/PDF/worldstainless_CO2_Emissions_Report.pdf (Accessed: 24 September 2024).
- Wright, L.A., Kemp, S. and Williams, I. (2011) 'Carbon footprinting': towards a universally accepted definition', *Carbon Management*, 2(1), pp. 61-72. doi: 10.4155/cmt.10.39. Available at: <https://doi.org/10.4155/cmt.10.39>.
- WSP Parsons Brinckerhoff (2015) *Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 Iron and Steel*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416667/Iron_and_Steel_Report.pdf (Accessed: 11 October 2023).
- Wu, H.H. *et al.* (2021) 'The environmental footprint of electric vehicle battery packs during the production and use phases with different functional units', *International Journal of Life Cycle Assessment*, 26(1), pp. 97-113. Available at: <https://doi.org/10.1007/s11367-020-01836-3>
- Xu, H. *et al.* (2022) 'Life cycle greenhouse gas emissions of biodiesel and renewable diesel production in the United States', *Environmental Science & Technology*, 56(12), pp. 7512-7521. Available at: <https://pubs.acs.org/doi/abs/10.1021/acs.est.2c00289>.

- Yablonovitch, E. and Deckman, H.W. (2023) 'Scalable, economical, and stable sequestration of agricultural fixed carbon', *Proceedings of the National Academy of Sciences*, 120(16), p. e2217695120. Available at: <https://www.pnas.org/doi/full/10.1073/pnas.2217695120>.
- Yadav, S. and Mehra, A. (2021) 'A review on ex situ mineral carbonation', *Environmental Science and Pollution Research*, 28(10), pp. 12202-12231. Available at: <https://link.springer.com/content/pdf/10.1007/s11356-020-12049-4.pdf> (Accessed: 2 May 2021).
- Yan, J. *et al.* (2022) 'SeeCarbon: a review of digital approaches for revealing and reducing infrastructure, building and City's carbon footprint', *IFAC-PapersOnLine*, 55(19), pp. 223-228. Available at: <https://doi.org/10.1016/j.ifacol.2022.09.211>
- Yue, Y. *et al.* (2015) 'Life cycle assessment of High Speed Rail in China', *Transportation Research Part D: Transport and Environment*, 41, pp. 367-376. Available at: <https://doi.org/10.1016/j.trd.2015.10.005>.
- Zemo Partnership (2024) *Vehicle life cycle GHG emissions study to show the role of renewable fuels in meeting net zero*. Available at: https://www.zemo.org.uk/LifeCycleGHG_2024 (Accessed: 1 February 2024).
- Zeng, N. (2008) 'Carbon sequestration via wood burial', *Carbon Balance and Management*, 3(1), pp. 1-12. Available at: <https://cbmjournal.biomedcentral.com/articles/10.1186/1750-0680-3-1> (Accessed: 10 May 2021).
- Zuo, C. *et al.* (2018) 'Reducing carbon emissions related to the transportation of aggregates: Is road or rail the solution?', *Transportation Research Part A*, 117, pp. 26-38. Available at: <https://doi.org/10.1016/j.tra.2018.08.006>.