EngD Thesis:
Modelling and Managing The Charging of Massed Electric Vehicles on Constrained Residential Power Networks

SR Broderick June 2020

UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

Transport Research Group

EngD Thesis

Modelling and Managing The Charging of Massed Electric Vehicles on Constrained Residential Power Networks

Stephen Redmond Broderick

srb3g13@soton.ac.uk or sr.broderick@zoho.eu

Volume 1 Version 1.3

with minor corrections

(see also Volumes 2 - 4: Results Analyses)

June 2020

EPSRC
Engineering and Physical Sciences Research Council

Scottish and Southern Energy
Power Distribution

.

The Version 1.3 document is the final corrected version

of the December 2019 v1.2 Thesis Submission,

following Viva late April 2020

ABSTRACT

This thesis investigates how Electric Vehicles (EVs) and UK residential 230 V Low Voltage (LV) networks interact, as EVs supplant fossil-fuel cars. Home EV charging can provoke LV overloads, invisible to analyses set at higher voltages using averaged data.

The Feeder Phase Balancer (FPB) simulator is presented, which models EVs on an LV network. FPB simulates various EVs driving independent trips, with charging control by a local manager and/or a 3rd party Aggregation service. Vehicle to Grid, Demand Response, Fast Frequency Response and Time of Use services are modelled.

Impacts on EV and LV conditions are recorded; the EV support capability of various LV networks is explored and remedial options assessed. New knowledge is found concerning seasonal EV need to charge and of ability of networks to support Winter / Summer charging. Recommendations to DNOs and interested parties are formed.

The FPB has simulated over 4.9×10^9 independent EV trips, finding:

a) LV networks, built to historic guidelines for gas-heated homes, <u>cannot support EVs replacing cars 1:1</u> without reinforcement and / or local ICT control;

b) Replacing gas-heating with Heat Pumps <u>adds far greater load</u>, <u>forcing network reinforcement</u> for the great majority of UK LV networks.

c) Localised LV overloads (faults and blackouts) rise with EV charging duties;

d) Network conditions, EV numbers and characteristics, ambient temperature and driven distances affect overloads, seen as EVs reach 10% ~ 30% homes

e) <u>There is seasonality</u>: cold Winters provoke overloads (possibly simultaneous)

f) Local ICT management of charging helps limit overloads, but can cause undercharging. Vehicle to Grid EVs can reduce undercharging.

g) Top-down control is found <u>not beneficial</u> e.g. Time of Use constraints can cause undercharging when imposed and “crowd-rush” overloads when lifted;

h) Destination charger use has great seasonality (x4 to x22 rise in Winter); failing to charge threatens stranding vehicles in the evenings.

The above outcomes are dependant upon assumptions (e.g. battery characteristics) which are described. A repository of results data is available.

Table of Contents

Frontpage i

Abstract iii

Table of Contents iv

Table of Figures xx

Index of Tables xxvi

Glossary of Terms xxxiii

Chapter 1: Introduction..1

1.1 Thesis Aims and Objectives..2

1.1.1 A Holistic Approach..2

1.1.2 Scope of Work..3

1.2 Results and Outputs..3

1.3 Contributions..4

1.4 Overview of the EV Charging Problem..4

1.5 Concerning Network Assessment..6

1.6 Example of Utility of Results..6

1.7 Published Papers..8

1.8 Chapter Summary..8

Chapter 2: Background and Investigations..11

2.1 Overview of the UK Power Network..11

2.1.1 General Structure..11

2.1.2 The CEGB and Privatised Network Structures..12

2.1.3 Bought Services..14

2.1.4 Safety and DNO Quality Compliance..14

2.1.5 Residential Low Voltage Distribution..15

2.1.6 Distribution Cost Management....17
2.1.6.1 Build to ADMD not Instantaneous Peaks....18
2.1.6.2 Distribution (Cyclic) Rating....21
2.1.7 Other LCT Loads: HP and Auxiliary....22
2.2 DNO EV Projects in the UK....22
2.2.1 Low Carbon London (LCL)....24
2.2.2 LCL Key Documents and Findings....24
2.2.3 Customer-led Network Revolution (CLNR)....26
2.2.4 CLNR Key Documents and Findings....27
2.3 My Electric Avenue and *Esprit*....29
2.3.1 MEA Key Documents and Findings....29
2.3.2 Variations on *Esprit*....31
2.3.3 Impact of MEA on UK Charging Policy....32
2.3.4 Learning Points from MEA....32
2.4 Use of Vehicle and Mileage Driven....34
2.5 The Parsons Brinckerhoff Study....35
2.6 Electric Nation - A Contemporary Project....35
2.7 Further Concerns....38
2.7.1 The Risk of Elevated Transformer Ageing....38
2.7.2 Harmonics....39
2.8 The Coming of the Smart Grid and Smart Meters....41
2.8.1 General Practice Pre Smart Grid....41
2.8.2 What Is a Smart Grid?....41
2.8.3 The Origin of the Smart Grid - Blackouts in America....42
2.8.4 Key Smart Grid Tools....43
2.8.5 A Market Connection....43
2.8.6 Differences between UK and US Distribution Systems....44

2.9 Benefits of the Smart Grid in the UK....45
2.9.1 The Need to Manage LCT Loads....45
2.9.2 Purpose of the Smart Grid....46
2.9.3 Presently LV Supportable EV Population....46
2.9.4 Managed Charging of EVs....47
2.10 Smart Meters in the UK....48
2.10.1 Types of UK Smart Meter....49
2.10.2 Smart Meter Communications via DCC....49
2.10.3 The Smart Meter / DNO Disconnect....49
2.10.4 DNO Use of Smart Meter Data....50
2.10.5 Realised Utility of Smart Grid / Smart Meters in the UK....50
2.11 Vehicle to Grid....52
2.11.1 V2G has High Losses....53
2.11.2 Meeting the Cost of Battery Damage....53
2.11.3 Cost of Communications....53
2.11.4 Costs of Modifying Retailer Billing....54
2.11.5 Excess Charge Loss....55
2.11.6 Excess Vehicle Delay / Conflict of Interest....55
2.11.7 No Mass UK FFR Market of Scale Visible....55
2.11.8 DR Does (nearly) All That V2G Can....56
2.11.9 Comparative Merits of DR and V2G....56
2.11.10 Where Does V2G Shine?....57
2.11.11 V2G in Summary....57
2.12 A Potential Dependency Trap....57
2.13 Literature....58
2.13.1 Early Enthusiasm: Monetising Electric Vehicles....58

2.13.2 Markets and Profits....59
2.13.3 V2G Battery Damage and Costs....60
2.13.4 UK Market Situation and Projection....62
2.14 UK Relevant Literature....63
2.15 Summary of Key-Points....77
2.15.1 Concerning NGESO Issues....77
2.15.1.1 Concerning DNOs and Local Networks....77
2.15.2 Concerning EVs....78
2.15.3 Concerning Smart Grid and Control....78
2.15.4 AOB....79
2.16 Chapter Summary....80
Chapter 3: Approaches to Simulation....81
3.1 Why Simulate?....81
3.1.1 Potential Alternatives to Simulation....82
3.2 Simulators....83
3.2.1 Limitations of Past Simulations....83
3.2.2 INSim - an Attempted Simulator....85
3.3 Approaches to Simulation....85
3.3.1 Phase Hopping....85
3.3.2 A General Intelligent EV on LV Network Simulator....88
3.4 Intended FPB Degrees of Freedom....89
3.4.1 EV Characteristics....90
3.4.2 How EVs are Driven....91
3.4.3 LV Network Data....91
3.5 Techniques of Simulation....91
3.6 Chapter Summary....93
Chapter 4: The FPB Simulator and Concepts....95

4.1.1 General Overview....95
4.1.2 General Design Implementation....96
4.2 Key Assumptions....97
4.2.1 EVs and Charging....97
4.2.1.1 People's Charging Behaviour....97
4.2.1.2 Battery Life Policies / BLPs....98
4.2.2 The Vehicles Modelled....98
4.3 EV Management Objective....99
4.3.1 EV Departure Stance....99
4.3.2 EV Arrival Stance and AFH....100
4.4 Simulator General Components - Three Main Blocks....100
4.4.1 Block 1: Data Preparation and Synthesis....101
4.4.2 Block 2: Simulator Execution Suite....101
4.4.2.1 Single Thread Simulation....102
4.4.2.2 Multi-Threaded Simulation....103
4.4.3 Block 3: Post-Processing and Analysis....104
4.5 The Charging Simulation Models....105
4.5.1 Phase kW Available Headroom....105
4.5.2 The EV Types: Dumb, SV1G and V2G....106
4.5.3 The EV Electrical Model....106
4.5.4 The Effects of Ambient Temperature....107
4.5.5 The EV Behavioural Model....108
4.5.6 EV Battery State (SOC) Calculation....108
4.5.7 Mandatory, Opportunistic and Discretionary....109
4.5.8 Discretionary V2G Dispatch....111
4.5.9 The Tranche-based EV Intent Model....111
4.5.9.1 Sample Tranches for EV Charging....113

4.5.9.2 Sample Tranches for V2G EVs....116
4.5.9.3 Tranche Assessment and Priorities....117
4.5.10 The MCS Method: Seek Maximum Throughput....117
4.5.11 Modelling The LV Feeder....119
4.5.11.1 DNO Design Method....119
4.5.11.2 FPB and OpenDSS Feeder Views....121
4.5.11.3 Non-Uniform and Branching Feeders....122
4.5.11.4 LV Network Ratings - Weak, Typical, Strong....122
4.5.12 Electrical Simulation....123
4.5.13 EVSE Disconnectors aka "Clamps"....124
4.5.13.1 Clamping Mode - Hi Limit Clamp....124
4.5.13.2 Clamping Mode - Transformer Limit Clamp....124
4.5.13.3 Public Reaction to Clamping....125
4.5.13.4 No Forecasts....126
4.6 The Simulation Engine....126
4.6.1 The Standard FPB Simulation....126
4.6.2 Simulation Dataflow....127
4.6.3 Running the Schedule....128
4.6.4 Departing and Arriving an EV....130
4.6.5 FPB Per Period Processing....132
4.6.6 Pragmatic Optimisations....133
4.6.6.1 Crowding and Anti-Crowding via Partial Charging....133
4.6.6.2 Phase Balancing....134
4.6.6.3 V2G and Clamps....134
4.6.7 Pragmatic Simplifications....135
4.6.7.1 FPB Ignores Losses....135
4.6.7.2 FPB Ignores VArs....135
4.6.7.3 FPB Electrical Error Quantification....135

4.6.7.4 Impact of Simplification Errors on FPB Results....................................136
4.6.7.5 Other Error Sources....................................136
4.6.8 Concerning Clamp Statistics....................................136
4.7 Software Development Methodology....................................136
4.7.1 Development Quality Assurance....................................138
4.8 FPB Scenarios....................................139
4.8.1 Batch Script Controls....................................139
4.8.2 FPB Input Data and Format....................................139
4.8.3 LV Network Parameters (FPB View)....................................141
4.8.4 Residences and Residential Load Input Data....................................141
4.8.4.1 Residential Data Sourcing and Preparation....................................141
4.8.4.2 Residential Data Preprocessing....................................142
4.8.5 Electric Vehicle Data....................................144
4.8.6 EV Trip Synthesis....................................145
4.9 FPB Outputs - Results Data....................................146
4.9.1 Overview of .CSV Data Format....................................146
4.9.2 Data Output Format....................................147
4.9.3 Results Data .CSV Files....................................147
4.10 Configuring and Running the Simulator....................................148
4.10.1 Configuring - General....................................148
4.10.2 Configuring Simulation Scenario Parameters....................................149
4.10.3 Simulation Duration....................................150
4.10.4 LV Network Data....................................150
4.10.5 Other Data Used....................................151
4.11 Verification of System....................................151
4.11.1 Verification vs Real-World....................................151
4.11.2 Verification vs. Similar Works....................................151

4.11.2.1 Comparison of FPB vs Esprit....152
4.11.2.2 Comparison of Daily Load Curves....153
4.11.2.3 The Effects of BLPs....155
4.11.2.4 A Warning re Averages and Peaks....156
4.12 Other Programming Methods....157
4.13 Pseudocode for Key Algorithms....159
4.14 The Validity of Simulation Results....164
4.15 Chapter Summary....165
Chapter 5: Methodology....167
5.1 Statistical Basis of Methodology....167
5.1.1 Limits to Confidence....168
5.2 Data Sourcing and Preparation....169
5.3 Concerning Networks....169
5.3.1 Network Types: Weak, Typical, Strong....169
5.3.2 Transformers and Distribution Rating....170
5.3.3 Clamps....170
5.4 Residential Loads and Feeder Plots....171
5.4.1 Sample FPB Output Feeder Plot....172
5.4.1.1 Losses Line....172
5.4.1.2 Other Lines: Hi_Limit line and Clamp lines....172
5.4.2 Broaching Assessment....173
5.5 Introduction to Simulation Sequences....173
5.5.1 Overview of Sequence Execution....175
5.6 Sequences Investigated....175
5.6.1 Overview of Sequence Sets....175
5.6.1.1 Sequence Set 1: No Control Mechanisms....176
5.6.1.2 Sequence Set 2: Clamp Only Control....177
5.6.1.3 Sequence Set 3: Clamps with V2G....177
5.6.1.4 Sequence Set 4: Remote Aggregator Control....178

5.6.1.5 Sequence Set 5: Managed Charging System (no clamps)..................178
5.6.1.6 Sequence Set 6: Managed Charging System (with clamps)...............178
5.6.1.7 Set 7: Special Situations..180
5.7 Running a Simulation Sequence...181
5.8 Analysis / Post Processing..182
5.8.1 Post-Processing Workflow..183
5.8.2 Generation of Meta Spreadsheets..186
5.8.3 DR/FFR Assessment (PEH)...191
5.8.4 System Verification..192
5.9 Chapter Summary..192
Chapter 6: Results..195
6.1 Introduction..195
6.1.1 Review of Sequence Structure...196
6.1.2 Accessing Results in the Data Repository..197
6.1.3 Locating Results..197
6.1.4 Use of BLPs and OpenDSS..198
6.1.5 Data Logging..198
6.1.6 Method of Analysis...198
6.2 Sequence Set 0: Residential Load Profiles..199
6.3 Sequence Set 1: Uncontrolled EVs..200
6.3.1 Synthesised Coincidence (ADMD) Plots..200
6.3.2 Sequence Set 1 Broaching Events...202
6.3.3 Sequence Set 1 Winter / Summer Plots (Typical network)........................204
6.3.4 Sequence Set 1 Observations:...208
6.3.5 Limits for Severe Undercharging...209
6.3.6 Traffic Lights Presentation Format...209
6.4 Sequence Set 2: EVs with Peak Load Clamping...210

6.4.1 Legend Meanings....211
6.4.1.1 DRFFR:....211
6.4.1.2 C1 / C2: Clamping Prioritisation:....211
6.4.1.3 Dumb / Default Trips:....212
6.4.1.4 Home / Away / All Perfect Plugins....212
6.4.1.5 Static Batteries:....212
6.4.2 Sequence 2.1.2: DRFFR with C2 Clamps....212
6.4.3 Sequence 2.1.2.8: C2 Clamps Only (Dumb Trips)....213
6.4.4 Sequence 2.1.2.9: C2 Clamps Only (Default Trips)....214
6.4.5 Sequence 2.2.2: DRFFR with C1 Clamps....214
6.4.6 Sequence 2.3.2: Home Perfect Plugins (C2 by default)....214
6.4.7 Sequence 2.3.2.1: Static Batteries (C2 by default)....214
6.4.8 Sequence 2.3.2.2: Static Batteries with C1 Clamps....214
6.4.9 Sequence 2.3.2.9: Home PP sans DRFFR....215
6.4.10 Sequence 2.4.2: Home Perfect Plugins with C1....215
6.4.11 Sequence 2.5.2: All Perfect Plugins (C2 by default)....215
6.4.12 Sequence 2.6.2: All Perfect Plugins with C1 Clamps....215
6.4.13 Sequence Set 2 Summary Observations....215
6.5 Sequence Set 3: Clamps with V2G Support....216
6.5.1 Sequence 3.1.2: V2G with MCS and C2 Clamps....217
6.5.2 Sequence 3.2.2: V2G, MCS and Aggregator Intervention....218
6.5.2.1 Aggregation V2G DSR May Not Escape LV Network....219
6.5.3 Sequence Set 3 Summary Observations:....220
6.6 Sequence Set 4: Remote Aggregator DSR Control....221
6.6.1 Sequence 4.1.2: Aggregator Control Sans Clamps....221
6.6.2 Sequence 4.2.2: Aggregator Control with C2CT Clamps....221
6.6.3 Sequence 4.3.2: Agg Control, C2CT Clamps, 1 in 4 V2G EVs....223

6.6.4 Sequence Set 4 Summary Observations....224
6.7 Sequence Set 5: Local MCS Control (not clamped)....225
6.7.1 Sequence 5.1.1: MCS with V2G on the Weak Network....225
6.7.2 Sequence 5.1.2: MCS with V2G on Typical Network....226
6.7.3 Sequence 5.1.2.1: As 5.1.2 with Lower Residential Loads....226
6.7.4 Sequence 5.1.2.2: As 5.1.2 with Higher Residential Loads....226
6.7.5 Sequence 5.2.2: As 5.1.2 with DRFFR....226
6.7.6 Sequence 5.3.2: As 5.1.2 with FFR and Agg ToU (DSR)....227
6.7.7 Sequence 5.4.2: As 5.2.2 with Static Batteries....227
6.7.8 Sequence 5.5.2: As 5.4.2 with Winter PV....228
6.7.9 Sequence 5.6.2: As 5.1.2 less V2G....228
6.7.10 Sequence 5.7.2: As 5.1.2 with 1 in 4 EVs Agg ToU Control....228
6.7.11 Sequence 5.1.3: MCS with V2G on the Strong Network....228
6.7.12 Sequence Set 5 Summary Observations....228
6.8 Sequence Set 6: Local MCS Control with Clamps....229
6.8.1.1 Set 6 Summary Observations....230
6.8.2 Simulations in Sequence Set 6....230
6.8.3 Seq_6.1.2: MCS Control With Clamps....232
6.8.4 Seq_6.2.2: MCS Control, Clamps, DRFFR....233
6.8.5 Seq_6.2.2.1: MCS Control, Clamps, DRFFR, No PreBurn....233
6.8.6 Seq_6.2.2.2: Dumb EVs, MCS, Clamps, DRFFR, Static Bats....233
6.8.7 Seq_6.2.2.3: MCS, Clamps, DRFFR, V2G Saver....233
6.8.8 Seq_6.2.2.4: MCS, Clamps, DRFFR, Alt_Winter....234
6.8.9 Seq_6.2.2.5: MCS, Clamps, DRFFR, Winter Pre Heating....234
6.8.10 Seq_6.2.2.9: 6.2.2.5 with 10% Uplift in EV Numbers....234
6.8.11 Seq_6.3.2: MCS, Clamps, DRFFR, Agg ToU DR....235

6.8.12 Seq_6.3.2.1: Summer MCS, Clamps, DRFFR....235
6.8.13 Seq_6.3.2.2: MCS, Clamps, No V2G, DRFFR in Summer....236
6.8.14 Seq_6.3.2.3: Summer MCS, Clamps, FFR....236
6.8.15 Seq_6.3.2.4: Summer MCS, Clamps, FFR, Agg ToU....236
6.8.16 Seq_6.4.2: MCS, Clamps, DRFFR, 1 in 4 Agg DR....237
6.8.17 Seq_6.5.2: Withdrawn....237
6.8.18 Seq_6.6.2: Withdrawn....237
6.8.19 Seq_6.7.2: MCS, Clamps, DR-B without FFR....237
6.8.20 Seq_6.8.2: MCS, Clamps, 40 kW Hi_limit....237
6.8.21 Seq_6.9.2: Withdrawn....237
6.8.22 Seq_6.9.2.1: DR-CFFR, 40 kW hi, PreBurn V2G Off....237
6.8.23 Seq_6.9.2.2: DR-CFFR, 40 kW hi, PreBurn V2G On....238
6.8.24 Seq_6.10.2: As 6.9.2.2 with V2G Removed....238
6.8.25 Seq_6.11.2: MCS, DR-CFFR, 9 SB, 24 kW Hi_limit....238
6.8.26 Seq_6.12.2: MCS, Clamps, DR-CFFR, 9 SB, 32 kW hi_limit....238
6.8.27 Seq_6.13.2: Winter PV, DR-CFFR, 9 SB, 39 kW hi_limit....238
6.8.28 Seq_6.1.3: MCS Control, Clamps, DRFFR....239
6.8.29 Seq_6.1.3.1: MCS Control, Clamps, DRFFR, 20HP....239
6.8.30 Sequence Set 6 Summary Observations....240
6.8.30.1 Winter Observations....240
6.8.30.2 Summer Observations....241
6.9 Undercharge to Severe Undercharge Correlation....241
6.10 Sequence Set 7: Special Situations....243
6.11 Findings in Précis....246
6.11.1 General....246
6.11.2 Set 1 Findings....248

6.11.3 Set 2 Findings....249
6.11.4 Set 3 Findings....250
6.11.5 Set 4 Findings....251
6.11.6 Set 5 Findings....252
6.11.7 Set 6 Findings....253
6.11.8 Set 7 Findings....255
6.12 Chapter Summary....255
Chapter 7: Discussion and Conclusion....257
7.1 Research Direction....257
7.2 Key Findings....259
7.3 Interpretation of Sequences (Learning Points)....261
7.3.1 Learning: Sequence Set 1....261
7.3.2 Learning: Sequence Set 2....263
7.3.3 Learning: Sequence Set 3....264
7.3.4 Learning: Sequence Set 4....265
7.3.5 Learning: Sequence Set 5....265
7.3.6 Learning: Sequence Set 6....266
7.3.7 Learning: Sequence Set 7....267
7.3.8 Collated Learning Points....268
7.4 Discussion of Findings....270
7.4.1 Sources and Degree of Functional Errors....270
7.4.2 Sources of Contextual Errors....270
7.4.3 Other Error Sources....271
7.4.3.1 Concerning Data Errors....271
7.4.3.2 Concerning Simulation Errors....271
7.4.4 Discussion: Whole Network View....272

7.4.5 Discussion: DNO / Local Network Concerns....273
7.4.5.1 Without a Managed Charging System....273
7.4.5.2 With a Managed Charging System....274
7.4.6 Discussion: The EV View....277
7.4.7 Discussion: Destination (AFH) Charging Seasonality....278
7.4.8 Discussion: Value Added Services....280
7.4.9 Discussion: Other Aspects....282
7.5 Conclusion....282
7.5.1 Intent and Approach....283
7.5.2 Major Findings....283
7.5.3 Limitations of Approach....285
7.5.4 Contributions....286
7.5.5 Significance....287
7.5.5.1 Potential for Influencing Policy Direction....287
7.5.5.2 Potential for Cost Savings....287
7.6 Summary....288
Chapter 8: Recommendations and Further Work....289
8.1 Recommendations for DNOs....289
8.1.1 General Concerns....289
8.1.2 Awareness of EV Characteristics and Use....291
8.1.3 Suggested Actions....291
8.1.4 Accelerated Asset Ageing....294
8.1.5 Unclear Ofgem Stance re Clamping / Undercharging....294
8.1.6 Using an MCS to Defer Reinforcement....295
8.1.6.1 Other MCS Benefits for DNOs....295
8.2 Recommendations for Regulators....295
8.3 Recommendations for EV Manufacturers....296

8.4 Recommendations for EVSE Manufacturers..296
8.5 Recommendations for EV Owners..296
8.6 Further Work (FPB Development)...297
8.6.1 Quality Assurance..297
8.6.2 FPB Functionality Enhancements...298
8.6.3 Further Use as a Simulator...300
8.6.4 Construction of a LV System Assessor..301
8.6.5 Reuse of FPB Generated Data..301
8.6.6 Possibility of Multiplexing / Multi-Charging...302
8.6.7 Possibility of µMCS - a Simple MCS...302
8.6.8 Other Applications..304
8.7 Beyond Mid-Century...305
Chapter 9: List of References..307
Appendix A: FPB Design Assumptions..319
A.1 Concerning EVs..319
A.2 Concerning Drivers, Homes and Utilisation..320
A.3 Concerning Power and Data Networks...321
A.4 General Settings...321
Appendix B: The UK Power Industry...323
B.1 General Organisation...323
B.2 Ofgem and Market Regulation..325
B.3 The Energy Networks Association (ENA)..325
B.4 National Grid Electricity System Operator...325
B.5 DNO Regions and Licenses...325
B.6 Network Balancing Services...325
B.6.1 Demand Reduction / Demand Response (DR, DSR)..................................326
B.6.2 Frequency Balancing / Frequency Response (FR, FFR)..............................326
B.7 Aggregators...327

B.8 Losses, Voltages and Current....327
Appendix C: Output .csv File Samples....329
C.1 Feeder_load_output.csv....329
C.2 EV_output.csv....332
Appendix D: Post Processing and Plots....335
D.1 Sequence Workflow - From Simulation to Analysis....335
D.2 Sample Timeline Detail Plots....336
D.2.1 Feeder kW Loading (per pd for a week)....336
D.2.2 EV Arrive / Depart Plot (per pd for a week)....336
D.2.3 EV CICD Plot (per pd for a week)....337
D.2.4 Sample EV Rolling Fleet Energy / Distance Plot (per pd)....339
D.3 Samples of Meta_mpd Charts....339
D.4 Samples of End of Week Histograms....345
D.5 Sample of Data Distribution Inspection....349
Appendix E: Analysis Samples....351
E.1 Sequence 2.1.2....351
E.1.1 Seq_2.1.2 in Précis....352
E.1.2 Seq_2.1.2: Feeder and EV Plots....353
E.1.2.1 Seq_2.1.2: 27mpd 40EVs....353
E.1.2.2 Seq_2.1.2: 27mpd 100EVs....354
E.1.2.3 Seq_2.1.2: 49mpd 140EVs....355
E.1.3 Data Tables Seq_2.1.2....356
E.1.3 Seq_2.1.2 Summary....361
E.3 Sequence 2.1.2.9....363
E.3.1 Seq_2.1.2.9 in Précis....363
E.3.2 Seq_2.1.2.9: Feeder and EV Plots....364
E.3.2.1 Seq_2.1.2.9: 27mpd 40EVs....364
E.3.2.2 Seq_2.1.2.9: 27mpd 100EVs....365

E.3.2.3 Seq_2.1.2.9: 49mpd 140EVs....366
E.3.3 Data Tables Seq_2.1.2.9....367
E.3.3 Seq_2.1.2.9 Summary....369
E.4 Sequence 6.9.2 (Later Withdrawn)....370
E.4.2 Seq_6.9.2: Outcomes....371
E.4.3 Seq_6.9.2 Feeder and EV Plots....372
E.4.3.1 Seq_6.9.2: 27mpd 40EVs....372
E.4.3.2 Seq_6.9.2: 27mpd 100EVs....373
E.4.3.3 Seq_6.9.2: 49mpd 140EVs....374
E.4.4 Data Tables Seq_6.9.2....375
9.1 Seq_6.9.2 Results Summary....380

Table of Figures

Figure 1-1: Thesis Structure Map....1
Figure 1-2: Simulated 3-phase residential load dataset for 100 houses (No EVs)....5
Figure 1-3: Simulated 3-phase load for 100 houses plus 100 EVs driving 27mpd....5
Figure 1-4: A 3-phase residential load dataset for 100 houses (no EVs) (Large)....10
Figure 1-5: Simulated 3-ph. load for 100 houses, 100 EVs driving 27mpd (Large)....10
Figure 2-1: Simplified structure of UK Power Supply....11
Figure 2-2: Mid-20th Century / CEGB era UK Power industry....12
Figure 2-3: Post-privatisation UK Power industry structure....13
Figure 2-4: Averaged UK Winter Domestic Load....15
Figure 2-5: UK / EU 230 V distributed from substation to many houses via feeder....15
Figure 2-6: Traditional Passive Substation and Feeder....16
Figure 2-7-Transformer and 3-phase busbars in pillar (manuf. 1960, photo 2015)....17
Figure 2-8: Feeder cable (Phases 1, 2, 3, N with Earth outer) and a house take-off....17
Figure 2-9: National View of Demand over 2 Days (DECC, 2014)....18
Figure 2-10: View of Household Energy Use over 2 Days....19
Figure 2-11: Load kW of 100 houses over 2 days, as seen by the LV *substation*....19

Figure 2-12: Simulated ADMD coincidence curve for a 3.6 kW load............................20
Figure 2-13: (Scottish Power, 2015): A transformer accumulating ageing over 24hrs....21
Figure 2-14: The Major UK EV Trials 2010-2019...23
Figure 2-15-UKPN's B2 Fig.9: LCT Load projection...25
Figure 2-16: UKPN’s B2 Fig. 12: EV Load by Day of Week..25
Figure 2-17: Wardle et al., 2015: Weekday Average Demand.......................................27
Figure 2-18: Wardle et al., 2015, Fig. 41: Households With and Without EVs................28
Figure 2-19: *EA Tech, 2016* Fig. 14: Revised domestic ADMD with EV...........................30
Figure 2-20: EA Tech, 2016 Fig. 16: Esprit impact for N EV per 100 homes...................31
Figure 2-21: Quirós-Tortós, 2015: Weekday vs. Weekend MEA loads...........................33
Figure 2-22: EA Tech, 2016: 3.5 kW and projected 7 kW EV load probability................33
Figure 2-23: RAC, 2009: Car driving distances by income and location.........................34
Figure 2-24: WPD, 2018c: EV Owners and Charging Activities......................................36
Figure 2-25: WPD, 2018c: Number of Home Charging Events in Hour..........................37
Figure 2-26: WPD, 2018c: % of EVs Controlled (32A = 7.4 kW).....................................37
Figure 2-27: UKPN & Halsey, 2018: ADMD plots for 7kW and 3kW EV charging............38
Figure 2-28: WPD, 2018d: EVs on Urban Networks: Thermal and Harmonic Limits.......40
Figure 2-29: WPD, 2018d: EVs on Rural Networks: Thermal and Harmonic Limits.........40
Figure 2-30: US Household load profile...44
Figure 2-31: Generalised US LV system with transformers set by houses......................45
Figure 2-32: Market saturation causes revenue collapse (NGET-Ricardo, 2011)............62
Figure 2-33: (P. Papadopoulos et al, 2009) Fig. 5 LV Segment Volts Fall........................63
Figure 2-34: (Strbac, 2010, Fig 5-14)...64
Figure 2-35: (Strbac, 2010, Fig 5-16) A conflict: Network or Market Priorities?.............66
Figure 2-36: (Huang & Infield, 2011, Fig.1) Probability of car leaving home..................67
Figure 2-37: Acha’s How control options affect local load...68
Figure 2-38: (Boait, Ardestani, & Snape, 2013, Fig. 1) DSR Control Mechanism............69
Figure 2-39: (Boait, Ardestani, & Snape, 2013) Figs. 4 and 6: Load flattening................69
Figure 2-40: (EA Technology, 2012) Fig. 0.1 UK Distribution costs: BAU vs. Smart.........70
Figure 2-41: (EA Technology, 2012) Fig. 3.6 Load sources, Scenario 1...........................71
Figure 2-42: Neaimeh’s Fig. 2. EV charging preferences, Urban vs. Rural......................72

Figure 2-43: Neaimeh's Fig. 8, Table 2: Urban vs. Rural penetration results..................73
Figure 2-44: Haye's Fig. 3: Day-ahead forecast vs. recorded residential demand...........73
Figure 2-45: (Wang, Huang, & Infield, 2014) Fig. 12. Main feeder load.........................75
Figure 2-46: (Wang, Huang, & Infield, 2014) Fig. 7: V2G and Battery SOC.....................76
Figure 3-1: (ONS, 2012) from Table KS404E..84
Figure 4-1: Simplified overview of FPB concept..96
Figure 4-2: Impact of Varying Timing of Battery Use (Discharge, Charge, Rest).............98
Figure 4-3: Simulator Overview: The Three Main Blocks..100
Figure 4-4: Simulation stack executing one simulation thread....................................102
Figure 4-5: Simulation stack executing multiple simultaneous FPB threads................103
Figure 4-6: Samples of intermediate / auto-generated Feeder and EV CICD plots.......104
Figure 4-7: The EV losses model, calculated using values defined per EV_type...........106
Figure 4-8: (FleetCarma, 2018) Li-ion Average Range vs Temperature Curve..............107
Figure 4-9: Headroom, Mandatory and Opportunistic Chargers.................................109
Figure 4-10: When headroom is inadequate, EV charging is curtailed (clamped)........110
Figure 4-11: V2G shown lifting feeder headroom (but clamps still needed)...............110
Figure 4-12: A "tranche" of time, covering EV Arrival and Depart from home............111
Figure 4-13: Basic charging: SOC accumulates with time..112
Figure 4-14: Examples of Tranches and its Regions...113
Figure 4-15: A tranche sample...113
Figure 4-16: SOC accumulation within the example...114
Figure 4-17: Falling EV_Timeline of EVs charging, from proof-of-concept tests...........115
Figure 4-18: Plot of an EV charging, recovered from early proof-of-concept tests.......116
Figure 4-19: Socket load and SOC for a V2G EV over a week.......................................116
Figure 4-20: Feeder views for FPB and OpenDSS...121
Figure 4-21: Feeder plot showing clamping lines at axis...125
Figure 4-22: FPB simulator general schema..127
Figure 4-23: FPB simplified internal operation..128
Figure 4-24: FPB simplified schedule operation...129
Figure 4-25: FPB simplified "Per Period Process"...132
Figure 4-26: FPB vs OpenDSS Error Plot with trendline...135

Figure 4-27: FPB proof of concept test: EV activity loads without Residential load.....138
Figure 4-28: Example of input data: Defining EVs in Excel...140
Figure 4-29: Example of input data: Residential Wh energy use in period..................140
Figure 4-30: Residential source data - before jittering..142
Figure 4-31: Residential source data - after jittering...142
Figure 4-32: *EA Tech, 2016,* Fig. 16: Esprit impact of N EV, per 100 homes.................152
Figure 4-33: FPB representation of impact of N EV per 100 homes (Winter only).......152
Figure 4-34: *EA Tech, 2016,* Fig. 14: Revised domestic ADMD with EV........................153
Figure 4-35: FPB output (Seq_1.1.2, no control) Monday household load profile.......153
Figure 4-36: Weekday MEA EV Connection Probability...155
Figure 4-37: Effect of BLPs on per period household load: With BLPs.........................156
Figure 4-38: Effect of BLPs on per period household load: Without BLPs....................156
Figure 4-39: A curve represented as a histogram...158
Figure 5-1: A residential load dataset for 100 houses as a feeder load plot................171
Figure 5-2: Feeder load plot: EVs exceed limits, transformer distress signal...............172
Figure 5-3: Examples of hi_limit clamp with hi_limit modulation...............................173
Figure 5-4: Configuring the FPB to run a Sequence...174
Figure 5-5: A Sequence of 16,000 simulated weeks, each varying the scenario..........174
Figure 5-6: Example of auto-generated Feeder and EV CICD plots..............................183
Figure 5-7: Post-processing workflow..184
Figure 5-8: Post-processing workflow showing generation of image plots..................185
Figure 5-9: Sheets in a Meta_mpd .xls, showing Summary and N EV tabs..................186
Figure 5-10: Meta sheet for Seq_1.1.2: Meta_27mpd EV stats (part 1 of 2)................187
Figure 5-11: Meta sheet for Seq_1.1.2: Meta_27mpd EV stats (part 2 of 2)................188
Figure 5-12: MetaMeta2.3_Seq_1.1.2 CompareMetas...189
Figure 5-13: FPB Performed Simulation Statistics..193
Figure 6-1: Sequences Overview and Relation to Meta Charts...................................196
Figure 6-2: Overview of results folders (on 16GB USB stick).......................................197
Figure 6-3: The “Standard Winter Week” Residential Loads (2013 coldest week).......199
Figure 6-4: The “Alternative Winter Week” Residential Loads....................................199
Figure 6-5: The “Summer Week” Residential Loads (2013 hottest week)...................199

Figure 6-6: Single (most loaded) Phase Synthesised Coincidence plot........................201
Figure 6-7: Transformer Synthesised Coincidence plot...201
Figure 6-8: Winter (Seq_1.1.2), Summer (Seq_1.1.2.2) Feeder plots, 27mpd 100EVs. 205
Figure 6-9: Winter (Seq_1.1.2), Summer (Seq_1.1.2.2) CICD plots, 27mpd 100EVs.....205
Figure 6-10: Pearson's r plotted for Seq_6.9.2.2, 27 mpd 100 EVs (PEH = 80.4%)........211
Figure 6-11: Seq_2.1.2 49mpd 140EVs group 8 Feeder (a) and EV CICD (b) plots........213
Figure 6-12: Seq_3.2.2 Aggregator forced V2G and V2G kWh dispatch......................219
Figure 6-13: Seq_3.2.2 forced V2G impacts network load only if not saturated..........220
Figure 6-14: Seq_4.3.2 ToU / DR: Afternoon charging prohibited, evening restricted. 223
Figure 6-15: Seq_4.3.2 Agg ToU / DR: EVs are not charged ⇒ Demand Backlog..........224
Figure 6-16: Seq_5.1.1 Unclamped EVs ignore MCS and tear-through the hi_limit.....225
Figure 6-17: Seq_5.3.2 EVs tear-through once Aggregator control lifted @ 11pm.......227
Figure 6-18: Seq_6.3.2.1 Feeder load and EV CICD plots for 49mpd 140 EVs..............236
Figure 6-19: Seq_6.1.3.1 Feeder load, EV CICD plots for 49mpd 140 EVs and 20 HP…240
Figure 6-20: Relationship between Undercharging and Severe Undercharging...........242
Figure 6-21: Comms fail (a) and Power Fail (b) scenarios...243
Figure 6-22: Power Fail + late comms recovery scenarios...244
Figure 7-1: Chapter Directory: Discussion and Conclusion chapter............................257
Figure 7-2: FPB Best-Case Winter per Home LV Network Capability Heatmaps...........260
Figure 8-1: Chapter Directory: Recommendations chapter...289
Figure 8-2: Use monitoring to log a running total of (i^2) of spikes over a limit..........293
Figure 8-3: Mark/space ratio: Mark fills space as N EV rises 40 (a) ⇒ 100 (b).............293
Figure 8-4: µMCS concept of operation: Only ranks >= 8.6 can charge.......................303
Figure B-1: Organisation of UK power industry under CEGB, 1957 - 1989...................323
Figure B-2: Organisation of UK power industry from 1990..324
Figure C-1: Sample of Feeder_load_output.csv seen in spreadsheet..........................329
Figure C-2: Sample of EV_output.csv seen in spreadsheet..332
Figure D-1: Post Processing Workflow (large)..335
Figure D-2: Uncontrolled network with 140 EVs...336
Figure D-3: A simulated MCS controlled network in load saturation with clamps.......336
Figure D-4: EV Arrivals / Departures plot...337

Figure D-5: Colourised EV CICD plot showing number of EVs in a State.......................337
Figure D-6: Timeline plots for a “Power-Fail”..338
Figure D-7: A typical Rolling Fleet plot showing sources of EV charge.........................339
Figure D-8: A Rolling Fleet for “starving” EVs..339
Figure D-9: Recap of Ply Cells in a Sequence..340
Figure D-10: MetaChart plot of Feeder loadings with Rising N EV...............................341
Figure D-11: MetaChart plot of Feeder conditions with Rising N EV...........................341
Figure D-12: MetaChart plot of Clamping Events with Rising N EV.............................342
Figure D-13: MetaChart plot of Fusing / Broaches Events with Rising N EV................342
Figure D-14: MetaChart plot of Undercharging Events with Rising N EV.....................343
Figure D-15: MetaChart plot of EV Power Sourcing..343
Figure D-16: MetaChart: Cumulative plot of Fleet AFH Charging................................344
Figure D-17: EoW Histogram: EV Home kWh Charged in Week..................................345
Figure D-18: EoW Histogram: EV Home kWh Dispatched (V2G) in Week....................346
Figure D-19: EoW Histogram: EV AFH kWh Charged in Week.....................................346
Figure D-20: EoW Histogram: EV Driven Miles per Day in Week................................347
Figure D-21: EoW Histogram: EV Home Plugins in Week..347
Figure D-22: EoW Histogram: EV SOC Held at end of Week..348
Figure D-23: Distribution diagram for fleet AFH charging on Saturday........................349
Figure E-1: Seq_2.1.2 27mpd 40 EVs group 8 plots. Weekly fleet km: 12,212.............353
Figure E-2: Seq_2.1.2 27mpd 100 EVs group 8 plots. Weekly fleet km: 30,876...........354
Figure E-3: Seq_2.1.2 49mpd 140EVs group 8 plots. Weekly fleet km: 77,327............355
Figure E-4: DRFFR defers Evening Charging to Overnight..362
Figure E-5: Seq_2.1.2.9 27mpd 40 EVs group 8 plots. Weekly fleet km: 12,212..........364
Figure E-6: Seq_2.1.2.9 27mpd 100 EVs group 8 plots. Weekly fleet km: 30,876.........365
Figure E-7: Seq_2.1.2.9 49mpd 140 EVs group 8 plots. Weekly fleet km: 77,276.........366
Figure E-8: Prior DR-B / FFR Signal (top), DR-C, Combined DR-C and FFR....................371
Figure E-9: Seq_6.9.2 27mpd 40EVs group 8 plots. Weekly km: 12,212......................372
Figure E-10: Seq_6.9.2 27mpd 100EVs group 8 plots. Weekly km: 30,876..................373
Figure E-11: Seq_6.9.2 49mpd 140EVs group 8 plots. Fleet drives 77,327 km............374

Index of Tables

Table 1-1: Network Built kW per House Heatmaps (Supported EVs per 100 Houses)......7

Table 2-1: LCL Key Documents..24

Table 2-2: Simplified *Esprit* Algorithm at Substation..29

Table 2-3: (WPD, 2018d, p23): EV test results vs. Harmonic Limits...............................39

Table 2-4: Realised Utility of Smart Meters in the UK (2018)..51

Table 2-5: V2G Study results: row “MORE” shows low values.......................................52

Table 2-6: Kempton’s Table 8. Cost to vehicle owner and value to utility.......................58

Table 2-7: (Shirazi & Sachs, 2018) V2G studies do not state V2G losses correctly..........59

Table 2-8: (Strbac, 2010, Table 1-1)...64

Table 2-9: (Strbac, 2010, Tables 6-1, 6-2) Cost of Transformers vs. Feeders..................65

Table 2-10: (Poursharif, Brint, Black, & Marshall, 2017, Table 1)...................................70

Table 3-1: Types of Simulation Engines used in 73 papers to c. mid 2016.....................83

Table 3-2: Mahmud and Town's Table 4 classifying simulation tools.............................87

Table 4-1: Seq_6.1.2 Averaged weekly V2G kWh injection...105

Table 4-2: Possible tranches for an EV arriving at 8pm, departing at 8am..................114

Table 4-3: A possible set of V2G tranches, for an EV arriving home at 8pm................117

Table 4-4: General MCS Method..118

Table 4-5: Example UKPN ADMD LV design values..119

Table 4-6: Pseudocode: EV Departs from Home...130

Table 4-7: Pseudocode: EV Arrives Home...131

Table 4-8: Pass 1: External synthesis tool generates libraries of trip Departures.........145

Table 4-9: Pass 2: FPB constructs trip Arrivals..146

Table 4-10: *Output* .csv file header (field / column headers not shown).....................147

Table 4-11: Imposed phase stress energy coefficients..157

Table 4-12: Adjust battery C rating due to temperature..159

Table 4-13: Per PD Step 1: Assess headroom remaining after residential loads...........159

Table 4-14: Per PD Step 2: Assess all EV needs (presently connected EVs only)...........160

Table 4-15: Per PD Step 3: Allocate charging and Trial Balance the Feeder.................160

Table 4-16: Per PD Step 4: Advise EV models what they are doing..............................161
Table 4-17: Per PD Step 5: Logs and Running Totals...162
Table 4-18: OpenDSS..162
Table 4-19: Auto-Scheduled events..163
Table 4-20: Other Scheduled events...163
Table 4-21: Tranche Modes..164
Table 5-1: Sequence Set 1: No Control Mechanisms...176
Table 5-2: Sequence Set 2: Clamp Only Control..177
Table 5-3: Sequence Set 3: Clamps with V2G..177
Table 5-4: Sequence Set 4: Remote Aggregator Control..178
Table 5-5: Sequence Set 5: Managed Charging System (no clamps)............................178
Table 5-6: Sequence Set 6: Managed Charging System (with clamps)..........................178
Table 5-7: Set 7: Special Situations..180
Table 5-8: Sample of parameters gathered per Sequence Ply Cell...............................189
Table 5-9: Meta-Meta Chart: Parameters Gathered per Sequence Ply Cell..................190
Table 6-1: Sequence Set Analysis: Results and Findings hotlinks................................195
Table 6-2: Sequence Code Numbering...197
Table 6-3: Winter Broaches in 500 simulations: Seq_1.1.1 Weak network (1.2 kW)....202
Table 6-4: Winter Broaches in 500 sim'ns: Seq_1.1.2 Typical network (1.5 kW)..........203
Table 6-5: Summer Broaches in 500 sim'ns: Seq_1.1.2.2 Typical network (1.5 kW).....203
Table 6-6: Winter Broaches in 500 simulations: Seq_1.1.3 Strong network (2 kW).....203
Table 6-7: Comparative AFH Charging: Winter (Seq_1.1.2) vs. Summer (Seq_1.1.2.2) 204
Table 6-8: AFH Charging Visits: Winter (Seq_1.1.2) vs. Summer (Seq_1.1.2.2)............206
Table 6-9: Sequence Set 1 Traffic Lights results..209
Table 6-10: Sequence Set 2 Supportable EVs as Traffic Lights.....................................210
Table 6-11: Sequence Set 3 Supportable EVs as Traffic Lights (cf 2.1.2.9)....................217
Table 6-12: Sequence Set 4 Supportable EVs as Traffic Lights.....................................221
Table 6-13: Severe Undercharging per EV (weekly averages) *for 4.2.2 vs. 2.1.2.9*........222
Table 6-14: Severe Undercharging per EV (weekly averages) *for 4.3.2*........................223
Table 6-15: Sequence Set 5 (Weak Network) Supportable EVs as Traffic Lights...........225
Table 6-16: Sequence Set 5 (Typical Network) Supportable EVs as Traffic Lights.........226

Table 6-17: Sequence Set 5 (Strong Network) Supportable EVs as Traffic Lights..........228
Table 6-18: Degrees of Freedom in Sequence Set 6..231
Table 6-19: Sequence Set 6-A (Typical Network) Supportable EVs as Traffic Lights......232
Table 6-20: Sequence 6.2.2 PEH metrics...233
Table 6-21: Ratio 6.2.2.5 vs. Summer 1.1.2.2 *EV AFH N events (weekly averages)*......234
Table 6-22: Sequence Set 6-B (Typical Network) Supportable EVs as Traffic Lights......235
Table 6-23: Sequence Set 6-C (Typical Network) Traffic Lights results.........................238
Table 6-24: Sequence Set 6 (Strong Network) Supportable EVs as Traffic Lights..........239
Table 6-25: General Findings - LV Networks...246
Table 6-26: General Findings - EVs...247
Table 6-27: Findings - Set 1 (Uncontrolled)..248
Table 6-28: Findings - Set 2 (Clamps only)...249
Table 6-29: Findings - Set 3 (Clamps with V2G)...250
Table 6-30: Findings - Set 4 (Aggregator managed)..251
Table 6-31: Findings - Set 5 (MCS without clamps)...252
Table 6-32: Findings - Set 6 (MCS with clamps)..253
Table 6-33: Findings - Set 6 ctd. (MCS with clamps)...254
Table 6-34: Findings - Set 6 ctd. (MCS with clamps)...255
Table 6-35: Observations - Set 7 (part, Special Situations)...255
Table 7-1: Sequence 1.1.2 Broaches on Typical (1.5 kW ADMD) Network...................262
Table C-1: Example of Feeder Load Output .csv file...330
Table C-2: Example of EV Output .csv file..333
Table E-1: Demand Reduction regime for DR-B with plot of DR-B plus FFR.................351
Table E-2: 2.1.2 Overall Usable EV Bands..352
Table E-3: 2.1.2 Unused kWh (weekly averages)..356
Table E-4: 2.1.2 Difference: Per EV AFH N events (weekly average of away connects).356
Table E-5: 2.1.2 Counts of Undercharging events per EV (weekly averages)................357
Table E-6: 2.1.2 Dumb vs Dumb+Clamped per EV AFH kWh (weekly averages)...........358
Table E-7: 2.1.2 Counts of Severely Undercharged EVs in Week, per EV.....................359
Table E-8: 2.1.2 MCS Clamps (weekly averages)..359
Table E-9: 2.1.2 DRFFR Percent Effective Hours (weekly averages).............................360

Table E-10: 2.1.2 Difference in LV Losses kWh (weekly averages)................................361
Table E-11: 2.1.2.9 Overall Usable EV Bands...363
Table E-12: 2.1.2.9 Unused kWh (weekly averages)..367
Table E-13: 2.1.2.9 EV AFH kWh Uptake (weekly averages)...367
Table E-14: 2.1.2.9 Per EV N AFH (count of away connects, weekly averages).............368
Table E-15: 2.1.2.9 Counts of Undercharging events per EV (weekly averages)...........368
Table E-16: 2.1.2.9 Counts of Severely Undercharged EVs in Week, per EV.................369
Table E-17: 6.2.2.2 MCS Clamps (weekly averages)...369
Table E-18: 6.9.2 Unused kWh (weekly averages)..375
Table E-19: 6.9.2 Per EV AFH kWh Uptake (weekly averages)......................................375
Table E-20: 6.9.2 Per EV AFH N events (count of away connects, weekly averages)....376
Table E-21: 6.9.2 Counts of Undercharging events per EV (weekly averages).............376
Table E-22: 6.9.2 Counts of Severely Undercharged EVs in Week, per EV....................377
Table E-23: 6.9.2 MCS Clamps (weekly averages)...377
Table E-24: 6.9.2 V2G kWh dispatch per EV (weekly averages)...................................378
Table E-25: 6.9.2 Average LV Losses Comparison...379
Table E-26: 6.9.2 DRFFR Percent Effective Hours (weekly averages)............................380

this page deliberately left blank

DECLARATION OF AUTHORSHIP

I,...[please print name]

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

EngD Doctoral Thesis: "Modelling and Managing The Charging of Massed Electric Vehicles on Constrained Residential Power Networks"

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. None of this work has been published before submission.

Signed: ....

Dated : ....

Acknowledgements

My EngD has been assisted by the SSEPD team of Nigel Bessant, Stewart Reid and David MacLeaman, with Kerry Berrisford and Dr. Rob Weller of BUUK, Dr. James Cross and Dan Hollingworth of EATL. Thanks to supervisors Dr. Andy Chipperfield, Dr. Ben Waterson, Dr. Sebastian Stein, Prof. Suleiman Sharkh and Prof. Andy Cruden who recruited me to the role. Lastly great thanks to the Claro / CSW team especially Jan Harrison, who kept me almost sane. This was a lot of work.

Dedications

To members of my family claimed by old age, each passing alone within weeks:

Uncle Bill	Jock Small - *husband to Olive*	9th December 2015
my Mother	Joyce Ruby Broderick - *sister to Olive*	16th December 2015
Aunt Olive	Olive Small	12th January 2016

The Way Back Home *from Kevin Gilbert's "The Shaming of the True" track 13*

http://youtu.be/jIPvc0jOhRI

I was lost in the city when I chanced on a man who said he was Jesus.
As he held out his hand I tossed him a quarter, said:
" I'm your biggest fan … d' you know the way back home? "

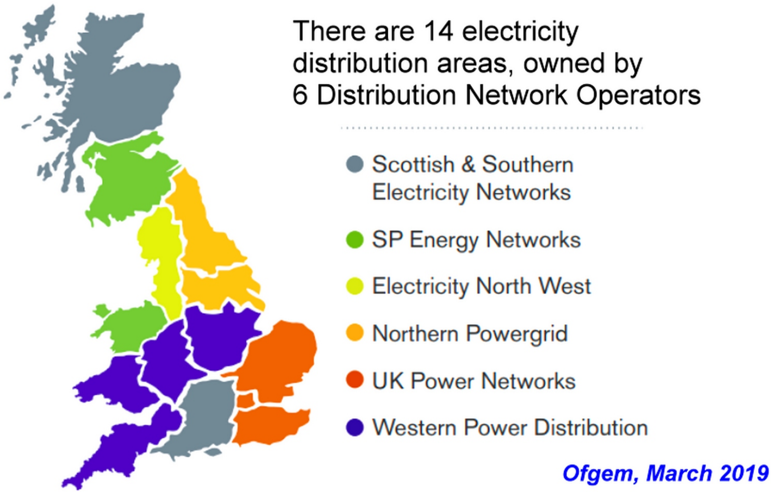
And the planet sits waitin' for this man to appear
who will solve all our problems and make everything clear
'cause we are all prisoners of apathy and fear.
We've lost the way back home.
...
I'm walking on pavement where old illusions fall
I'm struck by a sadness,
lonely here inside these walls.
...
And the man who was Jesus lit his last cigarette
and he spoke in a whisper, with a voice of regret,
" You've all heard the answer, but you're not listening yet.
Love is the way back home. "

Glossary of Terms, Abbreviations and Jargon

These are combined to remove need to search multiple tables. Key terms are **bold**.

Term	Meaning
AC	(1) Alternating Current; (2) Air Conditioning
ACE 49 / A.C.E. 49	A report on a statistical means to assess 90% probability of total residential loads, determined by field trials on housing LV networks in the UK, c. 1979. Used to estimate necessary asset build for LV.
ADMD	After Diversity Maximum Demand. A measure of load by coincidence of all connected loads. Presently in UK < 1 kW per house. Used to anticipate asset loadings. An alternative to ACE 49
ADR	Automatic Demand Reduction. Signal a large co-operating user (of power) to disconnect load e.g. during peak periods
AFH	Away from Home i.e. at destination charging
Agg, Aggregator	A party commanding a number of small network-connected generators as a body, so to mimic a power station. Aggregators sell aggregated Balancing Services to NGESO. See also VPP
ampacity	Term for maximum normal cable rating e.g. 365 Amps
Aux (iliary) Heating	A second heat source to boost radiator, room or water temperatures especially in cold periods. Used with Heat Pumps. See Flow Boiler.
AEVA 2018	Automated and Electric Vehicles Act 2018 (from UK Parliament)
BAU	Business as Usual
BEV	(pure) Battery Electric Vehicle i.e. not a Hybrid. EVs are BEVs.
black start	restarting the UK power system after complete shutdown. This can pose difficulties as instant load can be much higher than average.
BLP	(FPB jargon) Battery Life Policy: a way to extend EV battery life e.g. by interspersed cooling periods during charging (and other methods)
broach	(FPB jargon) fusing or excess load causing substation shutdown. Limits: phase load > 1.4 x cable rating **or** total load > 1.5 x transformer rating for >= 18 minutes. The number of acceptable broaches is zero
C	(1) EV battery Capacity, i.e. a 30 kWh battery, (2) Rate of charging of a battery as “full charges per hour”. Charging a 15 kWh battery at 2C implies it will receive 15 kWh in 1/2 hour
cable	an insulated set of conductors usually 3 phases, Neutral and Earth
clamp	(FPB jargon) a switch cutting power to an EV, located in the EVSE. Required by AEVA 2018. Has two duties: (a) limit overloads (hi_limit clamp), (b) limit transformer overheating (transformer clamp)
CEGB	Central Electricity Generation Board (extent c. 1957 to 1990); a UK nationalised body building and managing power systems

CICD plot	(FPB jargon) time plot of EV activity, showing EVs **C**harging (green fill), **I**dle (cream or grey), **C**lamped (red), **D**ispatching / V2G (blue). Grey = finished, clear = not plugged-in, black = count of EVs at home. Green line, SOC of 1st quartile best charged EV. Can be vertically aligned with feeder or Arrive/Depart plots for same period to show activity
CML	Customer Minutes Lost. A way to track DNO performance by counting lost (undelivered) supply minutes per year. Reported to Ofgem
conductor	(1) A path allowing free-flow of electricity e.g. metal or ionised medium; (2) overhead line carrying electrical power at high voltage.
congestion	maximum power draw through a network; any more would cause overload. Congested system have no margin and tend to volt-drops, overheating damage, increased losses and reduced asset service life
current	volumetric movement of a charge-carrier (e.g. electrons) past a point
curtailed	aka clamped / disconnected; the act of preventing EVs from charging
cycles / cycle life	Batteries degrade in use. Cycle life is number of charge / discharge sequences a battery can perform with useful capacity (often taken as 80% of original kWh) and a complex function of individual battery chemistry, duty and temperature. A typical design goal is 1,000 cycles. Batteries also suffer "calendar ageing" i.e. standing deterioration
DCC	Data Communications Company. Perform Smart Grid data transfer
DECC	Department of Energy and Climate Change (UK governmental body subsumed into Department of Business, Energy & Industrial Strategy)
DES	Discrete Event Simulation - a method to process a list of events, each causing a specific state change within a simulation model
DfT	UK Department for Transport
discretionary dispatch	(FPB jargon) V2G vehicles cannot always dispatch: they deem when they can or cannot (hence discretionary). When available and needed, V2G EVs dispatch under MCS control
dispatch	the act of supplying power to the grid e.g. generation, V2G
disruptive load	loads which interferes with power quality e.g. injects harmonics able to reach other parties, lowers local voltages below minimum etc.
DNO	Distribution Network Operator. Owns assets and licensed to manage and maintain a regional network to deliver power to customers. Does not sell electricity and converting to DSOs. The present DNOs are: • SSEN: Scottish & Southern Electricity Networks • SP: Scottish Power Energy Networks • ENW: Electricity North West • NPG: Northern Powergrid • UKPN: UK Power Networks

	• WPD: Western Power Distribution 
DSO	Distribution System Operator. A dynamically managed DNO network (DNO networks being predominantly passive). DNOs are to transition to DSOs i.e. gain network management capability and role.
DOD / DoD	Depth of Discharge (an aspect of SOC and a %). The amount a battery is allowed to run-down from a peak charge % to the point where it is to be recharged. Limiting DOD typically increases battery life
DR also DRB, DRC	Demand Reduction is the action part of DSM - the act of turning off customer loads. Automated DR (ADR) is the primary means for SG to achieve power regulation - to turn off (usually thermal / HVAC systems, hopefully for short times). Often, DR is DS i.e. load is shifted timewise. DR-B and DR-C are DR tests patterns used by FPB.
DS	Demand Shifting, a synonym of DR. Demand is relocated timewise
DSM / DSR	Demand Side Management or Reduction. A scheme which manages the load or demand on a network via a remote command signal
DTU	Demand Turn-Up. See Sunshine signal
dumb EV	(re approach to charging). Implies cannot communicate via Smart Grid to receive and act on commands; "dumb" may be elective
EATL	Electricity Association Technology Ltd, often "EA Technology". A consultancy specialising in power systems asset management, formed from the privatisation of the nationalised Electricity Council Research Centre. Not to be confused with ERA or ENA
EPRI	Electric Power Research Institute, a US technical / research body
EN	Electric Nation, an extensive EV trial by WPD c. 2017-2019
ENA	Energy Networks Association, a technical body for the UK power and gas industries, writes regulations.
equitable fairness	maximising throughput whilst ensuring each user receives a level of resource according to need. See proportional fairness
ERA	ex-Electrical Research Associates, now ERA Technology. A UK technical

	research body founded in 1920, involved with electrical power issues, standards, operating methods etc. Not to be confused with the Energy Retail Association who brand themselves ERA.
ESMU	"Energy Storage and Management Unit" - a roadside system with a 10 kWh battery and an ESS. Balances current between phases, stores and releases power. Possibly power quality services i.e. VAr injection
ESS	Energy Storage System aka "Static Batteries", ESMU. A means to retain electrical energy (often in another form) and connected to the Grid e.g. pumped water storage, large batteries
ESQCR	Electricity Safety, Quality and Continuity Regulations. Health and Safety guidelines for the power industry.
EV	Electric Vehicle e.g. a car or small van powered by an electric traction system (typically using batteries). EV is a synonym for BEV
EVSE aka EVCP or pile	Electric Vehicle Supply Equipment / EV Charge-Point. Post AEVA-2018 Smart types must have a control mechanism (clamp) to halt charging.
feeder	cable taking 3-phase, Earth and Neutral circuits from a substation to customers, typically buried in-road. The simplest form is a herring-bone system; the feeder being the backbone with lines (service cables) to properties. Feeders can be long, bifurcating, meander with roads and possibly join other feeders. There is no standard form.
Flow Boiler	high-power (e.g. 9 kW) flash water heater (similar to electric shower) often used with Heat Pumps to boost outflow temperature.
FPB	Feeder Phase Balancer, written by the author to simulate EVs on a network, now with reduced phase balancing capability.
FFR or FR	Fast Frequency Response seeks to stabilise national AC frequency by correcting deviations, by load modulation or power injection
G2V	Grid to Vehicle (normal EV charging)
headroom	unused system delivery capacity; the gap between instantaneous kW load and kW delivery rating. May be single or 3-phase. See unbalance.
hi_limit (kW)	(FPB jargon) limit to which a phase can be loaded. See lo_limit
HV	High Voltage i.e. 132 kV and above
I	Symbol for current. The mechanical flow of charged particles passing a point (1 Amp is about 6.25 x 10^18 electrons per second)
ICE	Internal Combustion Engine i.e. a fossil fuelled car
ICT	Information and Communication Technology (computers + telecoms)
imbalance (voltage)	unequal phase voltages, often cased by unequal load and supply. Of no regard on 1-phase systems, voltage imbalance of as little as 2 - 3% can shorten 3-phase motor lifespan (rotor imbalance and bearing failure). See also unbalance (current)
imbalance (market)	a market trading energy, to correct imbalances of power supply / demand

INSim	the author's intended Improved Network Simulator, a SG with V2G EV layer on OpenDSS and a derivative of ACPSim, an Excel simulator
kV, kW	kilo Volt and kiloWatt i.e. 1,000 V and 1,000 W
kVA	magnitude of product of instantaneous volts and current
kWh	kilo Watt hour. A measure of electrical energy, being 3.6 million Joules
$kWh^{\mathbf{b}}$	kWh in EV battery (battery view). Due to losses, the network and battery see different total energy situations
LCL	Low Carbon London, a set of LCT trials (HP and EV) c. 2010-12
LCT	Low(er) Carbon Technologies: ways to reduce carbon (CO_2) emissions
LCV	1) Light Commercial Vehicle; 2) Low Carbon Vehicle
lo_limit (kW)	(FPB jargon) load below which MCS element of FPB does not attempt to balance phases. See hi_limit
load shedding	the act of disconnecting one or more loads during power shortages
loss	electrical energy loss via heating (Joule losses) caused by conduction through cables and within transformers (Copper and Iron losses)
LV	Low Voltage; in the UK 230 V +10%, -6% and also under 1,000 V as per ESQCR. 230 V is used as at this pressure electricity will not self-arc
mandatory charging	(FPB jargon) EVs which must charge regardless (so force the issue) e.g. a dumb EV. See opportunistic charging, discretionary dispatch
Mandatory Managed Charging	(TRL jargon) the use of disconnectors (clamps) via some form of ICT to manage charging load, similar to Aggregators
MCS	Managed Charging System; controls/optimises EV charging via ICT
µMCS	"micro-MCS" - a putative simplified MCS; see section 8.6.7
MEA	"My Electric Avenue" a real-world EV trial run by SSE and EATL. See section 2.3 My Electric Avenue and Esprit
MV	Medium Voltage. Between LV and Transmission level voltage (HV)
My Electric Avenue	an EV trial run by SSE and EATL. See MEA
N EV	(FPB jargon) The number of EVs present on a feeder per 100 houses
NGESO	National Grid Electricity System Operator plc. A private company tasked with procuring and managing the UK electricity supply
NGET	National Grid Electricity Transmission, now NGESO
NTS	Nation Travel Survey, a UK government maintianed dataset
ODSS	short for OpenDSS
Ofgem	a UK Government body regulating the electricity business. From https://www.ofgem.gov.uk/about-us/who-we-are: *"Ofgem is the Office of Gas and Electricity Markets. Our principal objective […] is to protect the interests of existing and future electricity and gas consumers."*

OLEV	Office for Low Emissions Vehicles (UK government quango)
OOB	Out of Balance: dissimilar feeder 3-phase loads
OpenDSS	A capable open source power simulator from EPRI. See also http://smartgrid.epri.com/SimulationTool.aspx
opportunistic charging	(FPB jargon) an EV with time in hand to complete charging. If spare (not otherwise used) network headroom is available the EV can "opportunistically" charge. This defrays risk of not being able to charge later. EV must be Smart and needs MCS management. See mandatory charging, discretionary dispatch
parc	on-road and SORN vehicles i.e. the national set of viable vehicles
parity-case	1 EV per house driving the average distance. However there may be more than 1 vehicle per house
PEH metric	(FPB jargon) Percent Effective Hours. A coefficient quantifying the % of weekly hours for which an DR FFR signal is effective.
PCC	Point of Common Coupling: a shared electrical supply point
pd	(1) (FPB jargon) a period or span of time being 10 per hour and integer part of **st**; (2) potential difference: volts between two points
peak shaving	reduction of load peaks; the goal of Demand Reduction
penetration	(of EVs) the proportion of EVs as a part of the vehicle fleet i.e. 10% penetration implies 10% of all domestic vehicles are an EV. May interchange with parity (1 EV per house) in literature. **!! Some papers** consider 100% penetration to be 1 EV per house, not 1:1 replacement of cars by EVs
Perfect Plugin / PP	(FPB jargon) mandating EVs to always plug in to power when parking e.g. HomePP, AwayPP, AllPP
pf	power factor. Ratio of real vs apparent power; inductive is lagging
phase	1. AC supply, of 1 or 3 phases. Phases are 3 sine-waves 120° apart; 2. cyclic relationship between similar waveforms, usually in degrees
PHEV	Plug-In Hybrid. A car both fossil fuelled and chargeable EV (e.g. Prius)
PLC	Power Line Carrier: radio-frequency data-link over a power conductor
PIV	Plug-In Vehicle (synonym of EV)
Preburn V2G	raises headroom by adding 60% of known V2G capacity. Improves EV charging; allows support of overloads from remaining V2G capacity
Primary station	The transforming station supplying a substation. Accepts power at 33 or 66 kV and emits 6.6 or 11 kV, forwarded by cable to substations.
proportional fairness	maximising system throughput with each user receiving a minimum level of service. In the limit all get the same. See equitable fairness
protection	power systems suffer faults e.g. an overhead phase conductor snaps and trails over another phase and to ground. This is a complex short-circuit. Protection systems monitor for faults and trip (disconnect) on detection,

	often in milliseconds. Many faults are possible.
pu / p.u.	"per unit" e.g. a ratio (but not scaled by 100 as is %). Useful when discussing transformers. Regardless of turns ratio if there is input voltage of 1.21 pu on the primary, the secondary will emit 1.21 pu. Also used for power levels
quango	"quasi autonomous non-governmental organisation", an authority spun off from Government for a role e.g. define/monitor standards
reinforce	a network upgrade or refurbishment to higher kW capability
RIIO	quote: *"Revenue=Incentives+Innovation+Outputs is Ofgem's performance-based framework to set the price controls."* Ofgem's carrot and stick requirements on DNOs, often with financial penalties
SEC, SECAS	Smart Energy Code (of practice) administered by a dedicated UK company, SECAS also known as SECCo.
service cable	a cable (rated at say 20 kVA) which connects a feeder to a property
severe undercharge	EV depart SOC < (minimum to complete present trip and return home). Without a source of charge, the EV will be stranded
SG	Smart Grid. A network made intelligent via ICT, data monitoring and controllers (Agents). Has data dialogue and decision making ability
SM	Smart Meter. Provides an ICT link and data flow. Designs vary; most provide remote control e.g. SMETS2 can switch 5 appliances
smart	a system able to communicate, negotiate, react and track its situation in a context. Usually indicates a heuristic / agent enabled ICT device i.e. a computerised component like a "Smart Meter"
SMETS	Smart Metering Equipment Technical Specifications (1 and 2)
SMMT	The UK Society of Motor Manufacturers and Traders
SP	Scottish Power, a UK DNO
SOC	State of Charge of battery as % of capacity e.g. 60%. SOC is likely not useful charge remaining; for life extension purposes the battery may not be used under a level e.g. 12%. Useful charge is: 60 - 12 = 48%. However it is common to hide any lower or upper bounds from users and only refer to the useful middle range. FPB does not do this.
SSEPD	Scottish and Southern Energy Power Distribution, part of SSE / SSEN, a UK DNO
st	(FPB jargon) a moment in simulation time. See also stphr. st is a real number written "st 17.8"
StatBatt	Static Battery, a form of ESS connected to a network to support load
stiff	power industry term for system able to support load without incurring volt-drops or overcurrent
stphr	(FPB jargon) how many solves represent 1 hour. Used with rates, flows, other time related conversions. FPB uses stphr = 10
substation	the transformer, disconnecter and distribution cabinet converting 11 kV to

	400 V (230 V ph-Neutral) or LV, for onward distribution to households. See also Primary station
Sunshine signal	a network-issued signal, indicating an excess of power due to abundant renewable energy (the sun is out, wind-turbines are harvesting much power etc.). Implies: Use this power now
SV1G	(FPB jargon) an EV which can be commanded to start charging as well as stop charging. Used with a SG system to optimise renewables e.g. SG detects renewable energy availability so signals "Start charging" to SV1G EVs. Defers EV charging from fossil-fuel based sources.
ToU / Time of Use Tariff	Timed bands of different retail charges per kWh sold. Likely to be dynamic / change in real time; when power is in shortage prices go up etc. The intent is for the SG to send this data to customers (including households) to encourage them to decrease / increase load
tranche	(FPB jargon) a time-bound repository of EV intents, split into 3 bounds of alternatives determined by EV SOC. See section 4.5.9
trip	(1) an EV performing a round-trip with a home depart time, distance travelled and return time defined. Note that NTS describe a "trip" as individual legs, thus this journey NTS would count as 2 trips. FPB considers this as one trip. (2) a switch element in a power system moving to OPEN due to a fault e.g. to protect network assets. The network which has lost power is said to be "tripped".
TRL	Transport Research Laboratory (TRL Ltd.)
TSO	Transmission System Operator, responsible for moving electrical power (about the nation) from generation points to distribution. In the UK, subsumed into NGESO
unbalance (current)	conductors in a cable may carry unequal loads. An unbalance metric is (highest load - mean load) / mean load. High unbalance reduces headroom thus cable carrying capacity, as the phase of future loads is unknown. See also imbalance (voltage)
undercharged	EV depart SOC < (depart_target - 5%). See severe undercharge
V1G	an EV which can stop charging on command. See SV1G
V2G	Vehicle to Grid. i.e. returning power to the local supply from the EV. Depletes EV battery so is temporary (needs replenishing). High round-trip losses i.e. 100 units in, 50 - 60 units out. See Preburn V2G
V2H	Vehicle to House. A Nissan initiative for houses / EVs to share power.
V, Volt	A measure of electrical pressure between a point and a reference; the relative pressure exerted on a charged particle and implicitly a measure of potential energy. AC voltages are RMS values
VAr	Volt-Ampere reactive; the quadrature element (90° out of phase) of inductive or capacitive load, represented by complex numbers
VAS / VASS	Value Added Service (Supplier): an Aggregator offering to perform a contract

	e.g. of an energy balancing service sold to NGESO
Voltage drop	Loss of voltage along a conductor due to load and cable impedance. Excess load may cause an in-situ feeder cable to deliver voltage below regulation
VPP	Virtual Power Plant. Coordinated operation of a group of power sources (e.g. V2G EVs) so to supply / consume power as one unit
WPD	Western Power Distribution, a UK DNO

this page deliberately left blank

Chapter 1: Introduction

As this is a large work, the document structure map Figure 1-1 below may aid.

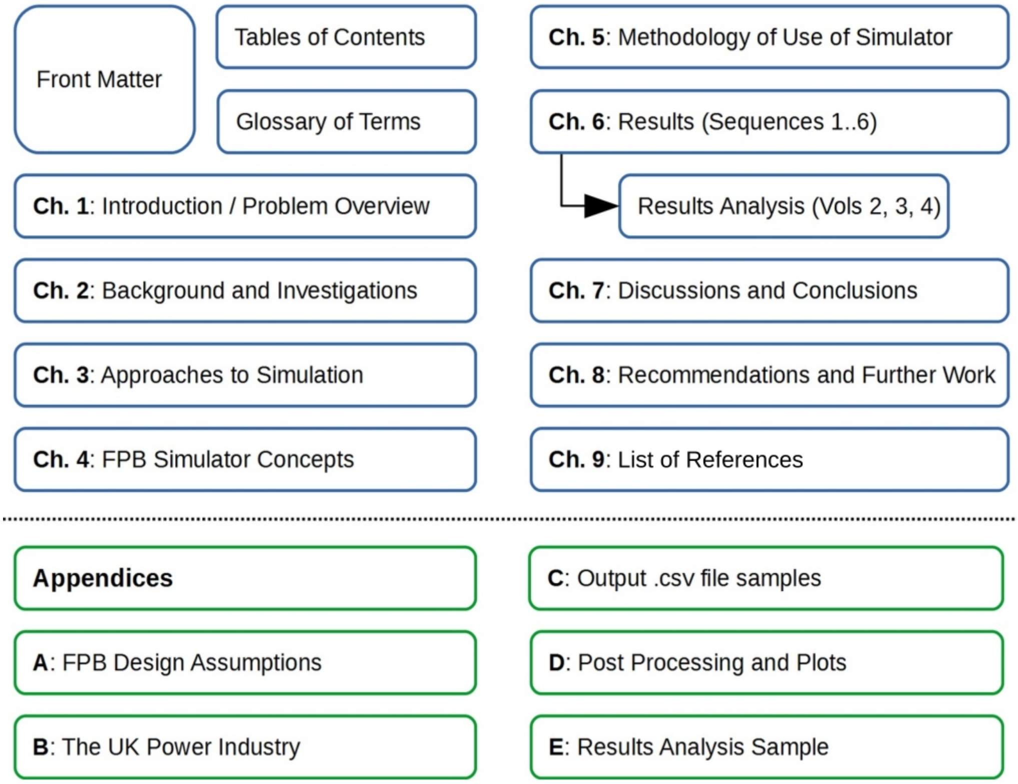


Figure 1-1: Thesis Structure Map

It is suggested to read the thesis using a .pdf viewer, to allow Bookmarks, image zooming and to navigate using highlighted hot links. Blue text is an internet link. The front matter includes a Glossary of Terms (link in odd page footers). Pdf readers use Alt-LeftArrow to return from a link back to the original page. Use Ctrl-Scroll to zoom in and out of images.

UK is a signatory to: UNFCCC Kyoto Protocol and Paris Agreements with enabling legislation:
The Climate Change Act **(HM Gov, 2008)**,
The Clean Growth Strategy **(BEIS, 2017)**,
The NO2 Plan **(DEFRA, DfT, 2017)** and
The Road to Zero **(HM Gov., 2018d)**
Net Zero **(Committee on Climate Change, 2019a))**

The UK Government seeks to delay Climate Change and is signatory to the UN Framework Convention on Climate Change (UNFCCC), Kyoto and Paris protocols.

The Climate Change Act is the UK primary legislation, mandating 5 year plans to lower Carbon Dioxide (CO_2) emissions using “Low Carbon Technologies”

(LCT). The Clean Growth Strategy bans sales of CO_2 emitting vehicles from 2040, with Heat Pumps replacing gas for home heating. The “Road to Zero” and “Net Zero” protocols are further steps to effective de-carbonisation. The immediate intent is to replace fossil fuel vehicles, initially cars, with LCT substitutes. Electric and Hydrogen fuel-cell vehicles are the primary choices, with electric vehicles (EVs) more mature and rapidly coming to market.

The energy used for transport is to be supplied as electricity to EVs. Many will charge at home, however the last mile of network to houses was built for lighter duties. A modern EV charges at c. 3 to 7 times traditional per house local network capacity; only a portion of EVs can charge simultaneously. This does concern network operators, but there are difficulties assessing both the problem and remedial options, which potentially incur costs in the multiple £bn. range (**EA Technology, 2012, Fig.0.1)**, Figure 2-40.

1.1 Thesis Aims and Objectives

The thesis aims to offer visibility of the UK residential network situation by exploring mass home charging of EVs, to aid a successful transition to home EV charging. This includes the dynamics of EVs as they interact with networks. The intent is to offer pragmatic insights. **Note** future EV characteristics are projected, introducing uncertainty.

The objectives are to investigate Electric Vehicle charging on residential networks, so to understand the issues arising. The work trials various management policies for EVs, including traditional UK power industry control methods and the author’s own approaches. The impacts and benefits of these approaches are assessed.

1.1.1 A Holistic Approach

This is an interacting multi-disciplinary topic, involving:

1. electrical power engineering,
2. the characteristics of future EVs,
3. the habits of people using EVs as cars,
4. the expectations of industry regulators (Ofgem, ENA) and
5. 3rd parties offering Value Added Services to the UK network via EV control.

Previous research typically investigates one perhaps two of the factors. For example, network power studies focus on electrical impacts and might calculate EV battery consumption, but do not reflect the ongoing EV situation and impacts thereon. EV usage (mileage driven) and starting battery charge affects later charging demand, which in turn affect networks. Each group has differing priorities; these may conflict or be impractical. An aim of this thesis is to form a holistic view of the subject, as is likely to be experienced.

The primary method of investigation is simulation, using UK data for network load and car driving profiles. A bespoke simulator is developed to model aspects 1-5 above, using established discrete simulation methods plus novel techniques.

1.1.2 Scope of Work

The scope is set in the UK context and includes:

- low-rise residential areas (primarily urban)
- served by low-voltage (LV) cables, known as “feeders”, to deliver single-phase 230 V AC to homes
- given EVs replace private cars en masse and charge at home
- excluding non-domestic vehicles i.e. commercial vehicles and taxis.

Although formally out of scope, replacement of gas home heating by Heat Pumps (HP) is anticipated for the decades following mass EV adoption. At the time of writing there is no legislation in place, but there are recommendations for such a policy **(Committee on Climate Change, 2019b)**. It would be foolish to form EV related recommendations which are incompatible with Heat Pumps, so a test is included in Section 6.8.29.

1.2 Results and Outputs

Outputs are to include reports which offer understanding of EV residential charging issues, identifying the key parameters of the problem and any likely warning signs indicating:

- which networks may be troubled
- the EV populations which cause problems
- the problems experienced by EVs when managed, i.e. impacts on charging
- under what circumstances these problems may be expected.

Outputs will quantify the utility of remedial options. The results can aid network owners to direct interventions, by being aware of the merits and impacts of options.

1.3 Contributions

The contributions arising from this research are:

1. a novel means to model EVs and charging characteristics, using a heuristic method which does not require forecasts,
2. a high-level appreciation of effects arising from EV charging at home, based on large scale simulations of c. 5 x 10^9 driven trips, and
3. insights into the effects and impacts of methods to manage home charging.

The developed simulator is a major contribution and offers the ability to model EVs with no control, a local ICT controller or remote control. EVs drive individual UK style trips and mimic UK car characteristics to determine charging needs. Such a simulator is relevant to both academia and industry when modelling EVs on constrained networks.

New knowledge from simulator outputs include:

4. the seasonality of use of destination (public) charging, Winter vs. Summer. This arises from cold-period network congestion and the physics of Li-ion batteries.

   Compared to Summer, Winter destination charging is c. ~ 4 to 22 times higher. This implies need for a great build-out of public chargepoints, many of which will be unused much of the year. Conversely if in Winter EVs find charging unavailable then an increase of stranded vehicles can be expected;
5. the impact of proposed DSR (which seeks to prevent EV charging at peak times) provokes local overloads,
6. driven distances (hence, location) is a major factor as well as numbers of EVs.

This is relevant to UK policy and spend on network support, which has potential to run to c. £50+ bn. European countries and others with similar residential networks may benefit.

1.4 Overview of the EV Charging Problem

The challenged networks studied are the last-mile networks, providing 230 V mains (called Low Voltage or LV) to houses. An estate may be built with assets fit to supply 1.5 kW per 3-bed semi-detached house. An EV charging at 7.2 kW needs the capacity of:

$$7.2\,kW / 1.5\,kW = 4.8\,houses \tag{1}$$

However the house itself may be taking say 800 W. The vehicle may then only access the spare capacity (termed headroom) which is:

$$available\ circuit\ capacity - house\ load = 1{,}500 - 800 = 700\ W \quad (2)$$

thus charging an EV needs the spare capacity of: $7.2\,kW / 700\,W = 10.3\ houses$ (3)

Of 100 houses on supply, no more than 10 can have an EV charging at any one time without causing overloads. Yet many homes have more than 1 car, with 1.7 vehicles per house seen when including works vehicles driven-home (Hants entry in **(ONS, 2012)**).

The simulator can show the load impact before and after EVs are placed on the network. Figure 1-2 has **No EVs** and shows the load profile for 100 houses, over a Winter week, and Figure 1-3 has **100 EVs**, driving an average of 27 miles per day and able to charge at home (with Figure 1.2 residential loads shown in yellow).

The test network has a phase hi-limit of 52 kW, quite able to cope with Winter residential loads. Yet modern EVs typically home charge at 7.2 kW, substantially higher than usual per-house residential load. The EVs modelled here drive UK-style patterns.

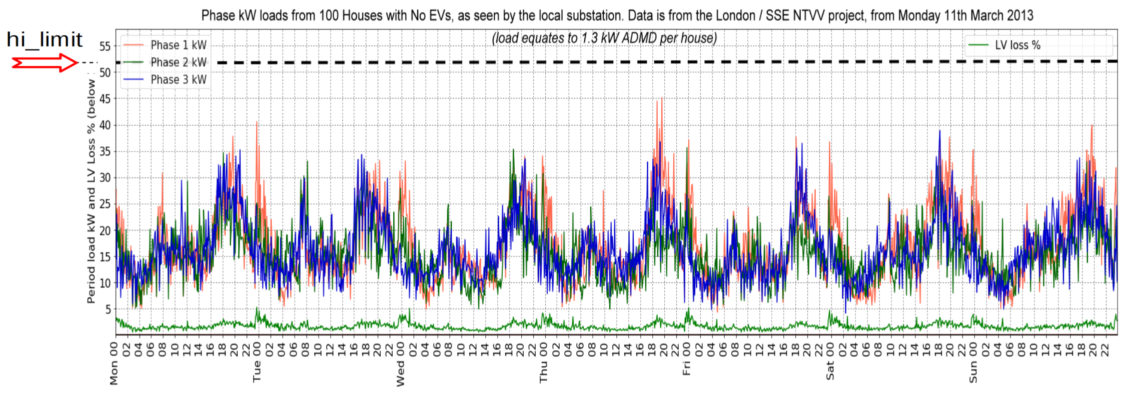


Figure 1-2: Simulated 3-phase residential load dataset for 100 houses (No EVs)

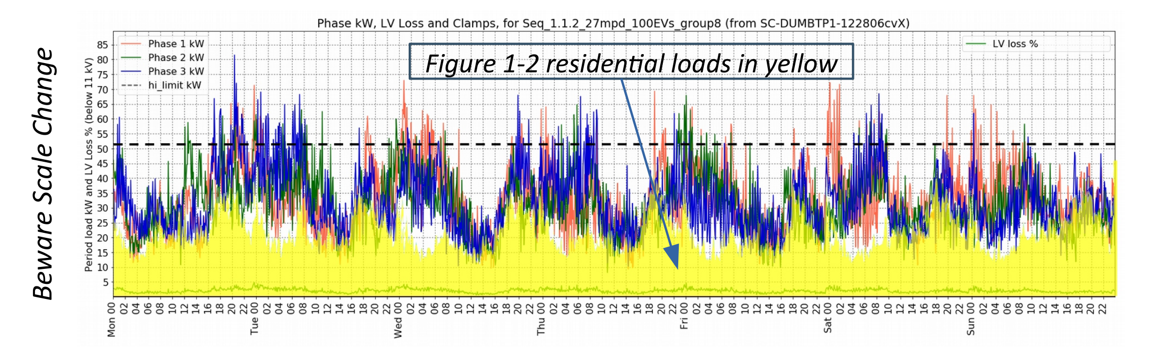


Figure 1-3: Simulated 3-phase load for 100 houses plus 100 EVs driving 27mpd

See also large plates Figure 1-4 and Figure 1-5 of Figures 1-2 and 1-3 respectively, at the end of this chapter.

EVs are departing and arriving at typical times, yet their charging may cause overloads and local power failures. However there seems little concern, as:

a) high-level analyses see combined averaged demand (averaging masks local peaks);

b) EVs are not yet ubiquitous,

c) network margins permit an occasional EV to charge; LV overloads are not yet seen

d) US early EV adopters met no difficulties (US household provision is c. 10 - 14 kW).

1.5 Concerning Network Assessment

There is currently no requirement on builders to record and publish built network capabilities. Construction now spans a century; the records of managing organisations (Distribution Network Operators, DNOs) can be fragmented or in error. EA Technology do hold outline UK statistics, which were used to estimate UK LV network upgrades **(EA Technology, 2012)** as c. £48 to c. £62 bn. arising from LCT.

A report from the My Electric Avenue trial **(Cross, 2015)** confirmed LV overloads are possible. This found network upgrades are necessary if 40% - 70% of cars are Nissan Leaf EVs, for ~ 312,000 of UK's c. 1 million LV networks. Cross says: *"feeders [with] problems due to EV penetration [typically have] spare capacity below 1.5 kW per customer"*.

However, modern EVs demand more than a Nissan Leaf, implying more networks effected. Assessing impact of contemporary EVs is handicapped by a lack of simulators combining aspects 1 .. 5 in 1.1.1 A Holistic Approach, as well as a paucity of data re future EVs.

A suitable LV with EV simulator is needed to model, observe and detail events.

1.6 Example of Utility of Results

Table 1-1 shows network strength needed to support EVs, overviewing 2 x 10^8 results from the developed "Feeder Phase balancer" (FPB) simulator. Table values are built per house LV kW capacity (coloured in 0.5 kW bands), indicating network ability to support EVs in Winter. **N EV** is number of EVs per 100 houses and **mpd** the driven miles per day. Table 1-1 (a) has received adjustments**†**; see also Key Findings 7.2.

Table 1-1 (a) has no local control i.e. are self-managing EVs. The mustard (2-2.5 kW built) network may support 80 EVs if their location implied 24 mpd average daily driving.

Table 1-1: Network Built kW per House Heatmaps (Supported EVs per 100 Houses)

(a) Number of 2020 Dumb EVs Supported (per 100 houses) by built LV kW

N EV:	10	20	40	60	80	100	120	140
17 mpd:	1.24	1.28	1.66	2.24	2.32	2.9	2.98	3.06
24 mpd:	1.24	1.58	2.16	2.24	2.32	2.9	2.98	3.56
34 mpd:	1.54	1.58	2.16	2.24	2.82	2.9	2.98	3.56
44 mpd:	1.54	1.58	2.16	2.74	2.82	2.9	3.48	4.26

(b) MCS Controlled: N EVs + V2G Supported (per 100 houses) by built LV kW

N EV:	10	20	40	60	80	100	120	140
17 mpd:	1.2	1.2	1.5	1.5	1.5	2	2	2
24 mpd:	1.2	1.2	1.5	1.5	2	2	2	2
34 mpd:	1.2	1.2	1.5	2	2	2	2	2
44 mpd:	1.2	1.5	1.5	2	2	2	2	2.5

† Table 1-1 has received two adjustments to correct known sources of error:

- *mpd is reduced 10% to allow for a simulation approximation, and*
- *(a) has a small kW uplift to allow for contemporary EVs, not future types.*

Table 1-1 (b) is with a simulated local Managed Charging System (MCS) controlling EV charging, showing an improved ability to support EVs. This needs a local Smart Grid.

Example Heatmap Table Use

In UKPN areas (London, East Anglia and the South-East), built substation and cabling for 100 homes may modestly exceed 150 kVA duty, as UKPN require a minimum 1.5 kW per house. For a specific network, actual build might be 1.8 kW per house. At 1°C ambient temperature then, given the local EV fleet drives 24 miles a day, 20 EVs per 100 houses can be supported by this network. A Smart Managed Charging System, Table 1-1 (b), can support 60 EVs.

Notes

a) values are indicative, being similar to the My Electric Avenue trial **(Cross, 2015)** and are best cases for an ideal network, given thesis assumptions (Appendix A);

b) historically, many local networks were built fit to supply c. 1- 2 kW per 3-bed semi

c) limitations arise due to exceeding the capabilities of in-situ transformers and cables, which take supply to houses.

1.7 Published Papers

The author has published two peer-reviewed papers:

1. Broderick, S., Cruden, A., Sharkh, S., & Bessant, N. (2016). "An improved network simulator for EV/V2G studies." In IET CIRED Workshop 2016 Proceedings. IET.
2. Broderick, S., Cruden, A., Sharkh, S., & Bessant, N. (2017). "Technique to interconnect and control co-simulation systems.", IET Generation, Transmission & Distribution, 11(12), 3115–3124.

Plus potential to influence Government policy by replying to **(DfT & OLEV, 2019)**, to aid awareness:

3. Broderick, S. (2019). Response to UK Department of Transport Open consultation: "Electric Vehicle Smart Charging."

A four-page paper summarising findings has been reviewed and accepted by CIRED: "Saturation Simulation of Mass EV Charging on Congested 230V LV Networks." However this paper is not yet published. A more extensive paper is planned, detailing possible DNO options to manage EV loads, given the simulation outcomes.

1.8 Chapter Summary

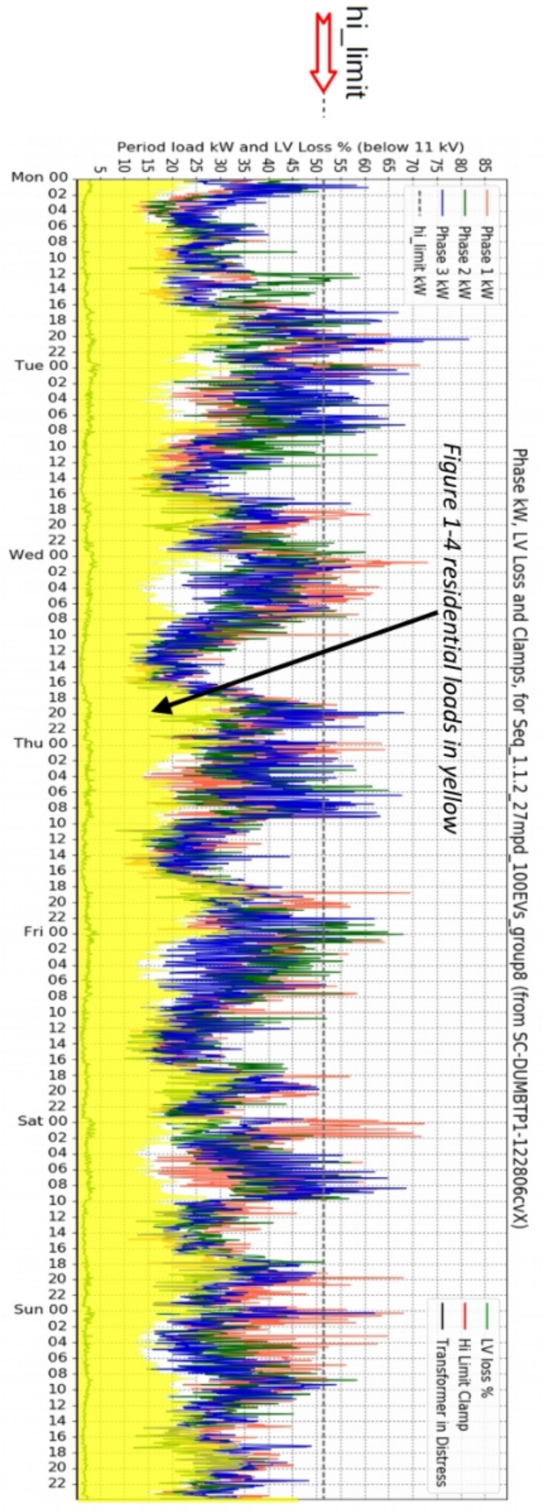
To reduce CO_2 emissions, domestic transport and home heating is to be electrified. Yet there are practical problems concerning the last-mile of electrical power delivery. The challenge (indeed, risk) posed to mass home charging of EVs on LV power systems has been introduced, together with the need to model UK 230 V LV networks.

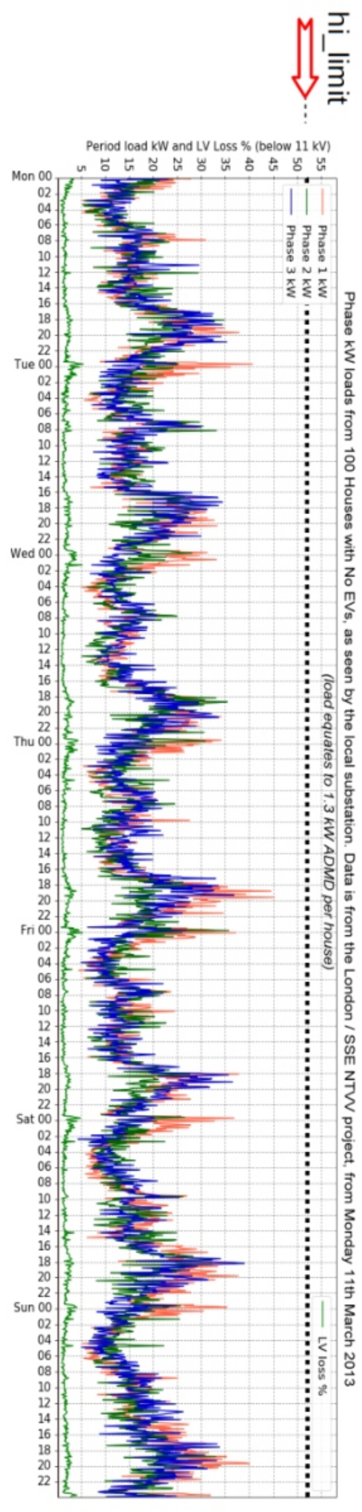
The aim is to investigate home EV charging by developing a simulator, to use this to explore the situation and determine impacts and remediation steps, given the concerns of the power industry and anticipated use of EVs. Heat Pumps are due to follow EVs and add further load. There is need to consider joint (or compatible) EV and Heat Pump solutions.

The contributions of this work are described, which include a simulator, insights regarding EV charging with discovery of a marked charging seasonality, and a simplified network assessment method. The work is relevant to the near-term (c. 2025) UK and EU situations, and may be of interest to nations using similar LV systems. The learning gained may inform UK policies to direct or defer multiple £bn. spend. Nations with highly capable LV systems (US, Norway) and new-build nations (China) may have less interest.

The next chapter looks at the background of the UK power system and the progress made in understanding the issues, by industrial and academic investigators.

Note This is a large document. To aid intelligibility there is a degree of repetition, so to help reading individual chapters.





(Right / Top)	*Figure 1-4: A 3-phase residential load dataset for 100 houses (no EVs) (Large)*
(Left / Bottom)	*Figure 1-5: Simulated 3-ph. load for 100 houses, 100 EVs driving 27mpd (Large)*

Note Figures 1-4 and 1-5 are to the same scale.

Chapter 2: Background and Investigations

This chapter presents an overview of the UK power industry and EV related investigations, including real-world EV trials and the academic literature concerning the issue.

The EngD necessitates considerable power industry understanding, presented below so sense can be made of later content. The UK power industry is complex and has much niche jargon (see the Glossary of Terms). Appendix B gives further power industry details.

2.1 Overview of the UK Power Network

The UK power industry was nationalised following World War II to 1990, run for the majority of that time by the Central Electricity Generation Board (CEGB). The CEGB undertook system design, commissioned large works and completed the build-out of electricity supply to the bulk of the UK's rural areas; see (Simmonds, 2002).

The present network includes many legacy systems and standards from the CEGB.

2.1.1 General Structure

Historically the UK power system was a top-down hierarchy, power cascading from Generation to customers as per Figure 2-1:

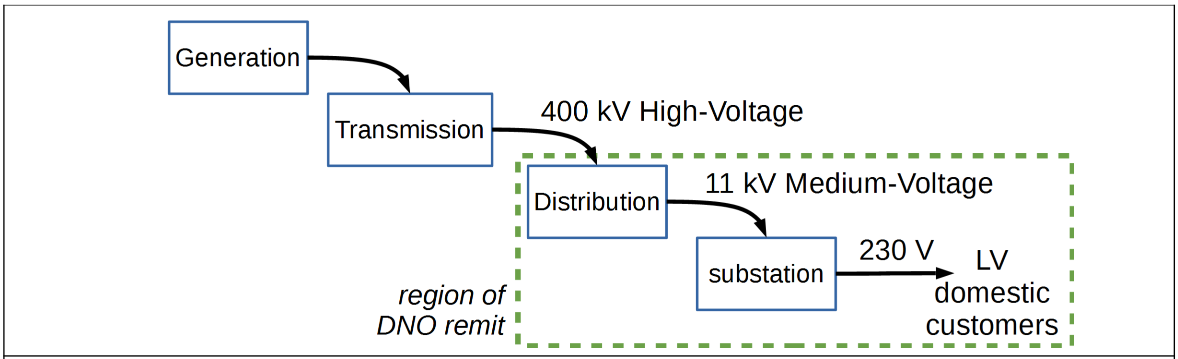


Figure 2-1: Simplified structure of UK Power Supply

The Transmission system was the National Grid, initially the name of a method and later a business. Transmission moves power about the country via high-voltage cables on steel towers (pylons) from points of generation to population centres, where it was distributed by regional Electricity Boards.

Distribution networks receive high-voltage and convert to lower voltages, suitable for customer use. There is an accompanying web of (typically buried) cables operating at Medium Voltage (MV) and Low Voltage.

2.1.2 The CEGB and Privatised Network Structures

Following World War II disparate city and region electricity suppliers were nationalised through several stages, ending as the CEGB, Figure 2-2.

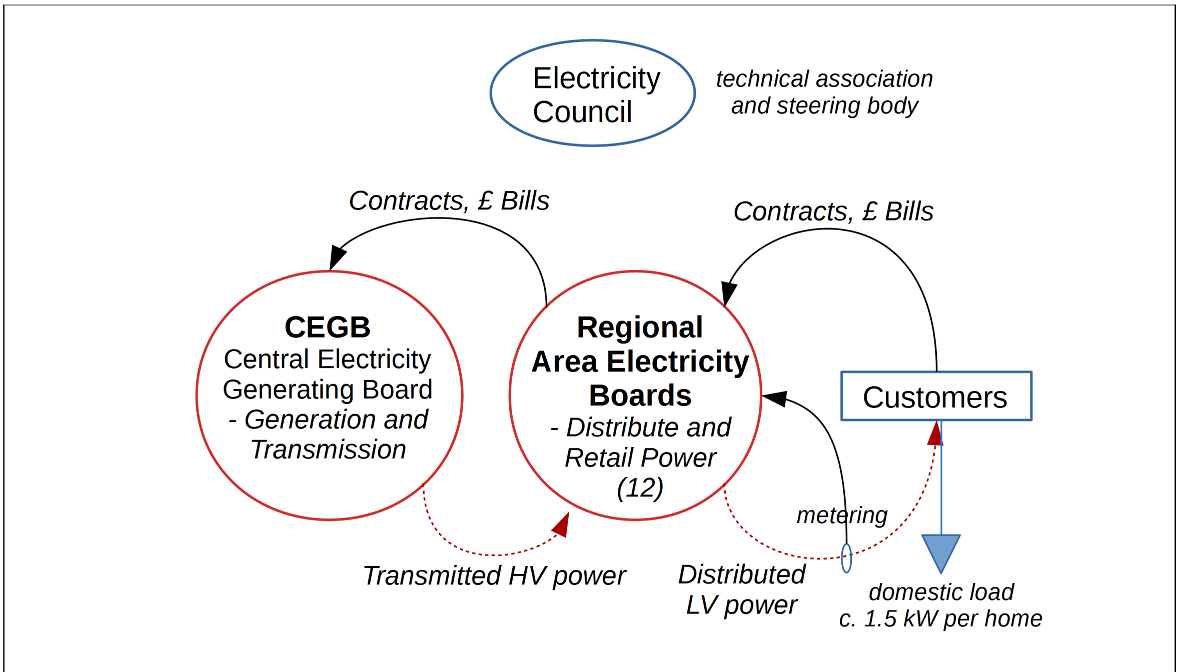


Figure 2-2: Mid-20th Century / CEGB era UK Power industry

Area Electricity boards both distributed and retailed electricity to customers, forming a natural monopoly. Both expertise and control were centralised, as potentially were finances. Privatisation occurred c. 1990 (Figure 2-3); the Regional Boards being de-bundled into two major parts: Distribution Network Operators (DNOs) who manage the physical networks and suppliers, who retail power to customers. In practice, the suppliers have little to do with the built system. The post-privatisation organisation has actors:

Aggregators: businesses competing in markets to supply power-related services to NGESO e.g. Balancing Services

DNOs (soon becoming DSOs): distribute power at reduced voltages to customers,

Elexon: a financial clearing house to resolve industry trades

ENA: technical standards / regulation overview to complement Ofgem. A quango

Energy UK: trade association and round-table for major participants

NGESO: (to 2019 "NGET") transmit power about country and operate the system, and

Ofgem: regulates finances and markets; has overall final control. A quango.

DNO regions are licensed; Ofgem manages the licences. Ofgem is the authority of last resort and closely manages industry financial activity, from permitting project spend to limiting DNO profit taking. The purpose of this is to provide best value for customers, by ensuring spend is both justified and effective, and to constrain any profiteering.

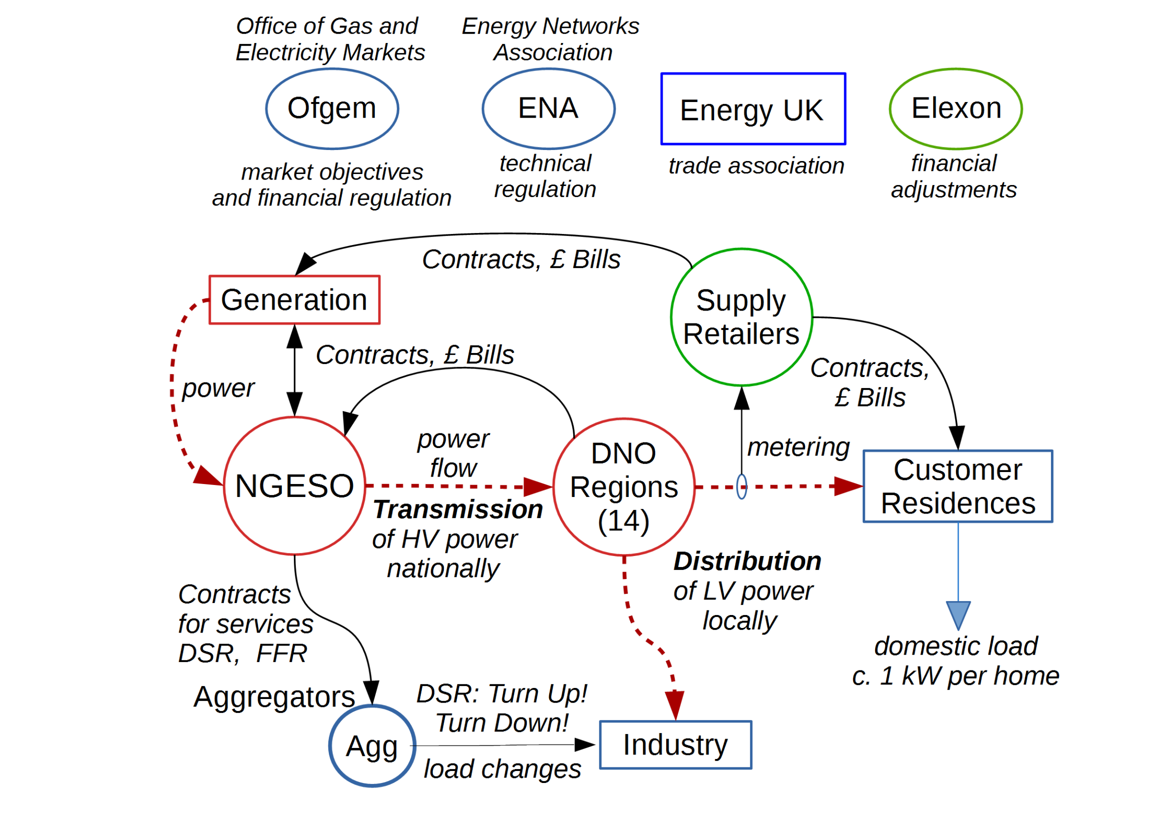


Figure 2-3: Post-privatisation UK Power industry structure

In 2019 National Grid plc reorganised, with the Electricity Transmission arm (NGET) becoming the Electricity Systems Operator (NGESO), tasked with whole-systems management. Both NGET and NGESO will be seen; for our purposes they are the same.

DNOs are transitioning to DSOs, Distribution System Operators. The distinction is that whereas DNOs manage predominantly static networks (fixed topology, few controls); DSOs will manage active networks (dynamic topology and pervasive ICT controls). **Note** domestic electricity use has fallen, due to energy efficiency measures.

Specialist quangos often arise e.g. OLEV, SECAS, DCC.

2.1.3 Bought Services

NGESO buy both Generation and Balancing Services via reverse auctions for:

- Demand (side) Reduction (**DR / DSR**): to reduce power consumption (e.g. contingency to cover loss of a power station), by either:
    - turning load off
    - injecting extra 3rd party power
- Frequency Response (**FR / FFR**):
    - control power system AC frequency (correct deviations from 50 Hz) by:
    - rapid injection of load or supply (reduce or increase instantaneous load).

Note that the privatised structure features:

- assumption of commoditisation (use of off-the-shelf components)
- Balkanisation into profit-centres with accompanying expertise siloing,
- loss of the overarching systems architecture role, compensated by siloed topic-specialist quangos who import skills e.g. OLEV.

2.1.4 Safety and DNO Quality Compliance

If permitted, electricity can kill. Two common modes include:

- direct electric shock (c. 1,000 instances pa with c. 30 fatalities)
- setting fires (about 20% of UK fires, c. 3,000 pa, are ignited electrically: www.gov.uk/government/collections/fire-statistics-great-britain).

Fires occur in stressed network assets or under-volted appliances (stalled motors overheat), which can arise during excessive network load. To limit risk, DNOs are mandated by regulation **(HSE, 2017), (BSI, 2010)** and **(ENA, 2013)** so:

- delivered voltage is 230 V -6%, +10%, and
- power is free of brown-outs (voltage sags), harmonics and flicker.

Note fatal situations due to power loss exist. DNOs track “cannot lose power” vulnerable households to ensure they remain supplied, if necessary by small generators.

Regulation requires the tracking of power lost due to network issues (Customer Minutes Loss (CML) ratings). Ofgem require DNOs to report incidents together with operational costs and network losses; CML non-compliance can attract financial penalties.

2.1.5 Residential Low Voltage Distribution

This work considers the DNO distribution transformer and cabling closest to residences.

An averaged UK household load profile **(EA Technology, 2012, p183)** is shown in Figure 2-4..

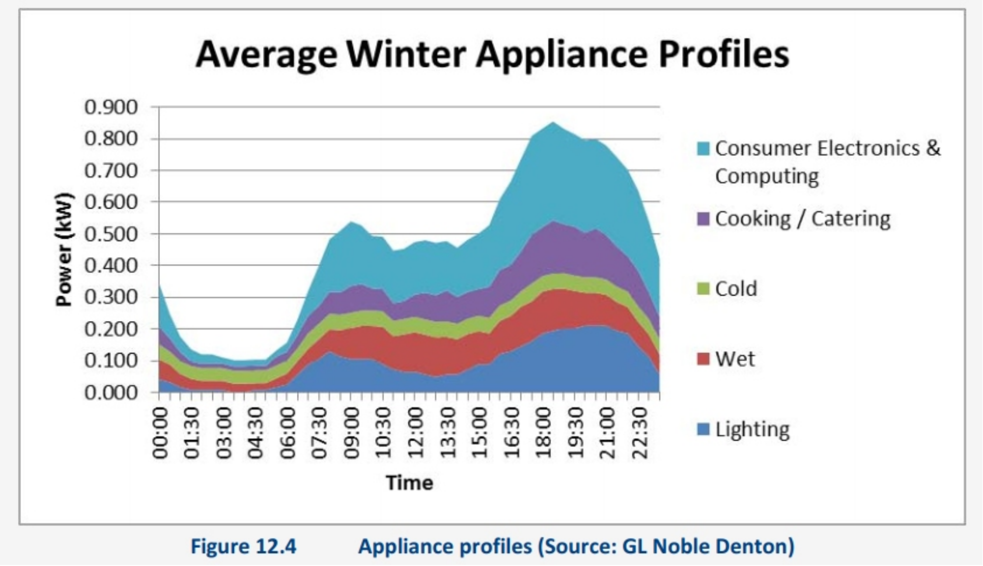


Figure 2-4: Averaged UK Winter Domestic Load

Winter peak load is under 1 kW. Other than refrigeration ("Cold"), none may be turned off without affecting the user. Such low load plus 230 V operation allows a single transformer to serve many houses (perhaps hundreds), Figure 2-5..

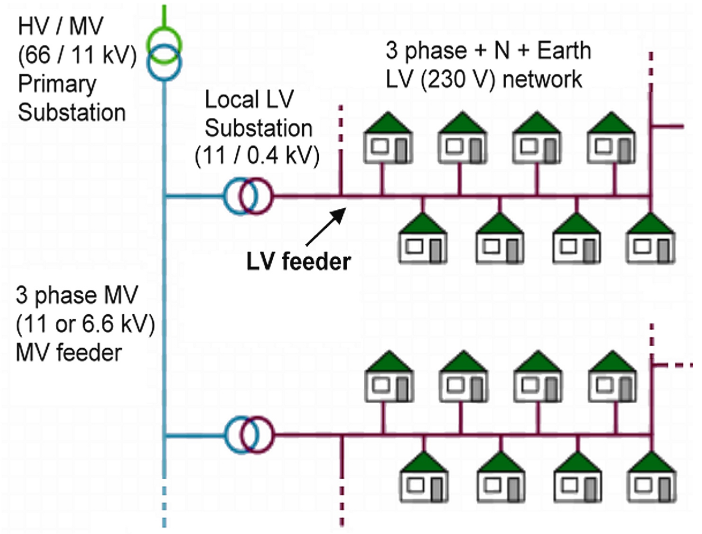


Figure 2-5: UK / EU 230 V distributed from substation to many houses via feeder

(Anon & Broderick, 2018)

The supply is at 11 kV from a Primary substation, to a transformer local to residences.

The local transformer with support equipment (the set being called a substation) converts the 11 kV to useable 230 V (aka Low Voltage, LV). Power is distributed from the substation by 3-phase feeder cables to customer houses.

One substation may supply several feeders. Feeders are long backbone style cables typically buried in-road, which connect to houses by service lines, the simplest arrangement being a herring-bone layout with a 1 phase service line to each house.

For pragmatic reasons feeders use public Rights of Way (roads) with meandering tributaries, which follow roads to houses. There is no common feeder topology.

The system is passive and intended to be maintenance-free. Figure 2-6 shows the main components of a substation:

- a disconnector switch
- an 11 / 0.4 kV transformer with manual tap-changing, for voltage adjustments
- LV phase fusing (each feeder is individually fused).

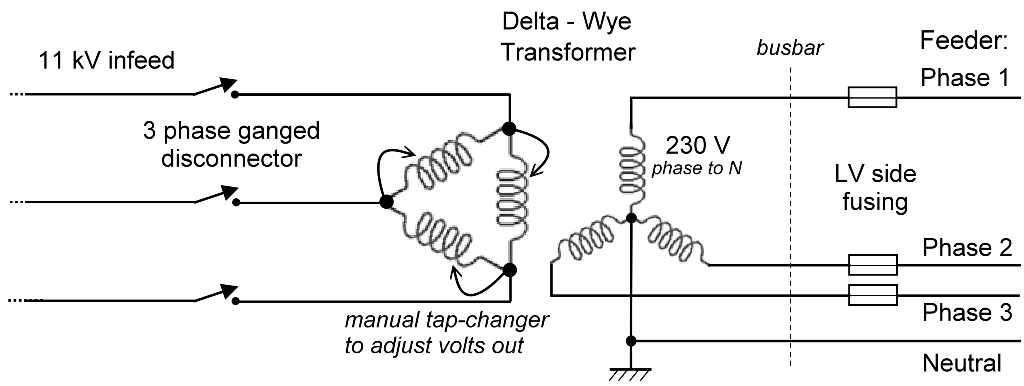


Figure 2-6: Traditional Passive Substation and Feeder

The transformer may be set to emit an excess voltage (246 V out is typical) to counter feeder volt-drops. Other feeders may connect via more fuses onto the busbar.

Each house connects to Neutral and one phase, ideally in phase 1-2-3 order. An excess of houses (hence load) on one phase is usual, causing “load unbalance”, which may see the 3 phases loaded at 70%, 40% and 25% capacity. This has little impact on single-phase loads but is undesirable, as the cable is deemed to have only 30% spare capacity.

Many LV systems are decades old but often fully serviceable. Figure 2-7 and Figure 2-8 show a typical installation:

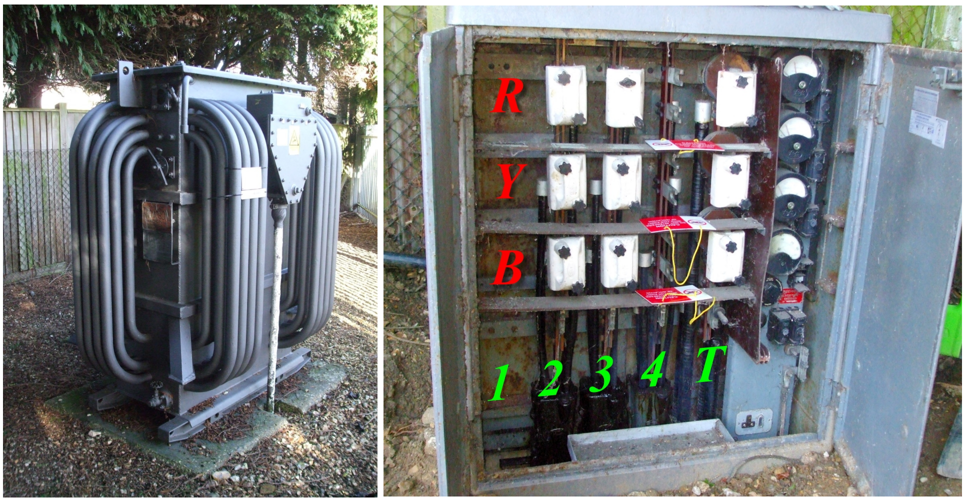


Figure 2-7-Transformer and 3-phase busbars in pillar (manuf. 1960, photo 2015)

The 230 V busbar has phases labelled R, Y, B. Numbers are feeder identifiers. This particular installation has: Feeder 1 spare and feeders 2, 3, 4 in use. T is the transformer circuit.

***Note** the rectangular white items, these are the feeder phase fuses.*

Figure 2-8: Feeder cable (Phases 1, 2, 3, N with Earth outer) and a house take-off

A freedom of information request to Ofgem stated that the UK had 584,000 LV substations supplying LV feeders, of length 30m to 500 m. Some feeders “taper” (thinner cables) as they progress, adequate as carried load drops. Three thicknesses of cable are shown.

2.1.6 Distribution Cost Management

Given that LV networks include elements up to a century old, it is difficult to estimate the value of the system. A figure of between £750 and £5,000 per supplied home is possible. Taking a midpoint of £3 k, then the value of a replacement programme to supply the UK’s 30 million homes is near £90 bn. These costs impinge on customer bills.

Two methods are used to reduce costs, hence bills:

1) a method known as ADMD rating (described below), and
2) fitting slightly under-sized assets (a practice called “distribution rating”).

Ofgem is keen to minimise spend on the Distribution system, to which end the following approaches are taken:

2.1.6.1 Build to ADMD not Instantaneous Peaks

After Diversity Maximum Demand (ADMD) is a commonly-used technique detailed in **(Northern Power Grid, 2018)** section A2.2. The idea is to accrue the load of many parties and to work with the diversified (spread) net load, not individual peaks.

At large scale, individual peaks disappear. Figure 2-9 shows 2-days of UK national demand (part from Chart 2 of **(DECC, 2014)**). Load is highest in the afternoon and evening with a regular profile; variations take hours to occur and span c. 40% of maximum load. Generation can supply this for long periods i.e. is <u>peak net load orientated</u>.

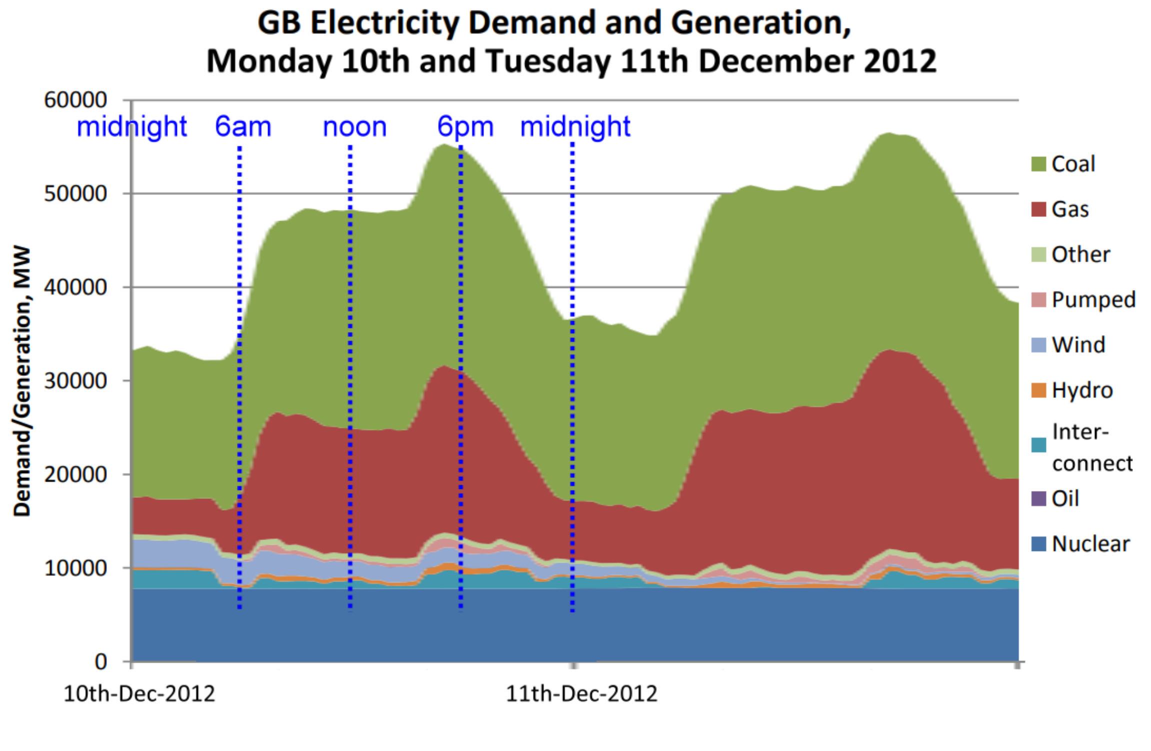


Figure 2-9: National View of Demand over 2 Days ***(DECC, 2014)***

Figure 2-10 below shows the energy use of a single home, also over 2 days. There is no discernable pattern and is highly variable with a range ratio exceeding 20:1 with brief peaks. Also, day 1 and 2 are quite different. This plot is based on real-world household energy use (from Wh metering). **Note** UK Winter household load is c. 800 W (Figure 2-4).

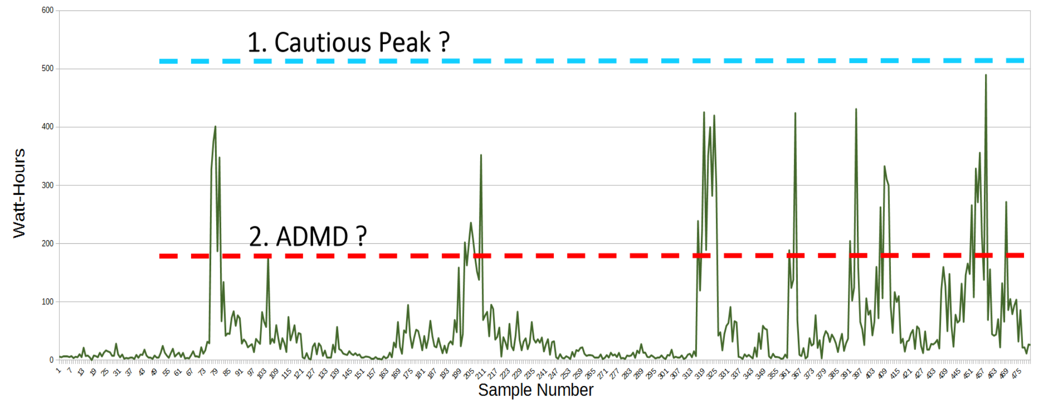


Figure 2-10: View of Household Energy Use over 2 Days

If peak-load-capable assets were fitted to LV systems, the assets would exceed typical use hence are overly expensive. A method such as ADMD allows reduced capability assets to be used, which lowers customer bills. That is to say, assets installed for Figure 2-10 duty are not intended to supply a peak up to level 1, rather are fit to supply the calculated sufficient level 2. This is practical as LV peaks last 10's of minutes not 10's of hours.

Figure 2-11 shows the load of 100 houses for two days, as seen by the substation phases.

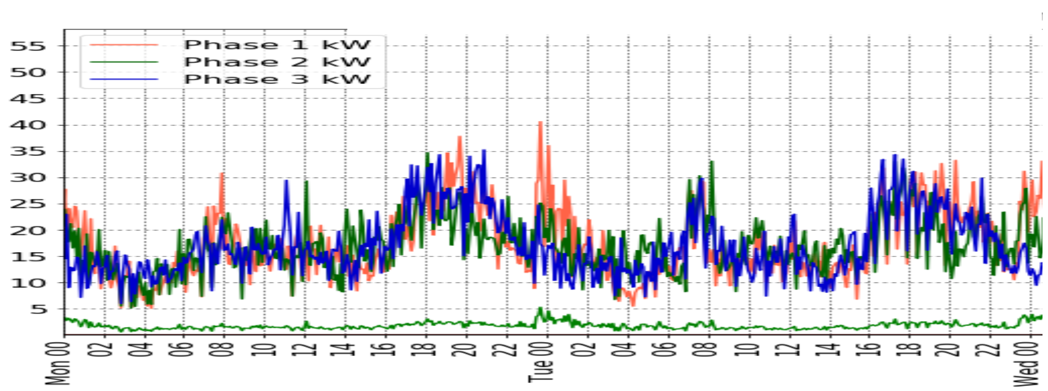


Figure 2-11: Load kW of 100 houses over 2 days, as seen by the LV substation

With c. 33 houses per phase, the overnight load has lifted but individual peaks tend to miss, so rarely add. Non-simultaneity is termed low coincidence (high diversity) and is the basis of the ADMD system. The national load profile can be seen to be forming.

The effect of non-simultaneity on pro-rata load, as number of loads rise, is in Figure 2-12:

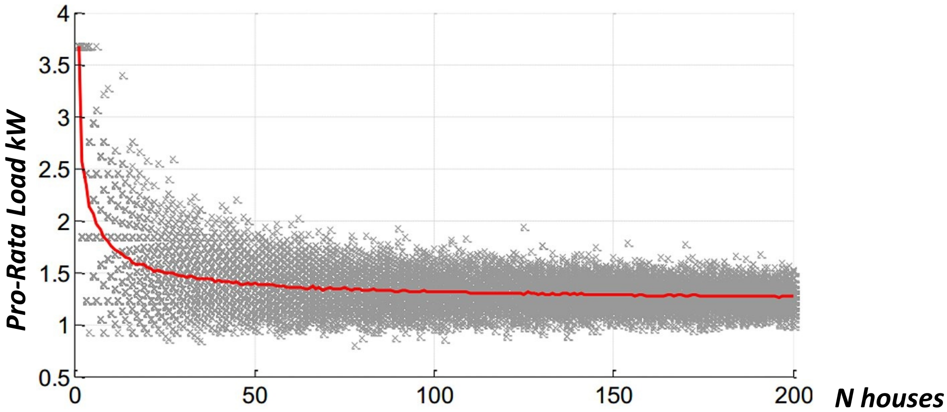


Figure 2-12: Simulated ADMD coincidence curve for a 3.6 kW load

Data generated by the CREST tool ***(Richardson, Thomson, Infield, & Clifford, 2010)***.

Figure 2-12 shows a 3.6 kW load ON for a few hours per day per home. As the count of randomised houses rise a great reduction of net load per property is seen. Thus for the case shown, a supply to 100 houses do not need assets rated at 360 kW, but at c. 180 kW, for the diversity has lowered the average load, so offering a saving on capital assets.

ADMD relies on assumptions which historically have been reasonable:

- the number of loads N supplied has been high (hundreds of houses on a feeder),
- high loads are brief so few overlap, and
- background load levels are low.

However, diversity does not assist for low numbers of customers or long duration loads.

Each DNO has its own interpretation, often a simplification presented as tables of property type (size, type of heating) e.g. **(UKPN, 2014, p10)** 4.5.11.1 or **(Scottish Power, 2016, p20)**. Given a house ADMD as 1.8 kW, a possible rule might be:

$$estate\ rating = 1.8\ x\ number\ of\ houses\ kW + 15\ kW \quad (4)$$

Eqn. (1) finds the assets for 100 houses is cabling for 200 kW and a 200 / 1.25 = 160 kVA transformer (transformers may be derated, see next section). If the nearest standard transformer was 180 kVA that may be used; if a recovered 250 kVA unit was available that may be used. The determined rating is a minimum which built systems arbitrarily exceed.

Yet some forms of load do not qualify for an ADMD treatment. Houses with electric overnight storage heaters need heating loads included at face-value, for these are synchronised by a common timer (such as Economy 7) and may run for many hours overnight - too long to experience meaningful diversity.

A modern treatment of ADMD, part of the Low Carbon London study, is in **(Konstantelos, I., Sun, M., & Strbac, G. 2014 Section 4.5)** and the more recent **(TNEI & NPG, 2019)** which overviews the methods. TNEI are using learning Bayesian statistics. This operates on household Smart Meter load data and makes dynamic refinements as data accumulates.

ACE 49 **(ENA, 1981)** is an alternative design approach. This aids building housing estates by offering statistical rules to size transformers and cables, finding a capability able to cover 90% likely loading. The method is known to yield lower ratings than ADMD.

Note in the US, the transformer to homes typically supplies 1 to 4 customers, has little diversity and may be rated c. 50 kVA. See **(Kempton et al., 2008, section IV)**.

2.1.6.2 Distribution (Cyclic) Rating

A second means of cost saving is distribution or cyclic rating. This relies on the effect: Ageing is a function of the square of duty. This suggests bursts of rapid ageing can be offset by long periods of inactivity.

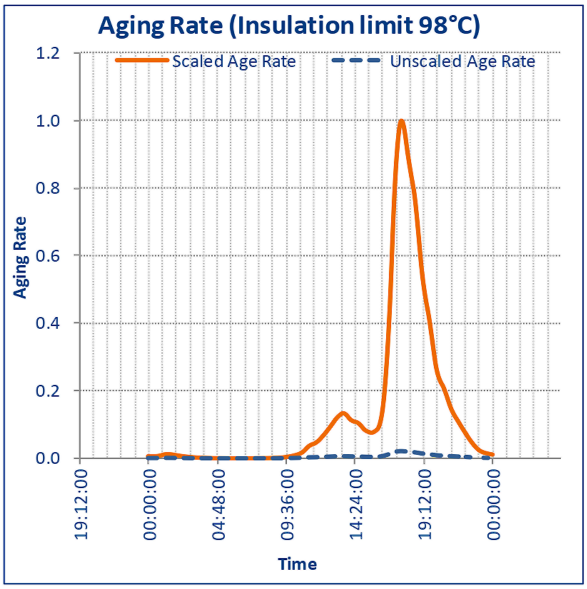


Figure 3-10 Aging Rate

Figure 2-13: (Scottish Power, 2015): A transformer accumulating ageing over 24hrs

Figure 2-13 is a plot of duty (blue dotted) causing transformer ageing (orange) in a residential network. Peak power occurs during the evening for several hours. However, transformers have a nameplate rating for continuous duty (expressed in kVA or MVA). The narrowness of the peak implies that at other times the transformer is hardly used, hence no need to fit a transformer capable of the sustained peak rating.

Fitting units under-rated by c. 25% results in: overheating during the peak of duty, with long periods (overnight) in which to cool. This method works but relies upon the use period being no more than c. 1/4 of a day. For example see **(EON, 2006)** page 157 section 3.3.3.4 which suggests 30% or 50% overloads as acceptable for various units.

Together with ADMD, the author estimates these methods save roughly 1/10th of the total costs of a 230 V LV system (planning, manpower and roadwork costs are not affected, only asset costs). Given an asset base of c. £90 bn. then c. £9 bn. has likely been saved nationally. All DNOs use variants of these systems.

2.1.7 Other LCT Loads: HP and Auxiliary

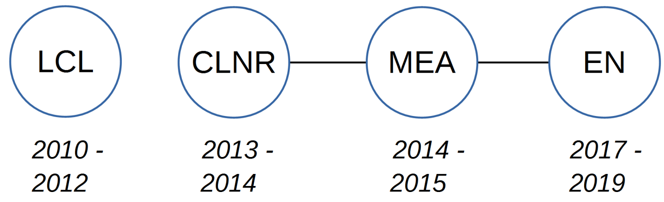
Heat Pumps (HP) are anticipated over the near decades as well as EVs. HP bring “auxiliary” loads for electric cooking and heat boosting, such as flow boilers (similar to shower heaters). Auxiliary load may exceed HP load; see **(Navarro-Espinosa & Mancarella, 2014)** and **(Good, Zhang, Navarro-Espinosa, & Mancarella, 2015)**.

HPs and auxiliaries are a major concern for they invalidate ADMD diversity assumptions. Over-night charging of EVs also invalidate the Distribution (Cyclic) Rating concept: the transformer has less time to cool. Even limited to the nominal peak level the transformer will likely overheat, so accelerating ageing.

2.2 DNO EV Projects in the UK

The introduction of LCT, initially EVs then HP, abrogates both ADMD and distribution rating methods. New, high kW loads are imposed, likely for long periods e.g. overnight.

The DNOs have been concerned as to whether their networks will be able to support EVs, so have been involved in a number of UK trials involving many EVs. Studies were run by a managing DNO and EATL as technical co-ordinator, often with universities and special interest bodies. EVs were privately owned so there was interest in how EV drivers would react to the experience; social studies often ran alongside. Leaf EVs had “Carwings” installed, Nissan’s remote monitoring and control data link (superseded by “NissanConnect”). Carwings sees all EV events; as a result most studies have considerable data. Data is not generally available due to confidentially issues, however was visible to the DNO / EATL. Other vehicles likely had various charging and driving loggers installed.



LCL:	**Low Carbon London** (72 vehicles) running 2010 - 2012
CLNR:	**Customer-led Network Revolution** (143 vehicles) running 2013 - 2014
MEA:	**My Electric Avenue** (various counts in hundreds) running 2014 - 2015
EN:	**Electric Nation** (700 vehicles) running 2017 - 2019.

Figure 2-14: The Major UK EV Trials 2010-2019

Note to 2017 small battery vehicles were trialled e.g. Nissan Leaf: 24 kWh battery and charging at 3.6 kW.

Four large projects (Figure 2-14) have run to date with DNOs and Universities, with varying goals to explore various LCT impacts on electrical systems (e.g. management at MV level), however the EV related successes were:

1. LCL and CLNR: confirmed LV problems with EV charging in city, urban and rural settings and looked at:
   a) Customer acceptance of Demand Response (DR) and Time of Use tariffs (ToU)
   b) LCT load profiles, including:
      i. EVs both private and commercial
      ii. HP and similar thermal load devices
   c) equipment thermal monitoring
   d) middle layer control and management;
2. MEA: attempted charging management, identified practical routes forward
3. EN: a recent large project covering similar areas using a mix of EVs including modern, large-battery types charging at 7.2 kW. A form of predictive modelling and control (to meet headroom limits) was performed at 11 kV using two methods.

LCL and CLNR trialled control over EVs via pricing and social imperatives (to motivate drivers as to when to connect their EVs, i.e. not automated remote control).

CLNR and MEA were run at a technical level by EATL, with MEA adopting equipment and study zones from CLNR. MEA monitored then attempted the direct control of a fleet of several hundred Nissan Leaf EVs, generating many learning points. MEA managed charging via a disconnect switch, operated by a local controller running a system called *Esprit*.

The EN project has a mixed fleet with at least two forms of Managed Charging System (MCS) and has produced several informative reports. It is apparent that, released from range anxiety, EV use is similar to traditional car use. Home charging is popular.

2.2.1 Low Carbon London (LCL)

UK Power Networks (UKPN, the DNO for London, East Anglia and South-East England) committed c. £21 mn. to the LCL project to study LCT impacts on MV and LV distribution. Partners included Smarter Grid Solutions and Imperial College London.

2.2.2 LCL Key Documents and Findings

These are at: http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Low-Carbon-London-(LCL)/ including (Table 2-1):

Table 2-1: LCL Key Documents

A Series (10 documents): Distributed Generation and Demand Side Response
B Series (5 documents): Electrification of Heat and Transport
C Series (5 documents): Network Planning and Operation
D Series (6 documents): Future Distribution System Operator

Some 88 further documents detail other aspects in, plus related papers and reports issued by Imperial College. The key document is the Summary Report **(UK Power Networks & Low Carbon London Learning Lab, 2014)** which (for EVs and Heat Pumps) points to "*B2:Impact of Electric Vehicles and Heat Pump loads on demand profiles*", **(UKPN, 2015a)** with interesting content from p.26. Conclusions are unexpected as LCL found:

- the great majority of LV systems can cope
- existing (planned replacement) programs need only be advanced by c. 2 - 3 years to cope using a BAU reinforcement method with minimal cost impact, and
- EV impacts contribute 0.3 kW peak demand to domestic loads
- Heat Pumps contribute a further 0.6 kW on average to peak load, although this was extremely temperature variable and greatly increases in very cold conditions.

Note the author, attending conferences in 2018 heard the UKPN Head of Innovation speaking of their *"...there is no issue with EVs"* stance.

Report B2 is a summary and shows in Figure 2-15 HP dominating EVs, with per EV load profiles for each day of the week, Figure 2-16, with Thursday seeing the most demand. These EVs take substantially less power then seen in other places, equating (assuming all vehicles are Nissan Leaf 24) to c. 12 mpd.

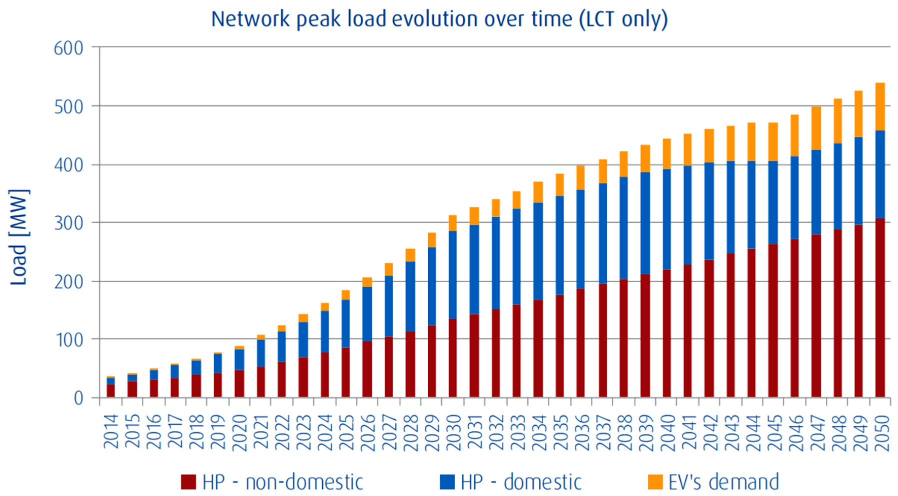


Figure 2-15-UKPN's B2 Fig.9: LCT Load projection

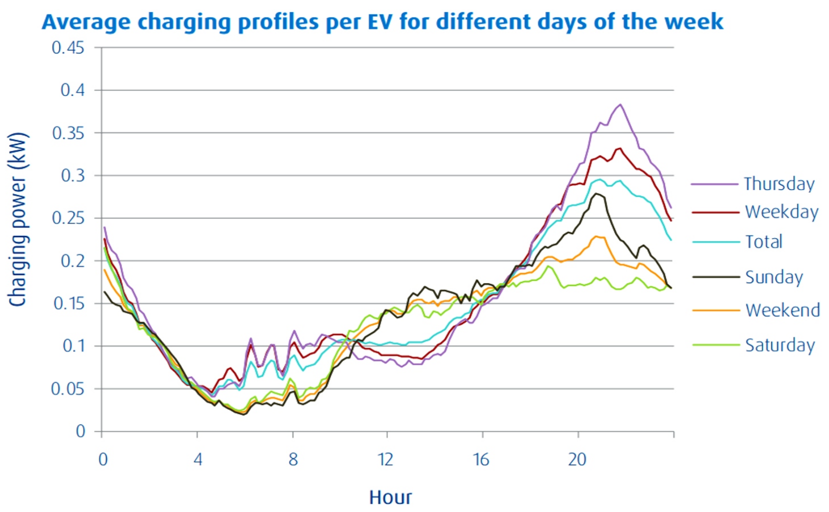


Figure 2-16: UKPN's B2 Fig. 12: EV Load by Day of Week

Factors which may influence this are: in London most commuting is by public transport, and/or cars are for going away in (charge on Thursdays for a Friday out of London trip), and/or cars are for shopping and run-about duties i.e. are second use only (the Nissan

Leaf 24 has about 70 - 90 miles real-world range, less in Winter). Finally, a scarcity of chargepoints in 2010 limiting confidence in availability of destination charging, implying long trips are avoided. No long trips means reduced network load.

Heat-pump load projections are at c. x2 EV load (see document B4, **(UKPN, 2015b)** page 6; in extremes HP raise household ADMD to 4.5 kW). However the take-aways are:

a) EV use is situational
b) EV use may vary by region,
c) EV use may vary by the nature and capabilities of the EV
d) EV use may be affected by expectations of recharging availability
e) charging patterns may vary over the week, due to variations of charge-to-hand and the expectations of the driver.

The next project, CLNR, was run in the North-East of England so may vary vs. LCL.

2.2.3 Customer-led Network Revolution (CLNR)

The Customer-led Network Revolution project ran 2010 - 14, again delivering a library of reports and papers (see: http://www.networkrevolution.co.uk). These state CLNR involved c. 11,000 domestic and 2,000 industrial and commercial customers in the North-East of England. Northern Power Grid (NPG, a DNO) headed the project with technical help from EATL and Universities of Durham and Newcastle. CLNR trials covered two broad areas:

- customer survey and responses to living with:
    - solar PV, Electric Vehicles, Heat Pumps, Micro-CHP, Smart Appliances
    - Time of Use Tariffs, General Load Customers
- network technology trials which included:
    - Real Time Thermal Ratings, Electrical Energy Storage and “Grand Unified Scheme”
    - Network Monitoring and Enhanced Automatic Voltage Control (EAVC)
- and gathered real-world data for inclusion in the TRANSFORM model.

TRANSFORM is a model of the UK power system focussed on asset management, to assess expected scenario power-flow vs. existing equipment capability.

The network monitoring and social studies aspects of CLNR became carried into MEA i.e. clients were shared, with CLNR undertaking the broader picture and MEA undertaking EV specific studies with focus on control.

The CLNR project did not control EVs via some form of Smart ICT, but did attempt "passive intervention" via social nudging using smart apps to encourage use of special deferred charging tariffs. These were found effective.

2.2.4 CLNR Key Documents and Findings

CLNR resources are at: http://www.networkrevolution.co.uk/ with key findings in bands:

- MV / Middle Layer view
- LV / Delivery Layer View
- LV networks are very different one to another; each has a specific profile which may be unique in the region
- EV specific findings.

Key CLNR papers include: "Insight Report Electric Vehicles" **(Wardle et al., 2015)** which states why so many Leafs were available (the Nissan Leaf is manufactured in the study area). The document includes graphs for household load (Figure 2-17 and Figure 2-18), with the total load (solid blue line) by eye c. 0.2 kW above TC1a (plain household load). Many similar graphs are presented before concluding that load from charging is an interplay between new arrivees connecting and earlier vehicles completing their charging.

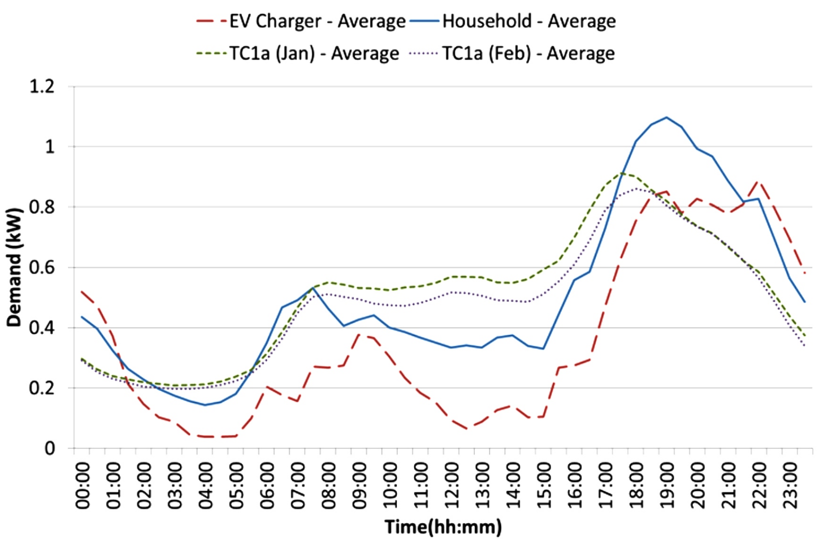


Figure 2-17: Wardle et al., 2015: Weekday Average Demand

Artefacts of sample selection arose when comparing households with and without EVs (Figure 2-18): EV users (blue) had lower daytime loads than the control. This was traced to more retirees in the control group (TC1a); the dip was due to TC6 parties being at work.

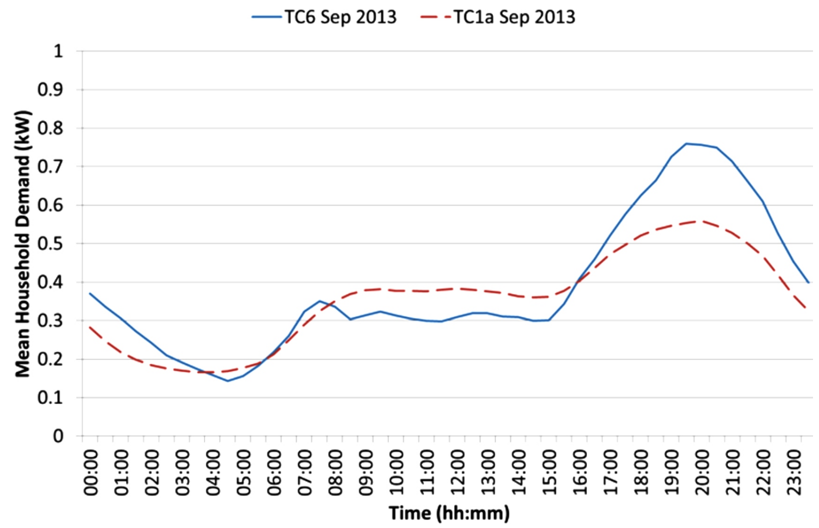


Figure 2-18: Wardle et al., 2015, Fig. 41: Households With and Without EVs

Some owners charged on overnight tariffs e.g. Economy 7 (c. midnight to 7am). The load profiles are c. 0.2 kW lower late evening, continuing to c. 2 - 3am then diminishing, consistent with an average charging duration of 2 - 3 hours (peak EV load: 3.6 kW).

CLNR was quite aware of the marginality of the Leaf EV technology as a car replacement, and saw an EV able to mimic the ICE car as more of a network threat. CLNR also pinpointed the rate of charging issue: larger batteries are needed for longer trips; present chargers are too slow / impractical for such batteries thus kW charging rates must rise (although this was foreseen as more of an issue for motorways).

The CLNR Closedown Report **(Northern Power Grid & Sidebotham, 2015, p14)** says that EV owner households retained typical domestic use of electricity with the EV load added, that there was a lot of variation in the EV loadings with a peak seen about 8pm on weekdays. Heat Pumps doubled peak load. The work concludes that EVs have a major impact on the LV network, but is not yet a problem. Promoting off-peak charging was suggested as a way to reduce the EV load impact.

This document also presents the costs analysis of network HV / MV reinforcement and control options explored (omitted from this thesis, but an interesting source).

2.3 My Electric Avenue and *Esprit*

My Electric Avenue (MEA) was a logical outgrowth of CLNR. Operated by EATL and SSE, MEA attempted incentivising charging habit changes and an active, ICT form of Demand Side Response (DSR) to curtail load growth. The mechanism for this was "*Esprit*", a local controller at the substation. This monitored feeder phase loads and operated an EV chargepoint switch, so disconnecting the EVSE and EV from power during high load.

Table 2-2 shows a simplified *Esprit* algorithm (which captures the core principle, see **(Cross, 2015, Section 3.3)**:

Table 2-2: Simplified Esprit Algorithm at Substation

- for each phase:
  - wait for a period then:
    - calculate headroom = cable phase rating - measured load
    - if headroom was positive:
      - find the "least time on charge" open EVSE disconnector:
        - reconnect the EVSE *(NB only one reconnect per period)*
    - if headroom was negative:
      - turn **all** phase EVs off i.e. open all on-load EVSE disconnectors

The method is simple and:

- offers proportional fairness i.e. everybody gets the same time-on-charge
- follows net load peaks from residential loads, and
- does not need to know the EV internal State of Charge (SOC), reducing comms needs.

Esprit successfully curtailed overloads yet on occasion some EVs were undercharged. An unexpected problem was communication difficulties, thought due to technology choices.

2.3.1 MEA Key Documents and Findings

The MEA website http://myelectricavenue.info/project-deliverables resources include the project Close-down Report **(EA Technology & Roberts, 2016)** describing commercial arrangements and whole-project learning. Figure 2-19 shows the EV load per house, and

Figure 2-20 shows induced thermal load (as %) vs. number of EVs, with *Esprit* curtailing overload (the 3 dashed lines) as N EV rises.

Without *Esprit*, the Winter plot (Figure 2-20, solid blue) reaches thermal limits at 20 EVs (per 100 houses) yet in Summer (solid green) supports 50 EVs. There is no reason to suppose *Esprit* could not similarly control 7.2 kW charging.

The success of *Esprit* raises the spectre: A curtailment system allows an arbitrary number of EVs on any network. Excess EVs remain turned off. How, then, do these get charged?

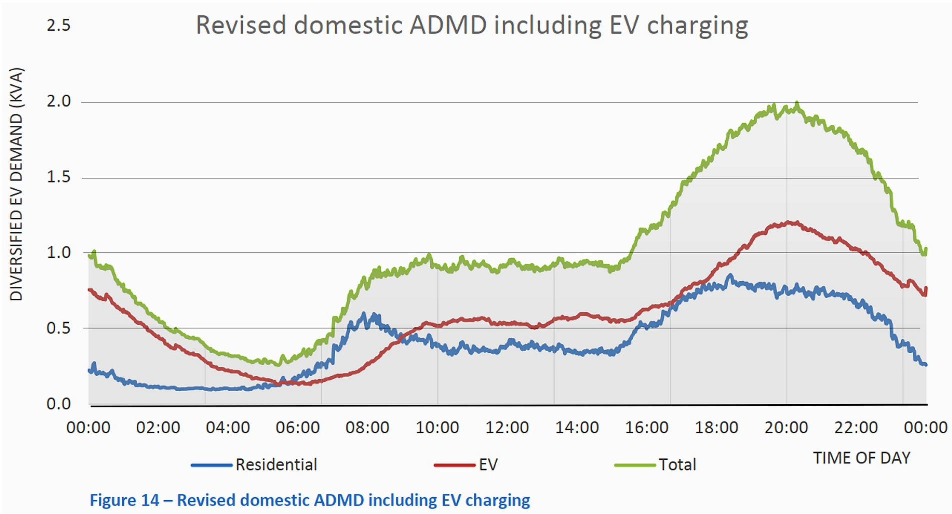


Figure 2-19: EA Tech, 2016 Fig. 14: Revised domestic ADMD with EV

Concerning the merit of the *Esprit* system. Is *Esprit* a beneficial way forward to address LV charging issues? James Cross considered this in *"An assessment of how much headroom an Esprit type solution would yield"* **(Cross, 2015)**.

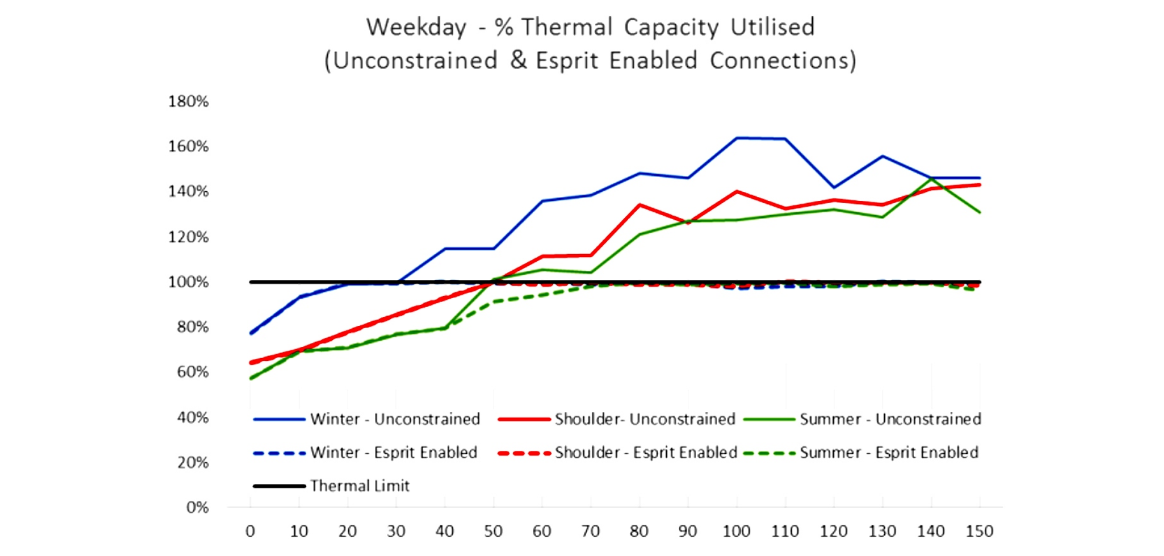


Figure 2-20: EA Tech, 2016 Fig. 16: Esprit impact for N EV per 100 homes

He relates that MEA's *Esprit* system operated over 7,000 times to curtail excess demand; found that EV charging lifted the evening peak from 0.8 to c. 2 kW; that EVs cause thermal overloads and voltage problems on LV systems and (projecting MEA results) suggested that otherwise c. 312,000 UK feeders would need reinforcement to support 70% EV penetration. He considers that an *Esprit* derivative would need deployment from c. 2021 in selected areas, and the value of spend deferred to be c. £2.2 bn. He then highlights the major constraints on MEA:

a) the Leaf is not representative of likely future EVs
b) charging rates will likely become higher, and
c) the area is volatile as new standards and EVs emerge.

However reading around the subject the author met a major area not as yet considered. This is transformer ageing and formally out of scope, accelerated by solutions such as *Esprit*, due to sustained not cyclic high loads. Accelerated ageing must be anticipated and is discussed in section 2.7.

2.3.2 Variations on *Esprit*

Examples are Quirós-Tortós's "Control of EV Charging Points for Thermal and Voltage Management of LV Networks" **(Quirós-Tortós, Ochoa, Alnaser, & Butler, 2016)** and "HPC-Based Probabilistic Analysis of LV Networks With EVs: Impacts and Control" **(Procopiou, Quirós-Tortós, & Ochoa, 2017)**, a follow-on work which applies High Performance

Computing to Quirós-Tortós' method. A parallelised multi-path approach is used, an iterative (i.e. game-playing / path seeking) approach to finding best outcome.

The overall concepts are similar to what has been seen. Present loading hence possible extra loading is determined, an objective function is solved and EVs are turned on and off according to the solution.

Both papers focus on electricals, testing LV voltage levels at key points. Realistic networks are employed and the suggested EV switching is applied to an OpenDSS LV model. A new metric "Customer Impact Level" (CIL) is used, quantifying the impact given EV drivers suffer by their EV not being charged when wanted. CIL consists of a series of histogram bins for the "time to charge vs. expected" ratio. CIL is the bin number, 0 … N. The objective is to balance the network and minimise CIL rating. Both use Nissan Leaf charging profiles of 3.5 kW and assume EVs connect once daily and charge in one burst. Both use multi-minute control cycles, as in MEA / Esprit trials.

2.3.3 Impact of MEA on UK Charging Policy

UK Charging Policy is impacted by MEA, although the form is not clear. SSE has formally requested an amendment to Smart Meter operation **(SEC & Hartshorn, 2018)** which is not yet resolved. This seeks DNO ability to disconnect or modulate individual EV charging.

2.3.4 Learning Points from MEA

The learning points from MEA are presented in **(Quirós-Tortós, Ochoa, & Lees, 2015)** as:

- weekday charging varies compared to weekend (Figure 2-21)
- weekday day-to-day charging is similar, but not identical
- there is minor seasonality e.g. charging rates in Autumn are higher than Winter
- there is c. +/- 2% seasonality in driving distances across the year.

These reflect UK commuting on weekdays vs. weekends and is cultural. Any solution must not depend on curve shape, for this may change e.g. a special event or area emergency.

MEA authors projected 7 kW home charging from MEA data, as Figure 2-22. This is based on Nissan Leaf usage, very much a town runabout rather than a true car replacement.

Also, users of the 2014 Nissan Leaf 24, without <u>assured</u> destination charging, would not

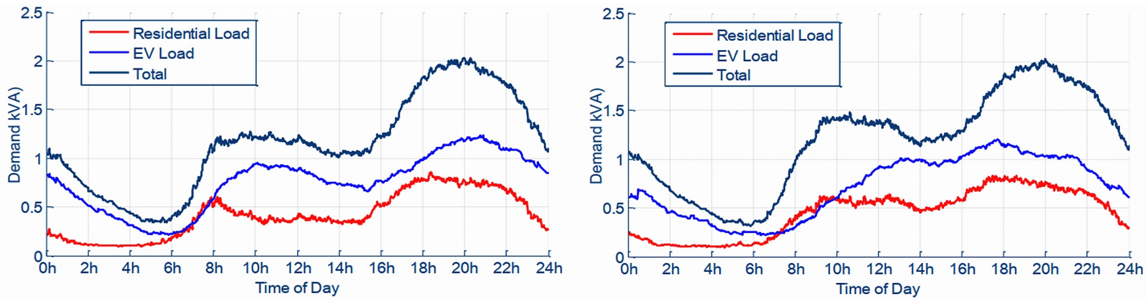


Figure 13. Diversified winter weekday profile: Residential + EV Demand.

Figure 14. Diversified winter weekend profile: Residential + EV Demand.

Figure 2-21: Quirós-Tortós, 2015: Weekday vs. Weekend MEA loads

.

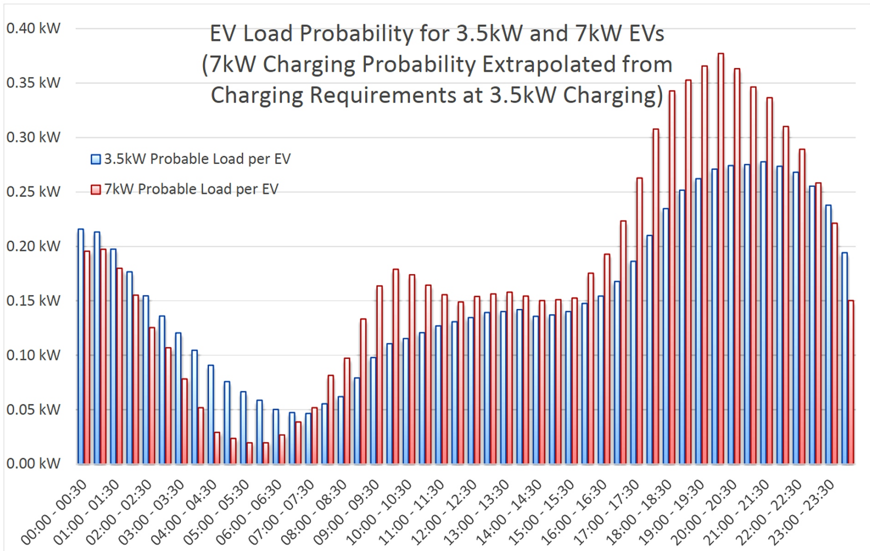


Figure 15 – Average daily load profile for 3.5kW and 7kW chargers (extrapolated from 3.5kW data)

Figure 2-22: EA Tech, 2016: 3.5 kW and projected 7 kW EV load probability

willingly take a trip in Winter to a location beyond 20 miles away. From this it is seen that MEA conclusions suffer on at least two fronts:

- the Leaf does not have the charging load of a contemporary 7.2 kW EV, and
- 2014 MEA results cannot represent the consumption of driving energy (taken from a home EVSE) in Winter; Leaf range is inadequate so is either not driven or is charging elsewhere (not drawing necessary kWh at home).

Given the reported range anxiety of MEA participants, Leaf drivers likely used alternative transport (especially in evenings) to avoid being stranded the next day. Does MEA then represent the likely demand of a future EV fleet? MEA is suspected to understate:

- instantaneous domestic + charging load
- total energy load (in all other than in short range situations i.e. in a major city)

thus MEA measured loads do not reflect the energy demands of long-range drivers, for the Leaf was not capable of such use. Leaf energy draw is capped for driving 70 - 90 miles (Summer), 40 - 50 miles (Winter). Using a Leaf means charging away from home.

Assuming EVs replace cars, EVs will likely be driven as a car. How then are cars driven?

2.4 Use of Vehicle and Mileage Driven

The RAC Foundation **(RAC, Le Vine, & Polak, 2009)** analysed UK driving behaviour forming the summary plot Figure 2-23. What is seen is: Both location and income affect how far people drive. It is assumed by the author that these are the most significant factors which relate; others (e.g. temperature, rain, terrain etc.) are less significant.

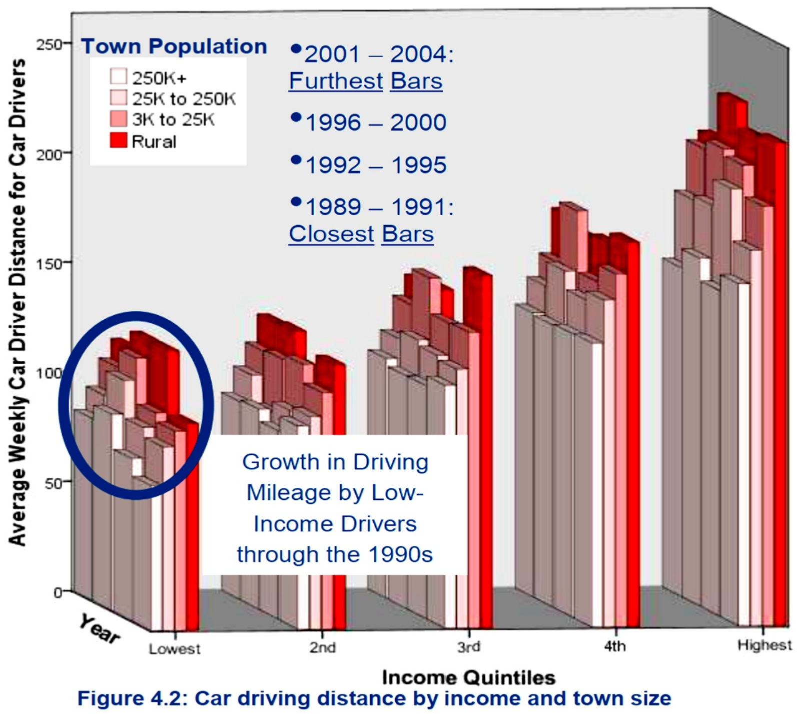


Figure 2-23: RAC, 2009: Car driving distances by income and location

From Figure 2-23, in general:

- the smaller the conurbation the individual lives in, the further they drive, and
- the higher the income, the further individuals drive (although it is also seen that in recent years, relative poverty also promotes driving).

Further, it is seen in present society people of similar means are (broadly) co-located i.e. neighbours are economically similar; stratification is between neighbourhood areas.

Thus, the author will take a step of generalisation:

- neighbourhoods have similar wealth thus similar driving range,
- spanning 80 - 220 miles per week i.e. 12 - 32 miles per day.

2.5 The Parsons Brinckerhoff Study

A substantial, detailed study of sample UK DNO networks from 132 kV to LV was undertaken for ENA by the Parsons Brinckerhoff / DS2030 Consortium **(King, ENA, & Parsons Brinckerhoff, 2016)**. This analysed projections for 2030, complete with HP, PV, local storage and EVs. The work is included for completeness. The study is in depth and formalises much of the material seen so far.

2.6 Electric Nation - A Contemporary Project

A further live-trial of EVs “Electric Nation” **(Electric Nation, 2017)** aka “EN” commenced late 2017. This was run by WPD **(WPD, 2018a)** with EATL and others (Lucy Electric, TRL and various EV / EVSE suppliers). EN continues the spirit of MEA with the following differences:

- many more EVs (c. 700)
- many marques / models
- many use 7 kW charging
- batteries are sufficient to approximate the range of a traditional ICE car.

The purpose of EN (https://www.westernpower.co.uk/projects/electric-nation) was to form approaches to allow EV load growth to be managed, including tools for assessment and an exploration of control methods with LV network monitoring.

This is performed by running trials to gather data, simulating a MCS similar to *Esprit*, now with V2G. An EN trials video is released at https://youtu.be/wFBhvdjlc5A. A network assessment tool (NAT) is to be produced, the subject of a separate report **(WPD, 2018b)**.

The October 2018 report update **(WPD, 2018c)**, presented data shown in Figure 2-24, Figure 2-25 and Figure 2-26. An early report **(WPD, 2017 Section 4)** relates driver habits:

- plug-ins are more sporadic / as needed vs. habitual (MEA)

  => EN drivers do not suffer the endemic range anxiety of MEA drivers,

- there is diversity of habit:
    - from the “regular plugger-in” (as if a Smart Phone charged over-night)
    - to “plug-in only when it needs it” (like fuelling a car as and when needed),
- some do use timers to access cheap-rate Economy 7 power.

Note that EN experiences the following:

- of 673 vehicles, only 130 are large battery (>35 kWh) types,
- vehicles are dispersed i.e. not supplied via one feeder
- maximum EV density is 30 %, and
- charging management is simulated at 11 kV level, not LV.

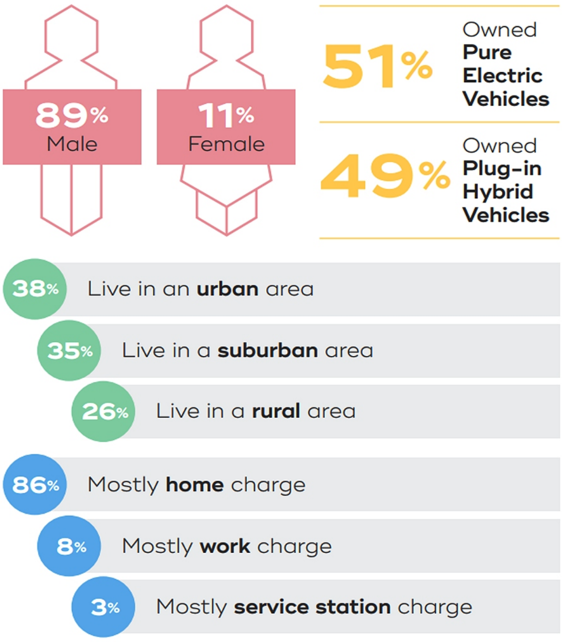


Figure 2-24: WPD, 2018c: EV Owners and Charging Activities

Electric Nation provided insights into people’s charging behaviour and motivation to change charging habits, but is of limited use re LV studies: EVs still have small battery sizes, penetration levels are low and the electrical focus was on MV loading, not LV. There is no mention of Heat Pumps. As in MEA, EN found communications problematic, with the Internet inadequate/unreliable..

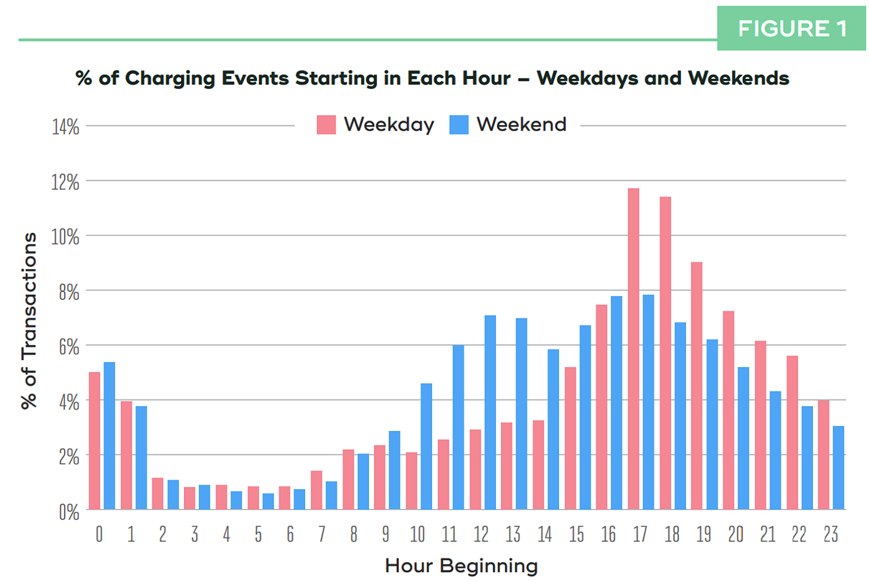


Figure 2-25: WPD, 2018c: Number of Home Charging Events in Hour

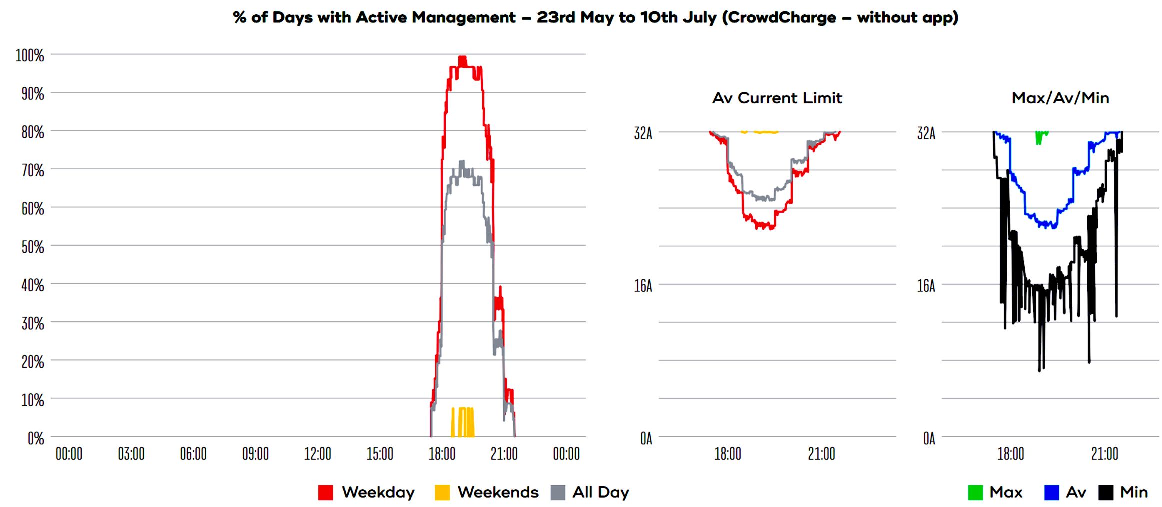


Figure 2-26: WPD, 2018c: % of EVs Controlled (32A = 7.4 kW)

The Electric Nation project has been watched by other DNOs, prompting an apparent change of heart at UKPN. In **(UKPN & Halsey, 2018)** UKPN used early EN data to plot the diversity of 7kW EV vs. N customers (Figure 2-27). This shows 100 EVs draw c. 100 x 0.25 x 7 kW i.e. 175 kW (not including household domestic or other loads).

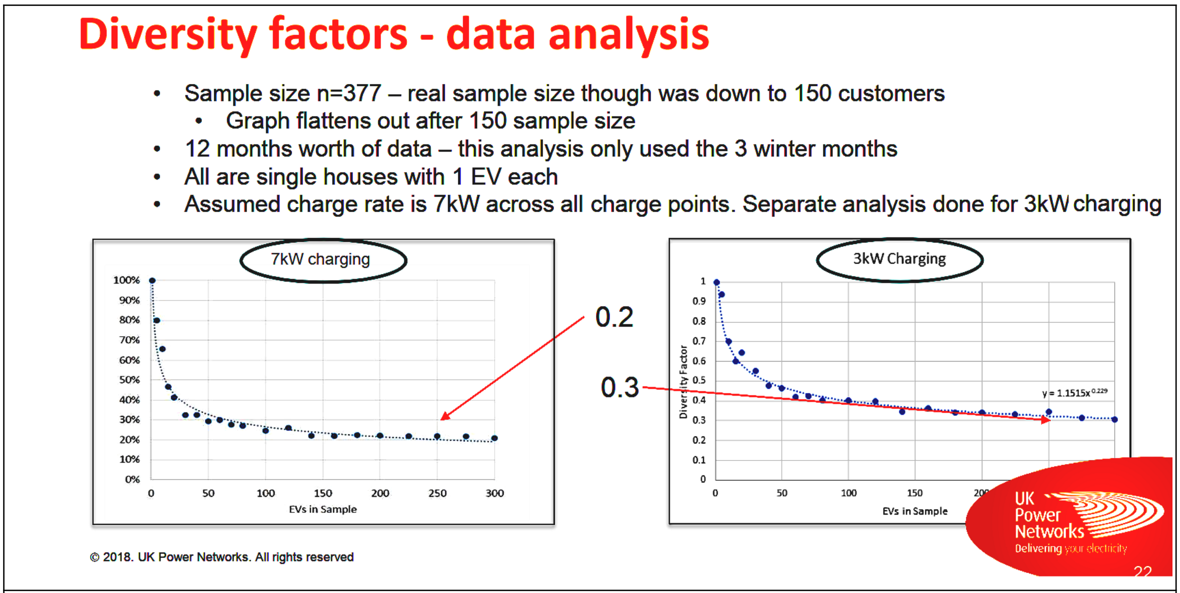


Figure 2-27: UKPN & Halsey, 2018: ADMD plots for 7kW and 3kW EV charging

2.7 Further Concerns

The power industry has further concerns due to EVs: Excessive transformer ageing and excessive harmonics. These are not in scope but impact DNOs, so will be described.

2.7.1 The Risk of Elevated Transformer Ageing

The paper "Impacts of High Penetration Level of Fully Electric Vehicles Charging Loads on The Thermal Ageing of Power Transformers" **(Qian, Zhou, & Yuan, 2015)** finds EVs increase the rate of LV transformer ageing, supported by Scottish Power's "Enhanced Transformer Ratings Tool - Application Guide" **(Scottish Power, 2015)**.

Although methods such as Esprit halt immediate overloads, the method will cause the residential substation transformer to spend long periods at full duty. Present duty is a narrow peak; Figure 2-13 shows the evening peak causing a burst of ageing. This diagram illuminates why a transformer, given a peak duty of x1.25 rating, can operate for decades: Most times, distribution transformers are worked but lightly. The figure shows duty (age) accumulating for c. 4 hours a day.

By limiting peak loads and extending charging timewise, *Esprit* and similar MCS systems stop immediate network failure but increase the duration of sustained load, degrading transformer life. If EVs increased maximum throughput from 4 hours a day to 12 then the transformer ageing rate triples; calendar life drops to 1/3rd expected. Yet transformers are relatively simple to replace without great roadworks.

What sort of cost might that be? Consider a UK DNO with 150 k substation transformers. Assume 90 k suffer 1/3rd life - which would have been 120 years, but is now 40 years. Instead of replacing 750 units pa the DNO now replaces 2,250. Guestimate costs of the unit to be £40 k with £5 k other costs. This suggests an extra spend of £45 k * 1,500 i.e. c. £68 m pa. As far as the author knows, this issue has not yet been highlighted.

2.7.2 Harmonics

Another aspect is harmonic output of EVs, due to current distortion caused by inverters. Harmonics raise LV losses and interfere with other equipment. There are regulations (IEC 61000-3-2 and -12) to which electrical appliances (including EVs) are to comply. Also, the DNO is regulated to ensure they are not passing harmonics to other parties via their network; DNOs do not want harmonics entering their system.

WPD with RINA Consulting **(WPD, 2018d)** studied 24 individual EVs of various marques (2016 and 17 build), measured the harmonics from each then calculated the number of EVs the networks could tolerate. Harmonics test results (Table 2-3) are informative:

Table 2-3: (WPD, 2018d, p23): *EV test results vs. Harmonic Limits*

Vehicle	Charge Rate (kW)	IEC61000-3-2	IEC61000-3-12 (R_{sc}=33)	IEC61000-3-12 (R_{sc}=66)
2	7.2	Fail	Pass	Pass
5	7.2	Fail	Pass	Pass
6	7.2	Fail	Pass	Pass
8	7.2	Fail	Pass	Pass
9	6.6	Pass	Pass	Pass
10	7.2	Fail	Pass	Pass
11	7.2	Pass	Pass	Pass
12	7.2	Fail	Pass	Pass
16	7.2	Fail	Pass	Pass
21b	7.2	Fail	Pass	Pass
22b	7.2	Fail	Pass	Pass
23	7.2	Fail	Pass	Pass
24	7.2	Fail	Pass	Pass

Yet counts of thermally-acceptable EVs WPD plot (vertical bars) are of more interest (Figure 2-28, Figure 2-29). These are with interventions to assist meet harmonics regulations. Without such intervention, harmonics limits are met before thermal limits.

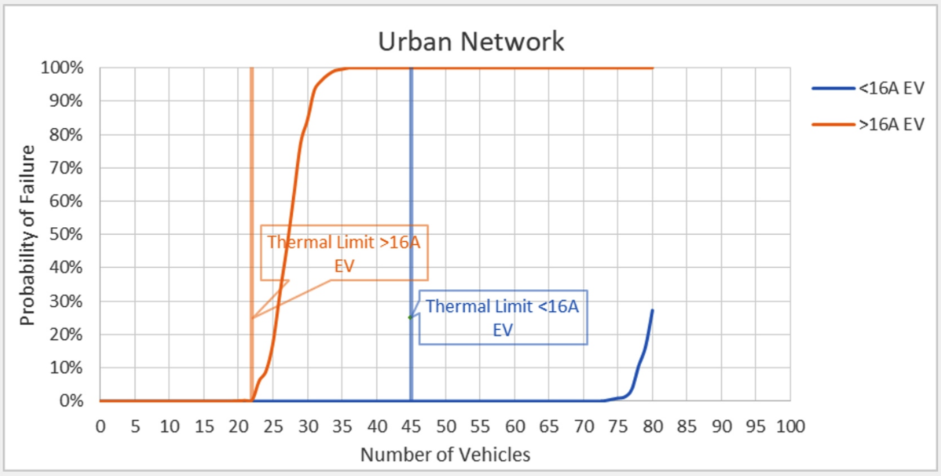


Figure 4-5: Urban network with a maximum source impedance of 0.127+j0.068 Ω with typical upper quartile EV harmonic current, WPD background harmonic distortion and Z_h calculated as per equation 2-2

Figure 2-28: WPD, 2018d: EVs on Urban Networks: Thermal and Harmonic Limits

.

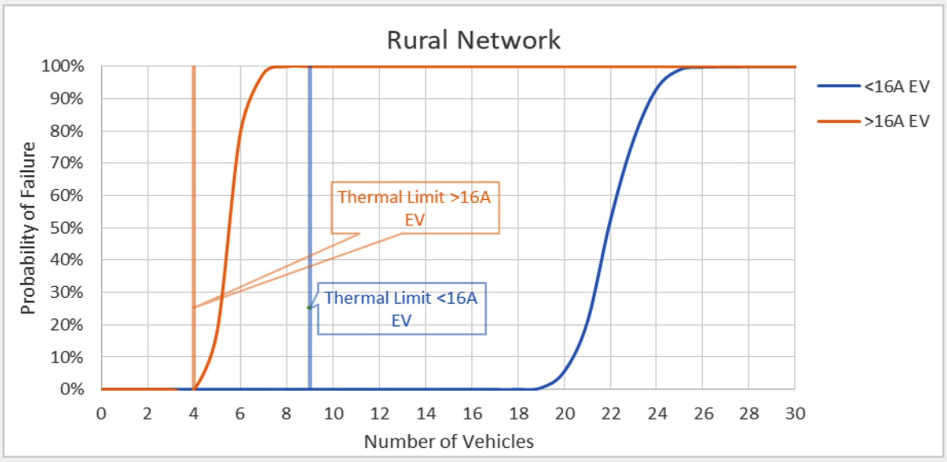


Figure 4-6: Rural network with a maximum source impedance of 0.21+j0.126 Ω with typical upper quartile EV harmonic current, WPD background harmonic distortion and Z_h calculated as per equation 2-2

Figure 2-29: WPD, 2018d: EVs on Rural Networks: Thermal and Harmonic Limits

This indicates 22 x 7 kW chargers or c. 45 x 3 kW chargers are thermally acceptable on an urban network (500 kVA i.e.) and 4 x 7 kW chargers or c. 9 x 3 kW chargers are thermally acceptable on a rural network (100 kVA), post harmonic reduction intervention. The work concludes that the DNO should lower LV network impedances back to source so to sink the excessive harmonics, the case modelled in the figures.

Traditionally, WPD fit c. 1.3 kW minimum for a 3-bed semi-detached house; a plausible build being 1.5 kW. Both Table 1-1 and Figure 2-28 show such a network fails over 20 EVs per hundred houses, so broadly agree.

2.8 The Coming of the Smart Grid and Smart Meters

2.8.1 General Practice Pre Smart Grid

The UK power networks has a system of information flow and control, typically from Transmission to DNO Primary level. This is implemented using Supervisory Control and Automated Data Acquisition (SCADA) systems **(Ujvarosi, 2016)**. SCADA and accompanying control systems could sense, communicate and accept commands to change device settings. The primary SCADA tasks were:

- data logging
  - power flow monitoring
  - voltage sensing
- sensing / controlling position of circuit breakers
- operating switching elements (dynamic network configuration)
- fault sensing and contingency management ("protection" systems)
- connecting and dialoguing with Distribution Management Systems.

These systems have been in use for decades and are very adequate. NGET reports uptime; Reliability of Supply in 2017 was 99.999962 % **(NGET, 2017, p7)**.

2.8.2 What Is a Smart Grid?

The Smart Grid is a US concept intended to aid network management. **(CRS & Sissine, 2007)** states the goals of the US Energy Independence and Security Act of 2007 are to use ICT systems to improve responsiveness, improve utilisation (of existing assets) and enhance system reliability.

The Smart Grid concept revolves about use of pervasive ICT to enable:

a) the ability to remotely turn off equipment, via
b) a control signal (in the UK known as Demand Side Response or Automated Demand Response)
c) also informing customers as to real-time costs (of changing electricity tariffs),
d) implemented by the flow of information between a Utility and a customer.

The Smart Grid included Quality of Service monitoring (regarding power outages, hi / lo voltages, power factor, harmonics), however load control (a) is the key benefit. See also collected papers from early years stating US hopes: **(TheCapitol.Net, 2009)**.

Note that this refers to the Utility, an entity no longer existent in the UK post privatisation. Instead, the UK has the network operator (DNO) and many retailers. The abilities of Smart Grid control, in the UK, are held by the retailer (who sell electricity, and have no contact or involvement with network practicalities).

An alternative source of information concerning the UK Smart Grid intent is the UKERC's "Scenarios for the Development of Smart Grids in the UK" **(UKERC, 2014)**.

2.8.3 The Origin of the Smart Grid - Blackouts in America

The US grid, circa 2000, was characterised by working for profit to (latterly found) rigid contracts, with poor equipment monitoring, repeated underinvestment (asset sweating) and control resources only sufficient for normal (not exceptional) operation.

On 14th August 2003 the North-East of the US and Canada suffered a wide area blackout **(Liscouski & Elliot, 2004)** for four days. 50 million people were affected and an estimated $4 - 10 bn. losses suffered. The outage precipitated in stages from:

- a period of high load,
- an out-of-service power station,
- a transmission line fault,
- operator confusion due to out-of-date data, and
- poor communication between parties.

The report found contributory issues as:

- too great an instantaneous load for the generation base to supply
- insufficient monitoring
- obsolescent IT systems
- insufficient preparation for contingencies
- inflexibility of contract terms
- unclear standards concerning operational practices

- occasional lip-service to standards
- inability to track and manage an evolving / cascading situation
- siloing with party A unaware of capabilities and actions of Party B.

The system was under-prepared and uninformed. An example: aspects of operational management relied on week-old printouts.

2.8.4 Key Smart Grid Tools

The key approach of Smart Grid is to improve ICT, allowing:

- load flow monitoring and
- active load management, enabled by
- the ability to turn off consumer loads via a Smart Meter (which can also report other data, including the present meter reading).

Implicitly, the reach is wide-area, viewed from a high node of the network hierarchy. **Note** this presupposes:

a) the grid is overburdened and
b) there are loads worth turning off.

Another possible application is dynamic "Time of Use” (ToU) tariffs. Here, a Smart Meter defers turning on load (e.g. a clothes drier) until electricity was cheap, so saving the customer money - and reducing the network’s need for more capable assets.

A variation was to pair the Smart Meter with a readout device advising customers how much electricity they used, aiding parsimony through improved awareness.

2.8.5 A Market Connection

A major element is "management by markets". The Smart Grid was a tool enabling market intervention, so providing services to meet instantaneous system needs.

The Smart Grid might monitor and report network states and identify shortfalls (an instantaneous demand for, say, frequency regulation) serviced by a for-profit actor, selected by market competition. Given the successful trade or exercise of an option, the Smart Grid operates connected equipment to fulfil the contract.

2.8.6 Differences between UK and US Distribution Systems

At the highest level, the US and UK electrical systems appear similar: electricity is generated and made to cascade down to customers. However, the LV systems are different. This is relevant, for assumptions re loads and LV system capability appear present in the Smart Grid concept, given a US not UK context.

In contrast to the UK's domestic mean load of under 1 kW, the US LV system needs serve power levels peaking over 10 kW to homes set further apart then in the UK. Figure 2-30 plots the daily load of two US houses: (a) a very small house and (b) a typical house **(Pipattanasomporn, Kuzlu, Rahman, & Teklu, 2014)**. Loads (b) peak near 14 kW.

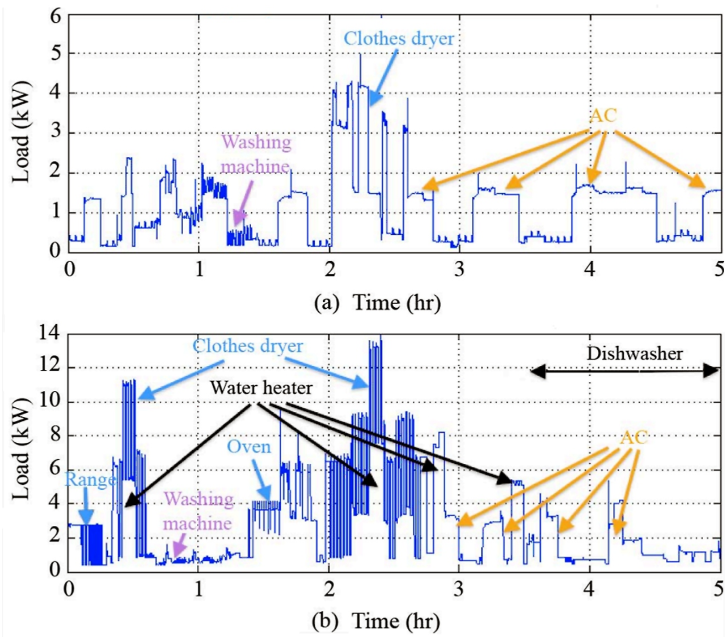


Figure 2-30: US Household load profile

An issue now faced is electrical energy loss, proportional to the square of current. This is problematic as to deliver a given power kW (where power = Volts x Current) the US 120 V system delivers twice the current as a 230 V system, quadrupling losses. Further, US houses are often set far apart; cable runs are long also promoting losses. To overcome these issues an alternative LV design is used (Figure 2-31, **(Anon & Broderick, 2018)**).

Power at 2 - 4 kV is distributed to houses by 1-phase laterals. The use of high voltage reduces current, hence losses. Each house (or small group, say 4) is supplied with bi-phase (anti-phase with centre tap: 120-0-120 V) via a pole-mounted transformer, set beside houses. This offers 120 V to small appliances or 240 V across extremes for large loads.

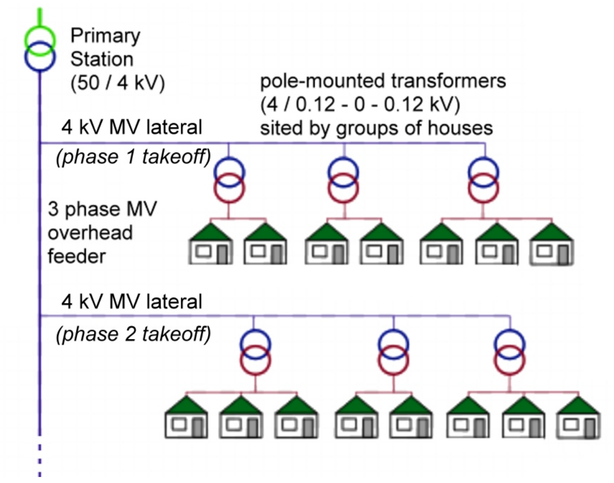


Figure 2-31: Generalised US LV system with transformers set by houses

Note US Utilities are not unbundled, so retail power and own the Smart Meters. The Utility can control thermal loads via the Smart Meter, to respond to network concerns. Thermal inertia allows brief load suspension with little impact to residents.

2.9 Benefits of the Smart Grid in the UK

The US Smart Grid strives to enhance system reliability while minimising spend on generation and transmission assets. These issues do not presently affect the UK grid. National Grid's uptime of 99.999962 % was obtained without a pervasive Smart Grid at LV; any immediate UK benefits are likely to be marginal. However, LCT loads are anticipated.

2.9.1 The Need to Manage LCT Loads

Low Carbon Technology (LCT) add new loads to the grid, often on the LV distribution network. Reinforcing these networks could result in a £62 bn. spend. Figure 2-10 **(EA Technology, 2012)** shows anticipated costs to enable 100% LCT:

- blue line to £62 bn. is Business As Usual - reinforce all weak networks (refit with higher capacity systems), and
- orange line to £18 bn. is a Smart enabled solution (the author suspects a kWh analysis; no specifics are presented as to how this cost reduction is achieved).

Managing LCT loads by a distribution aware Smart system leverages existing redundancy, dropping spend from c. £62 bn. to c.£18 bn. The EV Smart-enabled solution is called Managed Charging.

2.9.2 Purpose of the Smart Grid

In cost projections (2.14) and original concept (2.8.2), SG lowered costs by active network management to avoid physical constraints. Yet the purpose of the Smart Grid is now pulled in the “markets for-profit” direction not the “network management and cost reduction”. There are functional differences. Is the Smart Grid to:

- enable a reduction of capital expenditure, or
- enable a for-profit market in Value-Added Services (VAS)?

If the latter, must 2.14’s Scenario 0 £62 bn. be spent to “fix” DNO systems? That is to say, will profits offsetting £62 bn. be realised elsewhere but require network spend?

The author questioned ENA on this point, who said they are aware of the situation and are considering options, suggesting perhaps a local market. Quite what that does and how it might work is not clear, for the information the market needs is not extent. Households likely buy power from different retailers, each holding data as private and confidential; data is Balkanised. The market cannot readily form a real-time picture of:

- what other EVs are doing, about to do and how long for;
- the relative priorities of each EV's need for charge,
- what each residence (non-EV) loads are doing,and
- what capacity headroom is available and where.

A market also presumes drivers are willing to sell “their charging slot” to others, so forgoing the next day’s trip to work. This seems implausible.

But is restricted capacity a real problem? The following sections assess:

a) how many EVs can be charged by a sample distribution network today,
b) how many EVs might the same network accommodate, given a Smart enabled intelligent charging scheme.

2.9.3 Presently LV Supportable EV Population

A contemporary EV:

- typically charges at 7 kW, some models more
- at a time to suit the needs of the owner
- if controlled by markets, to meet the generator / transmission system needs.

It is possible for EV charging to overburden the LV system, which is now shown. Given a design ADMD of 1.5 kW for 100 houses, then the installed system is fit to supply:

$$1.5*100=150\,kW \tag{5}$$

$$150/7=21\,EVs \tag{6}$$

That is, 21 EVs at 100 homes may simultaneously charge - assuming no residential load, no unbalance and an even distribution of EVs across phases; often not the case. EV numbers beyond this threaten overload, which the DNO is presently <u>powerless to sense</u> or <u>take action to curb</u> (no real-time access to Smart Meter load control).

2.9.4 Managed Charging of EVs

A possible solution is to use a Managed Charging System (MCS) to stagger EV charging so charging events are not simultaneous, reducing need to support a simultaneous peak. This is shown potentially viable by the following calculation, for a household with low overnight needs and a supply capacity of 1.5 kW:

$$supply\ capacity\ c.\,1.5\,kW\ per\ home\,,midnight-6\,am\approx 1.5*6=9\,kWh \tag{7}$$

Can this charge an EV? The average car travel distance is c. 27 miles per day (mpd). Given that a small car consumption is c. 45 mpg aka 10 miles per litre (!) ICE fuel consumption, with an engine of c. 20% efficiency, plus a fuel energy density of c. 8.5 kWh per litre, then the daily fossil-fuel energy used to move the vehicle is approximately:

$$(27/10)*8.5*0.2=4.6\,kWh \tag{8}$$

An electric vehicle has to take on this amount plus cover losses, each approximated as:

- *η-inverter* = 0.92 (power supply charging inverter)
- *η-batttery* (charging) = 0.92
- *η-converter* = 0.94 (traction discharge inverter or converter)
- *η-batttery* (discharging) = 0.92
- *η-motor* = 0.96

the product of these terms being a net efficiency *η-net* = 0.7.

Allowing other loads 1 kWh per day (entertainment etc.) gives a daily total of:

$$1+(4.6/\eta-net)=7.6\,kWh \tag{9}$$

As supply of 9 kWh > 7.6 kWh needed, a Managed Charging scheme appears viable. This would scatter (multiplex) charging timewise overnight, ensuring EVs did not charge simultaneously. A Smart Grid, if able to be used as a Managed Charging System, can charge an EV per home within the plausible constraints of an LV network.

2.10 Smart Meters in the UK

Smart Meters (SM) are available to meter gas, water and electricity supplies. This work only considers the electrical SM. The following factors limit DNO benefits from Smart Meters as deployed (c. 2018):

i. in general, there are no large household loads to manage
ii. most loads are immediately customer-effecting, not deferrable / thermal,
iii. in real-time, SMs are invisible to DNOs as:
   - the retailer owns the data (is confidential),
   - data is gathered infrequently e.g. up to half-hourly, often daily or monthly
   - the DNOs cannot talk to or command SMs (as yet)

=> SMs offer the DNO no assistance re monitoring or management, undercutting the majority of intended Smart Meter benefit.

To incentivise uptake, UK Smart Meters are supplied with displays showing the household consumption. To date, these are found to be of limited use due to aspects i) and ii) above. Demand Reduction benefits are reported to be in the 2 - 3% region **(Mogles et al., 2017)**. The lack of major loads to turn off is not confined to the UK. Whilst at CIRED 2016, the author asked a round-table of European DNO managers:

> "What large loads do your customer homes have, which SM's can turn off?"

Their response: There are no such loads, other than in Norway where electricity is widely used for heating (households were described as taking up to 20 kW). The representative from Italy stated that their average household draw was under 1 kW. The European household (at this time) does not use Air Conditioning, so has no large thermal loads to suspend. The SM presently has limited purpose; however, this may change.

2.10.1 Types of UK Smart Meter

To date, there are two UK specifications for Smart Meters: SMETS and a replacement, SMETS2. SMETS2 **(DECC, 2013)** includes metering of energy and voltage parameters, remotely controllable load switching (a minimum of 5 “auxiliary switches”) plus ability to disconnect the whole supply. One auxiliary switch is provided to control an EVSE.

Note that appliances need be “Smart enabled” to be controllable i.e. able to connect to the SM via a comms channel and be willing to obey commands.

2.10.2 Smart Meter Communications via DCC

Meter readings and other measurements from Smart Meters are managed by the Data Communications Company (DCC), a UK quango regulated by Ofgem. DCC is to comply with the Smart Energy Code **(SECCo, 2017)**. DCC are a data clearing house, gathering encrypted SM data which is passed to the retailer; DCC do not read the data.

2.10.3 The Smart Meter / DNO Disconnect

The UK's post-privatisation unbundling (splitting a local Area Board into a DNO and competing retailers) mean that, at present:

- the DNO has no to-hand view of the dynamic loads on their network
- multiple retailers are interspersed in a region, so fragmenting SM data
- there is no clear path from DNO via the Smart Grid to Smart Meter to the load.

As a result, when disruptive LCT loads appear the DNO has today no mechanism to perform DR / load control, other than disconnecting the customer, which the DNO can do in extremis if the customer disrupts compliance to Distribution Codes (ENA, 2017).

The retailer can notionally control loads via Smart Meters, but these are likely:

- to be encased in a 1/2 hour or longer control cycle,
- to serve market priorities i.e. it is envisioned such abilities are sold to market
- have no view of the net LV network load.

Data also appears incomplete; the Smart Meter does not know to which feeder and phase it is connected to.

Thus, if a feeder has a 50 kW per phase rating then decisions about "Can this EV charge at 7 kW?" cannot be readily made, if phase loads are 46, 12 and 22 kW. This is termed phase unbalance. Unbalanced phases lower net LV headroom, for the example: 50 - 46 = 4 kW.

The original Smart Grid philosophy (control of loads to assist generation and transmission issues) appear adhered to, which sidesteps the fact that when challenged by LCT:

- the LV distribution assets are weakest part of the UK system
- which has no oversight or management; these were not needed so do not exist.

Concerning the latter point: in the US, the LV system is the strongest element and managed by the Utility provider, who has complete load visibility.

ENA appear to have the ability to push for changes to how the SG / SM system operates, and occasionally will do so. However, in correspondence with the author ENA state that the Smart system security model does not allow DNOs to access the SM control switches; only the supplier (retailer of power) has that ability.

ENA are aware of functional issues; that the local LV network may suffer overload and today there is nothing to be done about the situation. Perhaps the substation will blow a fuse or fault, disconnecting the local LV system and households.

2.10.4 DNO Use of Smart Meter Data

The DNO may benefit from analysis of Smart Meter voltage data. Data is likely weeks old, anonymised and is to be purchased. Retrospective Smart Meter data mining may identify networks needing reinforcement or a change to transformer tap setting. Given a lack of real-time data, it is not thought the DNO can gain further benefit (e.g. cannot see developing faults in real-time).

Note DNOs can fit their own Smart Meter if thought necessary; these are placed on the house Supply Board as Company fuses (DNO owned equipment) i.e. there are two electrical Smart Meters.

2.10.5 Realised Utility of Smart Grid / Smart Meters in the UK

The Smart Grid and Smart Meter combination has not yet delivered significant utility in the UK, as expressed in Table 2-4 below:

Table 2-4: Realised Utility of Smart Meters in the UK (2018)

Actor	Expectations	Realised Benefit (2018)	Comments
Government	Reduce power demand hence reduce capital costs of new power stations	Marginal benefits, ROI may be negative. Pushback due to worries (EMF radiation concerns, privacy, security) Gov. back-peddle from "compulsory" to "optional"	Deployment complex with connectivity problems esp. in rural areas, tower blocks and underground sites
Gen & Transmission	Reduced loading; potential for dynamic Time of Use tariffs and Automated Demand Reduction of household items	Few to date; benefits expected when 100% homes have SM	Possibility of "turn-up" as well as "turn-down", to flag "increase your load" (as renewable energy is plentiful)
Retailers	a) Externalise cost of meter (from an absorbed cost onto customers) b) Reduced costs of meter reading (no meter readers visiting homes) c) Reliable meter readings d) Possible to launch dynamic Time of Use tariffs e) Remote control including whole service disconnect	a) Yes b) Yes c) Yes d) Proposed but not known deployed e) Not used (?)	The existing electro-mechanical meter had limited capabilities but a 25 year life; new tech may not match this, being prone to technical problems, early obsolescence, standards revision and potential security issues
DNO	Minimal to none; the DNO has no ownership or timely sight of SM reading data. Potential for long-term data to help assay reinforcement needs.	None apparent, however there are initiatives pursuing large scale data mining in hand e.g. **(TNEI & NPG, 2019)**	Out of the loop; limited retrospective data available (anonymised, weeks old, £ purchase costs). Has long term potential
Customers	To save money	Marginal. Observed 2% net consumption drop **(Mogles et al., 2017)** Improved billing	Nothing significant to turn off which does not impacting lifestyle.

DNOs succeeded in militating Parliament (via the Automated and Electric Vehicles Bill 2018 also 32) to access EVSE to stop EV charging. This is thought for use to halt overloads and in this work is called a **clamp**. This also has potential to effect 3rd party services. The comms method is not clear, nor means to identify which EVSE to target.

2.11 Vehicle to Grid

The standard bridge AC to DC converter (by which EVs charge when at home) can run "backwards". An established method **(Prince, 1925)** moves a timing signal from (a) to (b):

a) Charge from grid: when the inbound (AC) supply has instantaneously higher volts than the battery, briefly connecting supply and battery will charge the battery

b) Supply the grid: when the supply instantaneously has lower volts, connecting supply and battery will discharge the battery; power flows to the grid.

The timed signal is necessary to enable (a); it is then relatively simple to cause (b). Consequently Vehicle to Grid (V2G) capability is notionally inherent to the EV charger inverter. **Note** that designs vary in capability and that DC V2G is more complex. V2G seems ideal to offer Value Added Services (VAS) to the grid, being:

- Peak Support and
- Firm (or Fast) Frequency Response (FFR).

A V2G study in Denmark by Nissan and collaborators **(Christenson, Marinelli, Andersen, & Amtrup, 2017, Table 1)** found bulk V2G (i.e. from a large fleet) is unlikely to be viable. See

Table 2-5: V2G Study results: row "MORE" shows low values

Name	Short description	Value for system	Value for owner	Tech./ standard support	Market/ regulatory support
Frequency regulation	Keeps the frequency in an interval around 50 Hz	High	High	Medium/High	High
Frequency regulation - very fast	Frequency regulation with ramping times and precision that go beyond what traditional generators can provide	High	High	Medium/High	Low
Secondary regulation	Replaces frequency regulation and restores the frequency to 50 Hz	Medium	Low	Medium/High	Low
Tertiary regulation	Replaces secondary regulation and fulfills a higher requirement to energy capacity and delivery timescale	Low	Low	Low	Low
Synthetic inertia	Mimics rotational inertia by taking advantage of the fast chemical reaction of batteries	Medium/High	Low	Low	Low
Adaptive charging	Delays or advances charging in time based on e.g. energy costs or renewable contents	High	High	Medium/High	Low
MORE - Mother of all regulation	Includes all the abovementioned traditional types of regulation in one - assuming a large fleet of EVs.	Low	Low	Low	Low

the MORE entry (last row) in Table 2-5. This shows a large fleet performing services scored "low value" in all areas. The following sections explore the issues behind this score. **Note** that frequency regulation and adaptive (managed) charging are found of interest. Many

EVSEs have advanced converters and electronics; for detail see **(Mouli, Venugopal, & Bauer, 2017)**.

2.11.1 V2G has High Losses

V2G suffers from large round-trip losses, seen to vary greatly (spanning 2% to 16%) by battery SOC and charging rate. The efficiency η at present (for wired charging) is roughly:

- inverter (2 passes) with η = 0.92
- battery (2 passes) with η = 0.92

giving net η = 0.716. Using inductive charging introduces another η = 0.92 loss element per pass, for a round-trip efficiency of η = 0.61 i.e. near 40% loss. In-EV power consumption takes a toll too. **(Apostolaki-Iosifidou, Codani, & Kempton, 2017)**, measured V2G round-trip losses and found η as low as 0.52 i.e. 1/2 energy loss (Table 2-7). Passing charge repeatedly between vehicles is presently impractical.

2.11.2 Meeting the Cost of Battery Damage

The utility cost of an EV battery, bought at £100 per kWh (below present costs) and rated for 1,000 full cycles is 10p per kWh, however used. All use, including V2G, impose costs.

NGESO's balancing services market is complex with 32 services, highly volatile and reportedly oversubscribed. Aurora Energy Research (https://www.auroraer.com/insight) track FFR prices which (Jan 2019) have ranged from £1.2 - 18.2 per MWh i.e. 0.12p to 1.82p per kWh. Although spot market prices may be instantaneously higher, the NGESO values are far too low to compensate battery damage of 10p per kWh.

To be viable, battery capital costs must reduce significantly. Given other costs of business and actor profit taking, the author considers battery costs per cycle need fall by an order of magnitude.

See also market prices at: https://www.nationalgrideso.com/balancing-data/system-balancing-reports.

2.11.3 Cost of Communications

V2G needs considerable communications to work. The manager must identify which vehicle is appropriately charged to offer a service. Further, local network conditions need to be taken into account for V2G support. This is as an hour of discharging might expect an hour-plus of recharge, which might not be possible due to local network constraints.

Thus a likely process, including communication, is:

- identify vehicle location on the network (substation, feeder, phase**:** it is not clear Smart Meters know such data)
- dialogue with the local DNO re available capacity (in real-time i.e. seconds)
- dialogue with Value-Added Service supplier (i.e. the commissioning aggregator) re the need for services and determine what may be offered vs. needed;
- adjust the EV activity as necessary
- repeat the above as charging continues.

Communication is not free. Whereas a dumb EV may never dialogue with a home base, the above scenario may imply dozens of data packet transfers per hour per vehicle which, for tens of millions of vehicles, might require a separate, secure comms network.

2.11.4 Costs of Modifying Retailer Billing

A V2G discharge will deplete battery State of Charge (SOC), spent on behalf of a Value-Added Service supplier (Aggregator). The charge spent will need replacing.

It is unlikely that the VAS supplier will wish to replace lost charge at retail (£0.15 per kWh); they likely prefer wholesale prices (often c. £0.06 kWh and highly variable).

Thus, the costs of the replacement charge must be billed at a different rate - and that bill sent to someone who is not the supply point retailer. However the charge will have been logged on the household meter; the excess “2nd billing” must be detected and the owner compensated and/or the retailer adjust the value. This is likely to become complicated.

From past contact with billing at a major UK utility, billing systems have teams of staff working on them for years. It is not credible that such changes would cost in the low £ millions, simply due to the potential complexity (there are many possible trades as well as a capability needed to perform corrections). Exhaustive regression testing is necessary (people are upset about wrong bills); this may be a major effort. Given there are several dozen retailers in the UK, billing systems rework is likely expensive.

2.11.5 Excess Charge Loss

With a good round-trip efficiency being η = 0.65, the lost charge must be returned to the vehicle. If regularly occurring in bulk at a national level, generation to supply this 35% loss must be available.

Given that losses are monitored and regulated by Ofgem (which strives for net 5 - 10% losses), a system management activity with 35% loss may not be acceptable.

2.11.6 Excess Vehicle Delay / Conflict of Interest

A vehicle ready to depart for home after work at say 5pm, which commences V2G dispatch at 5pm for an hour, will not be ready to depart with the same charge until:

$$5\,pm+1\,hr\,(V\,2G)+1.35\,x\,1\,hr\,(recharge)=7:21\,pm \tag{10}$$

This can be presented as: An hour's V2G cannot commence later than 2:39 pm, if the vehicle needs charge to depart at 5pm.

However, V2G may be wanted to support the UK's afternoon peak load. There seems to be potential for a conflict of interest here. If the V2G EV is to service the peak, then it must risk (or be scheduled for) later departure.

2.11.7 No Mass UK FFR Market of Scale Visible

The present FFR needs of NGESO are, according to Aurora, 405 MW and over-subscribed (e.g. https://www.auroraer.com/insight/gb-ffr-market-summary-august-2018/). Clearly this might change, however anticipating adding perhaps:

$$20\,x\,10^6\,x\,7\,kW=140\,GW \tag{11}$$

of EV capacity, into a market of c. 400 MW demand, will most likely find no takers.

The author can find no profit for such volume. In the short term, pro-rata'ing the available sales over the whole vehicle fleet implies individual EVs cannot plausibly break even. A related study **(NGET-Ricardo, 2011)** also sees no bulk market (see 2.13.4).

Many analyses for individual vehicles disagree, yet are not scaled for a national fleet.

However this refers to profits for the EV owner.

Parties such as Nissan offer V2G (https://europe.nissannews.com/en-GB/releases/release-149186#) and may be in a position to make profit, as costs others face are, for Nissan, existing sunk costs or costs passed on to others (a cost bundled in a monthly battery rental calculation i.e. costs of V2G are averaged with all EV owners paying; the author wonders if this happens and if such bundling is legal). However V2G faces yet another problem:

2.11.8 DR Does (nearly) All That V2G Can

Demand Reduction (aka DR or DSR) methods can match all V2G functions given that there is load which can be turned down. Clearly, as power sums to a point, having 100 units of supply at hand yet load of 105 units might be managed by:

a) finding and injecting another 5 via V2G, or

b) reducing existing load by 5 via DR, to bring net demand back to balance.

EVs, when used like cars, can expect to be parked for much longer periods than driven. Further, the period of charging may be hours shorter than time parked. Nationally there may be a pool of tens of millions of connected vehicles - but individually, only need charge for say 20% of their connection time. Such EVs do not care when they are charged, only that they are charged and ready for departure. Being nonchalant about a charging hiatus, or bringing charging forward, these EVs can offer DR and FFR services. Management of charging patterns becomes possible, in the manner the Smart Grid was intended to perform (2.8.4).

Note that EV charge levels, battery ageing, billing and departure time are not affected by such DR. There is no V2G solution which can match this.

2.11.9 Comparative Merits of DR and V2G

DR benefits over V2G:

- reduced communications load
- no billing problems
- no raised whole-cycle losses
- no loss of charge hence potential delay to departure
- reduced charge throughput thus no excess battery damage.

V2G benefits over DR:

- DR is unavailable if no deferrable load exists to turn down
- V2G can exploit flexible tariffs (buy power cheap, sell when value rises).

2.11.10 Where Does V2G Shine?

To the author, V2G offers benefits in these roles:

- as a measure of last resort,
- supporting loads which cannot be deferred e.g.
    - "Behind the meter" services at a high load facility. Here, parked EVs within the scope of metering can V2G support load, so reduce power inflow. At certain times (when energy costs are high) it is likely this can offer savings
    - there is a similar situation on DNO networks, where peaks need be reduced.

2.11.11 V2G in Summary

It is the author's opinion that - for the owner - mass EV V2G cannot break even in the UK, in general it will generate costs not profits, compounded by no market need for such volume of services. Oversupply follows and the market has no profit.

However, the FPB simulator has found a functional use for V2G, regardless of cost. This is the support of local EV charging during overload situations. For example, when an LV system can supply 50 kW but has 65 kW instantaneous non-deferrable demand, V2G can provide the missing 15 kW (but at a cost, as related).

2.12 A Potential Dependency Trap

NGESO are unlikely to rely on EVs for any critical duty for this creates a dependency. NGESO needs to ensure the UK power system always works - given comms failures, terrorism, enemy action in time of war, a national emergency, flooding etc.

Many power system assets can have half-century lifespans. Would a car manufacture consider how they support an EVs at 20 years old, as (say) the cellular network they use is decommissioned and mass numbers of EVs become unreachable overnight?

NGESO may wish to not depend on EVs, believing them too unreliable - being subject to the vagaries of people, weather, location, communication networks, communication standards, software (and ongoing updates / maintenance), the whims of car manufacturers and the second hand car market. It might be that NGESO decides to qualify / de-qualify EVs for service applicability (e.g. by a test at MOT). It might be that over the age of (say) 5 years EVs are regarded as unsupported by the manufacturer, so are automatically de-qualified. The possibility of such “horizon of utility” has not been considered in any of the works the author has seen; if this occurs it must be included in VAS calculations.

However DR solutions, via a DNO controlled switch, works for any load and EVs of any age.

2.13 Literature

Fossil-fuelled vehicles are inefficient and produce CO_2. The Digest of UK Energy Statistics “DUKES” **(BEIS, & MacLeay, 2016)** attributes 23 million tonnes consumption of oil pa to cars, from 65 m-tonne UK demand pa. Eliminating fossil-fuelled cars offers significant reduction, e.g. by driving EVs or Hydrogen vehicles. Similar intent is written into most EU countries legislation, with the UK ceasing sales of CO_2 emitting vehicles in 2040.

Interest in EVs is also driven by monetising their electrical capabilities. EVs are controllable and many spend hours connected to the grid, possibly offering services to the power grid. This includes control of ability to charge and/or return power to the grid, via V2G 2.11.

2.13.1 Early Enthusiasm: Monetising Electric Vehicles

The concept of Vehicle to Grid was espoused by **(Kempton & Letendre, 1997)** who calculated a notional at-home V2G EV in Delaware could sell services into the electricity supply system, finding “value to the utility” for a variety of vehicles Table 2-6:

Table 2-6: Kempton’s Table 8. Cost to vehicle owner and value to utility

Electric vehicle	Present cost to EV owner ($)	Present value to utility, by levelized avoided capacity costs		
		Low ($26/kWyr)	Medium ($73/kWyr)	High* ($180/kWyr)
GM’s EV1, sports car (Pb/acid)	955	850	2370	5850
Solectria’s Sunrise, passenger car (NiMH)	1930	2330	6550	16,150
S–10 light truck (Zn-Br_2)	910	1390	3900	9610

*The ‘High’ avoided cost figure includes deferral of investment in T&D equipment; low and medium do not.

This work was well accepted, even though:

- it referred to a market in a given place, on a given network, at a given time,
- for services of tradable value
- for one vehicle.

Kempton released further papers and built a V2G capable EV, demonstrated in (Youtube clip of Discovery channel on Kempton https://youtu.be/5639ceWg0us). Kempton et al's economic synopsis was seized by market conceptualisers looking to optimise profits.

2.13.2 Markets and Profits

The stance of many papers (reviewed in **(Green, Wang, & Alam, 2011)**) was: A market manipulating consequence-less numbers to create profit. This was profit for the trader, even robbing the EV of charge (if there was money in it) and stranding the driver, who may be passed some profit. Green pointed out this was not real-world, as there are:

- expectations of use of EV as a car,
- costs due to likely accelerating battery ageing,
- constraints imposed by physics:
  - capping the peak power-flow and
  - electrical losses, thus every transaction diminishes the commodity.

This was driven home in "Measurement of power loss during electric vehicle charging and discharging" **(Apostolaki-Iosifidou, Codani, & Kempton, 2017)** measuring V2G net efficiency as 53-62% (suggesting V2G may need much extra initial generation). A commentary on Apostolaki-Iosifidou's paper **(Shirazi & Sachs, 2018)** reviewed V2G round-trip efficiency in published papers, shown in Table 2-7:

Table 2-7: (Shirazi & Sachs, 2018) V2G studies do not state V2G losses correctly

Table 1
Comparison of empirical (first row) and assumed (all other rows) roundtrip efficiency (η_{rt}) from select V2G economic analyses.

η_{rt}	Study
53%–62%	[1]
73%	[9,11];
81%	[12]
85%	[13,14];
86%	[15]
100%	[16,17,18,19,20,21]

Table 2-7 shows as many papers ignore the issue as manage to understate it.

Measurements included a US household transformer, located between the EV and a Point of Common Coupling. The UK has no such transformer so empirical values might be revised upwards by c. 6 - 8%. **NB** The FPB is configurable, presently having *η* c. 70%.

(The author concludes from the above that electricity is not a fungible commodity as charge transfer incurs losses; it is the trade of contracts which is fungible.)

2.13.3 V2G Battery Damage and Costs

Whether or not V2G damages batteries is disputed, similar data being used to different ends. Charge throughput is known to age batteries, the root of the limited number of battery charge cycles (about 1,000 to 80% capacity remaining). If V2G performs 500 cycles, the battery has shed half its useful life so incurs a capital loss. Battery ageing is complex and driven by:

- ambient and internal temperature
- chemistry
- physical construction
- presence of contaminants / products of operation
- charge rates
- charging history
- the SOC the battery is stored at, with extremes ageing faster.

In the case of ageing due to high SOC level, **(Uddin et al, 2017)** argues V2G can notionally reduce ageing by removing excess charge, so EVs stand with, say, 70% SOC rather than 100% (the author does wonder why the EV charged to 100% if only 70% is needed).

In two papers, Dubarry cycled battery packs as if for V2G over a long period. A battery model was derived and used to explore V2G damage. "Electric Vehicle Battery Durability and Reliability Under Electric Utility Grid Operations" **(Dubarry, 2017)** reported that V2G discharge of 2 hours a day degraded battery life to under 5 years, approximately doubling the loss expected from driving.

A following paper: "Battery durability and reliability under electric utility grid operations: Representative usage aging and calendar aging" **(Dubarry & Devie, 2018)** found that elevated temperature and increased charging rates also degraded batteries. Further, when small SOC swings were applied capacity loss was faster, yet these small SOC swings are those proposed for FFR services. This shows that there is no V2G service free of battery damage, given present technology. However V2G remains a fixation and papers praising it are aplenty. When reading these, be aware of:

- the paper may describe a case in which one EV has profit, not 10's millions
- the economics and markets for power vary widely by country,
- power system capabilities may vary widely, especially 120 vs 230 V systems.
- Most studies are set in US or China; their situations are not like Europe or the UK
- studies in other lands need verification to show they apply in the UK,
- service needs vary by design approach, again noticeably between 120 and 230 V.
- Studies may have significant silent omissions:
    - failure to consider losses
    - low-cost (even free) alternatives to V2G may go unmentioned,
    - there may be unvoiced practical reasons to not use V2G, other than in extremis.

However the author does see V2G as:

- being suited for special one-off situations
- enjoying a very small market
- incurring high costs particularly battery capex loss
- likely dominated by niche players using simplified, low cost approaches e.g. recovered "second-life" batteries connecting to the grid at a convenient point
- but often upstaged economically by DR (see **note** below).

What would make V2G more palatable? In practical terms:

- reduced round-trip losses
- greatly improved battery ageing vs. duty
- far cheaper initial costs
- together with a UK market demand for V2G services, i.e. a return allowing many of the c. 40 million electrified vehicles (replacing cars and small works vans) to profit £ hundreds each pa. No such market or need is apparent. At the time of writing, the UK Balancing Services market is saturated and worth about £400 m pa.

Note: Anticipated UK EV loads are already excessive so require active control to restrain demand. A Demand Reduction (DR) signal may be placed on top of the necessary control mechanism, meaning the incremental cost to provide a DR service is minimal.

This thesis is set mid-21st century and expects EVs to replace cars en-masse. The DR capability of the UK fleet can be anticipated. Of the c. 20 million EVs: 10% charging, of which 10% may instantaneously defer charging of 7 kW i.e. 0.2 million x 7 kW = 1.4 GW, with perhaps marginal DR costs over the necessary and in-place demand control.

NGESO presently buy 200 - 400 MW capability. A further 1.4 GW of cost-free control will bear down on 3rd party economics. In the face of this, a DR market might not exist.

A market wishing to dispense £100 m plus as V2G services in the UK (so each EV can enjoy minimal income) is invisible to the author. In the short term, there may be a V2G market as mass numbers of EVs are not available. By mid-century, cost-free DR capabilities are expected to dominate, so causing V2G to (apparently) be needed rarely.

2.13.4 UK Market Situation and Projection

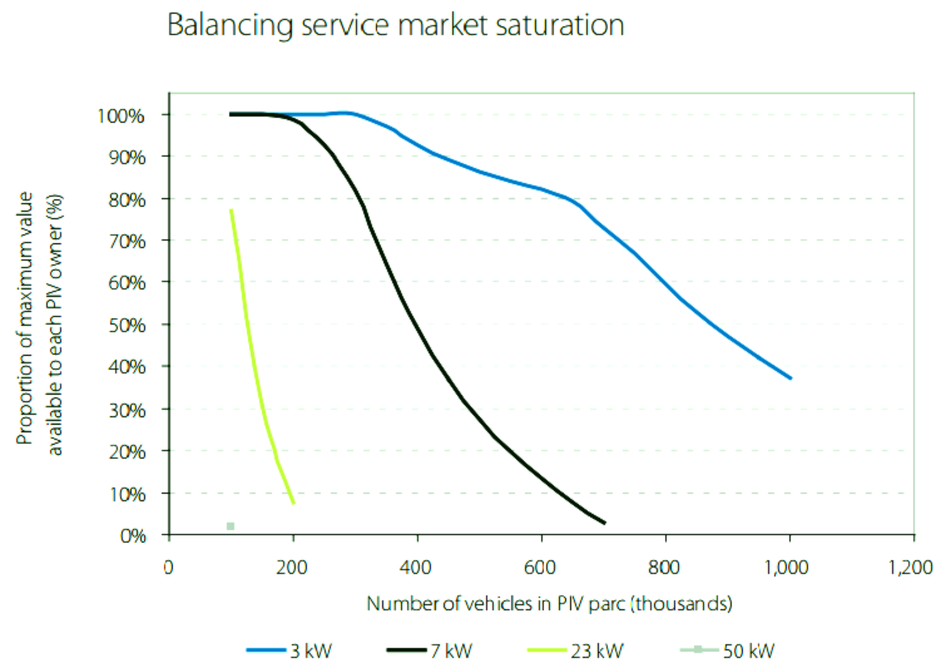


Figure 2-32: Market saturation causes revenue collapse ***(NGET-Ricardo, 2011)***

Kempton's 1997 US paper is not directly transferable to the UK, given: Constraints on UK power supply charging are severe, the service markets have different needs and values. Also, a calculation for a single EV cannot be pro-rata scaled as EVs mass-replace cars.

Supply surfeit arises, like to collapse the market as highlighted in “Bucks for Balancing” **(NGET-Ricardo, 2011, Fig.6, p12)**, Figure 2-32. Collapse occurs before 1 million vehicles.

2.14 UK Relevant Literature

Focus is on recent UK related literature and studies. Papers from outside the UK only relate if they consider constrained 230 V LV systems.

“ Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plug-in Hybrid Vehicles ” **(BERR & Arup/Cenex, 2008)** is a wide-ranging report on UK transport decarbonisation options and impacts (from manufacturing to battery recycling). Section 6 “Electricity Generation and Grid Impacts” (of Electric Vehicles, p.40) is of particular interest. It is stated that there is sufficient generating and power transmission capability, however the issue of overloading distribution networks is seen, stating that the problem may be solved by reinforcement. Later general comments (para 2, p.42) noted that EVs may invalidate the diversity assumptions for local power distribution construction. Other than noting the issue exists and that EV charging may coincide with evening load peaks, there is no quantification of the issue. The work states that it is necessary to perform Pilot Studies to assess the issue.

(Papadopoulos, Cipcigan, Jenkins, & Grau, 2009) This paper uses the “UK Generic LV Distribution Network” (UKGDS; an attempt to standardise sample LV networks and now fallow. See http://github.com/sedg/ukgds).

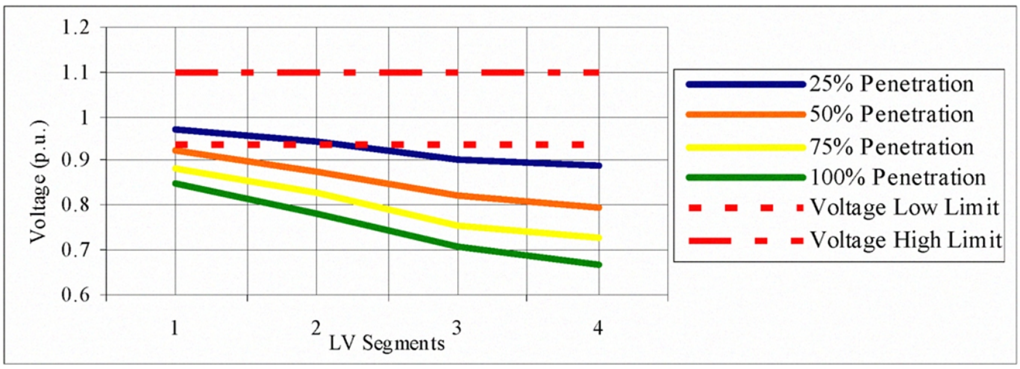


Figure 2-33: (P. Papadopoulos et al, 2009) Fig. 5 LV Segment Volts Fall

Household supply voltages are assessed for being within limits, with various charging rates and V2G considered. 96 customers with EVs are placed on a feeder either as a clump, or distributed along 4 segments of feeder. The former gives no problems. When distributed, the delivered voltages drop below limits as penetration rises (Figure 2-33). This shows placement of EV charging load is relevant. Measurements are in “pu” (per unit, a pro-rata measure: 1.0 pu = 230 V). It is DNO common practice to set transformers to emit slightly high volts e.g. 1.04 pu, 239 V. Here, the author sees no emitted pu voltage stated.

The analysis used PSCAD and IPSA+ simulators, electrical power-flow tools.

Note “100% EV penetration” here means “an EV at every house”, not 1:1 replacement of ICE cars with EVs. Car-owning households have c. 1.3 cars per house **(ONS, 2016, Table 48)** in the South of England, although this varies.

(Strbac et al., 2010) is a substantive study of MV / LV networks and collaboration between 18 parties. This considers how Advanced Smart Meters (ASM) aids the LCT transition for both EVs and HPs. ASM allows real-time data to aid network management, by measuring and scheduling load via a DR mechanism (as in Figure 2-34).

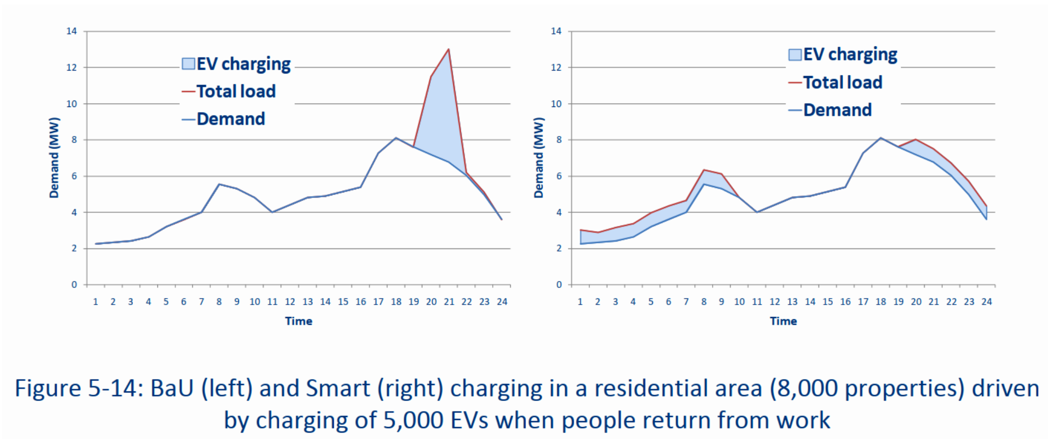


Figure 2-34: (Strbac, 2010, Fig 5-14)

The report also quantifies costs for Business as Usual (BAU) vs. a Smart system.

Table 2-8: (Strbac, 2010, Table 1-1)

Scenarios	NPV costs LV (£bn)		NPV costs HV (£bn)		NPV Value of Smart (£bn)
	BaU	Smart	BaU	Smart	
SCEN 10%	0.75 - 2.48	0.30 - 0.98	0.06 - 0.20	0.03 - 0.08	0.48 - 1.62
SCEN 25%	1.90 - 6.26	0.70 - 2.32	0.20 - 0.66	0.04 - 0.13	1.36 – 4.47
SCEN 50%	3.76 - 12.4	1.48 - 4.88	0.30 - 1.00	0.13 - 0.42	2.45 – 8.10
SCEN 75%	5.08 - 16.72	2.47 - 8.12	0.34 - 1.11	0.22 - 0.71	2.73 – 9.00
SCEN 100%	5.85 - 19.27	2.91 - 9.59	0.37 - 1.21	0.26 - 0.85	3.05 – 10.04

Table 2-9: (Strbac, 2010, Tables 6-1, 6-2) Cost of Transformers vs. Feeders

Table 6-1: Estimated GB Network reinforcement costs under a BaU operating paradigm

Penetration levels	LV (£bn)			HV (£bn)			Total (£bn)
	Transformer	Feeder	Total	Transformer	Feeder	Total	
10%	0.7	3.7	4.4	0.3	0.4	0.7	5.1
25%	2.1	8.5	10.6	0.8	1.6	2.4	13.0
50%	3.4	18.4	21.8	1.6	2.2	3.7	25.5
75%	3.8	25.9	29.7	1.6	2.6	4.1	33.8
100%	3.8	30.6	34.3	1.6	3.0	4.5	38.8

Table 6-2: Smart network reinforcement costs for the entire GB HV and LV distribution system

Penetration levels	LV (£bn)			HV (£bn)			Total (£bn)
	Transformer	Feeder	Total	Transformer	Feeder	Total	
10%	0.3	1.5	1.8	0.1	0.3	0.4	2.2
25%	0.4	3.8	4.2	0.0	0.5	0.5	4.7
50%	1.7	7.6	9.3	0.3	1.4	1.8	11.1
75%	2.5	13.2	15.7	1.2	1.7	3.0	18.7
100%	3.2	15.4	18.6	1.6	2.0	3.6	22.2

The study includes distribution Primary, Main and Substation transformers with cabling and feeders for LV supply. The difference between the BAU and Smart approaches is:

- BAU: add power capability to assets, in an essentially passive system and
- Smart: real-time management at local level. Here, by "100% penetration" Strbac means 1:1 replacement EVs for cars. Table 2-8 shows that costs are predominantly at LV level. Table 2-9 identifies the majority cost as feeder cables, not transformers.

As a result, the following cost-saving policies are recommended:

- use Advanced Smart Meter systems for real-time local control
- use solutions which emphasise transformers over feeders (e.g. install more transformers mid-feeder, thus each section carries less burden).

The concept of Time of Use (ToU) tariffs is considered; however the scope is broad, not location specific. The report states in para 6.15 that the optimal time for DR is specific to location and instantaneous need (i.e. demand ebbs and flows). High-level ToU tariffs failed to manage these at a local level, losing opportunities to avoid local reinforcement costs i.e. ToU was too broad a brush; without fine-grain finesse reinforcement is still needed.

Yet, without ASM the occurrence and location of loads are unknown. ToU tariffs are non-specific and cannot level local load, so either need the BAU solution or an alternative.

The team see a conflict between priorities and practicalities, top-down vs. bottom up as shown in Figure 2-35. Here, plot (a) shows EVs managed for local constant maximum throughput removing the peak, flattening and spreading load (red line). Yet to perform supply management (e.g. plentiful renewables) via a price mechanism to vary the load base, plot (b), is needed. However, the local networks may not be able to do this.

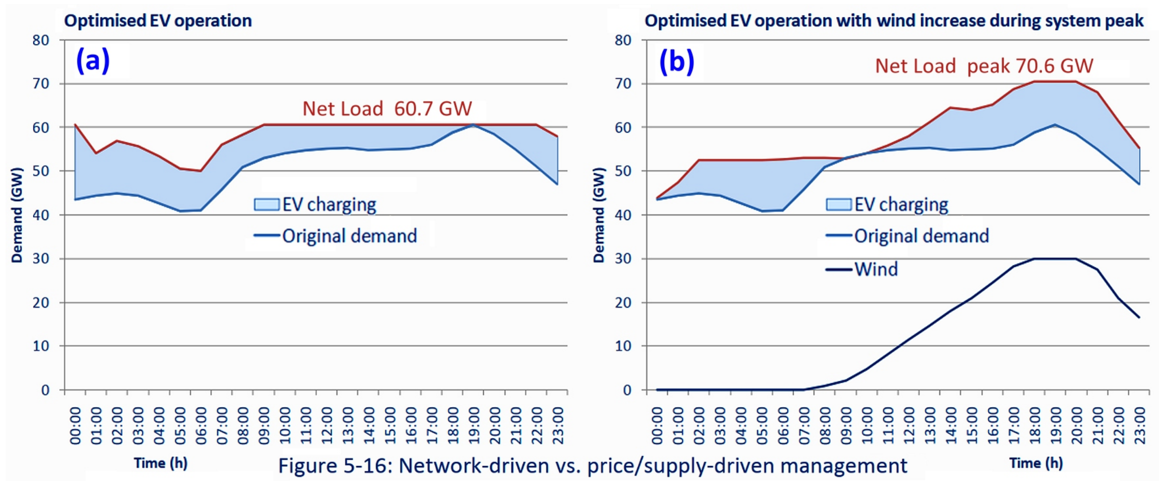


Figure 2-35: (Strbac, 2010, Fig 5-16) A conflict: Network or Market Priorities?

This highlights **conflict of interest**: a local capacity optimised (throughput maximised) solution, sustaining 100% throughput, <u>cannot respond to prices</u> as Network-optimising systems produce constant load. It cannot be turned up (for it normally runs at 100% throughput) yet turning below 100% creates a loss which can never be recovered.

Strbac et al do not investigate the consequences of this for market approaches, but to the author’s mind this is restrictive; a Smart response to market imperatives as in plot (b) is not feasible when a system managed for plot (a) caps the maximum capacity.

Splitting share on the same network does not help either. A remote party controlling, say, 30% of the EVs at a location may issue DR signals to turn load down. On seeing the reduction the throughput optimising controller may conclude that new headroom is available and respond by charging other EVs - giving no net change beyond the local network. If an Aggregator causes an EV to start charging the optimising controller turns others down; again no net change. Throughput optimised control <u>frustrates market management</u>. This conflict between optimising throughput and a market method has potential to be disruptive, causing the author to investigate DR and FFR network services.

Note: there are local and national Smart system imperatives - a view hitherto not seen.

In **(Green, Wang, & Alam, 2011)**, a mostly US orientated paper, Green et al reviews 33 approaches to modelling EVs. Green outlines the data to model and describes the core approach to a Smart controlled / managed distribution simulator. The model has a hierarchical grid supplying power to EVs, each an agent connected by ICT to a control hub and co-ordinated by an overarching manager. The key elements of a study are identified as the vehicle population, the trips driven and vehicle charging characteristics. Green also highlights:

- most studies ignore distribution systems impacts, and
- most ignore assessment of network reliability metrics (i.e. continuity of power delivery) and how the arrival of EVs may impair these.

(Huang & Infield, 2011) used Monte Carlo methods to animate EV loads on an LV system, using Time of Use UK Survey 2000 data; see Figure 2-36. The survey logged people's activity every 10 minutes, indicating probability of departures and arrivals home. The paper concludes that both distribution transformers and feeders need substantial upgrades. **Note** this study has no DR management to limit LV load.

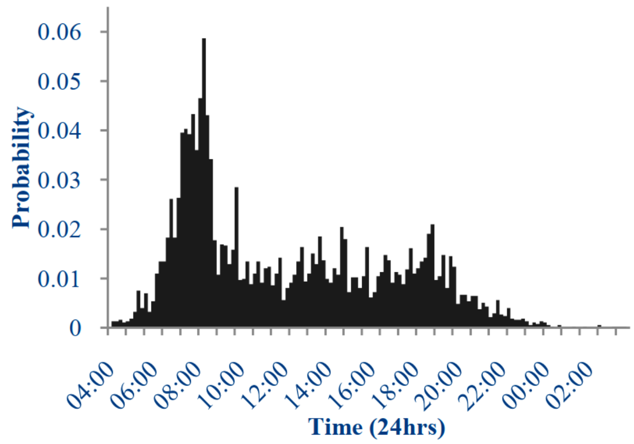


Fig. 1. Probability distribution of car left home on a weekday.

Figure 2-36: (Huang & Infield, 2011, Fig.1) Probability of car leaving home

EV charging for CO2 reduction is optimised in **(Acha, Green, & Shah, 2011)**, and is a case in point re omissions. By limiting scope (from generation to 11 kV) the findings are affected. In other regards this is a good paper, explaining what it is doing to simulate and optimise a time-coordinated optimal power flow (TCOPF) method. Acha concludes that the TCOPF tool can coordinate EVs, and that the networks can cope with the EV loads, which contradicts other works (e.g. Papadopoulos).

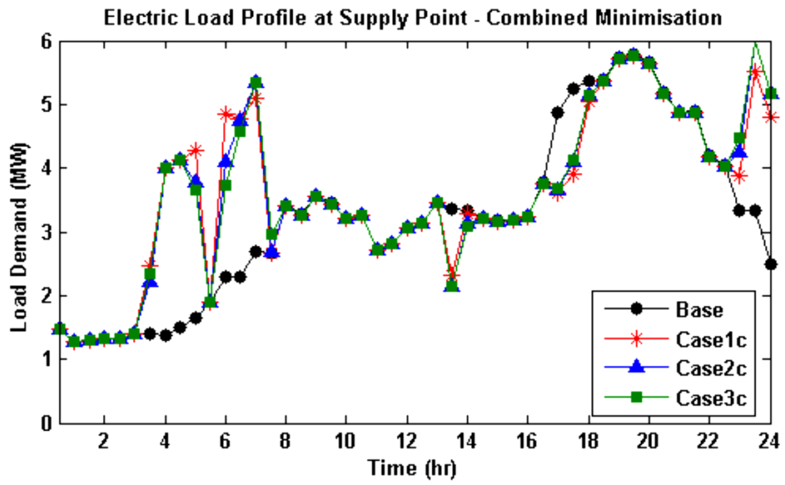


Figure 2-37: Acha's How control options affect local load

Given the limits to scope of the paper there is nothing defective about it; yet shows that a top-level market view, unconscious of lower level restrictions, can reach conclusions with silently limited validity. The work does show (Figure 2-37) that tracking carbon costs causes no increase of peaks and promotes overnight charging; however this is sans knowledge of what is happening at LV; the simulation does not respond to LV issues. Acha is aware the tool needs development for MV and LV systems suffering congestion.

(Qian, Zhou, Allan, & Yuan, 2011) considers an 11 kV UK distribution system (but not LV elements). He observes that congestion (cable overloads) arise at the head of (11 kV) feeders, with volt-drops at the far end. An evening increased peak load due to EV charging on arriving home is detected. This is compared to a Smart charging method which distributes EV loads away from the peak. He finds the time of commencement of charging impacts total load, and says that the significant loads observed on certain feeders become masked when using overall rather than specific load profiles. To avoid this the study must reflect the dynamic nature (implicitly, location) of EV loads on the feeder network.

Demand Side Response (DSR / DR) is used in **(Boait, Ardestani, & Snape, 2013)** via consumer appliances to regulate peak load. Loads from 1,000 houses are considered including 1 in 4 with an EV. The paper illustrates the thinking behind an imagined aggregator, able to moderate consumer demand, Figure 2-38 and Figure 2-39:

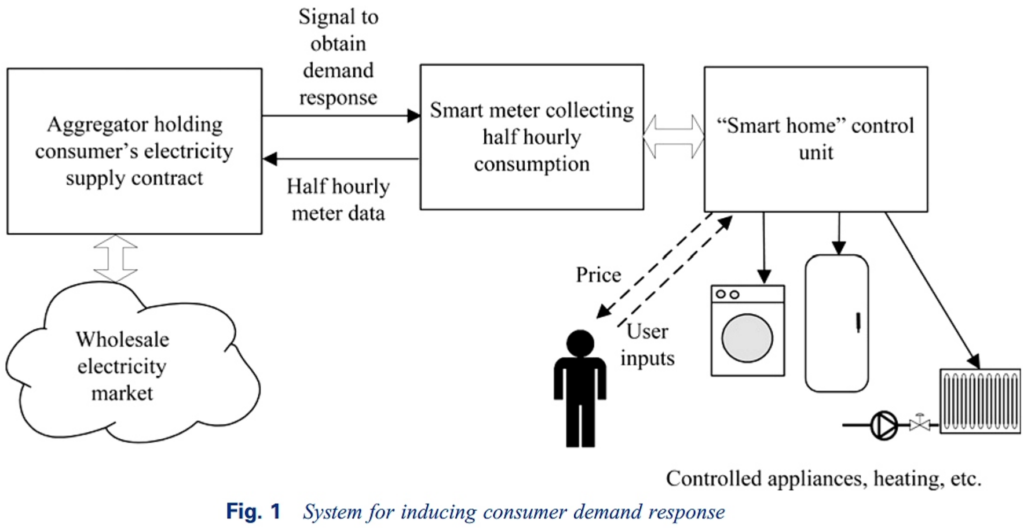


Figure 2-38: (Boait, Ardestani, & Snape, 2013, Fig. 1) DSR Control Mechanism

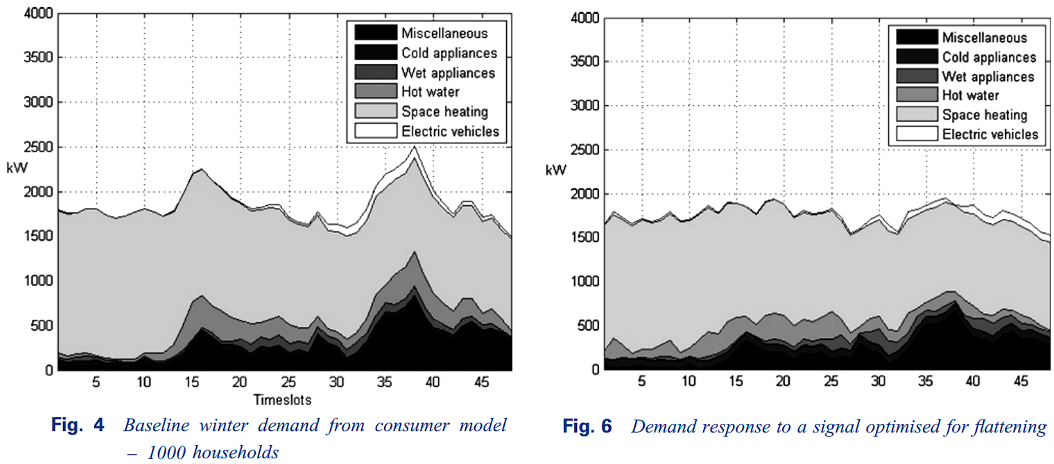


Figure 2-39: (Boait, Ardestani, & Snape, 2013) Figs. 4 and 6: Load flattening

Other than heating, this controls loads of hundreds of Watts. Assuming c. 10 W controlled per home, this suggests from a whole-UK view perhaps 300 MW of control (so useful). But from an LV view this is insufficient to manage local networks. However intent is shown.

(Navarro, Ochoa, & Mancarella, 2012) is concerned with LV cable sizing and sample periodicity. Longer periodicity (half-hourly data is the industry norm) is found to give less accurate results, yet 5-minute period results are close to 1-minute periods. In passing, he says laid cable cost is c. £140 k per km. The paper looks at controllable house loads such as refrigerators, and suggests they may be candidates for peak-shaving.

Data periodicity again surfaces in **(Urquhart & Thomson, 2015)**: especially impact of too-wide a periodicity, which understates losses from peaky loads due to averaging.

The issue is also met in **(Poursharif, Brint, Black, & Marshall, 2017)** in Table 2-10:

Table 2-10: (Poursharif, Brint, Black, & Marshall, 2017, Table 1)

Table 1 Inaccuracy percentages of loss and voltage level estimates as a result of varying time resolution of smart data

Time resolution, mins	Underestimation of losses, %	Overestimation of voltage levels, %
5	−9	0.14
10	−12	0.23
15	−15	0.38
30	−23	0.58
60	−30	0.77
120	−35	0.87

(EA Technology, 2012) is a substantive report by EATL for ENA with 14 industry sources and part of WS3 for the UK Smart Grid Forum; see Figure 2-41, Figure 2-40.

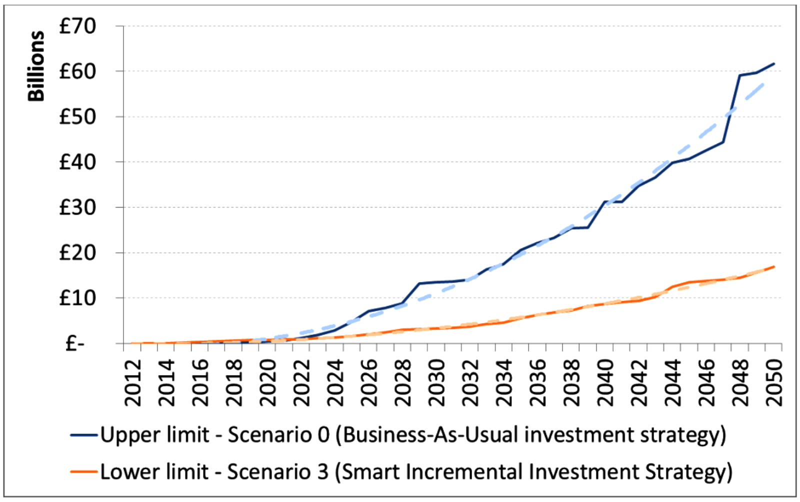


Figure 0.1 Spread of GB network related investment (non-discounted cumulative totex showing the most extreme scenarios) to accommodate projections in Low Carbon Technologies connecting to the electricity distribution network

Figure 2-40: (EA Technology, 2012) Fig. 0.1 UK Distribution costs: BAU vs. Smart

The purpose of the work is to identify and cost alternative approaches the UK may adopt to LCT and assist develop TRANSFORM, a tool to explore implementation options. This a definitive work in terms of future options. However, it appears not maintained.

Note Heat Pumps demand c. 40 GW load vs EV’s 18 GW; HP are the greater LV load.

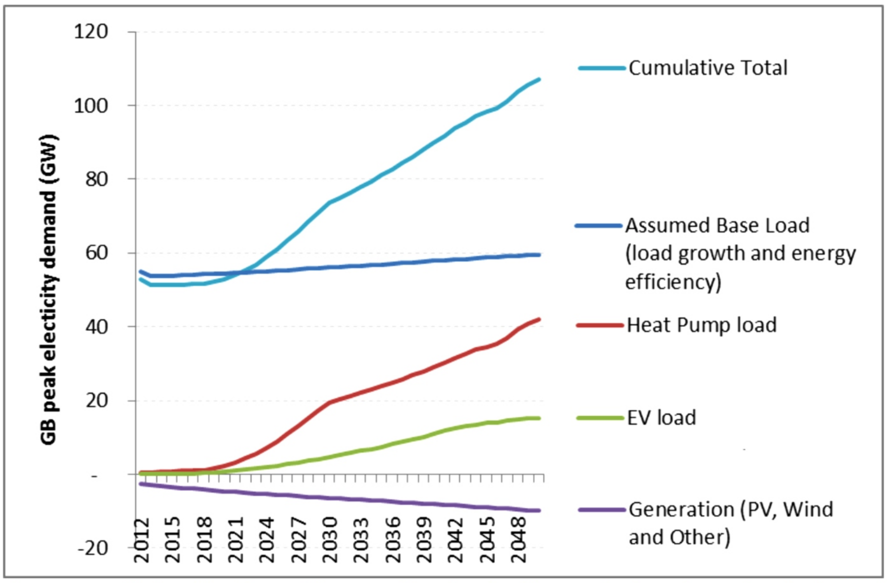


Figure 3.6 Peak electricity demand for Scenario 1 showing the contribution of EV and HP load, together with the demand reduction effects of PV. The base load factors in load growth and demand reduction

Figure 2-41: (EA Technology, 2012) Fig. 3.6 Load sources, Scenario 1

The report summary offers the key observations:

- Technology uptake: LCT uptake is not uniform; clustering is likely
- networks variability: networks are not uniform. Power needs and supply implementations vary; headroom (spare capacity) also varies
- Technology options: a method is needed to determine which to use and when. Conventional and "smart-grid" methods need be integrated in some manner.

The paper **(Shen & Dunn, 2013)** projects the availability of EV demand flexibility, for 2050 i.e. what loads EVs impose and available for reduction (DR). The anticipated daily peak is 8.8 GW overnight, becoming 7.8 GW during the day. The study includes V2G, which causes significant (2 GW) shifts. Shen suggests 7.8 GW of controllable load exists. The author is not completely happy with this; however his calculations indicate a similar total of which a proportion (only guessable) is useful i.e. willing to accept commands; perhaps the freely-controllable portion is nearer 1 GW - still a major asset for systems control purposes.

(Kuenzel, Kunjumuhammed, & Pal, 2013) is an introduction to the Frequency Response needs of the UK power system, as anticipated circa 2030. This paper describes the UK FR mechanism, why it is needed and how it operates.

(Neaimeh et al., 2013) considers whether excessive EV loading can be detected using EV loading profiles and Smart Meter data; see Figure 2-42, Figure 2-43. The method is to use data from the (then on-going) CLNR project and a smaller project, “SwitchEV” **(Blythe et al., 2012)**. A simulation model is developed based on the profiled data and calibrated against observation. The paper considers rural and urban EV homes and 4 sources of charge: home, work, public standard and public rapid (50 kW).

Figure 2-42 shows rural users charge more at home (dot-dash line) than urbanites, who also use more public charging. This is ascribed to the greater distances rural EVs drive and the relative non-availability of public charging at rural destinations. **Note** that the model used an MV (66 or 33 kV) network via several transformers to LV, with both urban and rural networks modelled.

Neaimeh finds few problems at 60% EV occupancy rates, so wonders if the alarm over troubled urban LV systems is overstated. Rural networks (Figure 2-43) saw voltages deteriorate to limits of acceptability. Rural runs tend to be longer and use thinner cables strung on poles, rather than buried cables. Long thinner lines raise impedance, exacerbating volt-drops. EV loads also erode headroom at peak time, so may interfere with new heat-pump loads.

The study has highlighted how home location impacts loading, but the author wonders: Why were EV numbers not increased over 60% penetration?

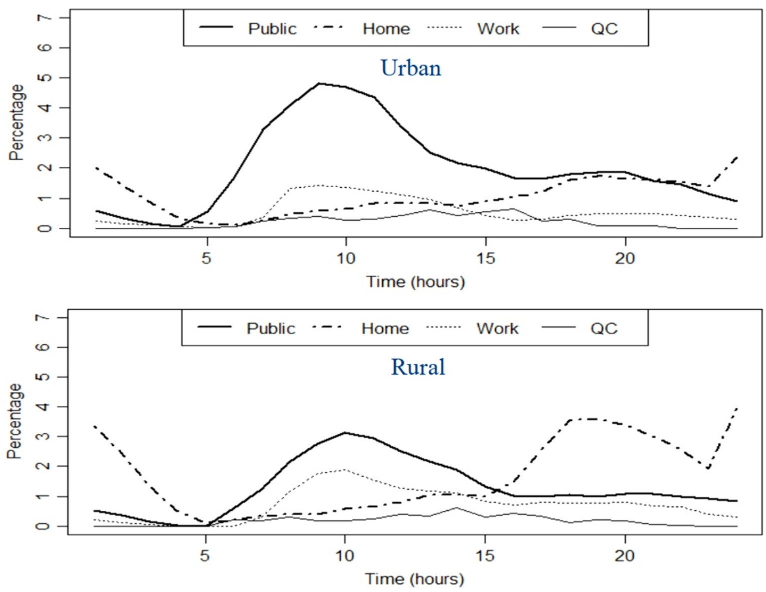


Figure 2. Percentage Energy transferred at each hour of the day at different charging locations. Urban Users (top figure), Rural Users (lower figure).

Figure 2-42: Neaimeh’s Fig. 2. EV charging preferences, Urban vs. Rural

.

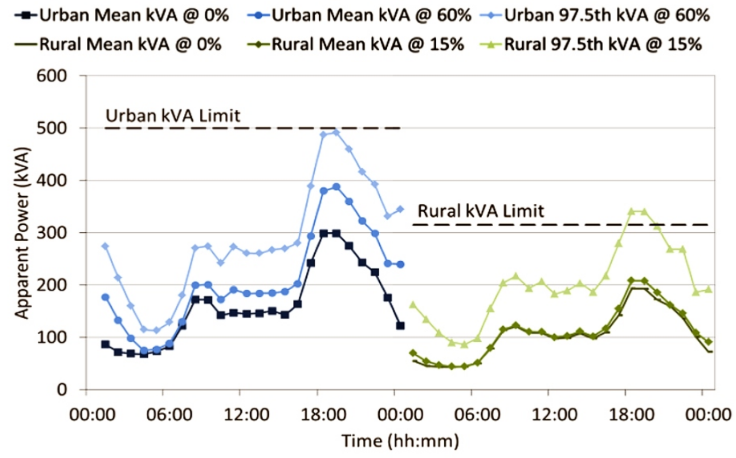


Figure 8. Test day critical demand for urban and rural network.

Table 2. Maximum voltage drops on the test networks.

	Mean Load 0% EVs	Mean Load 15% EVs Rural 60% EVs Urban	97.5% Load 15% EVs Rural 60% EVs Urban
ΔV - Rural	-2.33%	-2.52%	-5.39%
ΔV - Urban	-1.40%	-1.72%	-2.90%

Figure 2-43: Neaimeh's Fig. 8, Table 2: Urban vs. Rural penetration results

Forecasting inaccuracies caused by small population sizes is explored in **(Hayes, Gruber, & Prodanovic, 2018)**. Hayes uses Smart Meter data so has modern datasets, however with low populations forecast vs. actual household load can vary, shown in Figure 2-44:

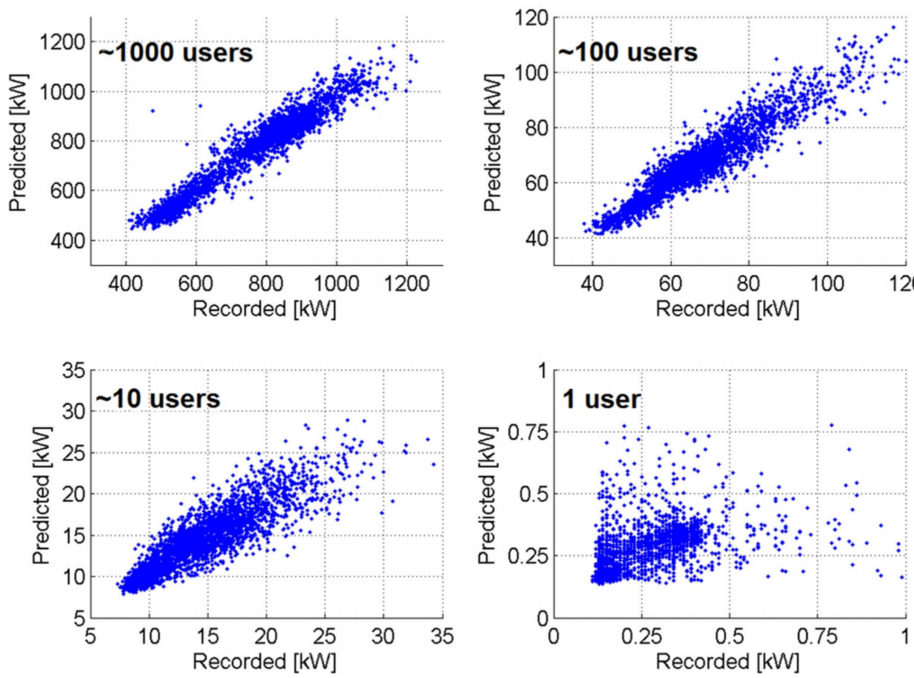


Figure 2-44: Haye's Fig. 3: Day-ahead forecast vs. recorded residential demand

Given the LV phase context where 300 houses are supplied by 3 phases, then for 100 users a prediction of 60 kW load can be in the band 50 - 70 kW. This is a major problem, simply as the number of trials per day (with 1 million UK feeders hence 3 million phases) means that to limit national overload counts to a reasonable number, the error bands to cope with small populations need be excessive, worsened by the fact that people broadly synchronise habits due to their daily rote. Hayes found the problem difficult (but SM data did help). The issue is one of recognising limitations, as model fit and prediction accuracy depend greatly on the number of individual users aggregated together. These degrade the utility of standard methods when applied to small numbers of users.

The author has met this at a CIRED presentation, where a representative of TNEI looking at forecasting under such circumstances (small populations, large number of trials) found the problem highly intractable with no effective method yet known. Considering that mass EV charging will perform millions of trials / die throws daily, it may be simpler to adopt the stance of thinking all possible outcomes will arise at some point. This is tantamount to saying “consider the worst case, for this will happen eventually”.

(Ardakanian, Rosenberg, & Keshav, 2013) presents a US paper, proposing a distributed control mechanism. The authors cite major issues re approaches using forecasts of future network loads and EV use. Both may well be wrong, so need high safety margins. To combat forecasting problems, each charging EV is monitored as is the chain of power delivery i.e. from the subtransmission station to each EV (a US subtransmission transformer roughly equates to a UK Primary station, supplying multiple thousands of customers). Monitoring is extensive so to capture the real-time state of the whole network and supplied EVs, The method is repeated arbitration, to negotiate the charging of nodes across the extended network. The negotiation needs 100’s to 1,000’s of iterations to identify each solution.

The upshot is a proportional fairness allocation of resource to EVs, given local network headroom (the system capacity less local non-controllable loads). This needs considerable communication (each EV and controller dialogue every 20msec) plus a great degree of complexity, as a solution needs be fair to all parties. The network is wide area with many peers having different conditions. The balancing objectives are: EV owner satisfaction vs. a priced available capacity signal, per N nodes.

The method is said compatible with the network's protection regime, for it can see and sidestep potential protection events, instantaneously de-rating EV charging. (Protection is a topic out of scope.) The paper contrasts centralised vs. distributed solutions, finding heavy reliance on communications. The paper is aware of the shortcomings of forecasting, the need to manage fairness and presents a novel approach. However the solution is complex, computing resource intensive and needs a reliable local communication network of good bandwidth.

In **(Wang, Huang, & Infield, 2014)** Wang uses trips synthesised from UK Time Use Survey to animate EVs about a UK LV network supplying 42 houses. Household supply voltages and transformer load impacts are considered for rising number of EVs (to 100%), with and without workplace charging and home LV V2G support. Residential loads are modelled using data synthesised by the CREST tool **(Richardson, Thomson, Infield, & Clifford, 2010)**. There is awareness that substation transformers may be set over 1.0 pu to offset feeder volt drops. Yet the V2G duty is extreme. Other than stating V2G is uneconomic and to be avoided in real life, Wang is silent re battery ageing. Wang finds even low levels of V2G can assist the local network; without V2G the limit of penetration is found to be c. 40% (over 42 houses, 16 vehicles) as shown in Figure 2-45.

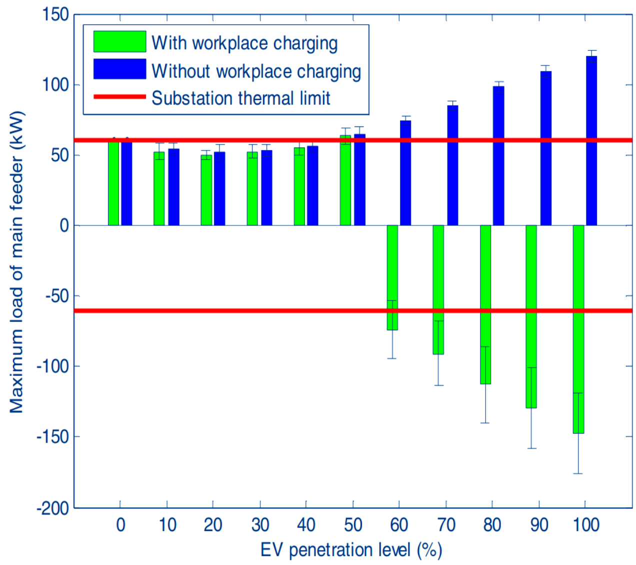


Figure 2-45: (Wang, Huang, & Infield, 2014) Fig. 12. Main feeder load

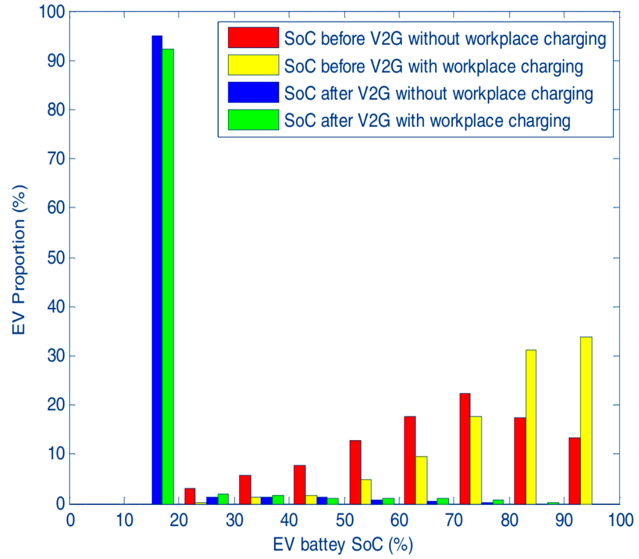


Figure 2-46: (Wang, Huang, & Infield, 2014) Fig. 7: V2G and Battery SOC

Figure 2-46 shows V2G impacts c. 95% of EVs, dropping start SOC (red and yellow) to c. 18% SOC (blue, green). Here V2G near fully depletes batteries, implying V2G use approaches driving the full range of the EV. The battery will likely suffer accelerated ageing as V2G consumes battery cycles intended for driving.

Jiang looks at maximising battery life for EVs in **(Jiang et al., 2014)** via Smart control (managing charging). This is combined with supporting the local network while managing EV charging, to meet the driver's expressed departure time and charge to travel a distance.

The suggested control method is to sense local volts and infer the capacity of the network to supply. Battery life (ageing impact of charging and grid support) is managed by modulating battery charging power. This paper introduces a battery model, describes battery ageing issues and a fuzzy-logic control system to moderate charging to meet the driver's needs, given battery ageing impacts. The concepts are built and tested on a computer-controlled rig managing a sizeable battery.

Four degrees of freedom are addressed: the battery model with ageing, the driver's expectations, network state and the logic of a controller. Although these issues are brought together, Jiang manages an individual EV. The issue of limited power availability is indirect, sensing network voltage with only 13 houses considered per feeder (which often supplying hundreds). However Jiang shows multiple degrees of freedom can be managed.

2.15 Summary of Key-Points

Real-world trials and literature have covered a lot of ground. The key points seen so far are now collated by topic area:

2.15.1 Concerning NGESO Issues

1. Broadly, the UK has sufficient generation and transmission capability to allow for overnight EV charging,
2. Aggregators are imagined able to provide DR / DSR services, however controlling existing UK appliances offers small effect vs. possible local overloads,
3. there is potential to use time-shifting / ToU tariffs to avoid peaks.

2.15.1.1 Concerning DNOs and Local Networks

1. Distribution networks may be constrained in so far as they are built to service a limited historical need; local reinforcement may be necessary
2. DNO costs are primarily in the LV system; feeder cables are more expensive to upgrade than transformers;
3. often undersized, power limitations are likely to affect transformers first.
4. LCT (initially EVs, then Heat Pumps) invalidate established LV diversity assumptions
5. HP are expected soon after or with EVs and to take c. x2.3 EV load, loading the same networks at approximately the same time of day
6. a separate analysis is needed for each LV network, as
7. overview analysis hides peaks occurring in isolated networks.
8. Unrestricted charging causes unacceptable evening peaks
9. voltage drops are an issue seen with unrestricted charging
10. congestion (feeder overcurrent) is observed at feeder heads, volt drops at ends
11. time of commencement of EV charging is a key factor
12. EV use, hence energy demanded, is likely to vary by locality,
13. raised transformer ageing is likely when spending extended periods on load.
14. Harmonics are an issue which need addressing both by:
    a) EV manufacturers (their vehicles are in breach of regulation) and
    b) DNOs (to limit back-feeding of harmonics to other customers).
15. It is necessary to curtail EV charging, as total load can exceed LV system rating,

16. an infinite number of EVs can connect to a supply whilst turned OFF, thus there is no limit to the number of EVs a curtailment scheme (*Esprit)* can manage.
17. As unlimited numbers of EVs may be allowed, then with a finite network capability there will be a population point beyond which EVs are insufficiently charged.

2.15.2 Concerning EVs

1. EVs are a controllable load, but what imperative to follow is not clear: Network vs. Market priorities; nor is it clear these are mutually compatible.
2. UK people-behaviour data (e.g. Time Use Survey) can model car movements (arrival, departure times)
3. EV uptake is not uniform i.e. tends to clump
4. most (c. 80%) EVs charge at home.
5. Vehicle drivers on the whole accept modest curtailment,
6. V2G can assist local networks but at a cost: battery ageing, over-billing for kWh
7. EV travelled distance effects the imposed load
8. location influences distance driven, which by proxy means location effects loading
   a) rural miles driven > urban miles driven, hence
   b) rural EV loads are higher.
9. Charge gained away from home can offset home charging needs, and
10. weekday charging varies depending on EV travel history and driver intent (the author considers inter-day variability a minor factor).
11. Only delivered energy can charge EVs; for high N EV counts on a constrained network many must be kept OFF; undercharging is then a likely problem.
12. Larger vehicle drivers appear to plug-in only occasionally (when they must, otherwise by habit);
13. the alternative of induction charging in parking spaces can automate EV connection, potentially giving rise to "perfect plug-ins" and different charging behaviours.
14. There is little data concerning multiple EVs on the same LV network for vehicles larger than, and driving longer range than, the early Nissan Leaf.

2.15.3 Concerning Smart Grid and Control

1. A Smart management system might shave peaks i.e. spread time-wise, to aid networks

2. a Smart system flattening load (network priority) may operate to:
    a) frustrate DR instruction to individual EVs and
    b) be unresponsive to market price signals,
3. hence potential for conflict: market needs vs. network optimisation needs.
4. These form 2 potential Smart Grid approaches, a situation often overlooked.
5. DNOs are offered such limited visibility and control via the Smart Grid that the system borders on being a hindrance, frustrating a functional system;
6. the present Smart system cannot aid DNOs manage their networks in real-time.
7. ICT management solutions are possible, can become complex and involve various controller logic, yet needs a communication path to all loads.
8. Communications is a functional necessity but as yet not seen to be in place.
9. Control solutions may be dispersed, an alternative to being centrally managed, and
10. presently, there is no single identified best solution or strategy.

2.15.4 AOB

1. In London, the electrical burden of EVs is seen as low, imposing negligible extra load. The author would like to see this verified;
2. study praxis:
    a) limiting investigations to the considered “significant minimum” scope can remove observation of key factors: Therefore, simulate “one level beyond minimum”
    b) concerning simulation periodicity: shorter is better; 30 minute periodicity causes high network loss calculation errors, 5 minutes is similar to 1 minute.
    c) substation transformer LV output: did studies use 1.0 or 1.06 pu? Often not stated
    d) a useful means to forecast small-populations is either not available or inadequate
    e) what does EV “100% penetration” mean? Conflicting interpretations which may be c. 40% out: 1 EV per house or 1:1 EV to car replacement?
3. related (potentially interdependent) degrees of freedom:
    a) needs of local network,
    b) the driver’s needs,
    c) potential to impact battery ageing,

d) the modus operandi of a controller - several candidates, no ideal identified.

2.16 Chapter Summary

This chapter presented the 2020 era UK power industry structure, with DNOs responsible for electricity delivery but estranged from customers.

The attributes of the anticipated UK Smart Grid have outlined, showing how difficult it is for DNOs to leverage SG benefits to support their networks. A potential dichotomy is seen between market-goals, practical capabilities of the system and the hope of selling added value services to NGESO by adjusting EV loads.

There is awareness that generation and transmission elements are broadly adequate, but LV components may not be. The efforts of academia and industry to explore the problem were described. A pragmatic means to manage overloads has been shown: Disconnect charging EVs when load gets too high.

Further, the suggested replacement of gas home heating in the UK by electric Heat Pumps impose loads x2 or more larger than EVs, loads not amenable to ADMD methods and likely not supportable on most LV networks.

V2G is anticipated to have potential, but for large UK fleets neither income adequate for profit, nor market need has been demonstrated.

A major challenge latent in all the above is the rapid evolution of EVs. Data from projects may <u>not represent</u> future EVs replacing cars, resulting in repeated waves of EV trials as the situation matures.

The next chapter looks at simulators, by which the situation can be further investigated.

Chapter 3: Approaches to Simulation

This chapter reviews the decisions driving a course of action: To develop an EV on LV simulator which closely mimics the UK situation, for full EV replacement of cars.

In this context, a simulator is a set of mathematical models running on a computer to mimic aspects of a problem, allowing paths of interdependent decisions to be constructed i.e. to represent and explore cause-effect chains.

3.1 Why Simulate?

Simulation brings benefits:

- it is possible to model situations which are difficult, time-consuming, impractical or too expensive to physically realise,
- simulations can model what-if situations
- unusual outputs can be investigated to trace root causes,
- simulation is not intrinsically limited to discipline; an appropriate simulator can track and incorporate diverse aspects of interest.
- Individual, independent state-machines are possible, allowing construction of a system of systems able to exhibit behaviours based on interactions and memory of past events.

Simulation is a plausible way forward, but is sometimes fraught as software development is difficult. Computer programs can be incorrect, due to:

- misunderstanding the needs of the situation,
- programming defects (bugs)
- incorrect input data (wrong set of data values, data mistakes)
- inadequate post-processing causing poor analysis, hence wrong conclusions.

A strategy to minimise these effects is to adopt a proven simulator which reflects the likely habits of EVs in the UK. Fortunately, survey data is available re:

a) car use (from car travel, UK NTS survey and MOT data) which EVs can adopt,

b) people as EV drivers (MEA and EN projects)

c) EVs as electrical systems

d) electrical power networks

e) habits and practices of DNOs

f) habits of aggregators providing services to NGESO

g) habits and practices of Ofgem.

Simulations need to be reasonably accurate, pertinent (i.e. simulates the correct UK experience) and to express the degrees of freedom in the problem.

These all depend upon:

- knowing the problem domain including key interactions,
- being able to encapsulate those into a useful simulation
- providing relevant input states to allow simulation fidelity.

3.1.1 Potential Alternatives to Simulation

The core problem (too many EVs simultaneously charging) is not dissimilar to: How many people in a group have the same birthday - which for our purposes can be read as how many EVs want to charge simultaneously (given that only a finite number of chargers can be accommodated at any one moment). Determining the mathematics is non-trivial and has many possible forms, reviewed in *"The matching, birthday and the strong birthday problem"* **(DasGupta, 2005)**. DasGupta's section *2.4: Similar birthday triplets and p of a kind* for example:

$$P(W \geq 1) = 1 - \sum_{i=0}^{n/2} \frac{m!\,n!}{i!(n-2i)!(m-n+i)!.2^i.m^n} \tag{12}$$

where: i is the reference individual, n is the sample size, m is the number of coincidental birthday to assess, W the number of similar birthday triplets and $P(W\geq 1)$ the probability.

Whatever method is used needs to be given the instantaneous number of EVs present and looking to charge, and the number of charging EVs the power network can accommodate. This data is needed for each time-slice for the duration investigated. Determining these values suggests use of a simulator to track EVs and their SOC, with an awareness of the varying residential load. This allows discovery of available headroom, thus the number of coincidences which are tolerable.

A counter argument now forms: If a probabilistic method needs a simulator to track and discover the probability equation input conditions, why not directly count EVs, given all the necessary data is now at hand? A probabilistic approach was not adopted.

3.2 Simulators

A review of papers concerning EVs on power network was undertaken to identify the simulation methods used:

Table 3-1: Types of Simulation Engines used in 73 papers to c. mid 2016

Simulation Engine Used	Number of Occurrences
Matlab/Simulink	8
DigiSILENT / powerfactory	2
EnergyPlan	1
PSCAD/EMTDC	1
GridLab-D	1
PSAT	1
PSCAD/EMTDC	1
Not stated	58

The most promising was GridLAB-D, a US government initiative. This offers a full chain including data setup, simulation and an analysis suite. However the author suspected GridLAB-D used US LV network structures. In an exchange of emails this was confirmed by the GridLAB-D team-leader; distribution topology was fixed as the US system. It was also stated there were no plans to change; GridLab-D was not suitable for UK LV systems.

3.2.1 Limitations of Past Simulations

A common limitation was insufficient focus on pertinent EV simulation. The electrical aspects may be deeply studied but the EV demand estimated e.g. fixed or randomised, not real-world dynamic - or based on non-UK datasets. An example is the comprehensive study **(Quirós-Tortós, J., Ochoa, L. F., Alnaser, S. W., & Butler, T. 2016)** which modelled a UK LV system with EV data from Ireland, taken from their 2011 Smart Grid Demonstration Programme i.e. real-world data for a small fleet (2 - 7) of Mitsubishi iMiEVs. However, these EVs had different consumption patterns (predominantly charging in the morning) which are no longer typical of modern types. Any study looking to project future loads needs to be able to formulate likely UK EV loads, which implies modelling trips made by EVs as if cars driving UK patterns.

Another issue was not considering the number of EVs likely, given EVs are to replace cars. Often the levels considered were no more than 30-50% EV penetration, not realistic as many homes have more than 1 car, as shown in Figure 3-1 (includes small vans):

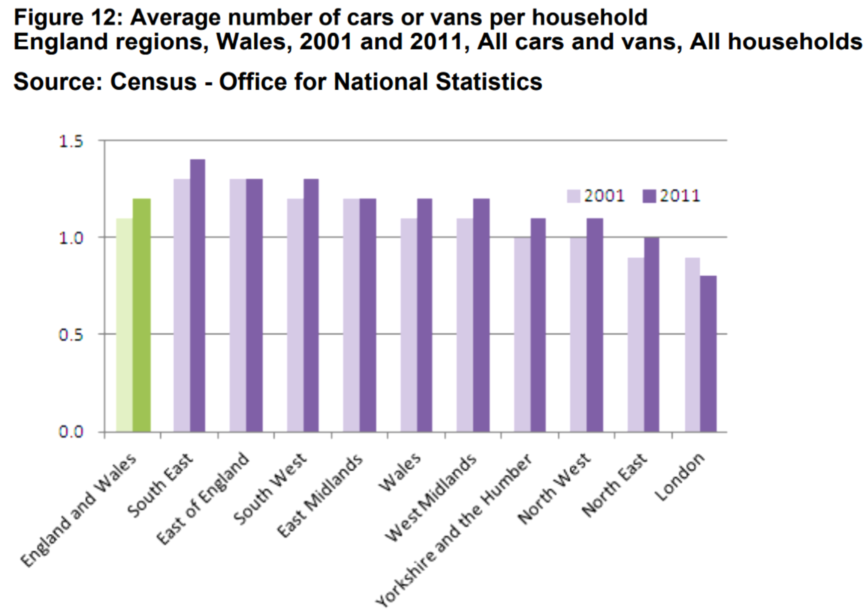


Figure 3-1: ***(ONS, 2012)*** *from Table KS404E*

Further, context has changed. Early approaches often assumed EV batteries are small so always exhausted, implying a need to charge immediately to 100% capacity. With modern EVs this is not the case. Further, the marked temperature sensitivity of Li-ion batteries was rarely considered. The high number of degrees of freedom and the interaction of consequences (e.g. EV battery arrival SOC is memory of past charging, so charging impacts are a function of charging history) so creating interdependencies. Minor reasonable approximations or omissions may make results diverge vs. what may be seen in real life.

For example, impractical time periodicity. Many simulations use power industry standard half-hour billing periods, even though overloaded fuses may blow in seconds to minutes. Using half-hour periods hides load spikes e.g. using a 12 kW shower for 10 minutes presents as a 4 kW load for 1/2 hour. Given fusing characteristics, this is unreasonable.

Finally, only occasionally did papers consider home EVs charging on constrained networks. EVs were often permitted to charge against market demands, with no limit on EVs charging simultaneously when the cost of power was low. This is reasonable on purpose-built systems, not domestic UK LV networks.

From this the author considers: historically, many researchers have applied tools, methods and data which are to hand, rather than standing back and considering what is necessary to effectively model the issues.

3.2.2 INSim - an Attempted Simulator

From late 2014 the author was developing a simulator, INSim. A highly capable tool developed for any possible user, this was flagged by the author (for a year) as too big a task to complete in available time and eventually abandoned in late 2016. Several core features including EV simulation were functioning, but the project was no more than half-finished in two years.

The author again searched for a suitable simulator. The paper “A review of computer tools for modeling electric vehicle energy requirements and their impact on power distribution networks” **(Mahmud & Town, 2016)** considered 125 simulation tools for ability to model EVs on distribution networks. This paper included a key table: Table 3-2. Mahmud’s review also drew a blank, failing to find a Smart Grid + power network analysis tool capable of modelling a UK LV network plus the internal states of EVs.

An EV simulator was needed which could be interfaced with the available electrical power simulation tool, OpenDSS (competent and free tool). Techniques to work with OpenDSS had been developed for INSim, but no method to simulate EVs was to hand.

Note by end 2016 the author had written two simulators in Excel. These modelled MEA’s *Esprit* **(Cross, 2015)** with which the author was familiar after working with Dr. Cross for two weeks. However the Excel simulator had limited function and was very slow.

3.3 Approaches to Simulation

3.3.1 Phase Hopping

The initial post-INSim intent was to balance the load between phases in a manner similar to the Energy Storage and Management Unit (ESMU). The ESMU is an LV inter-phase power bridge / converter **(SSEPD, 2015)** which can load phases and convert the power to DC. The energy can be either stored in a battery, or be used to power an inverter to support another phase.

An EV simulator might model EVs "phase hopping" - charging on the least-loaded phase, repeatedly moving (hopping) to any subsequent least-loaded phase as needed. The opportunity existed to dispatch V2G on a highly loaded phase, so to electrically support it in a manner similar to the ESMU. Given the new direction, the author proceeded to develop a phase-hopping phase balancer, called the Feeder Phase Balancer or FPB.

A necessity for this is 3-phase at each house (common in some countries e.g. Germany).

The author found solving phase-hopping complex, potentially needing a deep iterative analysis, for there seems no perfect algebraic method. The task is a form of the computer science packing problem "Knapsack". Approximate solutions existed with unclear limits on when to stop attempting alternatives. The work developed two fast approximators using game-play. Early proof-of-concept tests were successful; hopping generated EV local allocations with closely matching overall phase loads.

In March 2017 (5 months from EngD completion) phase-hopping was deemed not appropriate as few UK houses have 3-phase; EVs are married to the house phase so cannot "hop". The EngD now had no substantive topic, no simulation tool or results and vanishing timescales. The author strove to develop an alternative simulator, being this work. Phase-hopping is excised from FPB, the only vestige being an (unused) option for public chargepoints to auto-connect new EV loads to the least loaded phase. Given availability of 3-phase, there is reason to believe the method would work as variants exist and are successful **(Kalesar, 2016)**. The author notes 3-phase at each house is promoted by REA and WPD **(REA & WPD, 2018)** as standard for new build houses.

Based on the initial phase-hopping progress, the author suggests that a proportion of public EV chargers be built with phase-hopping; this will aid balance feeder loads.

Table 3-2: Mahmud and Town's Table 4 classifying simulation tools

Table 4
Further classification of simulation tools from Table 1 by application and capability.

Tool	Vehicle modeling/analysis	EV control/ EMS	Power train	Emission	V2G	Electricity pricing/ scheduling	Electricity planning	Electricity distribution system analysis	Renewable energy	Distributed control
ADVANCE [13]	✓	✓	✓	×	✓	×	×	×	×	×
ADVISOR [14]	Analysis	✓	✓	✓	×	×	×	×	×	×
AVL CRUISE [15]	✓	✓	✓	✓	✓	×	×	×	×	×
CASPOC [16]	✓	✓	✓	×	✓	✓	×	✓	✓	✓
COMPOSE [17]	×	×	×	✓	✓	✓	✓	×	✓	✓
CYME Tool kit [18]	×	×	×	×	×	✓	✓	✓	×	×
DSATools [19]	×	×	×	×	×	✓	✓	✓	✓	✓
DYNA4 Simulation Toolkit [20]	✓	✓	✓	×	×	×	×	×	×	×
EasyPower [21]	×	×	×	×	×	✓	✓	✓	×	×
EDSA Paladin Toolkit [22]	×	×	×	×	×	✓	✓	×	✓	✓
EMCAS [23]	×	✓	×	×	✓	✓	✓	✓	✓	✓
EnergyPLAN [24]	×	×	×	×	✓	✓	✓	✓	✓	✓
ETAP toolkit [25]	×	×	×	×	✓	✓	✓	✓	✓	✓
FASTSim [26]	✓	✓	✓	✓	✓	×	×	×	×	×
GREET 2014 [27]	✓	✓	×	✓	×	×	×	×	×	×
GridLAB-D [28]	×	×	×	×	×	✓	✓	✓	✓	✓
GridSpice [29]	×	×	×	×	✓	✓	✓	✓	✓	✓
Grid 360/iEnergy [30]	×	×	×	×	✓	✓	✓	×	✓	✓
GTMax [31]	×	×	×	×	✓	✓	✓	✓	✓	✓
HOMER [32]	×	×	×	×	✓	✓	✓	×	✓	✓
HYPERSIM/ePOWERgrid [33]	✓	✓	×	×	✓	✓	✓	✓	✓	✓
iGRHYSO [34]	×	×	×	×	✓	✓	×	×	✓	✓
IKARUS [35]	×	×	×	✓	✓	✓	✓	×	✓	✓
InterPSS [36]	×	×	×	×	×	✓	×	✓	✓	✓
IPSA [37]	×	×	×	×	×	×	✓	✓	✓	✓
MARKAL/TIMES [38]	×	×	×	✓	✓	✓	✓	✓	✓	✓
MesapPlaNet [39]	×	×	×	✓	✓	✓	✓	✓	✓	✓
MiPower [40]	×	×	×	×	×	✓	✓	✓	×	×
Modelica Toolkit [41]	✓	✓	✓	×	✓	×	×	×	×	✓
NEPLAN|Electricity [42]	×	×	×	×	✓	✓	✓	✓	✓	✓
OpenDSS [43]	×	×	×	×	×	✓	✓	✓	✓	✓
ORCED [44]	×	×	×	✓	✓	✓	✓	✓	✓	✓
PLEXOS [45]	×	×	×	×	×	✓	✓	✓	✓	✓
POM Applications Suite [46]	×	×	×	×	×	✓	✓	✓	✓	✓
PowerFactory [47]	×	×	×	×	✓	✓	✓	✓	✓	✓
PSAT [48]	×	×	×	×	×	×	×	✓	✓	✓
RAPSim [49]	×	×	×	×	✓	×	×	×	✓	✓
Saber [50]	✓	✓	✓	×	✓	✓	✓	✓	✓	✓
Simpow [51]	×	×	×	×	×	✓	✓	✓	✓	×
SOMES [52]	×	×	×	×	×	×	✓	×	✓	✓
SPARD Power [53]	×	×	×	×	×	×	✓	✓	×	×
THYME [54]	×	×	×	×	×	✓	✓	✓	×	✓
V2G-Sim [55]	Design	✓	✓	×	✓	✓	✓	×	×	×
Xendee Tool [56]	×	×	×	×	×	×	✓	✓	✓	✓

Cross (×) indicates 'no', Tick (✓) sign indicates 'yes'.

3.3.2 A General Intelligent EV on LV Network Simulator

A revised, non-hopping FPB would investigate the impact of EVs on LV systems, show use of DR and V2G and strive for insights. A form of MEA's *Esprit* control method might be included, as well as the author's own ideas.

MEA studies found reinforcement of short sections allowed sample networks to be more capable, implying that a constraint was minimum built per house capability. Identifying and analysing by built capability is then the author's intent. This is married to the fact that there is no typical UK LV network.

The author therefore uses a simple network of <u>known minimum built kW capability</u>. This can determine <u>the EV support capability of an idealised network</u>, against which rules for imperfect (real-world) networks could be formed. Sections of feeder falling short of intended built kW can be identified by inspection, so becoming candidates for reinforcement. Without reinforcement the network must be de-rated.

The core of the FPB would be a power throughput optimiser with phase levelling capability, plus OpenDSS to investigate electrical aspects e.g. voltage drops, losses etc.

A key aspect is EV modelling. These need be plastic autonomous agents i.e. individuals, possessing their own situation and intents. The method needed to be able to model key aspects of future EV design, with focus on:

- charging and dispatch capabilities
- ability to operate so to have situational / plastic intents i.e. adaptable patterns of capability, to model possible manufacturer's programmed charging behaviour
- with and without communications (Smart Grid) capability
- in the context of an LV situation with other loads
- able to experience revised situations on the fly e.g. a power-fail, a comms fail etc.

Most of the ingredients for a simulator were understood at this time (early 2017) excepting:

- a mechanism to model future EV intent, and
- means to overcome the lack of relevant forecasting for LV. At this level, loads are extremely stochastic; there is little statistical mixing of the intents of people.

Both would be needed to construct a final simulator.

INSim work had used a timing window of 1/10th hour; this provided adequate resolution for most household appliances, is simple to program and understandable.

It was clear how to optimise use of kWh: route power to where most needed. How might that be done, in an environment which cannot be forecast? A method was developed by desk-checking situations to find retrospective least-regret rules i.e. “what should have happened”, that is, game-playing many cases on paper then generalising interpretations into a least-regret defensive strategy to form heuristics to minimise least-regret.

Heuristic example 1: If V2G is used and the vehicle battery depleted to a level such that the vehicle must recharge for departure, what guarantee is there that other loads will not consume needed kW, so frustrating charging? The EV risks failing to gain sufficient charge to depart. Here, the least regret view is: Do not deploy V2G unless the kWh used is spare i.e. above depart State of Charge (SOC). Similarly, there is no need to charge over depart SOC if others need power. Together, these form a rule: do not charge over SOC departure, unless the EV is a V2G type. **Note** calculations include some margin in SOC depart.

Heuristic example 2: This concerns which V2G to dispatch, from a set of available V2G EVs. The least-regret view found is: Dispatch from the EV next to depart. Post departure, the fleet left standing possesses more V2G kWh reserves than if a remaining EV had been depleted, so maximising future V2G deployment options.

Several least regret rules are embodied in code for the FPB’s MCS element.

3.4 Intended FPB Degrees of Freedom

As a minimum, the FPB is to understand: One transformer, one feeder from that transformer and 3 phases per feeder. All houses connect to a phase; all EVs are supplied at a house (or stand-alone EVSE public chargers, not used but present).

- Any network can be entered into OpenDSS
- FPB needs to be advised of:
  - OpenDSS “master.dss” definitions file
  - the network addresses of houses, as used in OpenDSS
  - household load (as Wh energy used) per simulation period

  - general network limits (cable power carrying capability, transformer rating)
  - default hi_limit, lo_limit settings (hi_limit defines maximum allowed load)
  - defined DR / FFR commands
  - local ambient temperature
- Concerning EVs, FPB needs to know:
  - model characteristics (battery size, charging rates, consumption, losses etc.)
  - definition of individual EVs, their ID and home house, driver plugin proclivity
  - EV trip definitions (per EV: depart time and distance) and a randomiser seed
  - numbers of EVs resident (N EV)
  - their daily driven distance (miles per day, mpd. This is the fleet average).
- Run-time set commands:
  - timed events e.g. power-fail / restore
  - timed commands e.g. an aggregator ToU rule (no charging after 6pm etc.).

3.4.1 EV Characteristics

Individual EVs are to be copies of defined types. Individuals have their own state, based on generic characteristics from the defined type. Each defined type details: battery size, consumption per distance driven; inverter losses, battery losses and system consumption. Also, each type must be one of: **dumb** (does not communicate / listen to instruction), **SV1G** (a fully communicating and cooperative EV), **V2G** (as SV1G but can dispatch).

Characteristics can be synthesised from existing EVs (Nissan Leaf, Tesla S etc.) and modified to match general UK car characteristics e.g. SMMT data **(SMMT, 2018)**, to invent EV models which mimic SMMT market categories. At the time of writing the models seen on the road are: the Nissan Leaf 24 or 30, the Renault Zoe and the Tesla S. Invented vehicles are to have the same proportion as SMMT reports market categories exist. Li-ion batteries are assumed. At the time of writing there is no clear successor likely to over-match the economics of bulk Li-ion battery production.

Note: A proportionate mix is used but may not be representative, for it supposes each area is “average”. Proportions are likely regional and wealth related. The proportions used may cause <u>bias towards a mean</u> i.e. <u>may not be usual, for most locations</u>. If time permits, the author intends to perform a sensitivity test to determine impact of vehicle sizes i.e. pools of 75% small, 25% large vs. 25% small 75% large. Also all simulations include a number of uncontrollable dumb EVs, which attempt to do as they wish.

3.4.2 How EVs are Driven

It is taken that EVs are ICE car replacements, not autonomous taxis. This allows use of UK National Travel Survey data **(HM Government, 2018b)**, MOT data sets **(DfT, 2017)** and advice generously offered by the RAC Foundation to researchers re finding data.

3.4.3 LV Network Data

LV electrical characteristics for cables are based on published equipment data, now long standardised. The substation transformers are somewhat less clear as new Amorphous types are being introduced (with reduced losses) and characteristics are not published, other than the headline reduction in losses **(Wilson Power Solutions, 2017)**. The implied internal characteristics have been projected. When operating in rated power ranges it is anticipated that inaccuracies here will have minor impact (this would not be acceptable if fault studies were being performed, however they are not).

Note the simulations assume the transformer has been adjusted (performed manually on site) to give a certain volts output, also counteracting effects of inaccuracies. The settings modelled give 246 V out, with the substation transformer off-load.

3.5 Techniques of Simulation

Discrete Event Simulators are well known, long used and covered in the author's two papers **(Broderick, Cruden, Sharkh, & Bessant, 2016)** and **(Broderick, Cruden, Sharkh, & Bessant, 2017)**. The concept is to define a set of state values and timed modifier events. A list of timed events then applies the indicated modifier to states; outputs are then the state values, given the situation and timing context.

Such systems may use mathematics to define the modifiers, but the major challenges are what states to log and by what process to modify them.

The aim is to build a simulator to look at network and EV states over time, under different operating regimes:

- ambient temperatures relating to season

- residential loads for that season
- for the charging conditions which arise from:
  - different networks
  - different control options
  - different EV duties (number of, driven ranges).

All input and output to use text or .csv data files, so making data human readable. The data sources are:

1. UK NTS (National Travel Survey) trip data (there is no one reference; a team of staff services enquiries)
2. NTVV (New Thames Valley Vision) household load data,
3. author-projected future EV data
4. output from DES simulation with:
   a) arbitrary timing with periodic assessment intervals for individual EV delta SOC accumulation (as per **(Broderick, Cruden, Sharkh, & Bessant, 2016)**),
   b) OpenDSS interface based on methods developed during INSim development.

Necessary but missing elements:

A. load data upsampling via pseudo randomised interpolation (converts 1/2 hour datapoints to 5 x 1/10th hour datapoints with the same energy envelope)
B. Monte Carlo generation of picks (data draws) to match a known probability profile
C. method to model diverse EV charging characteristics
D. MCS control algorithm to manage EV charging
E. scenario DES execution program (FPB core)
F. associated application stack elements:
   I. a management system offering multi-threaded operation
   II. post processing to make plots
   III. post processing for logged data assessment and summary results generation.

Any simulator needs be fast for there are many degrees of freedom, implying that multiple simulation runs must be performed to map the interactions e.g. holding M degrees of freedom static whilst adjusting a key input variable, then repeated holding M’ degrees static etc. Simulations are repeated in great numbers, hence the need for speed.

Note re Units internally FPB works in SI units (mks) however on output, distances may be converted from km to miles. Also, the author's programming habit is to postpend variables with the appropriate data unit e.g. phase_1_load_kW.

3.6 Chapter Summary

This chapter has covered the reasons why simulations are used (cost and convenience), and lack of an available simulator to cover UK LV power systems with EV modelling, of electrical aspects and of people's driving habits. The importance of functional context and input data relating to the UK has been described; without these results may not be relevant.

These issues culminated in a decision to construct a UK-orientated simulator, the FPB, able to model and manage EVs on a standardised domestic LV network. The balancing of feeder phases is (without phase hopping) now a minority capability. The original title "Feeder Phase Balancer" is obsolescent and FPB will be used.

The next chapter describes the key methods of operation of the developed simulator.

this page deliberately left blank

Chapter 4: The FPB Simulator and Concepts

This chapter describes the Feeder Phase Balancer/FPB simulator from generalities to specifics. FPB is intended to model and manage EVs on networks with some phase balancing, a minority duty. FPB faced several unique problems resulting in novel solutions: abandonment of forecasts, development of a method to model EV intent and a heuristic rule-set to by which to organise multi-vehicle charging.

The chapter also presents key assumptions (see Appendix A), the method by which EVs are managed and the functional blocks in the FPB suite. Simulation models are described, as is the discrete event simulation engine. Pertinent input data is key to simulation; data sourcing is described. The development quality assurance process is also described, as is the concept of simulation scenarios, sequences and formatting of output data. Simulation praxis in terms of configuring and running simulations is described.

Section 4.11 compares FPB output to My Electric Avenue results. These are found similar, hence the FPB is deemed plausible. Pseudo-code is also presented for major functions.

Note a key concern: That the EVs modelled (invented future types) are plausible. This is not necessarily a given as characteristics change over time, however FPB's EVs are:

- modelled to match profiles of existing cars, with
- energy consumption based on known EV characteristics.

EV characteristics are plastic and may be amended by editing .csv data input files.

4.1.1 General Overview

The FPB is a data-driven Discrete Event Simulator (DES) with a quantised clock, broadly similar to **(Olivella-Rosell, Villafafila-Robles, et al, 2015)** which applies "mobility patterns" to EVs on an MV network. A DES updates sets of known states to new values as events are encountered, e.g. increments EV State of Charge (SOC) with charging over time. The method relies on sets of input data to define starting conditions and a list of timed events.

Note FPB jargon: a period (pd) is a duration of time, and events occur at simulation time (st). A pd is an integer and an st is a real e.g. pd 6 spans to pd 7, so includes an event at st 6.32. FPB advances simulation 10 times an hour, giving periods 6 minutes long.

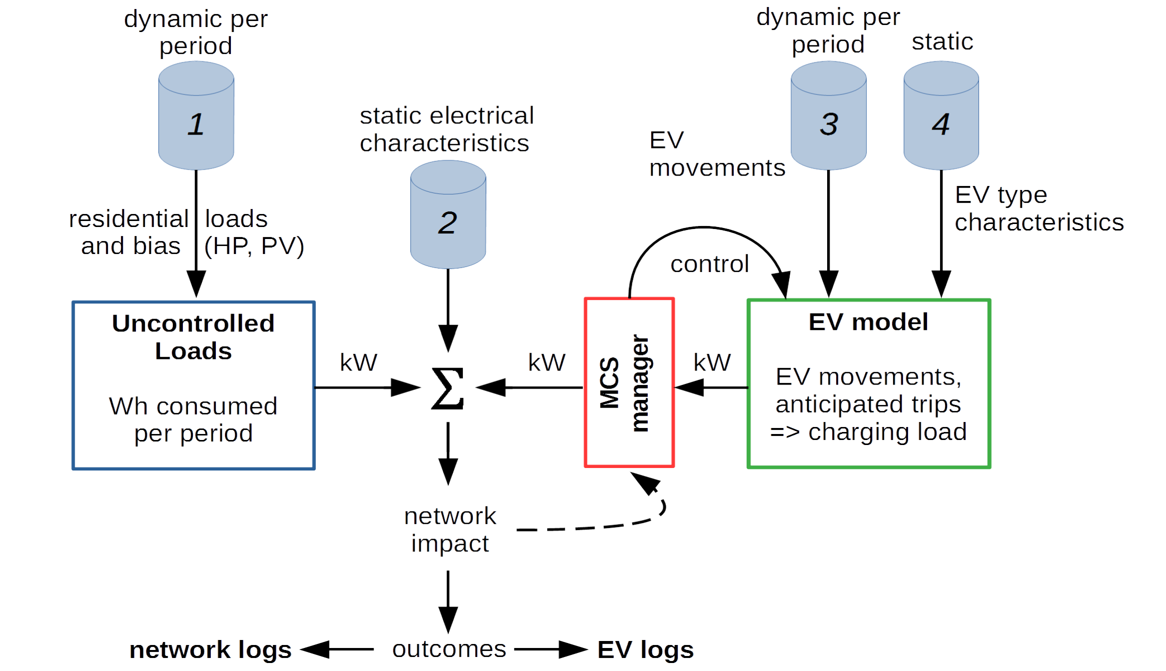


Figure 4-1: Simplified overview of FPB concept

Figure 4-1 shows 4 primary data reserves:

1. libraries of residential loads per house, per period and bias factors (e.g. HP, PV),
2. static electrical characteristics such as network capacity limits,
3. libraries of per EV timed trips (movements) with departure time and distance
4. EV characteristics (battery size, consumption rates for distance etc.)

The simulation cycle is every 1/10th hour over the simulated week. Loads are assessed per period as residential and EV charging loads. EVs are subject to no control or various external or Managed Charging System (MCS) "on the fly" i.e. each period.

Note that EVs possess memory so past states influence outcomes. This is also true of the transformer model (within the network impact assessment) which tracks heating. This necessitates a data conditioning run to discover starting states for EV initial SOC and transformer heating; a second run then generates output results.

4.1.2 General Design Implementation

The approach was to devise a solution on paper, expressed as a series of programmed elements i.e. a complex system was decomposed into digestible steps. This was implemented on a Windows PC, version 7 or later, using:

- python 2.7 **(Python Software Foundation, 2018)**

- using the Anaconda python development suite **(Anaconda, 2016)**, with the
- OpenDSS load flow power analyser **(Dugan & McDermott, 2011)**, **(EPRI, 2012)**.

FPB has c. 107 k lines of executable code written by the author. Some 7 k is the core simulator, another 37 k lines is an application support stack and analysis tools, and the remainder per-sequence repeated elements. All programs are run from a Windows command line. The INSim work provided insights into the DES method and techniques to connect with OpenDSS. FPB directly inherits c. 300 lines of INSim's 64 k lines of code.

4.2 Key Assumptions

All assumptions are listed in Appendix A with the most pertinent restated below.

4.2.1 EVs and Charging

EV battery charge is measured as State of Charge (SOC), a percentage. A battery for a contemporary EV will range from 25 to 100 kWh capacity, giving 60 to 300+ miles range. The EV is likely to have a home charging capability of 3.6 or 7.2 kW, AC, with 3-phase types drawing up to 22 kW. These characteristics are set per EV type and may be changed.

The following people-behaviour and (optional) BLPs are present in the built simulator.

4.2.1.1 People's Charging Behaviour

Observed early EV owner behaviour **(EA Technology Ltd., & Roberts, 2016)** related to vehicles with small batteries (24 kWh, My Electric Avenue trial). Drivers fought range anxiety by charging at home overnight, so the EV was ready for morning. Verbal reports stated that EVs were not used in the evening, the driver fearing insufficient morning charge. Later observations (EN early results **(WPD, 2017)**) suggest owners of large-battery EVs are more blasé, charging occasionally as if refuelling a fossil-fuel car. The driver can connect by cable to a charger (EV Supply Equipment, EVSE) or via an induction charging loop, embedded in a parking space. These options give rise to different behaviours:

- people often don't bother to plug in ("it's charged enough for now")
- vs. connecting automatically via induction loop on parking, with
- system losses of:
  - c. 16% via cable - inverter - battery, or
  - c. 24% induction loop - inverter - battery.

4.2.1.2 Battery Life Policies / BLPs

Batteries are affected by the manner of charging. Although not yet known implemented in EVs, there are simple strategies to optimise battery life **(Al-karakchi, Lacey, & Putrus, 2015)** and **(Dubarry, 2017)** which the author terms “Battery Life Policies” (BLPs):

- transfer energy when the battery is cool
- repeatedly pause charging, to cool / limit temperature rise
- calender ageing lifts at low and high SOC, so keep SOC in mid (20% - 80%) band.

Affecting charging patterns impacts network loading, so needs be in any simulator. The BLP methods relate to Lithium-ion batteries, and are reported to slow the rate of battery ageing by 17% (Al-lkarakchi) and potentially more (Dubarry):

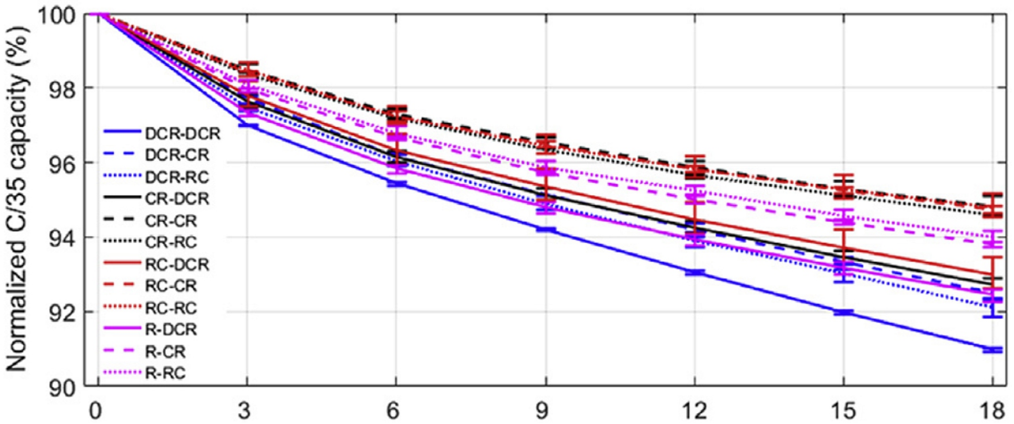


Figure 4-2: Impact of Varying Timing of Battery Use (Discharge, Charge, Rest)

***(Dubarry, 2017 Fig 3)** Varying timing of charge movements with / without rest affects battery degradation. Drive (home), Charge, Rest (DCR, blue line) ages batteries fastest, the present default charging pattern. Black dashes (CR-CR) halves the ageing slope.*

Figure 4-2 implies charging is best broken up (so not to immediately charging to 100% SOC on arrival home). Given such a simple method improves battery life (or allows a cheaper battery to offer comparable life) the author assumes: <u>BLPs will be adopted</u>.

4.2.2 The Vehicles Modelled

The modelled vehicles are those which hold primary traction energy in a battery. PHEVs are not separately modelled. PHEVs, when operating from battery, appear as small EVs. PHEVs do receive benefit from fossil fuels, thus charge less. FPB may mimic PHEVs, by adding an EV class with a small battery and low kWh rate of consumption.

UK SMMT classifications and sales ratios are used to apportion a spread of EVs types, however the mix used is average less top end vehicles (simply as these are rare).

This study is not "per future year", rather by EV penetration density **N EV**. The reason is: uptake hotspots are anticipated i.e. wealthy areas adopt EVs early. Further it is unclear how rapidly EVs replace cars; this is subject to political, economic and personal factors.

4.3 EV Management Objective

The Managed Charging System (MCS) built into FPB meets the objective function (13) by a series of calculations, concluding in a controllable EV load allocation (17). Combinations of EV loads (and V2G) can be considered for the LHS of (17). FPB calculates headroom and EV states using kW (real-power) estimates. OpenDSS can assess kVAr.

Objective: $$\left(\sum \text{point loads on phase}\right) \leq \text{phase hi limit} \tag{13}$$

where: $$\text{point loads on phase} = \left(\sum \text{uncontrollable}\right) + \left(\sum \text{controllable}\right) \tag{14}$$

and: $$\text{phase headroom} = \text{phase hi limit} - \sum \text{phase uncontrolled loads} \tag{15}$$

implying: $$\text{controllable load budget} \leq \text{headroom available} \tag{16}$$

i.e. $$\left(\sum \text{EV loads}\right) + \left(\sum \text{V2G dispatch}\right) = \text{controllable load budget} \tag{17}$$

The MCS component sees the available phase headroom and EV states only. These can be managed using disconnectors (clamps), V2G in two modes and prioritisation so to manage the EV situations to meet the load budget available. Given no reliable forecast method for small populations, there is no forward projecting or forecasting. Instead least-regret method is used, the rules for which being discovered through game-play.

4.3.1 EV Departure Stance

EVs strive to charge to an SOC needed for future use, yet always depart even if they have insufficient charge. This is as people will do this, planning to recharge elsewhere, and is an algorithmic simplification. To halt departures with very low SOC will complicate the EV's planned trip schedule and trip patterns, causing simulations to not be comparable one to another. As trips are unaffected, use of other charge sources is implicit. This allows study of how much and under what situations EVs charge when Away from Home (AFH).

Low SOC departures are recorded / logged as:

a) "undercharged" (vs. SOC goal for departure): insufficient to complete the foreseeable trips (all intended to end of day),

b) "severely undercharged": insufficient to reach their destination and return home without recharging i.e. the driver will be stranded if they cannot AFH charge.

4.3.2 EV Arrival Stance and AFH

On arrival home, SOC is decremented by trip use. Any negative SOC is detected and corrected to be plausible, on the grounds they must have recharged for they returned. For other vehicles, there is a possibility the EV recharged Away from Home (AFH). This is resolved by adjustable probability of AFH chance, defaulting to 0.3.

Note it is assumed that AFH charging is always available; non-use is the driver's decision, not a lack of public chargepoints. All AFH charging events and charged kWh are logged, both for the EV and the fleet. See also flowcharts and pseudocode in section 4.13.

4.4 Simulator General Components - Three Main Blocks

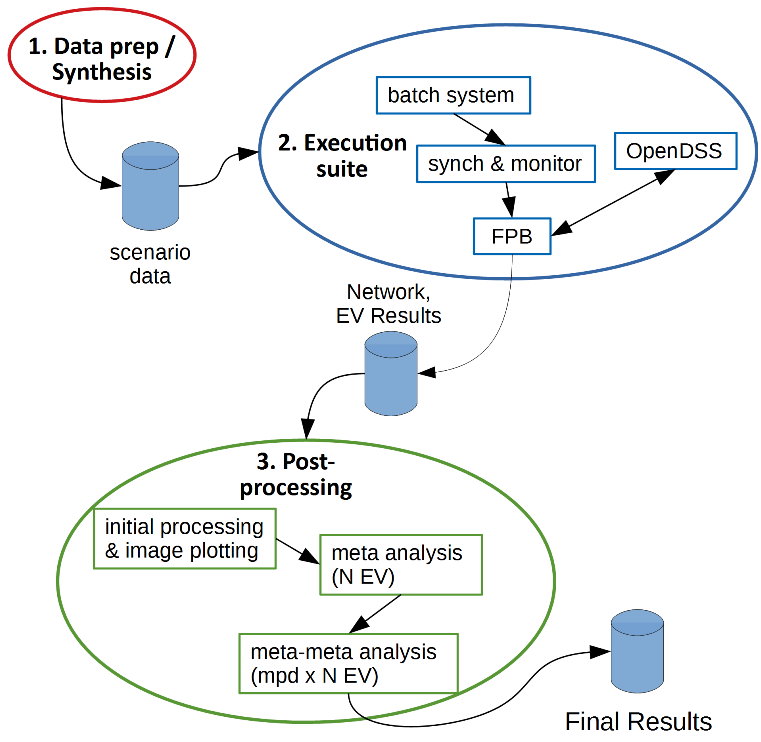


Figure 4-3: Simulator Overview: The Three Main Blocks

The simulator is organised into three blocks:

1. Data preparation - to synthesise libraries of input datasets;
2. Simulation Execution

3. Results Processing.

4.4.1 Block 1: Data Preparation and Synthesis

The simulator needs descriptions of networks, EVs and any scenario specifics (e.g. local temperature). Data sourcing is detailed in 5.2 and provides:

- residential load data,
- synthesised network characteristics data (transformer and cables) for OpenDSS,
- FPB settings (maximum limits etc.) with which to regulate the network, plus any special instructions e.g. DR times, various timed events.

The EV data includes:

- UK travel statistics from NTS data, vehicle ranges driven data from MOT statistics, and some RAC driven distances data
- which are used to synthesise vehicle driven distances, departure and return times
- EV characteristics projected from known models projected onto SMMT categories *NB these are guestimates about possible EV models.*

Scenario definitions are created by hand for the situation investigated. The degrees of freedom of these are listed in the FPB Manual **(Broderick, S. 2018)**, but include EVs, networks, switches to modify MCS management options and any special timed events.

All data (inputs and outputs) are in text form, as .csv files or text log files; a simple text editor or spreadsheet can view / edit the data.

4.4.2 Block 2: Simulator Execution Suite

While the FPB simulator is the core unit, there is a surrounding application stack which manages execution of multiple instances of FPB, varying conditions for:

- N EV, the number of EVs per 100 houses (up to 140)
- the trips the EV population undertake, with varied arrival times home

which are invoked by a batch system (Figure 4-4, Figure 4-5). This also sets flags, adds special events and performs housekeeping tasks e.g. zipping and storing of results data. To speed computation, up to 6 instances of FPB may run simultaneously on the PC.

Simultaneous simulation needs a synchroniser to prohibit data space clashes, and is made aware of FPB activity.

Given a set of batch commands and input data the FPB performs the simulation, calling OpenDSS as needed. Statistical saturation is gained by performing 500 trials of each scenario permutation (of which there are 32) giving 16,000 simulated weeks. This is a "sequence", a themed set of scenario trials and described further in Chapter 5.

4.4.2.1 Single Thread Simulation

The full drums in Figure 4-4 represent configuration data files. There are three:

- Base Scenario: the EVs, houses, network (FPB view), loads, DR / FFR signals. These are fixed for the simulation and are pre-built by hand,
- OpenDSS network data: network topology and electrical characteristics; rarely changes in the present system but can be any legal OpenDSS network;
- Batch Script: a set of configuration commands, flags and timed events, plus a list of EV trips with randomiser settings. These are selected to include charging conflicts. Trip patterns determine driven miles per day (mpd). Individual trips vary in range. Each script defines 2,000 trips, in blocks of 500 for 19, 27, 38 and 49 mpd average. These distances are chosen to represent city to deep rural driving ranges.

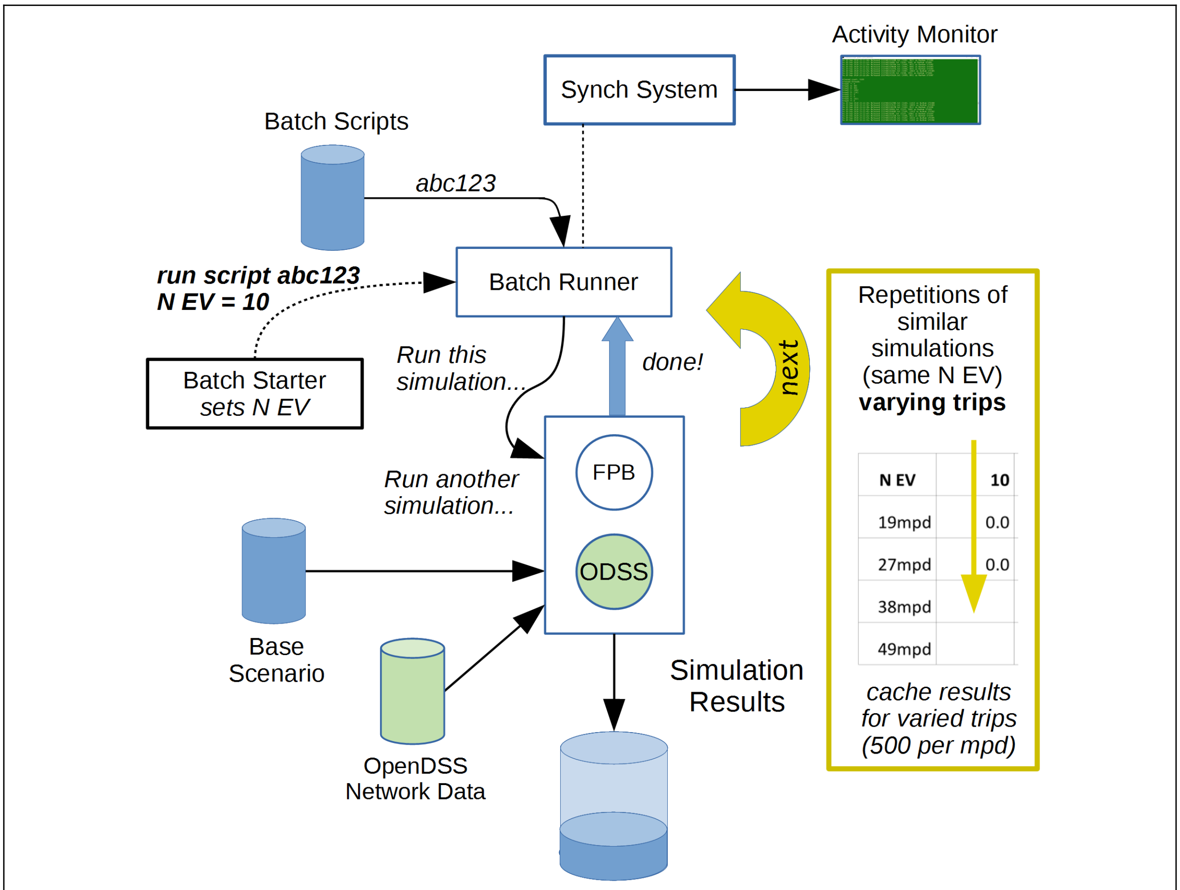


Figure 4-4: Simulation stack executing one simulation thread

Multiple instances (threads) of FPB can be run; this section describes operation of a single instance. Operation begins with the “Batch Starter”, which invokes “Batch Runner”. The Batch Runner parses the Batch Script, compiles a list of instructions, picks the next tripset and randomiser settings to use and starts FPB. The FPB processes these and runs a simulation, handing execution back to Batch Runner on completion. Before starting an FPB job, Batch Runner applies to another program for permission. This is the synchroniser, monitoring overall progress and performing gatekeeping to stop clashes.

4.4.2.2 Multi-Threaded Simulation

Microsoft Windows allows parallel threads to execute independently; as a result multiple Batch Runners can be started thus the system generates results faster.

The Batch Starter passes Batch Runner the script name, a set of comments and an N EV code. This starts a clone of Batch Runner for the set number of EVs, so running simulations with N EV set to 10, 20, 40, 60, 80, 100, 120 and 140 EVs per 100 houses.

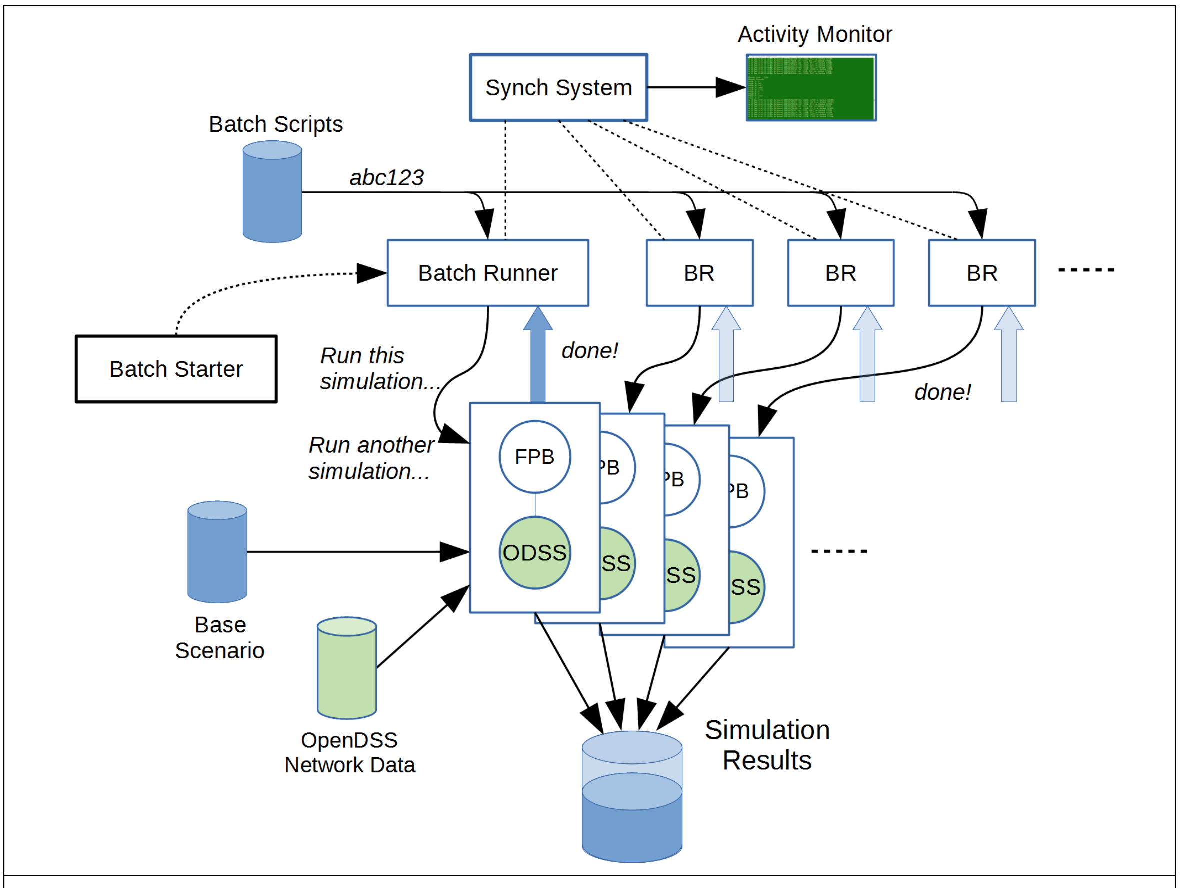


Figure 4-5: Simulation stack executing multiple simultaneous FPB threads

The output from a fully-plied (8 EV bands driving in 4 mpd bands, over 26 million EV trips) is c. 150 GBytes of data and too large to be retained. To limit space, summary logs for every run plus all data for the (1 in 20) OpenDSS runs are retained; other data is discarded. Compressed, retained data is about 7.2 GBytes.

4.4.3 Block 3: Post-Processing and Analysis

Sequence results are inspected for sensibility. Acceptable runs are given an identifier e.g. Seq_6.1.2. 60 parameters are monitored; these are described later. The data set is then processed into an intermediate form. Images for feeder and EV states are plotted and zipped into a data pack. Figure 4-6 shows plot samples (for Seq_6.1.2: 49mpd 140EVs).

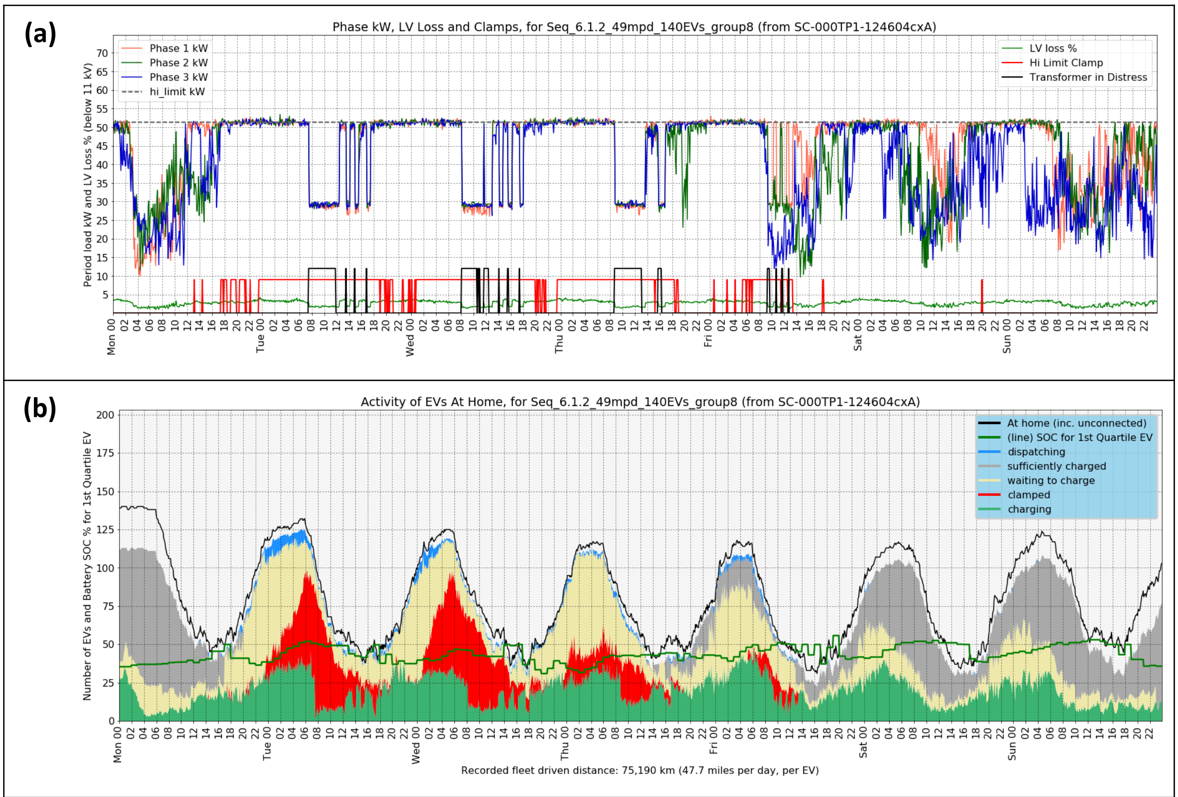


Figure 4-6: Samples of intermediate / auto-generated Feeder and EV CICD plots

These show: (a) Feeder phase loads with clamp actions (disconnections, the cherry red marks at axis) and transformer overheating (black marks). Plot (b) is a “Charging, Idle, Clamped, Dispatching” (CICD), showing instantaneous EV. CICD colours show EV activity as **Black**: count of EVs at-home, **Clear-gap**: not plugged in, **Blue**: V2G dispatch, **Grey**: finished (waiting to leave), **Cream**: waiting to charge, **Red**: clamped and **Green**: charging. The wandering **green line** is the fleet’s 25%-tile best charged EV SOC (see Appendix D).

Results data are next converted into 4 spreadsheets: one per simulated 19, 27, 38 and 49 miles driven per day, summarising cells of collected data. These are merged into a "meta-meta" sheet overview mpd x N EV tables, e.g. average weekly V2G kWh used, in Table 4-1:

Table 4-1: Seq_6.1.2 Averaged weekly V2G kWh injection

N EV	10	20	40	60	80	100	120	140
19mpd	0.0	0.0	0.1	0.2	0.7	2.4	4.7	10.3
27mpd	0.0	0.0	0.1	0.5	1.7	6.7	14.7	41.2
38mpd	0.0	0.0	0.2	1.1	4.3	22.7	64.3	311.2
49mpd	0.0	0.0	0.3	1.8	8.5	57.9	228.1	677.8

the "parity" (average mpd, 1 EV per house) cell is shown highlighted

Each ply cell is an average of 500 similar, trip timing-varied simulations of a week.

Data are available for c. 60 parameters of interest: EV situations, network headroom and losses to number of times an EV is undercharged or charged Away from Home (public charge-points). Varying scenario conditions (e.g. changing ambient temperature, providing DR services via the EV) drive observable changes to behaviour and network loads.

4.5 The Charging Simulation Models

The FPB needs to determine:

- instantaneous phase kW available for charging (aka headroom),
- the charging intent of each EV, and
- the net imposed load of (variously regulated) EV charging.

This is performed by modelling each factor, described in this section. These include EV electrical losses and charging behaviour for three general EV types, and an optional MCS which orchestrates charging and performs feeder balancing.

4.5.1 Phase kW Available Headroom

This is the difference between the LV (transformer or feeder) capability and the instant residential phase load, expressed as kW within FPB or complex kVA for OpenDSS.

Modifiers may be included to scale or bias the residential loads; these allow inclusion of timed loads such as HP and generation (negative loads) such as local PV.

FPB reads the data above from .csv files as Wh energy use, per 1/10th hour period.

4.5.2 The EV Types: Dumb, SV1G and V2G

The following types or classes of EVs are available in the developed simulator:

- **dumb** - charges as it wishes. Modern versions are expected to incorporate BLPs,
- **SV1G (**Smart V1G) - dialogues with a Managed Charging System and accepts charging control commands. NB V1G can stop charging on command; SV1G can start and stop charging on command. SV1G EVs use BLPs;
- **V2G**: as SV1G but can also dispatch (return power to the Grid).

There are aggregator controlled variants being **dumb_Agg_Ctrl**, **SV1G_Agg_Ctrl** and **V2G_Agg_Ctrl**. These are as per their base type, but will listen to an Aggregator. How can a "dumb" EV listen to an Aggregator? EVs may offer services to a singular trading party so are dumb to all but "my contracted controller" i.e. EVs may elect to be deaf.

4.5.3 The EV Electrical Model

The EV electrical model (Figure 4-7) applies to EVs connected at home, a method developed by the author in **(Broderick, S., Cruden, A., Sharkh, S., & Bessant, N., 2016)**.

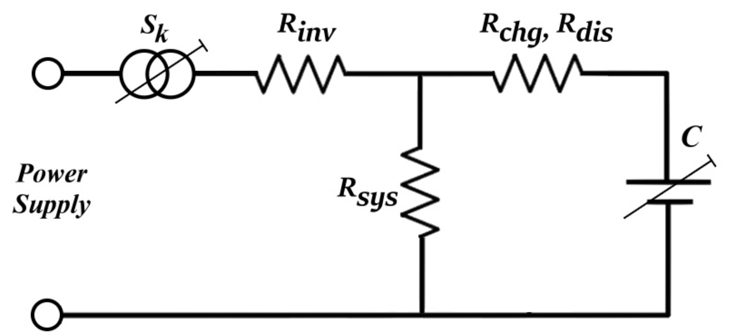


Figure 4-7: The EV losses model, calculated using values defined per EV_type

The model takes mains power via a converter (e.g. AC-DC inverter) with factors:

- loss $R_{inv} = mx + c$ (about 8% of throughput power)
- loss R_{chg} and R_{dis} are battery charging and discharging loss, c. 8% per transfer
- loss R_{sys} for internal power consumption e.g. of electronics and ICT equipment (assumed zero if not plugged in)
- C represents a traction battery as a perfect capacitive store of known kWh rating; this however is adjusted (derated) by a characteristic temperature curve,
- S_k is an adjustable constant socket kW (real power)

- the EV may be logically disconnected (**clamped**) by adjusting S_k to zero.

Nominal loss and C values are set in definition file EV_types.csv. Self discharge and ageing over the study period are ignored. The intent is to model the EV over days not years; if longer simulations were needed a more sophisticated model would be used e.g. from **(Tao et al., 2017)**. During charging, FPB calculates both kWh and SOC. Internally, for each charge rate the battery change per period (delta SOC per pd) is calculated and cached in a library of deltas for S_k socket kW duty, per EV type.

EVs are mildly capacitive loads but charge at constant kW. This arises as the current into the battery is managed to be a constant level, regardless of supply volts. Given near fixed battery cell voltage, this results in the system consuming near constant kW real power.

4.5.4 The Effects of Ambient Temperature

EV battery capacity C is derated by a Li-ion temperature curve, as for the Chevrolet Volt **(FleetCarma, 2018)**. At 0 ^{o}C battery Li-ion capacity drops to c. 59% of 20 ^{o}C rating.

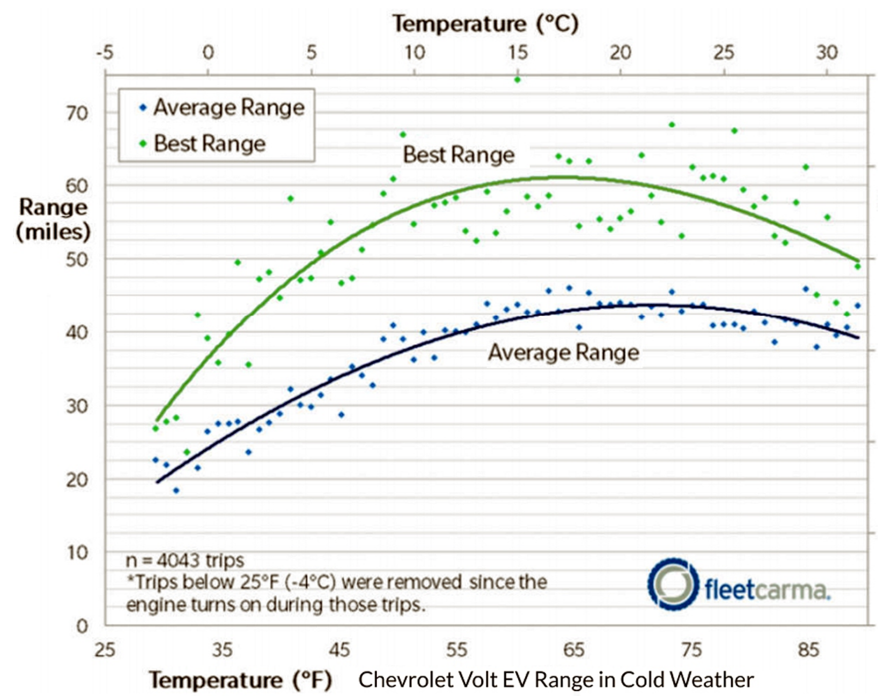


*Figure 4-8: **(FleetCarma, 2018)** Li-ion Average Range vs Temperature Curve*

Consumption is based on EV model kWh per km driven, with the peak battery capacity derated by the range loss ratio in Figure 4-8, the blue curve for ambient temperature.

FPB ambient temperatures are adjustable, Winter being 1°C and Summer 18°C. Thermal effects modify SOC depletion, ability to regenerate (recoup) braking and driver habits.

In practice, on long trips the EV battery warms - but charging capacity is limited to what can be held when parked i.e. cold. FPB therefore degrades battery capacity for ambient temperature. Vehicles use Heat Pumps for interior heating and cooling, as a result outside temperature modifies power use. The kWh consumed are best-guess values.

The FPB fleet (with V2G overheads) experience 39% range loss Winter vs. Summer. Users report eGolf has 37% loss, and the Tesla 3 30% loss. Losses depend on actual situations so are indicators; however this is a concern as battery technology is like to change. FPB estimates use the FleetCarma curve and the 2014 Nissan Leaf. This is an aspect likely needing to be revised for FPB to remain contemporary.

4.5.5 The EV Behavioural Model

The following sections describe several functional components brought together by the FPB's MCS, responsible for orchestrating appropriate outcome (see also section 4.5.10).

The EV needs to actualise the expressed needs of the driver, which are:

- to depart from home at a known time, and
- to be able to drive a certain distance (estimated to end of next day).

Other implicit goals are to maintain a charge margin for unforeseens, and to reduce costs where possible. Presently the greatest cost is battery capital loss, for batteries:

- age whilst standing not in use, especially at SOC extremes e.g. under 10%, over 90% (this will vary by chemistry), and
- age more rapidly when at elevated temperature, due either to ambient environment or charge-transfer (i.e. use).

A set of Battery Life Policies are included to reduce battery ageing; see section 4.2.1.2. It is likely BLPs will be used as EV batteries benefit / offer more capability.

4.5.6 EV Battery State (SOC) Calculation

This is calculated at a stage when the socket kW has been determined. The term "delta_SOC per period" is calculated (the electrical losses model is applied for the EV socket load, and the SOC rate of change found). The delta value is held for each EV, and used to revise the SOC value each simulation period. Determining the battery SOC over time is then straightforward, given known EV activity:

- if connected, delta SOC accrues with time at the present + / - rate,
- if not connected, SOC is static with time.

However, charging rates depend upon what the EV intends (and is permitted) to do. To aid model intent, the terms mandatory, opportunistic and discretionary are now introduced. **Note** the system is asymmetrical charge vs. discharge; when discharging all losses are supported by the battery. **Also note** per-trip consumed kWh is found in section 4.8.6.

4.5.7 Mandatory, Opportunistic and Discretionary

EV charging logic likely vary between manufacturers, also depending on the needs of the driver and instantaneous EV situation. The author developed the novel method below to model EV intent, expressed using “tranches”. To discover intent here means: if the EV intends to cool, to get charge, to dispatch etc. The intent categories used are:

- **mandatory** (charging): to desire (force) immediate charging e.g. dumb EVs,
- **opportunistic** (charging): can wait but will charge if spare power is available
- **discretionary** (V2G dispatch): offer by V2G EVs to supply power to the grid, plus
- an implicit “do nothing” or idle state.

Figure 4-9 shows phase load, with instantaneous **headroom** (phase kW capability less

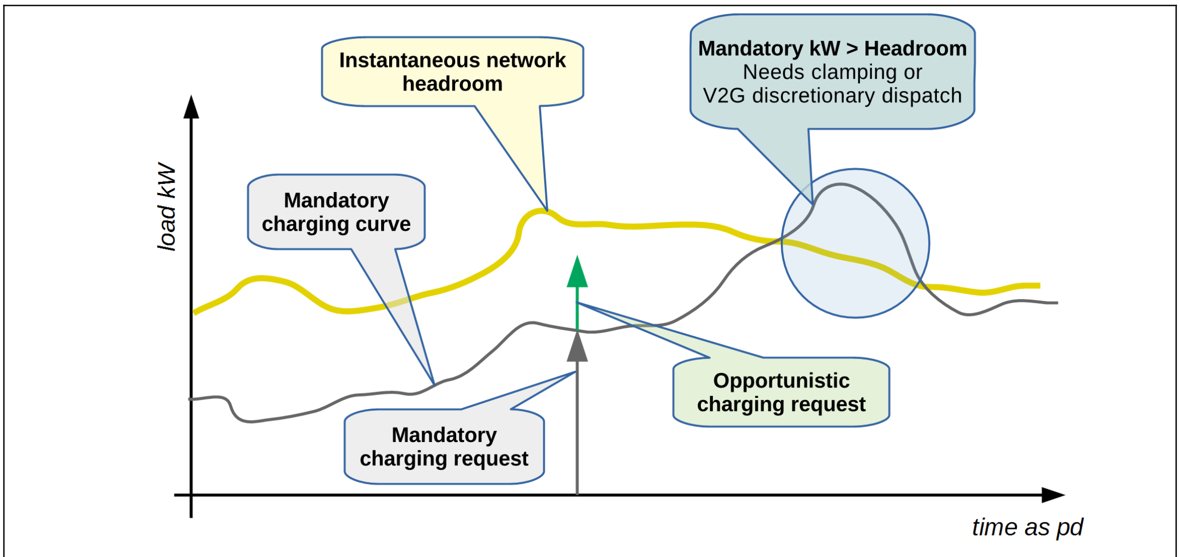


Figure 4-9: Headroom, Mandatory and Opportunistic Chargers

residential demand), mandatory chargers and opportunistic chargers (which are different EVs). **Note** that mandatories force charging but opportunistic chargers do not; mandatory chargers need to be restrained by an MEA style disconnector i.e. clamped.

See Figure 4-10 red area ; here, clamps prohibit charging which would have caused overloads. Residential (unregulated) load cannot be clamped.

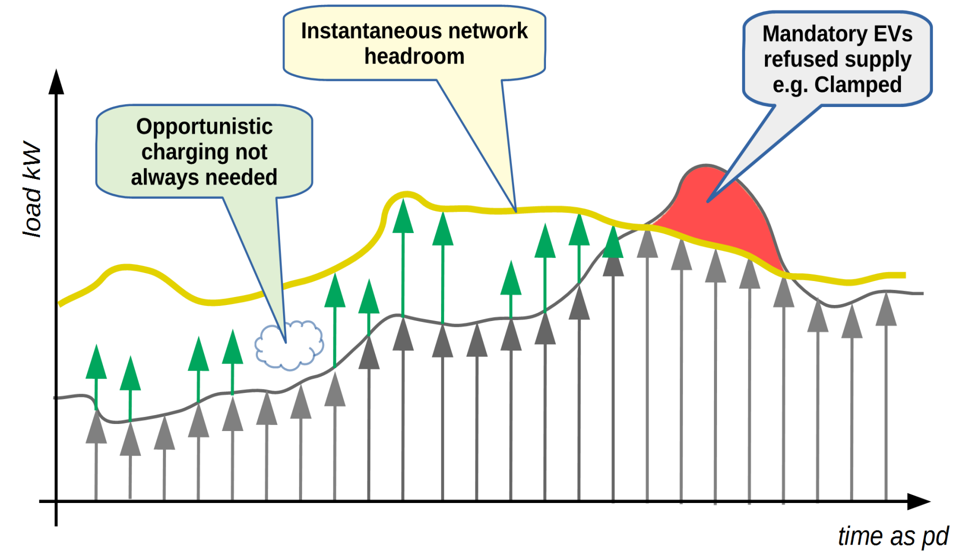


Figure 4-10: When headroom is inadequate, EV charging is curtailed (clamped)

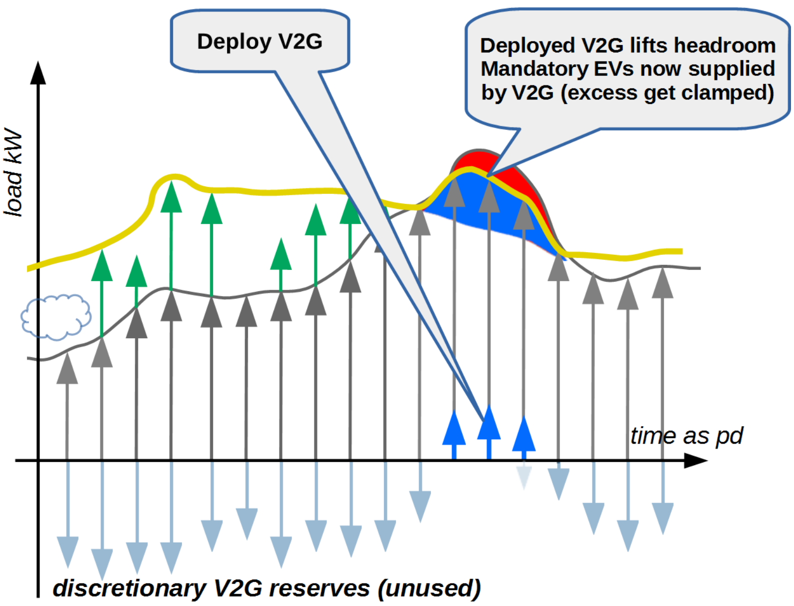


Figure 4-11: V2G shown lifting feeder headroom (but clamps still needed)

4.5.8 Discretionary V2G Dispatch

If available, V2G may dispatch, lifting headroom. V2G EVs must volunteer they are willing to dispatch; they may have insufficient charge for their own needs so are unable to help. However V2G support may not be sufficient for all demand, Figure 4-11.

A V2G EV can be in any mode, including a dual “opportunistically charge / discretionary dispatch” e.g. an EV needs 70% SOC to depart, presently has 78% so can consider either taking on more charge, or dispatching the excess 8%.

4.5.9 The Tranche-based EV Intent Model

EV intents are constructed in tranches. A tranche is a portion of the time the EV is at home and connected. The tranche tells the model what intents to have (what to strive to do) given the time to departure and whether the EV has low, medium or high SOC. Tranches are constructed when EVs arrive home and connect. The EV is assumed aware of the necessary depart time and SOC, by the driver answering:

- “When do you want to depart?” and
- “How far do you want to drive tomorrow?”.

The EV calculates necessary kWh, converts to SOC and adds margin to find **SOC_depart**.

Note that FPB calculates future range to drive by assessing all trip distances between now and midnight of the following day (to this end, trips are generated for 8 days to allow next-day look ahead on the 7th day of the week, Sunday).

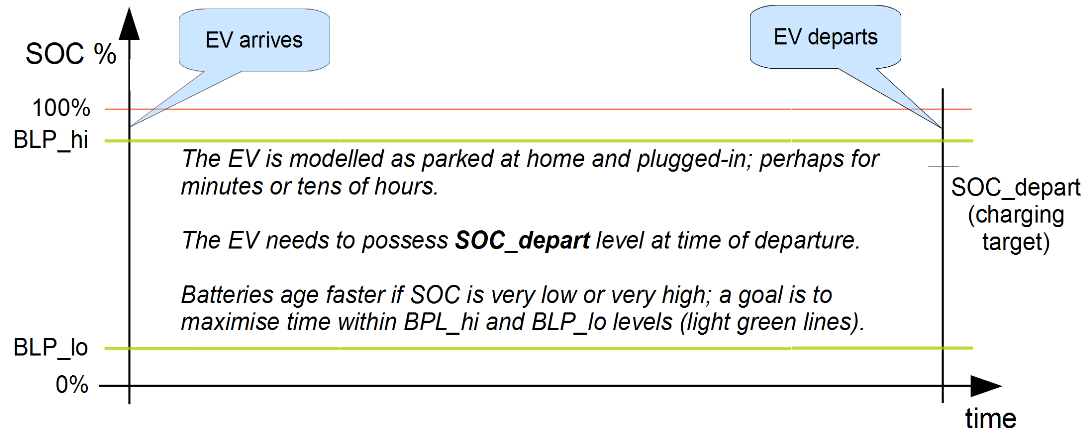


Figure 4-12: A “tranche” of time, covering EV Arrival and Depart from home

EV tranche formation is determined by available time. If time is short, only one tranche is needed. This causes the EV to immediately charge (Figure 4-13).

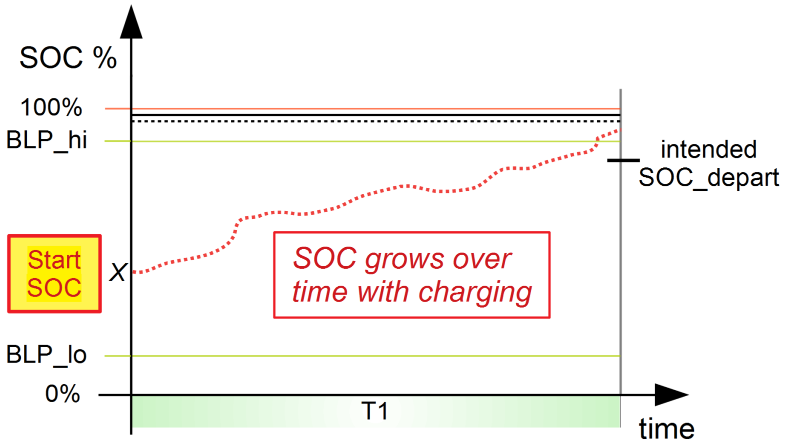


Figure 4-13: Basic charging: SOC accumulates with time

This is the traditional "dumb EV" charging method; gain as much SOC as soon as possible. Yet vehicles parked overnight have plenty of time in hand. A more sophisticated set of tranches can then describe EV activity to attain SOC_depart. There are variants for each EV type, however the approach is the same.

The first step is to break the time parked into a series of defined timed tranches, following one another sequentially. Vertically, tranches are partitioned into 3 SOC regions, being TN.0, TN.1 and TN.2. The .0 region starts at the 0% SOC; region .1 is above .0 and .2 from .1 up to 100% SOC (Figure 4-14). These regions are bounded / partitioned by two lines, "SOC-A" and "SOC-B" and define intents e.g. region T3.0 (with low SOC) is likely "mandatory charging".

The mechanism is to assign each region a mode, defining options. Each mode indicates a code routine able to assesses what to do in that region. The outcome might be "charge" or a more complex set of instructions. Modes are assigned during tranche setup.

For example, the first intent of the EV may be to cool the battery; thus all modes for T1 may be "do nothing". Typical mode allocations within regions are:

- TN.0: (very low SOC) mandatory charging, often at maximum rate
- TN.1: (middle-range SOC) opportunistic charging, perhaps at reduced rate
- TN.2: (often above SOC_depart) idle / no charging OR V2G dispatch.

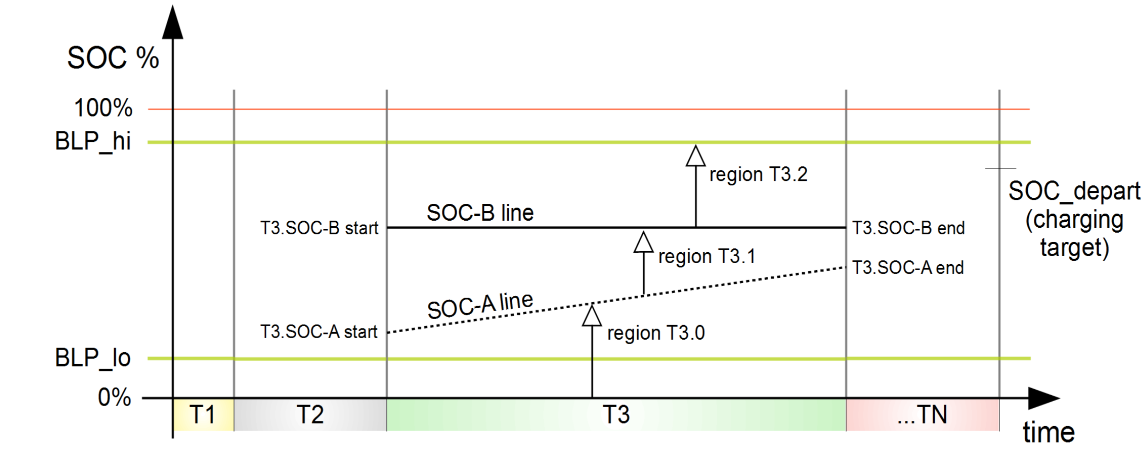


Figure 4-14: Examples of Tranches and its Regions

In execution, the EV model knows the current time thus the present tranche number, and the current SOC level, so can identify:

- the appropriate tranche region 0, 1 or 2, which
- nominates a mode, hence a set of behaviour options.

4.5.9.1 Sample Tranches for EV Charging

The tranches embody a general plan or intent, in the example to cool the battery on arrival and before departure, and to maximise time within the slowest ageing SOC region, BLP_lo to BLP_hi. The EV modelled (Figure 4-15) is an SV1G type, so is prepared for MCS to direct charging. Tranches determine intent and MCS controls charging; herding EV SOC towards SOC_depart.

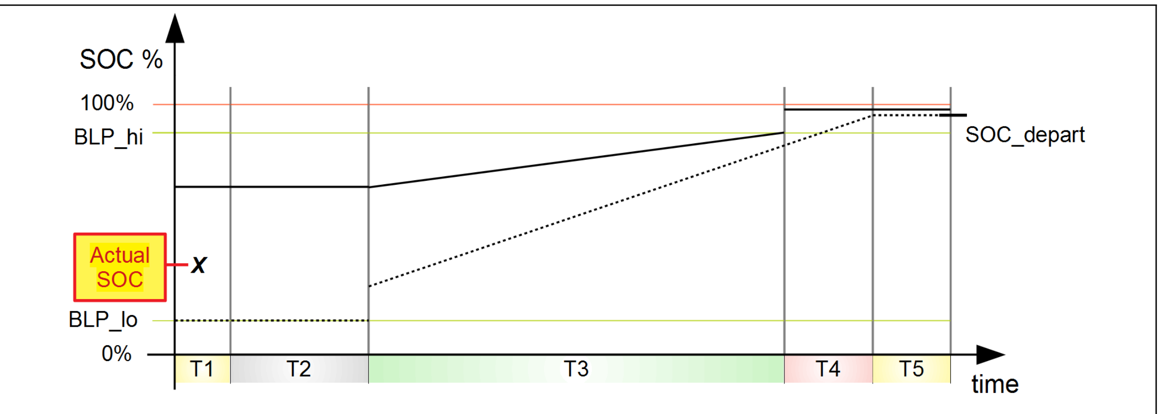


Figure 4-15: A tranche sample

Sample tranches. SOC-A line is dotted, SOC-B is solid. X is arrival SOC

The tranches are constructed on EV arrival home, with region behaviours:

Table 4-2: Possible tranches for an EV arriving at 8pm, departing at 8am

Tranche	Duration	Region	Intent	Programmed Mode
T1	60 mins	0, 1, 2	Cool the battery	Do nothing
T2	from 9 pm	0	Raise SOC to BLP_lo	Charge at low rate
		1, 2	Avoid activity	Do nothing
T3	from 11 pm	0	Charge ASAP at standard rate	"Mandatory charging" NB clamps can over-ride
		1	Opportunistic charging at low rate	"Opportunistic charging" MCS allows if there is unused network capacity
		2	Avoid	Do nothing
T4	from 5:30 am	0	Charge ASAP at standard rate	"Mandatory charging" NB clamps can over-ride
		1	Charge ASAP at standard rate	"Mandatory charging" NB clamps can over-ride
		2	Avoid	Do nothing

A modern dumb EV uses similar tranches, with no "opportunistic" charging as this implies a dialogue with an MCS (to manage dumb EVs, the MCS can only clamp the EV).

The slope of the SOC-A and -B bounds are often lower than the EV charge rate; as a result when a boundary is met there is a burst of charging, Figure 4-16.

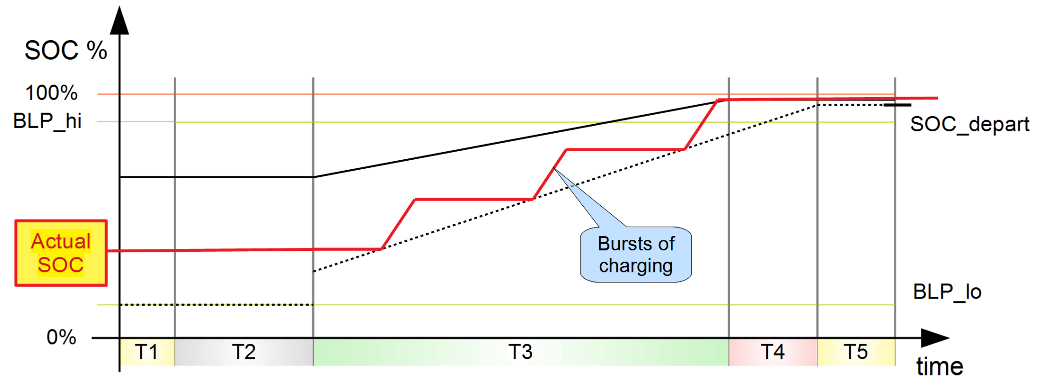
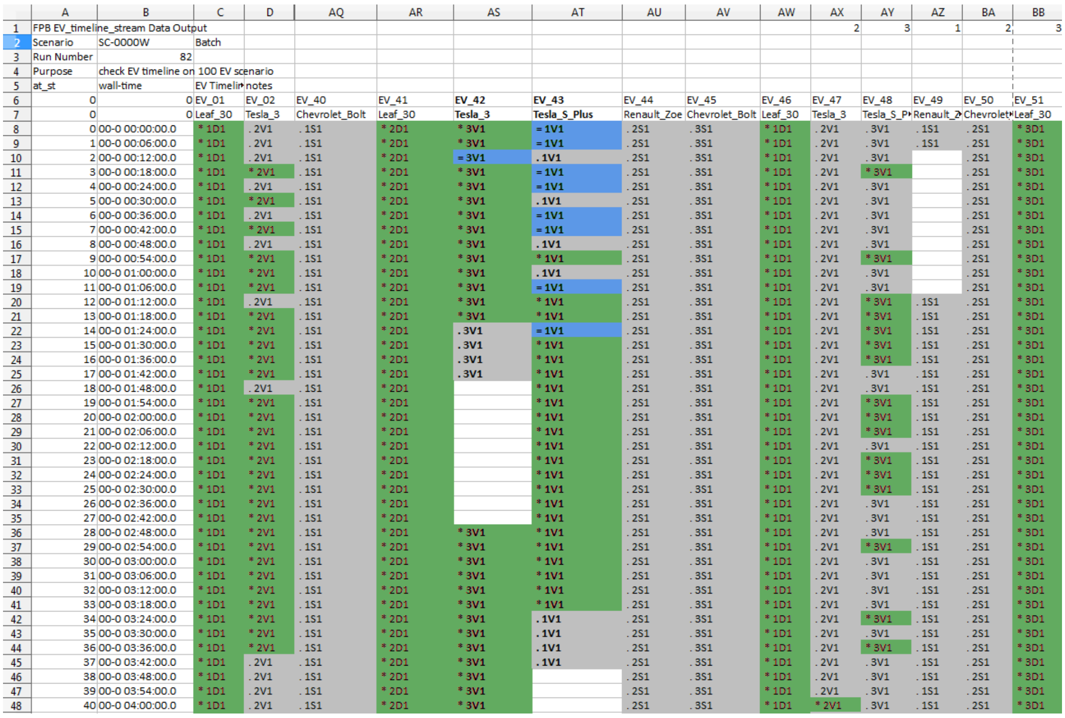


Figure 4-16: SOC accumulation within the example.

SOC accumulates then pauses as it finds itself in a higher region; an intended BLP-style action.

The following "EV_Timeline" graphic in Figure 4-17 has time down the page. Columns show EVs responding to their tranches and dynamics of the situation. The different slopes (of tranche bounds vs. charging rates) cause EVs to dip in and out of charging as per Figure 4-16, visualised as colour bands. These break up blocks of charging, aids battery cooling and spreads charge between EVs. Data is from early proof-of-concept testing.



	A	B	C	D	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB
1	FPB EV_timeline_stream Data Output											2	3	1	2	3
2	Scenario	SC-0000W	Batch													
3	Run Number	82														
4	Purpose	check EV timeline on 100 EV scenario														
5	at_st	wall-time	EV Timelin	notes												
6	0	0	EV_01	EV_02	EV_40	EV_41	EV_42	EV_43	EV_44	EV_45	EV_46	EV_47	EV_48	EV_49	EV_50	EV_51
7	0	0	Leaf_30	Tesla_3	Chevrolet_Bolt	Leaf_30	Tesla_3	Tesla_S_Plus	Renault_Zoe	Chevrolet_Bolt	Leaf_30	Tesla_3	Tesla_S_P	Renault_Z	Chevrolet	Leaf_30
8	0	00-0 00:00:00.0	* 1D1	. 2V1	. 1S1	* 2D1	* 3V1	= 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
9	1	00-0 00:06:00.0	* 1D1	. 2V1	. 1S1	* 2D1	* 3V1	= 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
10	2	00-0 00:12:00.0	* 1D1	. 2V1	. 1S1	* 2D1	= 3V1	. 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1		. 2S1	* 3D1
11	3	00-0 00:18:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	= 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1		. 2S1	* 3D1
12	4	00-0 00:24:00.0	* 1D1	. 2V1	. 1S1	* 2D1	* 3V1	= 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1		. 2S1	* 3D1
13	5	00-0 00:30:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	. 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1		. 2S1	* 3D1
14	6	00-0 00:36:00.0	* 1D1	. 2V1	. 1S1	* 2D1	* 3V1	= 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1		. 2S1	* 3D1
15	7	00-0 00:42:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	= 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1		. 2S1	* 3D1
16	8	00-0 00:48:00.0	* 1D1	. 2V1	. 1S1	* 2D1	* 3V1	. 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1		. 2S1	* 3D1
17	9	00-0 00:54:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1		. 2S1	* 3D1
18	10	00-0 01:00:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	. 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1		. 2S1	* 3D1
19	11	00-0 01:06:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	= 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1		. 2S1	* 3D1
20	12	00-0 01:12:00.0	* 1D1	. 2V1	. 1S1	* 2D1	* 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
21	13	00-0 01:18:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
22	14	00-0 01:24:00.0	* 1D1	* 2V1	. 1S1	* 2D1	. 3V1	= 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
23	15	00-0 01:30:00.0	* 1D1	* 2V1	. 1S1	* 2D1	. 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
24	16	00-0 01:36:00.0	* 1D1	* 2V1	. 1S1	* 2D1	. 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
25	17	00-0 01:42:00.0	* 1D1	* 2V1	. 1S1	* 2D1	. 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
26	18	00-0 01:48:00.0	* 1D1	. 2V1	. 1S1	* 2D1		* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
27	19	00-0 01:54:00.0	* 1D1	* 2V1	. 1S1	* 2D1		* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
28	20	00-0 02:00:00.0	* 1D1	* 2V1	. 1S1	* 2D1		* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
29	21	00-0 02:06:00.0	* 1D1	* 2V1	. 1S1	* 2D1		* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
30	22	00-0 02:12:00.0	* 1D1	* 2V1	. 1S1	* 2D1		* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
31	23	00-0 02:18:00.0	* 1D1	* 2V1	. 1S1	* 2D1		* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
32	24	00-0 02:24:00.0	* 1D1	* 2V1	. 1S1	* 2D1		* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
33	25	00-0 02:30:00.0	* 1D1	* 2V1	. 1S1	* 2D1		* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
34	26	00-0 02:36:00.0	* 1D1	* 2V1	. 1S1	* 2D1		* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
35	27	00-0 02:42:00.0	* 1D1	* 2V1	. 1S1	* 2D1		* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
36	28	00-0 02:48:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
37	29	00-0 02:54:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
38	30	00-0 03:00:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
39	31	00-0 03:06:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
40	32	00-0 03:12:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
41	33	00-0 03:18:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	* 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
42	34	00-0 03:24:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	. 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
43	35	00-0 03:30:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	. 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
44	36	00-0 03:36:00.0	* 1D1	* 2V1	. 1S1	* 2D1	* 3V1	. 1V1	. 2S1	. 3S1	* 1D1	. 2V1	* 3V1	. 1S1	. 2S1	* 3D1
45	37	00-0 03:42:00.0	* 1D1	. 2V1	. 1S1	* 2D1	* 3V1	. 1V1	. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
46	38	00-0 03:48:00.0	* 1D1	. 2V1	. 1S1	* 2D1	* 3V1		. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
47	39	00-0 03:54:00.0	* 1D1	. 2V1	. 1S1	* 2D1	* 3V1		. 2S1	. 3S1	* 1D1	. 2V1	. 3V1	. 1S1	. 2S1	* 3D1
48	40	00-0 04:00:00.0	* 1D1	. 2V1	. 1S1	* 2D1	* 3V1		. 2S1	. 3S1	* 1D1	* 2V1	. 3V1	. 1S1	. 2S1	* 3D1

Figure 4-17: Falling EV_Timeline of EVs charging, from proof-of-concept tests

Time is down the page. Sample EVs (of 100 animated) obeying their tranches.
Key: *Grey = idle / waiting, Green = charging, Blue = V2G dispatch, White = away.*

Note If any EV arrives home with insufficient time to fully charge to SOC_depart, the EV is treated as a dumb EV and only one tranche is used. All levels are set to 100% and mandatory charging as the mode option.

The plot in Figure 4-18 below illustrates a lone dumb EV charging on a network with static residential loads. Some EVs use an exponential charge-kW decay as near-target SOC is attained. For simplicity, FPB adopts static charge level values, which are also used by EVs (see **(WPD, 2017)** page 32).

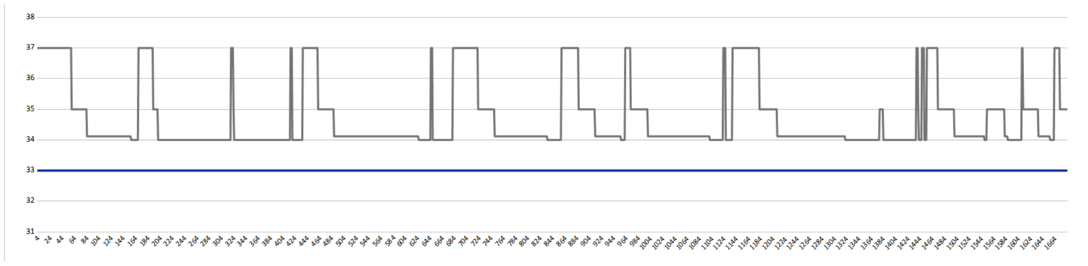


Figure 4-18: Plot of an EV charging, recovered from early proof-of-concept tests

Plot shows load kW (y-axis) vs. time. The EV undertakes trips over a week and recharges on a network with constant other load. The 4 level steps in grey show charging kW: Full rate charge, low rate charge, idle and away. The blue line is static load on other phases.

Figure 4-19 plots a simulated V2G EV load (orange), together with battery SOC (blue):

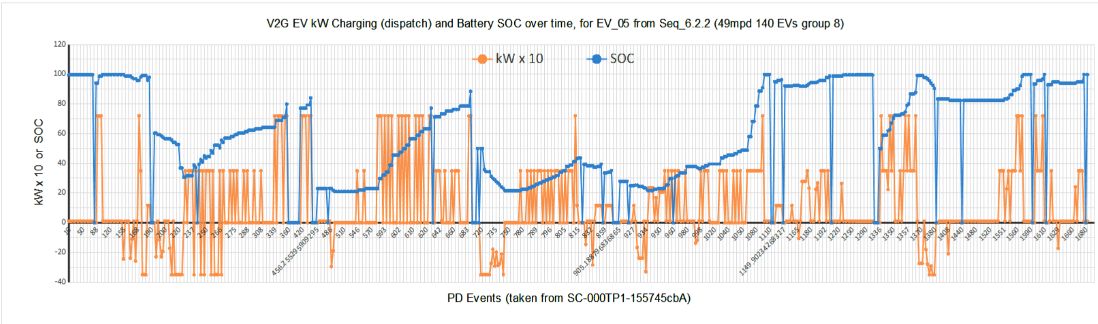


Figure 4-19: Socket load and SOC for a V2G EV over a week

Hourly socket load (orange) and SOC (blue) for a V2G EV. Spikes to zero occur when the EV is away from home. Negative load is dispatch. The EV charges at different rates and responds to MCS and tranches; occasional changes of SOC growth rate are seen e.g. slope of blue line about pd 1080 (2/3rds across). This is due to the tranche signalling to MCS: EV would charge, if capacity is free (low slope) vs. EV must perform mandatory charge now. MCS adjudicates an interplay of intent and possibility.

4.5.9.2 Sample Tranches for V2G EVs

Tranches for V2G (Table 4-3) are similar to SV1G with the change: any SOC above that needed for SOC_depart can be spent on dispatch. The EV still needs SOC_depart and, giving prevailing feeder congestion, there is no guarantee that any charge spent on early V2G can be replaced. Thus V2G dispatch is only performed when there is likely great time to redress deficits, or redress is not needed (as SOC > SOC_depart).

Further, MCS knows V2G is a minority option vs. turning things off, so preferentially halts charging before committing V2G. The option "Pre-Burn V2G" will commit V2G early by adding a proportion of available V2G capacity to the headroom level.

Table 4-3: A possible set of V2G tranches, for an EV arriving home at 8pm

Tranche	Duration	Region	Intent	Programmed Mode
T1	60 mins	0, 1, 2	Cool the battery	Do nothing
T2	from 9 pm	0	Raise SOC to BLP_lo	Charge at low rate
		1	wait	Do nothing
		2	support network	Dispatch at low rate
T3	from 11 pm	0	Charge ASAP at standard rate	“Mandatory charging” NB clamps can over-ride
		1	Opportunistic charging at low rate	“Opportunistic charging” MCS allows if there is unused network capacity
		2	Opportunistic charging at low rate OR support network (V2G dispatch)	“Opportunistic / discretionary V2G” (MCS directs what is needed)
T4	from 5:30 am	0	Charge ASAP at standard rate	“Mandatory charging” NB clamps can over-ride
		1	Charge ASAP at standard rate	“Mandatory charging” NB clamps can over-ride
		2	Idle OR support network	Idle or Dispatch at low rate (MCS instructs what is needed)

4.5.9.3 Tranche Assessment and Priorities

Tranche assessment is simple and extremely fast (python uses binary-chop in C):

- use present simulation time to determine which tranche the target EV is in
- use SOC to determine which region the EV is in and find the mode pointer
- run the code the mode points to; this determines the EV’s available options.

Each EV also generates a priority code: the effective charging rate needed i.e. (needed kWh / time) to meet depart SOC. Prioritisation changes as need and time pass. **Note** that the method has placed problem domain complexity into tranche plan setup. This is a deliberate strategy to speed run-time assessment; tranche assessment is tens of thousands per second per thread on a 2013 era PC.

4.5.10 The MCS Method: Seek Maximum Throughput

Note: the MCS can be logically disabled by making all EVs dumb and disabling clamping.

The primary goal of MCS is: Organise EVs so total residential and EV loads do not exceed a phase hi_limit, placing priority on charging for driving. Given that EVs must have charge to depart and a least-regret outlook, desk-exploration of strategies converged to the rules:

- EVs determine if they <u>must</u> charge: these flag mandatory charge
- EVs with time in hand can wait or opportunistically charge from spare headroom, using a rank order based on a charge (kWh) and remaining time priority
- V2G EVs may elect to flag "discretionary dispatch"; these are deployed in soonest-to-depart order (to best utilise V2G support before the EV departs).

Knowledge of the EV intents can then be:

1. applied directly (no overall MCS control, the EVs do as they want)
2. optionally having a modifier to allow an external Aggregator to control EVs. This is performed by "SOC spoofing", here the Aggregator overrides SOC sensing making the EV think its battery is full, so it does not wish to charge,
3. optionally with MCS orchestrating EV charging by both intent and priority, to timely reduce each EVs charge deficit to meet the intended departure SOC.

This gives a charging system with focus on the needs of the network and EVs, and allows Aggregator intervention. Once EV intent is known, MCS (which sees feeder headroom and EV intents) allocates EVs to charge by priority i.e. consumes available headroom:

Table 4-4: General MCS Method

pseudocode

- determine headroom available *(optionally: add V2G capability which commits use)*
- assign mandatories: *eg dumb EVs - these do not dialogue, so load is fixed*

  in <u>highest EV priority</u> order:

    assess headroom vs. mandatory EV charging load

    if headroom insufficient and clamping active:

      clamp the EV

    otherwise decrement headroom by EV load
- A: if headroom remains: assign any opportunistic chargers: *eg SV1G and V2G EVs*

    in <u>highest EV priority</u> order:

      assess headroom vs. opportunistic EV charging load

      if headroom is sufficient:

        set the EV to charge

decrement the headroom by charge kW

if headroom at **A** found negative: assign available V2G support

per discretionary V2G EV in soonest-leaving order:

if headroom is negative:

set the EV to V2G dispatch

increment the headroom by dispatch kW

4.5.11 Modelling The LV Feeder

The intent is to follow established DNO practices, as far as possible. A major issue is Wayleaves - the legal Right of Way to lay cable across land. Networks may cross the land of many owners so can be legally complex; as a result Public Rights of Way are used i.e. cables follow roads. Meandering paths are taken, resulting in diverse LV topologies.

4.5.11.1 DNO Design Method

Table 4-5 is an example ADMD design table **(UKPN, 2014, p10)**.

Table 4-5: Example UKPN ADMD LV design values

	ADMDs (kW)		DEBUT curve / units		
Type	Day	Night	Curve	Day	Night
1/2 Bed Gas C/h	1.2	0.3	URLC	3500	0
3 Bed Gas C/h	1.5	0.3	URLC	4400	0
4 Bed Gas C/h	1.8	0.5	URMC	5800	0
5+ Bed Gas C/h	2.4	0.5	URHC	7500	0
1/2 Bed Other C/h	1.5	2	ESEVEN	3500	2000
3 Bed Other C/h	1.9	2.5	ESEVEN	4400	2500
4 Bed Other C/h	2.1	3	ESEVEN	5800	3000
5+ Bed Other C/h	3.1	3.5	ESEVEN	7500	3500
E7 1 Heater / W/h	2.2	5.13	ESEVEN	5500	5000
E7 2 Heater / W/h	2.5	7.56	ESEVEN	5700	7500
E7 3 Heater / W/h	2.8	9.99	ESEVEN	6000	10000
E7 4 Heater / W/h	3.4	12.42	ESEVEN	7500	12000
15kW Boiler	4.5	16.2	ESEVEN	10300	16000
19kW Boiler	5.7	19.8	ESEVEN	12000	18800

The entries for the DEBUT design approach are not considered in this work.

A typical approach to residential LV design is:

- find the type of properties supplied e.g. house of X rooms, heated in manner Y
- identify design ADMDs for the properties (from DNO issued tables)
- locate a substation at a nearby point, and
- plan a run of suitable cable to the properties, in such a manner that:

  - the intended ADMD can be delivered
  - using the most economical and able assets
  - so to meet constraints (high, low limits) on terminal voltages.

Simulation modelling then faces three issues:

a) to model the design ADMD intents, and / or
b) to model terminal voltages and / or
c) the modelling of network topology impacts.

The method used is led by (a) ADMD, rather than (b) voltages, with (c) sidestepped by using a fixed topology (see Figure 4-20).

This is due to the geometric explosion of possibilities if attempting all possible networks (with each failing to be representative).

Other works may model by voltage rather than ADMD. However, to focus on voltages may ignore overloads due to power drain. If a network was designed, equipped and happened to correctly operate at a terminal voltage of 0.97 pu Volts, then drawing more power (until the regulation limit of 0.94 pu was met) may overstress the assets. Doubling the volt-drop implies doubling the power throughput. This ignores the situation of the transformer, for it may normally run at a capacity limit, as implied by using the common “distribution rating” method (installing under-capability transformers; see also 4.5.13.2).

Concerning the network topology chosen. This is deliberately simple, which brings the expectation that the results obtained for the chosen network <u>is a best case</u> i.e. represents the pinnacle of which might be expected; that is, <u>real-world networks will do worse</u>.

In Summary: the results obtained are:

- constrained within network ADMD design criteria,
- implying that raising N EV (beyond that found for a situation) will exceed capabilities i.e. will impose some form of abuse or overstress of asset
- the results obtained are for a simple idealised network; a real built network will most likely have degraded performance vs. the network investigated.

4.5.11.2 FPB and OpenDSS Feeder Views

As discussed, there is no standard LV system; FPB layout is simplified. Other than feeder and phase load, FPB has no concept of topology (yet a real-world topology can be given to OpenDSS). With **the provisos below**, as long as loads are stated correctly on feeder and phase, FPB will operate. The “hi_limit” is the notional peak phase load, in kW.

The provisos: FPB will then operate correctly if and only if:

- the built network kW minimum >= hi_limit kW in all places, and
- the transformer is the only source of grid power i.e. there is no cross-coupling to other LV systems (i.e. links bringing a backfeed supply from another transformer)
- (at present) only one feeder connects to the transformer busbars.

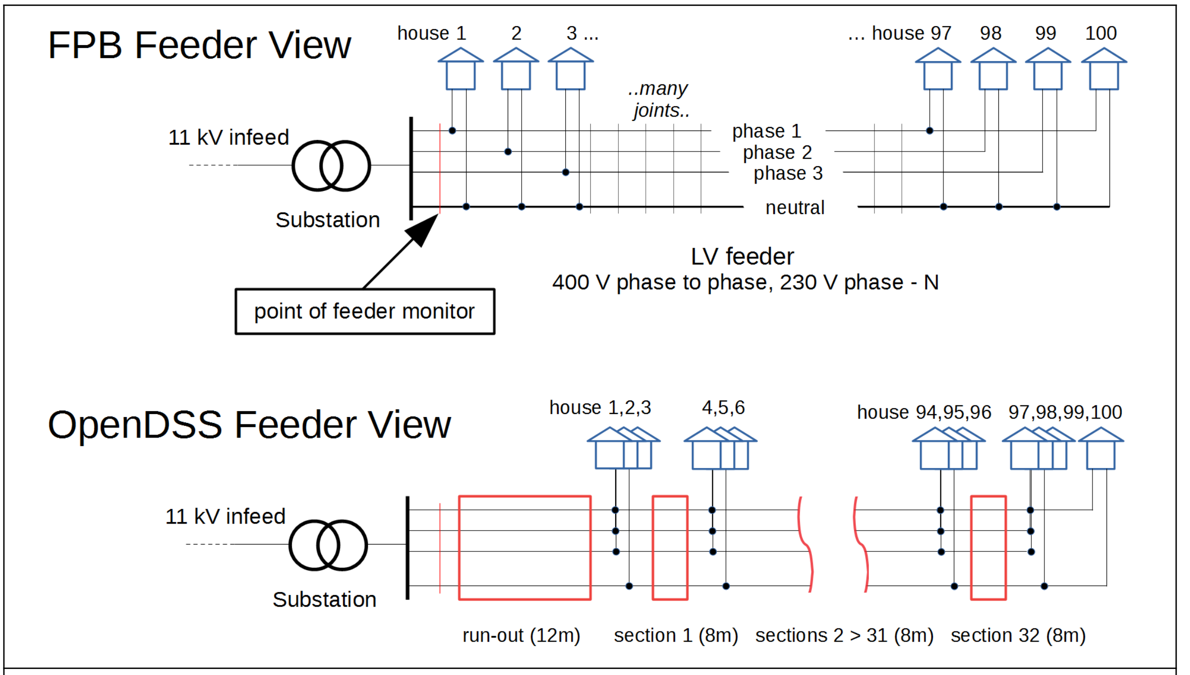


Figure 4-20: Feeder views for FPB and OpenDSS

Houses connect in repeating phase order i.e. house [1,2,3,4,5 ...] to phase [1,2,3,1,2 ...].

OpenDSS sees a “herringbone” network, a linear feeder with houses in simple phase order, placed as a (1-2-3) bunch at regular intervals. The layout is: 12m run-out from substation with take-offs supplying 3 houses every 8m. Feeder length is 268 m. This is perhaps shorter then some feeders, which the author is advised should be under 400 m / 1,200 ft. OpenDSS electrical characteristics are flexible and set for each network strength category. See also the substation schematic, Traditional Passive Substation.

Concerning feeder length. Feeders should not be so long as to cause excessive end-point voltage drop. In practice, the maximum feeder length is c. 400 m. However using a cable 400 m long would bias the study insofar as it would be preselected to be on the edge of experiencing volt drops at the remote end. The length of 268 m chosen means that, voltage wise, the feeder is not marginal i.e. sees no under-voltages in normal operation.

4.5.11.3 Non-Uniform and Branching Feeders

FPB feeder layout is the simplest practicable. Many built feeders branch or taper (there are 3 different size of cables in Figure 2-8), which can provoke far-end voltage issues. FPB ignores the issue other than for OpenDSS runs, in which customer volts are checked for being within bounds.

For voltages to not to be a problem within the FPB system, non-uniform limbs need comply with Eqn. (19):

max phase load = N houses on phase x (house ADMD + phase coincidence for N EV * 7 kW in Figure 6-7) (18)

non-uniform phase rating >= minimum (hi_limit, max phase load) (19)

That is to say, the limb must be rated to carry the with-EV load as normal practice without volt-drops. If this is not the case, the limb is under-rated for EV duty and voltage issues are possible. OpenDSS can detect these, if it has an accurate network diagram. **Note** a revised FPB may consider non-uniformity.

4.5.11.4 LV Network Ratings - Weak, Typical, Strong

Three sample built network ADMD ratings to supply 100 homes are used:

- “Weak”: able to support c. 1.2 kW per home. A 96 kVA continuous rating transformer feeds a cable with a max rating of 225 A per phase, similar to 95mm square section Aluminium;
- “Typical”: designed for 1.5 kW per home, 120 kVA continuous rating transformer, 351 Amp per phase cable (120mm square section Aluminium);
- “Strong”: to supply 2 kW per home from a 160 kVA continuous rating transformer, 461 Amp per phase cable (invented, not in specification brochures).

These strength ratings are not industry standard i.e. are the author’s terms.

Note that data re the relative proportions of UK installed LV kW capabilities is not readily available (ENA advise the author this is scattered throughout their proprietary TRANSFORM databases). Such data might have modified the ADMD choices.

In the last 5 years the author has heard of LV systems designed with ADMD from 0.8 kW to 1.8 kW per home. Today, many UK homes have modest appliance loads and use LED lights so may well draw (after diversity) under 0.8 kW. Sample design ADMD of DNOs, for a 3-bed gas-heated semi, are:

- SP: 1 kW
- UKPN: 1.5 kW
- SSEPD: 2.4 kW
- NPG: 2.1 or 3.95 kW from mid 2018, for houses likely to have EVs.

Network build is pragmatic e.g. a DNO smallest transformer might be 120 kVA, so is used to serve up to 150 houses. A 160 house development alongside might get the next standard transformer size up, perhaps a 200 kVA unit.

FPB was intended to work with arbitrary numbers of feeders from 1 transformer; however this has not been used (so not heavily tested) since inclusion. The hi_limit presently applies to the sum of all feeder loads, not per feeder (code changes are needed to enable true multi-feeder operation). In present form, FPB operates as a single feeder system.

4.5.12 Electrical Simulation

OpenDSS is used as the power simulation system. This is an open source simulator from EPRI **(EPRI, 2012)** with a long track history, here used to provide insights into the electrical system. The tool primarily runs under Windows 7 and up. OpenDSS has parameters for cable and transformer electrical characteristics, held in .dss files sent by FPB as needed. **Note** that OpenDSS is configured to represent house load as constant kW loads. OpenDSS calculates phase and Neutral current plus local volts relative to local Neutral (and Neutral to transformer ground). FPB tests these for being out of bounds.

The FPB view has parameter values for transformer, cable capacity and default hi_ and lo_limits set via a .csv text file. The substation model can experience programmed “trips” (disconnector opening events) i.e. a simulated power-fail.

4.5.13 EVSE Disconnectors aka "Clamps"

Given that EVs may be uncontrollable, DNOs have pressed for a kill switch disconnector in each EVSE home supply point, called herein as a clamp. The same switch might be known elsewhere as a: disconnector, breaker, curtailer, or be termed a "pause of charging" (EN).The presence of this switch is implied in legislation in the UK's Autonomous and Electric Vehicles Act **(HM Government, 2018)**, section 15, paras 2 a) and b). The method was successfully trialled in the 2014-2016 "My Electric Avenue" project (MEA) and the "Electric Nation" (EN) project.

Ofgem are aware of the need to clamp, but may not be warm to it. DNOs exist to supply, not disconnect customers. It is quite possible that Ofgem will penalise DNOs if they exceed a deemed reasonable amount of clamping. What though is "reasonable"?

In FPB there are two reasons to apply a clamp:

a) the EV is contributing to overload and must be stopped, or
b) the EV is contributing to transformer overheating and must be stopped.

Yet clamps may conflict with:

- the need to charge i.e. to use the EV as a car, and
- the supply of Value Added Services (VAS) such as aggregation duties.

Note that these are local LV issues. Applying clamps due to insufficient generation is performed by DR/DSR and considered later.

4.5.13.1 Clamping Mode - Hi Limit Clamp

To stop loads breaching the hi_limit, uncooperative EVs can be disconnected by clamp.

Clamping rules can be set in the Batch Script to any of 3 modes, plus a V2G option:

- random priority
- proportional supply by taken kWh (broadly mimics My Electric Avenue *Esprit*),
- equitable supply (those most in need have preference), and
- optionally with "Pre-burn V2G", which uses V2G to boost available headroom.

4.5.13.2 Clamping Mode - Transformer Limit Clamp

A common practice is use of under-rated transformers, aka distribution rating. Given that traditional residential load-profiles are periodic (with low load overnight, hence a cooling period) slightly under-rated units can be used. A "cyclic rating" of around 1.2 to 1.3 is applied to transformer name-plate (continuous) rating, resulting in a 200 kVA unit being fitted to a system designed for a peak duty of 250 kW. Consequently FPB, optimising LV throughput at the default hi_limit, may cause transformer overheating. To detect this FPB calculates load i^2t which is compared to the value implied by the transformer rating. Run-time thermal load is found by integrating a rolling 24 hour log of period load contribution to heating. A warning is raised which can trigger a hi_limit reduction (black line near axis in Figure 4-21) if the 24 hour integral exceeds daily rating.

The clamp is applied to allow the transformer to cool i.e. the distress warning here triggers a limit to EV charging. This is applied as a ratio of hi_limit and needs be severe e.g. 0.5 (adjustable). This clamp persists for 30 minutes beyond need, to introduce hysteresis.

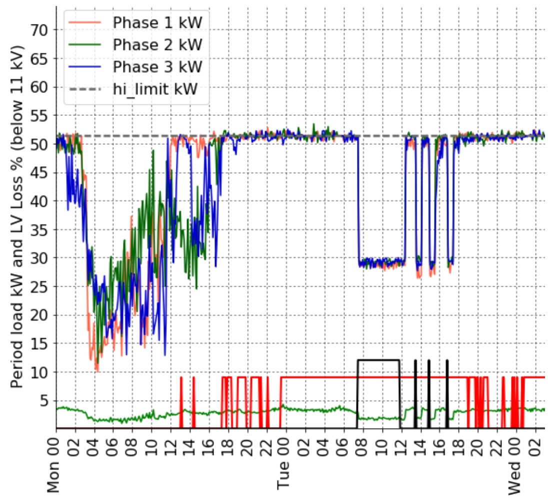


Figure 4-21: Feeder plot showing clamping lines at axis

Cherry Red line: hi_limit enforced, Black line: Transformer distress (overheating).
All images can be zoomed in .pdf.

Note that this implies that high duty-cycles (e.g. 90%) cannot be supported without lowering the hi_limit value; the transformer clamp effectively lowers the duty cycle.

4.5.13.3 Public Reaction to Clamping

Clamps limit ability to charge. Will people tolerate this? Adaptors are available to charge an EV from a UK standard 13A square-pin socket, offering c. 24 kWh charge overnight. These sidestep DNO controls so is a threat. The motivation here is dissatisfaction due to undercharging / being rationed. No DNO can stop drivers using a 13A socket adaptor.

MEA and EN trials show Smart control is broadly accepted, other than by individuals in MEA repeatedly undercharged, who are prime candidates to revert to a 13A socket.

4.5.13.4 No Forecasts

The method described uses no load profile or EV numbers forecasts. The author considered forecasts, but judged that with few households per phase (1 to 100) loads would be too chaotic, thus unsuitable for the profiling on which forecasts rely. Also, power engineering solutions use assets with half-century lifespans. Any forecast for a region in Year 1 is, frankly, unlikely to remain reasonable in Year 50; perhaps not even Year 2 as home occupancy, power use and economic factors change.

A least-regret method is instead used (see A General Intelligent EV on LV Network Simulator); this appears satisfactory but needs communication with all EV and EVSEs.

4.6 The Simulation Engine

4.6.1 The Standard FPB Simulation

The FPB uses a data-driven discrete event simulator processing a timed schedule, the primary duties of which is to hold a sequence of EV departures and arrivals and periodic assessment points (per 1/10th hour period). Other events can be present.

The standard simulation performed by FPB is:

- one week of 1,680 simulated 1/10th hour periods for data conditioning (initial battery SOC and transformer thermal states) followed by an identical week which carries prior SOC and thermal states in, with results logged. These consider:
- a linear or herringbone feeder composed of likely electrical elements, arbitrarily characterised as Weak, Typical or Strong
- 100 houses on the feeder, each with a unique, per period demand profile
- 10 - 140 individual EVs of various types, driven through a defined set of trips
- with timed events such as:
    - power fails
    - comms fails
    - changes to EV management algorithms
    - DR/FFR as if imposed by

- local control or
- external aggregators.

OpenDSS is optional and performs electrical analyses for feeder volts and losses, but is very slow and verbose. OpenDSS is limited to run every 20th simulation (25 times per mpd x N EV ply), so minimising detrimental impact. Output from OpenDSS is not included in any control loop; it may be disconnected (loosing data on network volts and losses).

As well as output .csv results files (e.g. of phase loads) the system produces considerable event / fault logs and summarised statistics, with output from “end-of-run” analysis e.g. 98th percentile load levels. The purpose of these is to aid results analysis.

4.6.2 Simulation Dataflow

FPB processes starting conditions to results, Figure 4-22 and Figure 4-23. Run-time operation uses data held in memory, with results regularly written to disk.

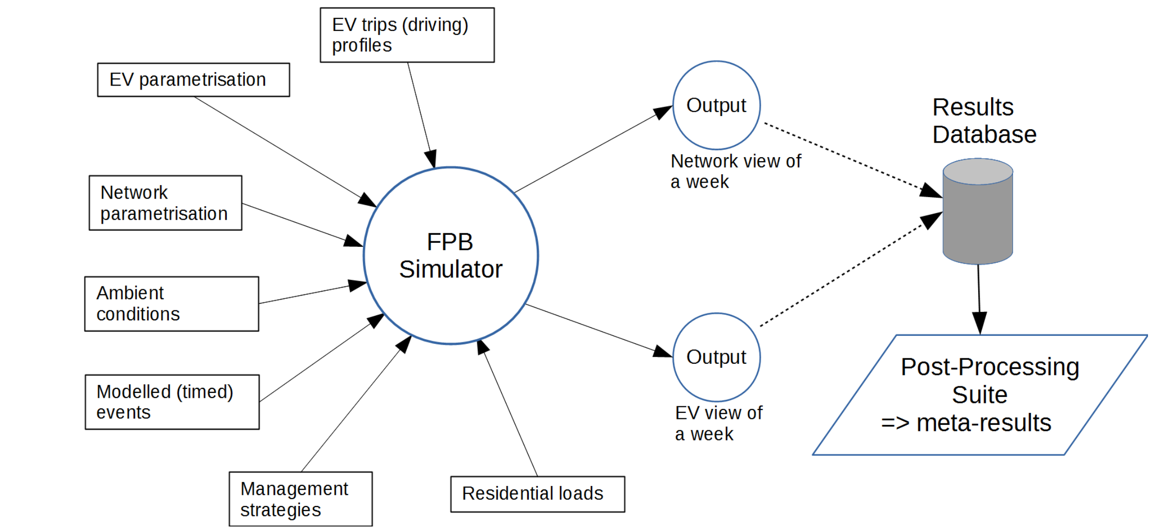


Figure 4-22: FPB simulator general schema

Logging is extensive and records the start-up conditions, the detection of items of concern (e.g. overcurrent, out of limits volts) and finally summary results as well as topic-related .csv files for spreadsheets.

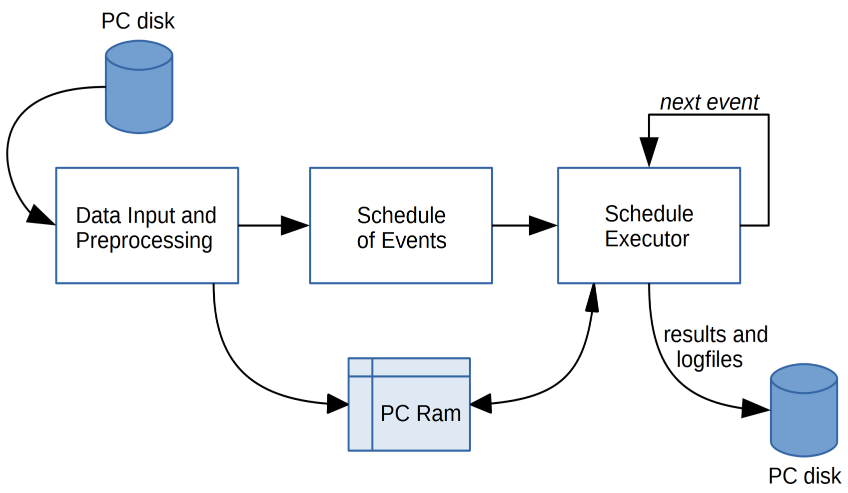


Figure 4-23: FPB simplified internal operation

Figure 4-23 overviews FPB internals based about a schedule. The schedule is built during data load and consists of:

- arbitrarily timed events e.g. EVs arrive, depart
- regular events e.g. per period EV updates and MCS operation.

4.6.3 Running the Schedule

This refers to the simplified flowchart in Figure 4-24. Each schedule entry contains:

- event time in st (stimulation time, a real number of 1/10th hours e.g. st 161.50 = 4:09:00pm). These span the week so range to st 1680,
- the event as a letter code or phrase, e.g. "PD" means: perform period processing,
- any necessary parameter data.

The schedule is a simple, static list of events in time order, built from EV movements plus any Batch command timed events. A "process pd" event occurs every 6 minutes. Housekeeping includes an hourly "parked EVs report", and at midnight results are formatted and written to disk.

There are 29 event types, mostly for debug and occasional changes e.g. amend hi_limit on the fly, make all EVs dumb etc.

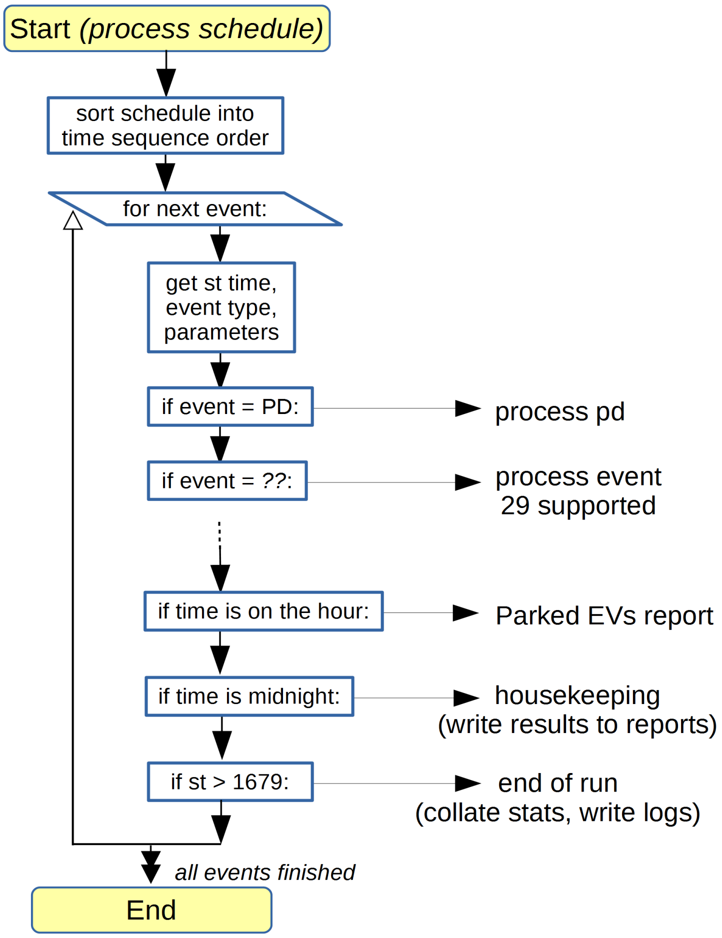


Figure 4-24: FPB simplified schedule operation

The events of most interest are:

- Depart and Arrive an EV,
- execute a per pd update (assess loads to determine headroom, discover EV states and run the local MCS).

FPB tracks electrical statistics in the background; on simulation completion FPB reports observed load kW peak values, percentile points and a load histogram to statistics files.

The event most prevalent in the schedule is a marker initiating per period processing, described in 4.6.5. EV Arrive and Depart code is presented as pseudocode (see 4.6.4).

Higher level processes prune and zip output, so to limit growing excessive volumes of data. Key data points are retained in summary logs.

4.6.4 Departing and Arriving an EV

Departures and Arrivals of EVs are timed events held in the schedule. Movements may occur at any time (e.g. st 128.76) so are not at quantised moments. However, due to the per-PD cyclic operation of the system, arriving EVs do not begin charging until the next PD.

Departing an EV is straightforward process, shown in Table 4-6 as pseudo-code. This is formatted using python's indent system; groups of indented code relate to the higher, less-indented line:

```
for some iterative loop:
    do this
    and this
now outside the for-loop
if understood:
    this example is redundant
else:
    please read again.
```

This is not a formal language; the purpose of the pseudo-code is to relate the main functions in English. Blue dots imply a task block.

Table 4-6: Pseudocode: EV Departs from Home
When used? Schedule informs FPB: EV (with this ID) is to depart **Output data:** Revised EV class instance flags
● if EV connected: revise EV SOC by the SOC delta from time of last assessment to now   set SOC delta to zero and disconnect from house and network ● update EV output log with the departure

Arriving is slightly complicated by Away from Home recharging. When Eqn. 20 is detected:

$$(depart\ SOC - trip\ consumed\ SOC) < 0 \tag{20}$$

it is deduced that, to be home, the EV must have gained charge:

Table 4-7: Pseudocode: EV Arrives Home

When used? Schedule informs FPB: EV (with this ID) returns home at this time

Output data: Revised EV class instance flags

- adjust EV SOC:

  decrement SOC by determined trip consumption

  if (SOC < plausible minimum) OR (AFH_prob dice throw): assume EV recharged AFH

  calculate necessary charge taken on (assume at trip midpoint)

  update EV SOC, update AFH stats: connection count, AFH kWh taken on

- determine if EV will connect to network at home

  if SOC < SOC for next depart (= ∑ SOC use from now => midnight tomorrow):

  driver has range anxiety (recharge is forced): connect EV to network

  else: (does driver happen to choose to recharge anyhow?)

  if home recharging mandatory flag: connect EV to network

  otherwise connect by driver claimed habit (decrementing count)

- if EV connected construct appropriate tranche for EV class:

  if time permits lazy / battery optimising charging:

  construct appropriate optimising tranche set

  else: default to immediate charging tranche

- Update EV output log with the arrival

4.6.5 FPB Per Period Processing

This is shown by the simplified flowchart in Figure 4-25 giving the basic processing occurring on each 1/10 hour period (pd), triggered by PD markers in the schedule. The simplified Per Period processing is:

find hi_limit: apply DR_Sunshine ratio to hi_limit or a “cool transformer” clamp

for phase 1, 2, 3: the same method is applied per phase

sum phase residential loads: as defined by input per house load profile, for houses on this phase, scaled or adjusted to inject ±kW bias as necessary (e.g. PV bias)

find headroom: headroom kW = hi_limit - ∑ phase residential loads

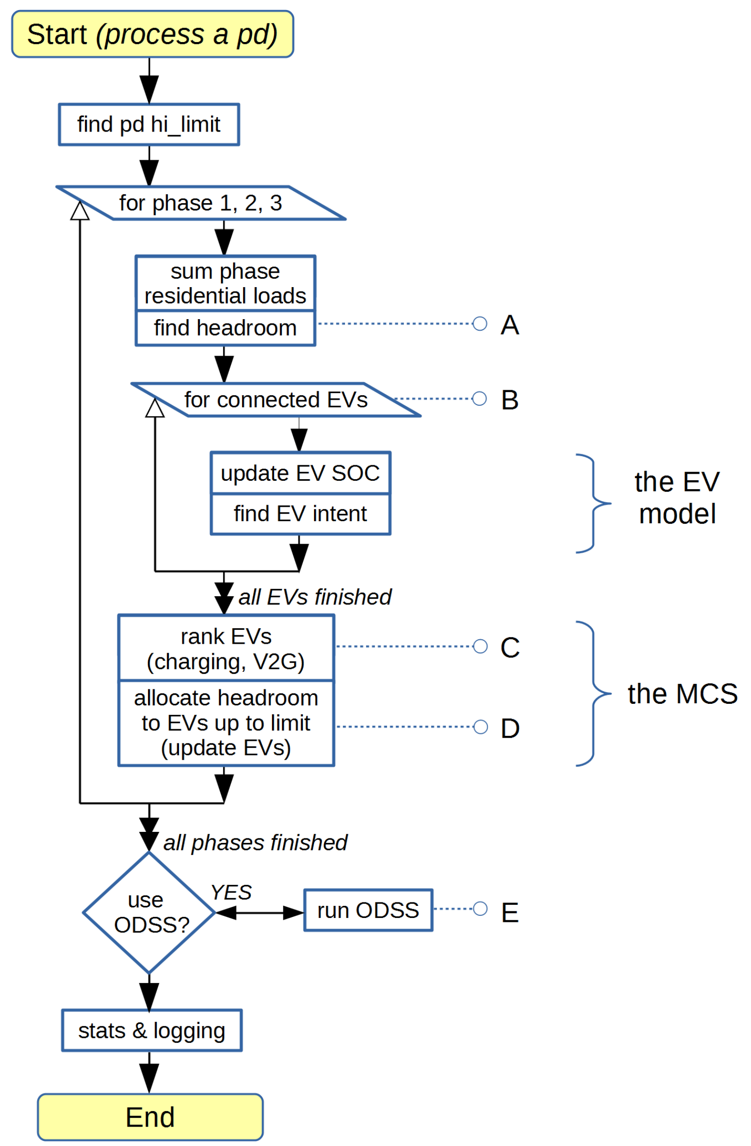


Figure 4-25: FPB simplified “Per Period Process”

A: this finds logical headroom, hi_limit - residential load, not “to cable limit”

B: for connected EVs: ignores those not at home or unconnected

The EV model

update EV SOC: EV SOC = EV SOC + delta_EV_SOC_per_pd (set by EV charging rate)

find EV intent: use tranches to discover EV options (idle, mandatory or opportunistic charge, dispatch, opportunistically charge or dispatch)

The MCS

rank EVs: by one of: random, proportional or equitable fairness and time to depart

C: proportional chargers = rank in least kWh received order, equitable chargers = rank in need (kWh to obtain / time remaining) order, potential V2G dispatchers = rank reverse depart time order **NB** a V2G can have both charging and dispatching ranks

allocate headroom to EVs to limit: assign available kW until headroom consumed

D: a 2-pass system with optional clamping and V2G injection; see Table 4-14

use OpenDSS: called as needed to assess electrical situation

E: FPB runs OpenDSS and checks output to confirm system is within voltage limits.

4.6.6 Pragmatic Optimisations

4.6.6.1 Crowding and Anti-Crowding via Partial Charging

It was found that hi-priority EVs, if allowed to charge at their maximum rate, consumed available kW displacing lower-ranked but-need-to-charge EVs. This group of EVs, forever deferred, would later "force the issue" and grab charge just before departing - a problem seen in the morning commute to work. The author calls this "crowding" as it is similar to a group of people trying to rush through a door at the same time. Overloads ensued. What was needed was to bring their charging forward in time, only if a small part, so departing EVs had a minimum charge to get to their destination.

The mechanism developed was to not immediately allocate all desired kW to the high-priority EVs, rather, to allocate the minimum they could charge before passing down the priority line. On completing the pass, if spare kW remained the allocation process repeats, so raising allocation for the highest priority vehicles. Thus when kW available to disperse was exhausted, more EVs received charge with high-priority EVs getting the most.

There are clearly variants on this, however two passes (half then full charging kW) noticeably reduced the crowding effect giving a visibly flatter feeder kW load plot, indicating better usage of available kW.

4.6.6.2 Phase Balancing

The author is not warm to the included "phase balancer" mechanism. The intent is to optimise power throughput by balancing phase loads, an ongoing concern of DNOs. However FPB loads phases with EVs as much as possible, so to optimise charging opportunities. Less loaded phases cannot be increased, for they are already loaded as far as they can be. As FPB cannot invent load, balancing can only be achieved by reducing throughput on the highest loaded phase. The unbalance objective metric is improved, but customers receive less power… to the author, turning things down to optimise a metric is an odd way to "maximise throughput" (and might provoke undercharging).

As a result, there are defeats built in i.e. if the system has a phase at the top limit - balancing by reducing phase load is dropped, as the system is deemed in distress.

Note setting lo_limit > hi turns balancing off. The default span is: lo_limit = hi_limit - 6 kW.

4.6.6.3 V2G and Clamps

V2G support allows other EVs to charge, so defrays clamping. But the V2G EV must recharge; the process has high losses. 1 kW of V2G needs c. 1.4 kW or more of recharge.

If V2G pre-burn is enabled, the headroom is raised by a proportion of the phase V2G. This forces use of V2G; however clamps may still be needed (see Figure 4-11). For example:

- hi_limit 50 kW,
- demand = 65 kW,
- V2G available = 8 kW.

Load is allowed to rise to 58 kW with the excess 7 kW clamped. Pre-burning V2G does reduce the number of clamps, but in extremis causes significant use of V2G such that battery ageing may be an issue.

To combat frequent use, a mixed mode is available with a "clamp budget". This mode is normally OFF. Here, rather than always pre-burn V2G, a proportion of clamps are allowed to operate. Once a budget is met, V2G pre-burn is enabled and operates as described. The budget is consumed pro-rata i.e. if there is a weekly budget of 500, at 1/10th of a week the budget is 50, beyond which V2G operates.

4.6.7 Pragmatic Simplifications

4.6.7.1 FPB Ignores Losses

FPB ignores network losses (c. 2 - 5%). Physical manifestations are heating of transformer and cable and volt-drop along the feeder; however OpenDSS will see the latter.

4.6.7.2 FPB Ignores VArs

FPB calculations are performed in kW not kVA. However OpenDSS accepts reactive loads (VArs). The household load data has VAr for pf 0.98 lagging. EV loads are near pf 1.0 (it is possible to cause inverters (as in the EV) to generate VArs). The Gridkey Electric Nation Closedown Report **(GridKey, 2018, Fig. 3 p9)** plots modern EVs during their charging phase, behaving as a constant power load while emitting a leading reactive component of 100-200 VAr. This tends to correct the lagging element of the assumed household VAr.

4.6.7.3 FPB Electrical Error Quantification

OpenDSS can assess losses and reactive elements, so can quantify errors. A spot-check of FPB output vs. OpenDSS produced the error plot shown in Figure 4-26. The trendline may be used to approximate the error and a correction made (but is not included at this time).

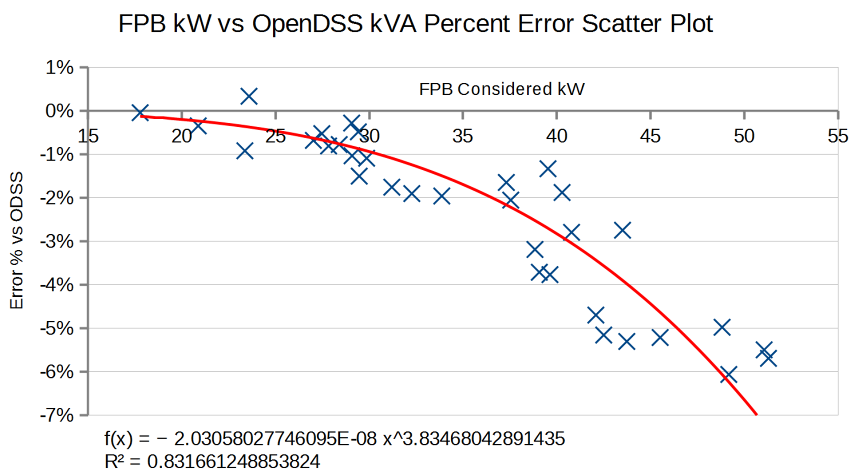


Figure 4-26: FPB vs OpenDSS Error Plot with trendline

The largest error was 3.3 kVA, FPB being 6% too low vs. OpenDSS. This was not exceeded in three other spot-checks. This error is larger than the author would like, yet to be fully rigorous would mean running and incorporating OpenDSS results into every FPB scenario, significantly slowing FPB operation (simulation time x10 increase). This may be advisable in the longer term. **Note** that this analysis is still subject to errors as shown in Table 2-10, arising from simulation periodicity induced averaging.

4.6.7.4 Impact of Simplification Errors on FPB Results

The impact is to hide load and heating i.e. FPB suggests the network is more capable than in reality, hence overstates ability to charge EVs by 6%, 1 in 16, worst case.

4.6.7.5 Other Error Sources

There are potentially many, simply as projections have been used re EV characteristics, battery thermal characteristics etc. Improving on these can be intractable given lack of data. For example, what kWh consumption should cabin heating be allowed? A spot check showed FPB guessed this to be c. 2.7 kWh for a Mondeo sized vehicle driven for an hour, assuming a starting (and outside) temperature of 1°C. Without knowing a host of factors (size and mass of the cabin, insulation, windage effects of cooling, cabin air exchange rate) such estimates are “best endeavours”. Hopefully such data will be forthcoming in the future. The author suspects 2.7 kWh is high, given experience of heaters in small spaces.

Note the only means to judge if assumptions about future EVs are reasonable is to review each instance i.e. a team walk through (desk-check) of the entire codebase.

4.6.8 Concerning Clamp Statistics

During MCS pd processing, if a phase reaches the hi_limit a commonly used option is to clamp i.e. to refuse charging by turning EVSE off. This is assessed per-phase and applied to mandatory chargers (hi-priority vehicles charging first, later ones are clamped).

The clamp count relates how many times the controller enforces clamping on a feeder phase, and is **not** a count of how many times EVs have been clamped. The maximum is therefore 3 x 1,680 = 5,040. One clamp event can affect all EVs on a phase, or just one. Later versions of FPB may wish to log EV experienced clamp events.

4.7 Software Development Methodology

The author is familiar with two methodologies:

- Waterfall (an early 1980’s design method) and
- stepwise refinement (aka iteration).

Waterfall flows through a series of cascading, reductive micro stages, and is:

- thorough,
- has visibility of:
    - the whole project
    - where you are in the project
    - what needs to be achieved next,
- can easily have a whole-system quality programme attached
- leaves a large paper trail from start to finish.

But:

- is ponderous i.e. slow, with high overheads at project start
- absorbs significant manpower to drive as a system.

If Waterfall is the "view from above", stepwise refinement is the converse, viewing the project from below. The basic approach is:

a) consider what you want to do,
b) prototype a method, refining until it reliably achieves desired outcomes
c) build into the project
d) test operation and rework if necessary until effective etc.

Yet this offers no mechanisms for:

- direction or
- overarching quality programme, for there is no top-down visibility
- thus runs the risk, for larger projects, of success at the micro scale but failure at the macro; the work is effective but does not contribute to a useful goal i.e. wasting time driving work in the wrong direction.

Waterfall is favoured by the author over a range of other methods as:

- he is familiar with it
- it is able to manage complex projects
- quality assessment can be readily included
- there is visibility of what was done, why, and what to do next.

Stepwise refinement was used for INSim and FPB, as the Waterfall design process was deemed to be taking too long.

4.7.1 Development Quality Assurance

The developed FPB code was verified during development by checking:

- at a functional (atomic) level: prototype code primitives operate as desired
- at module level: are the needed data transformations correct
- is whole system (end to end) function correct.

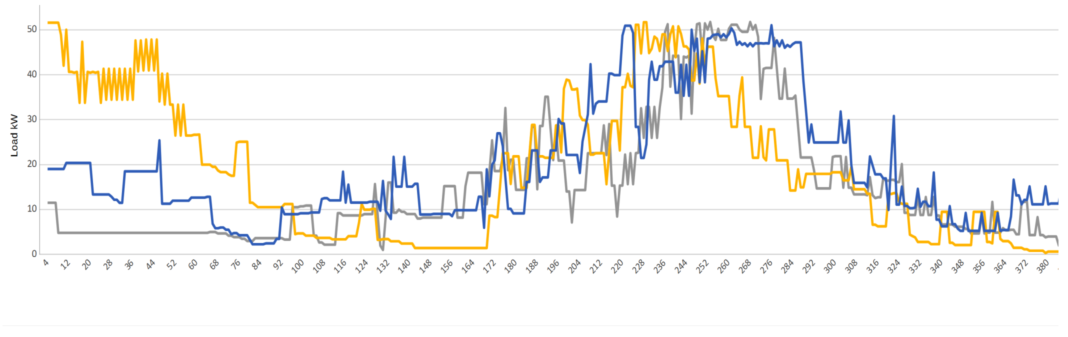


Figure 4-27: FPB proof of concept test: EV activity loads without Residential load

Occasional test runs were performed to inspect results e.g. running MCS with 20 EVs per phase but no residential loads, to show EV activity alone (Figure 4-27). The core simulator system was verified by desk checking output, tracking errors and revising until no errors were found extent. This was repeated at each level of abstraction including whole-system testing.

Furthermore, each scenario output was checked for evidence of desired function i.e. if V2G is requested, then V2G should be seen to be operating in spreadsheets and plots of feeder and EV activity.

See also section 4.11.2 which compares FPB output data with My Electric Avenue results.

Note that QA includes optimising algorithmic techniques e.g. of allocating charge to EVs, so that best capability is provided at high level of abstraction. For example, adjusting MCS logic able to fit the hi_level line as flatly as possible, to ensuring best use is made of available feeder kW before applying any other interventions.

4.8 FPB Scenarios

This section describes the major degrees of freedom ("control knobs") FPB possesses, for the LV network, the Residential loads and the EVs. The core simulation is a "scenario". This defines:

- the network to use, including electrical characteristics
- the EVs to use, including type and where normally resident
- the loads at each house in the simulation period.

There are a considerable number of options. These include:

- scale the residential load data so to vary the imposed load ADMD
- set and vary the hi_limit for phase maximum kW (to reflect the cable or transformer capability)
- varying the parking habits of the EV owner.

A scenario run simulates a week and takes from 7 to 70 seconds. Scenarios are invoked in 8 batches of 2,000 instances with OpenDSS called every 20th of these. The grouping of 16,000 simulated scenarios is a Sequence.

4.8.1 Batch Script Controls

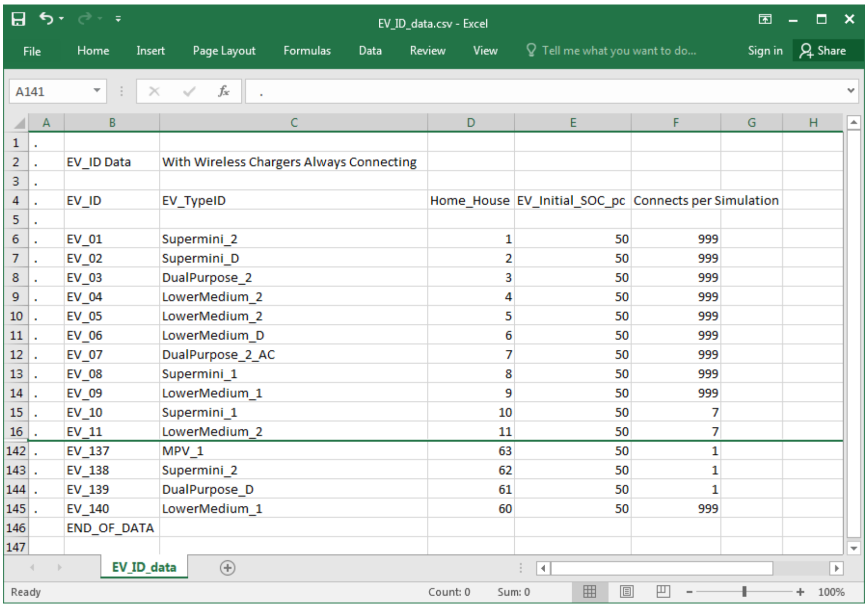
The Batch Script can contain timed (scheduleable) events to e.g.:

- signal to EVs as might an aggregator,
- configure Transformer clamps.

For a complete description, see the FPB Manual **(Broderick, S. 2018)**.

4.8.2 FPB Input Data and Format

Input data is via .csv files, usually generated by spreadsheet (Figure 4-28). **Note** that Excel is occasionally problematic with .csv. LibreOffice Calc is preferred, however Calc cannot presently read more than 2048 columns.



	A	B	C	D	E	F
1	.					
2	.	EV_ID Data	With Wireless Chargers Always Connecting			
3	.					
4	.	EV_ID	EV_TypeID	Home_House	EV_Initial_SOC_pc	Connects per Simulation
5	.					
6	.	EV_01	Supermini_2	1	50	999
7	.	EV_02	Supermini_D	2	50	999
8	.	EV_03	DualPurpose_2	3	50	999
9	.	EV_04	LowerMedium_2	4	50	999
10	.	EV_05	LowerMedium_2	5	50	999
11	.	EV_06	LowerMedium_D	6	50	999
12	.	EV_07	DualPurpose_2_AC	7	50	999
13	.	EV_08	Supermini_1	8	50	999
14	.	EV_09	LowerMedium_1	9	50	999
15	.	EV_10	Supermini_1	10	50	7
16	.	EV_11	LowerMedium_2	11	50	7
142	.	EV_137	MPV_1	63	50	1
143	.	EV_138	Supermini_2	62	50	1
144	.	EV_139	DualPurpose_D	61	50	1
145	.	EV_140	LowerMedium_1	60	50	999
146		END_OF_DATA				
147						

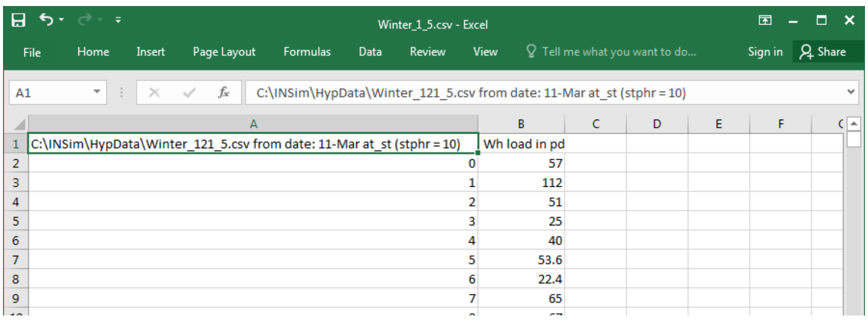
Figure 4-28: Example of input data: Defining EVs in Excel

However Excel can be used, with the proviso that leading cells are not empty. Excel will strip empty cells on save, unfortunately reordering the columns of <u>some</u> rows.

The format of input data is not cast in stone, however the majority use:

- 5 header rows
- following data rows have:
  - column 1 empty (or, for Excel, occupied by " ." i.e. space-dot)
  - N fields follow as needed, with data as ASCII text.

Input data .csv files terminate with the phrase "END OF DATA"; rows below are ignored and may be used for other element e.g. comments. Externally sourced linear lists of data (e.g. household loads) may take a different format (Figure 4-29):



	A	B
1	C:\INSim\HypData\Winter_121_5.csv from date: 11-Mar at_st (stphr = 10)	Wh load in pd
2	0	57
3	1	112
4	2	51
5	3	25
6	4	40
7	5	53.6
8	6	22.4
9	7	65

Figure 4-29: Example of input data: Residential Wh energy use in period

4.8.3 LV Network Parameters (FPB View)

These are held in "Feeder_Specs.csv" and include:

- transformer "label rating"
- cable phase capacity in Amperes
- the lo_limit in kW (usually hi_limit - 6 kW)
- the hi_limit in kW
- feeder_I2 (3 x cable phase rating ^2).

The following columns are obsolescent: N_houses, ADMD, Cable mm2. Data for standard cable maximum phase currents are from catalogue **(Aberdare Cables, 2008)** or similar.

4.8.4 Residences and Residential Load Input Data

The plain text .csv files define:

- house identifier
- house network address (for interworking with OpenDSS)
- the feeder number
- house phase and
- a flag to indicate that this is a residence or not (for public EVSE / charging points)
- household energy use per simulation period, in Wh (in a separate file per house).

The energy usages can have ADMD scaling factors, bias offsets and per-pd, per-phase magnitude adjustments applied.

4.8.4.1 Residential Data Sourcing and Preparation

The source of the live residential data is SSE's New Thames Valley Vision project **(SSEPD, & NTVV. 2015)**: (http://www.thamesvalleyvision.co.uk/project-library/research-data/

being Elexon Energy Usage data for c. 210 standard and Economy 7 customers, covering approximately 18 months from early 2013. The data is used with interpolated jitter added to synthesise 6-minute data from 1/2 hourly data. Jittering and interpolation are contrived so that integrating over 1/2 hour periods yields the original Wh values; see Figure 4-30 and Figure 4-31.

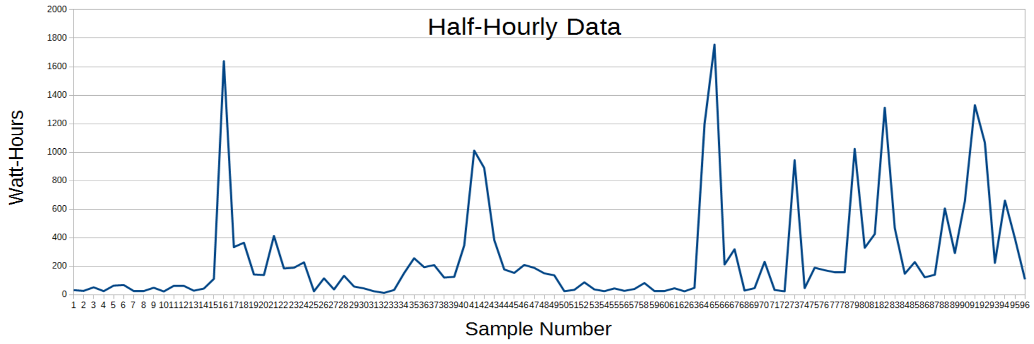


Figure 4-30: Residential source data - before jittering

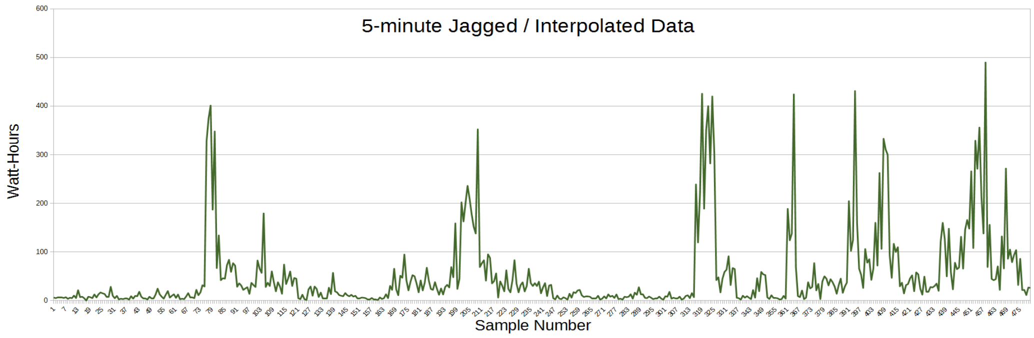


Figure 4-31: Residential source data - after jittering

This reduces errors arising when calculating losses **(Urquhart & Thomson, 2015)** plus produces a plausible electrical environment for EVs.

4.8.4.2 Residential Data Preprocessing

The nominated residential dataset contains Wh energy use per house, per pd with jitter interpolation as above. There are three further adjustments which can be applied during each simulation run:

- load ADMD kW scaling, stated as a target kW i.e. 1.3 kW from a dataset measured as 1.5 kW ADMD
- a Multiplier ratio defined per period, per feeder, per phase e.g. increase phase 2 loads by x1.2. Phase multipliers of not exactly 1 can be used to trigger injection of bias for that phase only. In this manner unbalanced loads can be formed on single phases, including both an offset and increased load variability
- a Bias per pd, either applied uniformly to each phase or applied to phases with a non-unity multiplier. This allows PV power injection or other loads e.g. Heat Pumps. Can be set ON or OFF.

The Multiplier and Bias files are optional. No file forces OFF. The ADMD scaling is used to adjust down the nominal residential dataset from 1.5 kW (as determined by a DNO numerical assessment method) to 1.3 kW. This is performed as data relates to homes in 2013; Tungsten lightbulbs were then normal. The ADMD adjustment removes c. 200 W per home to compensate for LED lighting (60 W bulb replaced by 8 W in several rooms).

The Multiplier can selectively raise / lower a residential load by a ratio applied per phase, assisted by the Bias which can either cause an all-phase or selected phase offset. Each has per pd timed values, which may be positive or negative. The per pd Bias Wh signal is applied to each house; using this household solar PV or HP can be mimicked, giving time-based power injection or removal.

Examples of action and Batch file commands:

- Normal operation: ADMD_kW, 1.3; 3ph_Mult, OFF; Bias, OFF
- Inject PV: ADMD_kW, 1.3; 3ph_Mult, OFF; Bias, ON
    - Bias file has a PV profile of 2kW peak per house, using **(Solar Sheffield, 2018)** insolation data
- Inject Heat Pump (HP) load: ADMD_kW, 1.6; 3ph_Mult, OFF; Bias, ON
    - The elevated ADMD_kW mimics auxiliary loads. Bias file has a timed HP home preheat profile, 4kW peak per heated house mostly 3am - 7am, reducing throughout the day and climbing in evening (see Bias file examples). Note that this data is invented due to lack of a data source;
- Inject imbalance: ADMD_kW, 1.3; 3ph_Mult, ON; Bias, ON
    - The Multiplier phase has a value of 1.000001 for phase 1 and 1.0 for phases 2 and 3. This results in Bias values being added to houses on phase 1 only, so adding phase imbalance to whatever is present in the residential load data.

Internally, FPB applies these adjustments to loaded residential data values before executing the simulation. Source file data is unchanged.

The author notes that misconfiguration occasionally arose due to losing track of the Mult and Bias flags coupled to default operation, given file presence (or not). This caused problems (i.e. the Batch file asserted a state which was not possible hence misleading). The state and effect of actions needs be explicit; the log file is explicit but is retrospective. It would be advisable to improve this area.

4.8.5 Electric Vehicle Data

The characteristics are held in .csv files. These set:

- vehicle model characteristics:
  - battery size
  - Smart class e.g. “dumb”, “SV1G” or “V2G”
  - driving kWh consumption rates
  - loss factors for charging and discharging

and per individual EV:

- home location
- a factor for probability of reconnection when arriving home.

These can experience:

- at simulation start:
  - different ambient °C (affects battery capacity, auxiliary losses e.g. cabin heaters)
  - an initial SOC state
  - a maximum number of EVs
- during simulation (i.e. a “timed event”):
  - changed Away from Home charging probability
  - change of Smart type (e.g. making a marque type “dumb” effectively cuts their “listening” to charging instructions as if there had been a comms failure)
  - a model may be under aggregation control i.e. “seized” and made to do things as if remotely managed,
  - to be force-parked at home, or
  - to be force-removed from the simulation.

The EV home residence is set in the EV configuration file, however, a “non-residential home” can be specified e.g. a public chargepoint. On return, such EVs park at any free EVSE i.e. on a random phase. **Note** when charging at a house EVs add load to the house phase. There is no limit as to how many EVs may charge at a house.

4.8.6 EV Trip Synthesis

A trip is a complete journey, with timed Depart from home to travel a known distance and an Arrival back home. Each trip is synthesised in two passes. Pass 1 is external to the FPB, synthesised in a trip generation tool. This tool creates "tripsets" with a nominal daily distance for the default 100 vehicle fleet, stored in a library directory.

Pass 1 synthesises sets of trip start times and distances, for each EV, written to the library of trips as .csv files; see Table 4-8.

Pass 2 (SOC use and arrival home times) is produced by the FPB, in Table 4-9.

Pass 2 is necessary as consumption is dependant on the type of vehicle driving the route, so cannot be calculated in Pass 1.

Generated trip distances slightly exceed target; this is deliberate and attempts to correct the impact of timing clashes which can cause trips to be discarded. The problem is: A long trip implies a late home arrival time, potentially after a scheduled departure. If the EV is not home to depart, the scheduled Departure becomes impossible so is discarded. This supports overall trip fidelity, but shortens modelled EV trip mileage.

Table 4-8: Pass 1: External synthesis tool generates libraries of trip Departures
pseudocode: • set fleet weekly fleet travel distance e.g. 27mpd => 100 x 27 x 7 = 18,900 miles • randomly pick 100 cars from RAC / MOT data with their miles per year, find their weekly travel distance and scale to the target distance for the fleet • from RAC / NTS data determine a selection of number of trips per day and assign to vehicles • for each EV: for each day: for each trip: pick a probability-profiled random time for trip start sum trip distances in the day and scale to meet trip distance • sum all trips for all EVs over a week and determine a scaling factor to meet the target weekly travel distance i.e. 18,900 miles.

Table 4-9: Pass 2: FPB constructs trip Arrivals
When used? During FPB startup, EV trip data (depart time, distance km) is read but this does not include arrival home times or SOC consumed, as these vary by vehicle. The data is generated and held in FPB memory.
pseudocode - load a nominated library of EV trip start times and distances - for each EV: per departure: create a probability-profiled random return time detect and regenerate implausibles (e.g. depart on a long trip with return minutes later) detect any clashes with subsequent depart times (vehicles cannot depart if not at home). Discard the clashing trip departure calculate SOC consumed in trip, given distance, EV characteristics and ambient temperature (internal heaters, battery C adjustment) enter into internal table: trip number, depart time, SOC used, return home time, distance km

4.9 FPB Outputs - Results Data

The primary outputs are:

- log files (setup conditions, events / errors during simulation, stats summaries),
- EV_output: per period EV events with hourly and daily synopsis
- Feeder_output showing electrical load activity
- Losses (OpenDSS runs only) breaking down the per-period losses.

4.9.1 Overview of .CSV Data Format

All .csv files start with a header block, being 5 rows stating the context of results:

1. what the file is
2. to what scenario the file relates
3. timestamps and run numbers
4. what the purpose of the file is
5. column header labels.

4.9.2 Data Output Format

Table 4-10: Output .csv file header (field / column headers not shown)

FPB EV Data Output	20180517:2038:SC-DFAGGTP1-188020cbF:0055:Scenario: SC-DFAGGTP1, Run Number: 188020, Machine ID: M3:6:UoS-206287
Scenario	SC-DFAGGTP1
Run Number	188020
Purpose	Trial of 20 EVs, being S_50 as a rerun of S_41. With FPB C2CT on Default Typical Trips, DR-B, FFR, PerfectPlugins, AggCmds to stop charging from 1pm to 6pm, then < 1/3rd SOC, normal from 11pm. EV trips are as per Trip assessment March 2018. Batch group call number 1
Timed results data follows	

The system outputs .csv results and log files in ASCII text form. Event times are usually shown as st and walltime, using the format “WW-D HH:MM:SS.S”. Events need not fall on a pd boundary. For example:

st: 949.1691484, walltime: 00-3 22:55:00.9

i.e. week 0, day 3 just after 10:55pm. Day zero is Monday, so the example is a Thursday.

4.9.3 Results Data .CSV Files

These include:

- Feeder_load_output.csv:
    - what the phase loads are, who is loading and any special events (e.g. out of limit warnings, clamp trips and dynamic system losses if OpenDSS is in use)
- EV_output.csv:
    - logs key EV events in time order, including hourly “who’s home” summaries
- EV_Timeline.csv:
    - a falling timeline of EV states (which may be manually colourised), showing charging, idle, dispatch etc. i.e. a visual summary of each EV’s activity
- ODSS_Branches_output.csv:
    - polar-form real-imaginary kVA, Amps, Volts values for each feeder branch (segment of cable) on each conductor (including Neutral)

- ODSS_Losses.csv:
  - the losses determined by OpenDSS for each electrical component, from transformer 11 kV busbars to household meter
- ODSS_Volts_monitor.csv:
  - feeder voltages at busbar to household meter with (some) intermediate locations. This file is very large so is heavily précised;
- ODSS_log.txt: all commands sent to OpenDSS
- stats1-histo.txt: a histogram of per-period peak phase kW, calculated after the simulation run
- stats2-OOB-Headroom.txt: feeder per period “out of balance” and headroom kW, headroom being the margin between highest loaded phase and the hi_limit
- FPB_log: a report detailing
  - startup conditions for a simulation run,
  - any untoward, interesting or significant events occurring during simulation,
  - various useful statistics on simulation completion including considerable summary data e.g. total kWh supplied, total V2G dispatched kWh, number of EVs short charging, amount of kWh taken locally or Away from Home etc.

Files Feeder_output.csv and EV_output.csv are detailed in Appendix C.

4.10 Configuring and Running the Simulator

See also The FPB Manual **(Broderick, S. 2018)**.

4.10.1 Configuring - General

The user needs to ensure the following general setup parameters are correct:

- C:\local\machine_id.txt - typically with 2 lines, which set:
  - a machine identifier (to track the PC on which the simulation runs), the number of threads it can support and a text description separated by ”:”

    e.g. M5:6:HP-16GB-Xeon
  - the destination directory for the results e.g. D:\local\FPB Archive\

    (these items are generally static / rarely changed)
- a pre-built copy of results data directories is placed in the target data area;

- a description file is added stating intent and primary characteristics of the simulation.

4.10.2 Configuring Simulation Scenario Parameters

The FPB is next configured "bottom up" from scenario level i.e. from fine to general details. The scenario is the core FPB configuration in terms of specifics. The Scenario is held in a directory of the scenario name (e.g. SC-000TP1) within the FPB input data space. The scenario directory holds at least:

- misc_setup_info.txt - specifies the OpenDSS network, how many houses in the simulation, house prefixes for residential load data and ambient temperature e.g.

  network_master:MasterTYPICAL.dss

  n_houses:100

  house_prefix:Winter

  ambient_C:1

- RunNum.txt - a text file with the last run number (auto-increments)
- ElectricalData (dir) - holds at a minimum the files:
  - Feeder_Specs.csv - transformer and cable ratings; values for hi_ and lo_limits
  - DR_SunshineSignal.csv - per pd ratios to apply to the hi_limit setpoint as a DR/FFR signal. If over 1.0 this is deemed to be a "turn up" or Sunshine signal, which encourages EVs otherwise "full enough" to take more;
- EVData (dir) - holds at a minimum the files:
  - EV_ID.csv - this names each EV required (e.g. EV_16), its marque type (e.g. Nissan_Leaf_40kWh), its home house identifier, the starting SOC, the number of times it is to usually plug in at home during the simulation;
  - EV_type_data.csv - a complex file defining for each marque type:
    - an SG class (dumb, SV1G or V2G),
    - battery kWh capacity,
    - minimum and maximum SOC,
    - rates of driving consumption,
    - the charge / discharge kW rates, and
    - various loss factors for the inverter and the battery;

    - EV_Trips_EV_(EV_ID).csv - the outbound trips each named EV takes, being a list of depart times and the distance of travel in km. NB this dataset can be over-ridden by the Batch system to select a "tripset" from a library, thus allowing more trips to be defined / used;
    - a description file which is recorded in the log system.
- HouseData (dir) - this holds:
    - a prefixed file (e.g. Winter_26_5.csv) for each house with per-pd energy consumption, stated in Wh;
    - optionally a Bias.csv file; a per-pd Wh value to offset add to all house loads.
    - Occasionally a 3ph_Mult.csv is present; this applies multiplier factors (per pd) to each phase.
    - Combinations of Bias and Mults allow unbalance, PV injection and HP to be simulated. See the FPB Manual for details.

These alone are not sufficient to define a simulation; there are other parameters which can be changed. These typically may vary "on the fly" during the simulation and are <u>scheduleable events</u> defined in the Batch control file. If these are not set by the Batch system, defaults are used. Examples: default scalings for ADMD for residential loads; timed events such as PowerFail and PowerRestore.

4.10.3 Simulation Duration

The simulation engine can perform arbitrarily long simulations, but is configured and supplied data for a week-long simulation. EV trips have 8 days data (to cover a week plus a 1 day forward view). This is simulated twice, a conditioning run to stabilise EV in-use battery SOC and transformer heat states from default values, then a data-gathering run which generates outputs. The post-processing and analysis suite is also configured to process 1 week duration simulations.

4.10.4 LV Network Data

The electrical characteristics are based on published cable **(DRAKA, 2011)** and transformer characteristics **(Wilson Power Solutions, 2017)**, converted by the author into OpenDSS readable .dss files. Household load data is synthesised from the New Thames Valley Vision (NTVV) project **(SSEPD & NTVV, 2015)** which recorded half-hourly energy consumption for several hundred houses, in Bracknell, UK. The synthesis process adds randomised intermediate values to raise sample frequency to 10 per hour, maintaining half-hourly consumption values (see 4.8.4).

4.10.5 Other Data Used

This includes PV output data **(Solar Sheffield, 2018)** and UK weather data for seasonal temperatures. The Li-ion battery characteristic was extracted from plots of recorded Chevrolet Volt range vs. temperature **(FleetCarma, 2018)**.

4.11 Verification of System

4.11.1 Verification vs Real-World

Verification in this context means ability to correctly duplicate the range of expressed outcomes as seen in the real-world, given the same conditions and inputs. However no dataset of results generated by modern real-life EVs is at hand. Given this, FPB verification vs. real-world must be deferred until the following are available:

- all EV data including movements (timing and distance driven) and charging (at home and away timing and amounts)
- on known networks,
- with known periodic household loads.

Such a dataset is not known to exist.

4.11.2 Verification vs. Similar Works

The most similar work is My Electric Avenue (MEA), for which general results not specific data is available. There are though differences:

- EVs in FPB simulations are more capable, specifically:
    - have sufficient charge capacity that they may be used in the evening as against rarely used (the case for the 2013 / 14 Nissan Leaf 24 kWh),
    - use of BLPs scatters charging over long periods (usually overnight) so to reduce battery ageing,
    - potentially a different use pattern (real-world local vs. FPB's UK-wide average)
- FPB EVs use 7.2 kW charging vs Nissan Leaf's 3.5 kW
- household loads in FPB are lower as LED lights are common vs. rare in 2014/15.

The FPB plots used have parity (1 EV per house) driving 27mpd; the driven distances in MEA are not stated.

4.11.2.1 Comparison of FPB vs Esprit

Figure 4-32 and Figure 4-33 compare MEA *Esprit* system and FPB's clamped simulation:

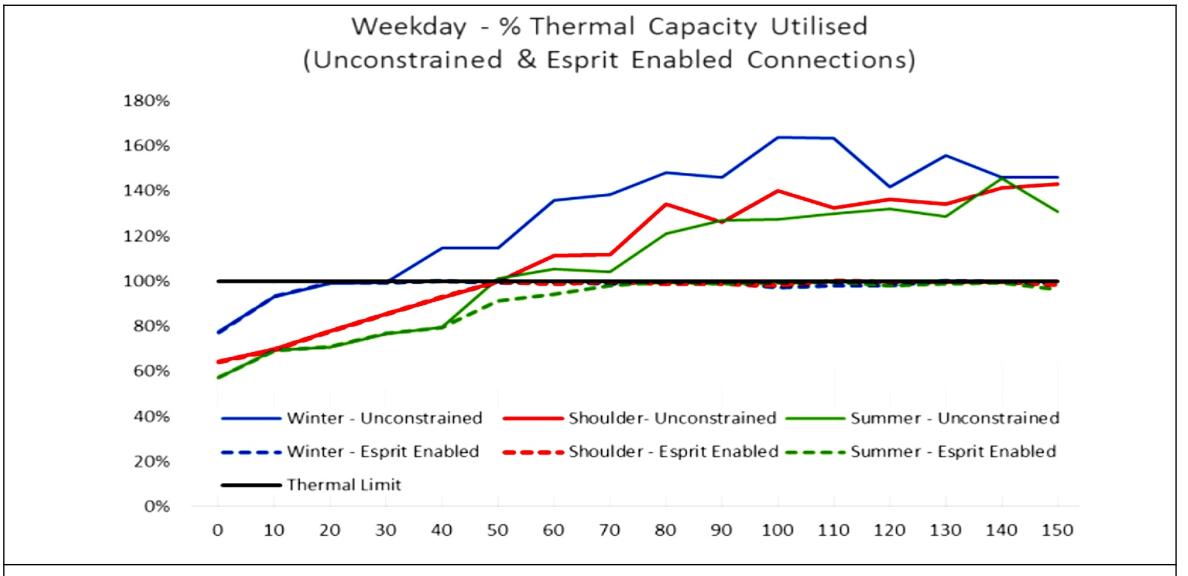


Figure 4-32: EA Tech, 2016, Fig. 16: Esprit impact of N EV, per 100 homes

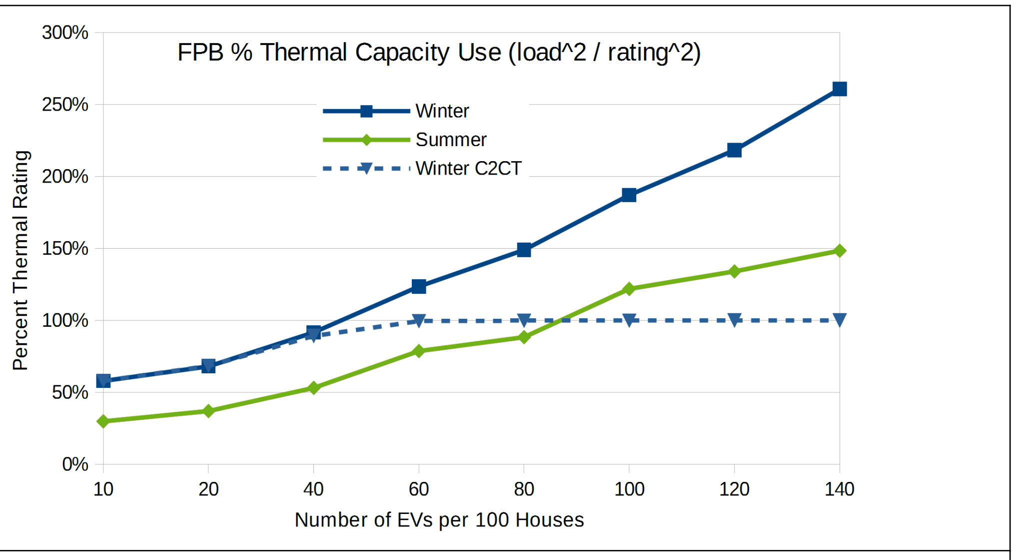


Figure 4-33: FPB representation of impact of N EV per 100 homes (Winter only)

The FPB's rate of capacity consumption is higher (Figure 4-33), likely due to either higher EVSE loading (7.2 kW vs. 3.6 kW), or that the underlying network capability is less. The similarity between curves is acceptable. The high N EV Winter curve drop (blue, Figure 4-32) past 100 EVs is surprising, usage per vehicle drops without stated reason. It is not known if this is sociological (EV users 100-150 drive less far in Winter) or another reason.

4.11.2.2 Comparison of Daily Load Curves

It is possible to present FPB data in a similar manner to MEA's daily ADMD plots, the key graphics being Figure 4-34and Figure 4-35 below.

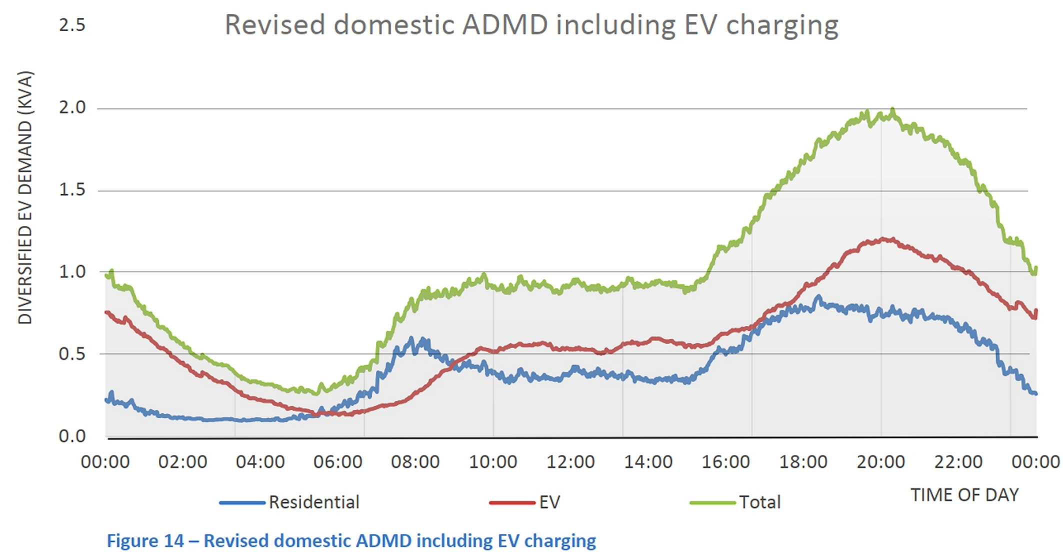


Figure 4-34: EA Tech, 2016, Fig. 14: Revised domestic ADMD with EV

Figure 4-34 is synthesised ADMD per home, using MEA (Nissan Leaf 24 kWh) data to project the load characteristics of a 7.2 kW charging EV.

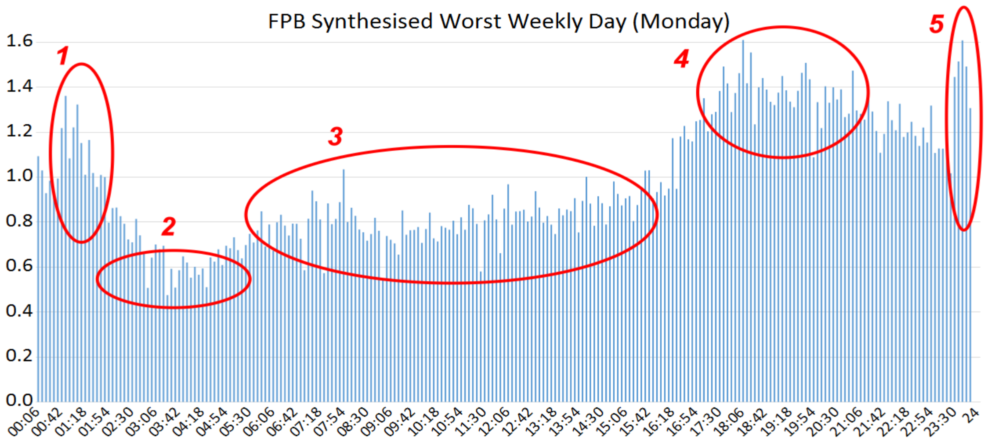


Figure 4-35: FPB output (Seq_1.1.2, no control) Monday household load profile

Figure 4-35 is FPB output for 100 EVs driving 27 mpd, averaged period loads over 500 trials for Monday, the most loaded day. Figure 4-35 is similar to Figure 4-34 and Figure 4-36 Weekday. Analysing kWh use in Figure 4-34: c. 22.4 kWh total (c. 9 kWh residential, 13 kWh EV charge).

Figure 4-35 has 23.3 kWh total. Subtracting known input residential load data (12.2 kWh) implies FPB EVs take c. 10 kWh, a drop of 23% in EV load vs. MEA. The cause of this disparity is not evident. Later week-view data suggests EVs take c. 9.8 kWh per weekday, confirming the estimate. This is not likely a deferral of charging beyond midnight. At this point, the author suspects FPB to be under-representing EV load, or to not be comparing similar situations (we do not know how far MEA EVs drive). Further, FPB allows EVs to charge AFH yet the situation is unknown for MEA vehicles. Given there may not have been ubiquitous AFH chargepoints in 2014/15, MEA may be without AFH charging; FPB includes AFH charging which lowers observed home charging.

Continuing to compare Figure 4-35 plots; region 1 shows a descent from a peak; region 2 is however less shallow and earlier than in Figure 4-34. This appears to be due to EVs performing pre-depart final charging. Figure 4-35's region 3 is comparable to the region in Figure 4-34, yet region 4 has a reduced peak and shallower loss of load vs. MEA. The minima (c. 11pm) of region 4 to 5 in Figure 4-34 and Figure 4-35 both approach 1 kW.

A new load is seen in region 5, absent in Figure 4-34. Closer inspection of **(Cross, 2015 Fig 8a)**, Figure 4-36, shows MEA experienced a similar pre-midnight burst of connections, which the author attributes to people behaviour: late arrivals home c. 11:15pm. It is thus justifiable that FPB modelled this event.

A notable in Figure 4-35 is FPB's peak evening load of 1.4 .. 1.6 kW, vs. 2 kW for MEA, in Figure 4-34, which the author attributes to lower residential lighting loads and BLP effects.

The author considers the outcomes plausible, given intended operation. **Note** the FPB is driven by NTS data in a Monte Carlo style; the load profiles are not programmed. Furthermore the residential load data has alternative origins vs. MEA; there is no reason to expect the same residential loads.

From the above, the author considers:

- there is clear similarity of spirit,
- there is no evidence of major disparity, although
- FPB may be under-representing load.

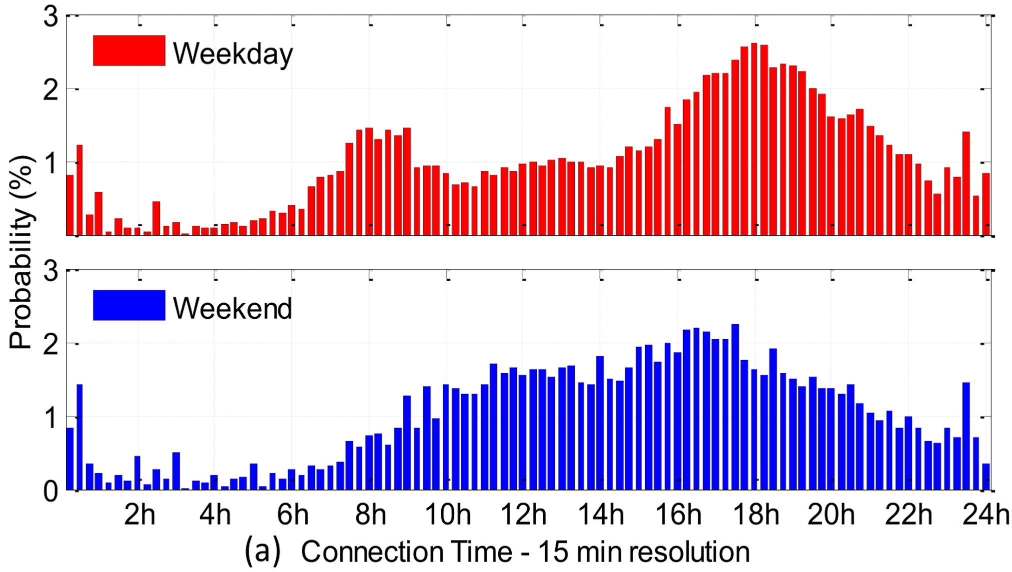


Figure 4-36: Weekday MEA EV Connection Probability

4.11.2.3 The Effects of BLPs

The author suspects BLPs lower load levels. Can this be confirmed? The figures below show whole week daily period averages and worst-case load values, for dumb EVs. Figure 4-37 has BLPs and Figure 4-38 is without; otherwise the simulations are identical.

Removing BLPs raises average, evening and overnight peak loads from c. 1.6 kW per house to 2 kW. BLPs cause EVs to disperse charging over time, lowering peaks and raising troughs. The intent is to maximise battery life by reducing heating; this also aids the network. **Note**: The driving profile is slightly different to previous examples.

Figure 4-38 is similar to Figure 4-34, the peak touching 2 kW at c. 9pm. However these plots illustrate sensitivity to whatever "reasonable assumptions" are used. Given a projection to mid-Century, then Figure 4-37 with BLPs is reasonable; but to consider EV impacts in the near-term Figure 4-38 without BLPs is more appropriate.

Note no EVs as yet are known to use BLPs (Update November 2019: Tesla are described as pacing charging overnight to manage battery temperatures, a similar system).

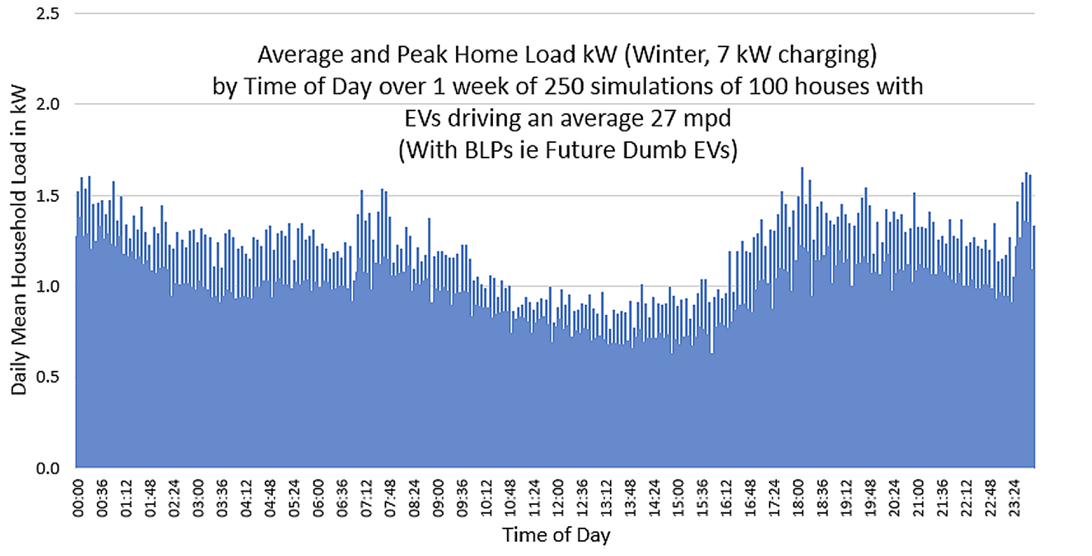


Figure 4-37: Effect of BLPs on per period household load: With BLPs

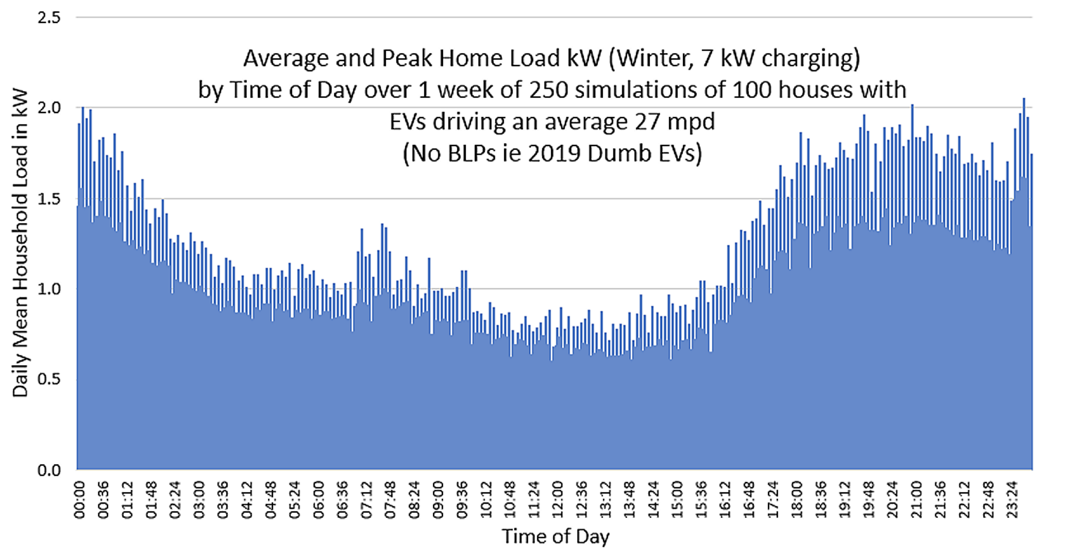


Figure 4-38: Effect of BLPs on per period household load: Without BLPs

4.11.2.4 A Warning re Averages and Peaks

It is possible to misconstrue the plots. Would the author build a system of say 1.6 kW capability, following Figure 4-35? No, because averages remove peaks. Both electrical forces and heating are square-law; a peak of say 10 times normal operation imposes forces and heating x100 normal operation. Such a situation is masked by averages.

The FPB simulation logs several on-the-fly statistics; one is an analysis of contiguous periods of overload seen during simulation (held in file stats1-histo.txt). These identify events contributing to i^2t heating, a simple energy coefficient for which is:

$$energy\ coefficient = n_{periods}\, x\, kW^2 \qquad (21)$$

A post-processor written by the author extracts this data and shows, comparing the length of contiguous runs from the 500 simulations of 27mpd 100 EVs plotted in Figure 4-35:

Table 4-11: Imposed phase stress energy coefficients

2 contiguous periods @ 96 kW (energy_coef. 18432, ie 2.91 kW per home)
3 contiguous periods @ 93 kW (energy_coef. 25947, ie 2.82 kW per home)
4 contiguous periods @ 95 kW (energy_coef. 36100, ie 2.88 kW per home)
5 contiguous periods @ 93 kW (energy_coef. 43245, ie 2.82 kW per home)
6 contiguous periods @ 92 kW (energy_coef. 50784, ie 2.79 kW per home)
7 contiguous periods @ 97 kW (energy_coef. 65863, ie 2.94 kW per home)
8 contiguous periods @ 92 kW (energy_coef. 67712, ie 2.79 kW per home)
9 contiguous periods @ 83 kW (energy_coef. 62001, ie 2.52 kW per home)
10 contiguous periods @ 76 kW (energy_coef. 57760, ie 2.30 kW per home)

The highest stress is for 8 contiguous periods (48 minutes) of 92 kW, c. 2.8 kW per home.

The capability heatmap (see Table 1-1) suggests that a built network of 2.5 kW ADMD could cope; however peaks contribute stress over 2.5 kW. From this, a 2.5 kW network copes by consuming overhead margin, the allowable peak being 1.4 × 2.5 kW i.e. 3.5 kW (see broaching, Broaching Assessment section 5.4.2).

This however is still not worst-case. Economy 7 (cheap electricity from say 1am) can cause problems if EVs use charging timers. At 1am all EVs go on charge. There is no diversity, so the ADMD load is charging load (7.2 kW per house) likely causing substation fuses to blow.

Yet, none of these peak load issues are apparent in Figure 4-34 to Figure 4-38.

4.12 Other Programming Methods

There are no further novel methods within FPB, although a probability picker developed is found useful. This converts the output of a flat probability generator (python uses the Mersenne Twister) to a pick from a probability graph, as may be expressed by a histogram i.e. Monte Carlo picks profiled to match the probability data supplied.

A numerical dataset needs to be available, forming a histogram (Figure 4-39, (b)). Illustration from **(MacKay, 1998).**

It is assumed that this describes data which has no discontinuities within results i.e. bin frequency (b) describes (a), a continuous curve.

The method implemented finds hits within a linear number list.

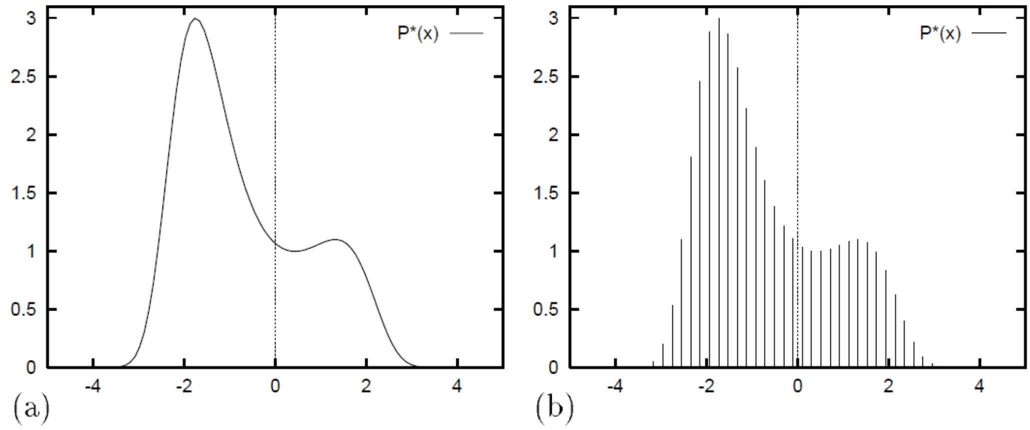


Figure 1. (a) The function $P^*(x) = \exp\left[0.4(x-0.4)^2 - 0.08x^4\right]$.

Figure 4-39: A curve represented as a histogram

A dataset describing the distribution probabilities is created, a normalized cumulative probability, listing accumulated probability from first to last bin.

An example distribution might be:

$$[0.05\ ,\ 0.1\ ,\ 0.25\ ,\ 0.4\ ,\ 0.6\ ,\ 0.75\ ,\ 0.9\ ,\ 0.95\ ,\ 1.0] \quad (22)$$

data are implicitly in sorted order. Python has a set of routines (implemented in C) which manipulate sorted lists, one being “bisect”, a binary-chop method to find a location in a sorted list. Asking bisect where 0.8 might appear in the list returns a pointer to the [0.75, 0.9] entries, the 6th frequency bin. A companion dataset is now used to resolve the boundaries of the 6th bin:

$$[15\ ,\ 16\ ,\ 17\ ,\ 20\ ,\ 23\ ,\ 26\ ,\ 30\ ,\ 42\ ,\ 48\ ,\ 50] \quad (23)$$

which is [26, 30]. Interpolation within the values is then used, hence the output is:

$$y = bin_{start} + bin_{span} * (x - probability_{start}) / probability_{span} \quad (24)$$

$$y = 26 + (30-26)(0.8-0.75)/(0.9-0.75)$$

$$y = 26 + 4(0.05)/(0.15) = 27.333 \quad (25)$$

Note bin sizes are arbitrary. The method allows rapid conversion of a random number to a probability profiled pick and, importantly, is repeatable (necessary when rerunning simulations). FPB uses this method to convert NTS driver behaviour probabilities to model UK driver habits. The model follows the probabilities reported by real-life surveys.

4.13 Pseudocode for Key Algorithms

Table 4-12: Adjust battery C rating due to temperature

When is this used and why?

During system startup. Lithium-ion battery capacity C reduces as temperature drops; this code de-rates EV nominal battery C using data taken from **(FleetCarma, 2018 Chevrolet Volt: Electric Range vs Temperature average values curve)**

pseudocode

- determine C scaling factor

  with advised temperature lookup table of C factors vs battery temperature (default is ambient °C)

  apply scaling factor to all EVs C rating for the entire simulation

.

Table 4-13: Per PD Step 1: Assess headroom remaining after residential loads

When is this used and why?

This is performed per feeder phase to find headroom kW.

pseudocode

- determine phase kW limit:

  target phase kW = hi_limit kW x present DR/FFR ratio

- find load on each feeder phase:

  for each phase:

    zero running total phase kW

    for each house:

      fetch period load from table of household load profiles

      increment running total phase kW by found load

    adjust total phase kW by applying any multiplier for this phase for this pd

    adjust total phase kW by adding any bias kW for pd

    phase headroom = target phase kW - total phase kW

.

Table 4-14: Per PD Step 2: Assess all EV needs (presently connected EVs only)

When is this used and why?

This discovers the intent of each EV, being present time and SOC vs EVs tranches

pseudocode

- determine EV options (must charge, charge if spare headroom, dispatch, idle; EV priority rank):

  update EV SOC using known EV delta_SOC_per_pd

  determine EV tranche position (present time and SOC) => region .1, .2 or .3

  for that region, discover a set of stances i.e. call nominated code for that region

  calculate priority rank = (kWh deficit to departure) / (time remaining)

.

Table 4-15: Per PD Step 3: Allocate charging and Trial Balance the Feeder

When is this used and why?

This distributes phase headroom kW to EVs and finds a "balanced" phase load total

pseudocode

- context: known feeder, phase and target kW limit
- per phase: find a trial distribution of phase headroom kW to EVs

  (process mandatory chargers)

  determine if V2G can offer support to this phase:

    if so revise headroom kW up by c. 60% of total available V2G kW

  for each mandatory stance EV in rank order:

    if headroom negative and clamping active: apply clamp to EV

    else: set EV to charge and adjust phase headroom kW

  # now process opportunistic chargers in either 1 or 2 passes

  (charging pass 1) if headroom is positive:

    for each opportunistic stance EV in rank order:

      if headroom > 0: set EV to half-charge and adjust phase headroom kW

  (charging pass 2) if headroom remains positive after pass 1:

    for each opportunistic stance EV in rank order:

      if headroom > 0: set EV to standard charge, adjust phase headroom kW

.

Table 4-15 ctd.Per PD Step 3: Allocate charging and Trial Balance the Feeder
continuation following charging pass 2 complete *# now process discretionary dispatchers* while phase load > original target kW limit: in order of soonest departure: set EV to dispatch and adjust phase load kW ● compare phase loads to see if meet criteria for balancing: rank phases in load ascending order if top-loaded phase is between feeder lo_limit and target limit kW apply balancing: new phase target kW = max (lo limit kW, load of 2nd most loaded phase)   for the most loaded phase, reallocate EVs to meet new target kW *(we now have a EV charging / dispatching solution for each phase, but not actioned)*

.

Table 4-16: Per PD Step 4: Advise EV models what they are doing
When is this used and why? This applies the discovered EV loadings and states to the EV model
pseudocode ● identify changed EV kW and advise EV for each EV: if new activity differs from old activity: advise EV model of new socket kW   determine EV new delta_SOC_per_pd and update EV instance data   update activity token for EV timeline log   accumulate EV load to the phase load total kW

.

Table 4-17: Per PD Step 5: Logs and Running Totals

When is this used and why?

This records the implemented actions to various logs and updates running statistics

The rolling load limit is: (transformer nameplate rating) ^2 x 240 (periods in a day).

pseudocode

- perform logging:

  send changed EV states to EV output log

  cache phase load kW in running peak loads log

  send feeder loads and sources of loads to the Feeder output log

  age-off the thermal load 240 periods (1 day) ago from the transformer thermal buffer, calculate and add present period load. Calculate transformer heating

- if transformer heating over rolling load limit:

  flag and log

  if transformer clamping active: assert transformer clamp (de-rates hi_limit)

.

Table 4-18: OpenDSS

Why and When is this used?

When mandated by calling routine (OFF, ON, or only if overload detected)

Note: OpenDSS is configured to express loads as fixed kW.

- for every network location (i.e. a house) determine point loads:

  create real load = sum (residential load, EV load)

  create reactive load for lagging pf 0.98 from residential load

  send kW and kVA for location to OpenDSS

- instruct OpenDSS to solve load flow

- recover results and solve pass/fail flag

  if solve failed retry up to 100 times

  if all retries fail issue OpenDSS solve fail warning to logs and exit

  if solve successful:

  convert results into polar (magnitude, angle) format

  calculate whole LV system loss from losses seen in each part

  cache all data (currents, losses, voltages) to ODSS logs

Table 4-19: Auto-Scheduled events
Why and When is this used? Housekeeping tasks
pseudocode ● on the hour: send “Parked EVs Report” to EV output ● at midnight: flush all logs and output buffers to disk (reduces disk thrashing) ● at end of Schedule: summarise statistics and write stats summaries to output

.

Table 4-20: Other Scheduled events
When is this used? Schedule informs FPB: Event X with parameters [….] has happened
pseudocode ● parse event: (see FPB Manual for list of legal events) process appropriate event code copy the occurrence of the event to logs stating any new flag values

.

Table 4-21: Tranche Modes
When is this used? These are assigned to the three tranche regions re battery State of Charge: 0% => SOC_A, SOC_A => SOC_B, SOC_B => 100% so to define EV intent
pseudocode mode_0: # no_duty / away mode_1: # idle (EV system load only; battery SOC is static) mode_10: # mandatory slo charge (EV attempts to force 3.6 kW charging) mode_11: # mandatory std charge (EV attempts to force 7.2 kW charging) mode_12: # mandatory max charge WITH Auto Step Down (7 => 3 kW) mode_13: # mandatory max charge NO Auto Step Down (Dumb EVs) mode_18: # mandatory Agg Signal as +/- factor of std charge mode_20: # opp.slo charge (if sufficient phase headroom, 3.6 kW charging) mode_21: # opp.std charge (if sufficient phase headroom, 7.2 kW charging) mode_30: # 'discretionary-support' dispatch at standard rate if phase > hi_limit mode_31: # 'discretionary-support' dispatch at standard rate if phase > lo_limit mode_32: # max dispatch support mode_35: # 'disc-supp-opp-charge' dispatch to hi-load phases OR charge mode_36: # 'disc-supp-opp-charge' dispatch to any hi-load phases OR charge mode_37: # dispatch at max rate to > hi-load phase, charge not hi

4.14 The Validity of Simulation Results

FPB results are similar to My Electric Avenue, however known errors understate load. Therefore FPB results may be seen as <u>broadly indicative, tending perhaps optimistic</u>. FPB operation and results has not been directly verified against real-world trials and, without knowledge of a specific LV system, existing LV loads and future EV characteristics, FPB results can only be deemed indicative.

The simulator is well placed to assess operation with option X, so allowing alternative X’ to be compared. This will tend to remove bias.

Sources of error (from simplifications, described in Pragmatic Simplifications 4.6.7) notwithstanding, the greatest uncertainties concern characteristics of future EVs. FPB EVs are projections of 2014 - 2017 Nissan and Tesla vehicle characteristics. The author is also concerned about the thermal effects model and would like more contemporary vehicle data, and a review of program implementation.

A trap for the unwary when applying FPB to the real-world is: The impact of network topology, simplified in FPB. Real-world topology can exhibit less N EV capability than FPB due to FPB not considering long, branching, tapering networks. End-point voltages may become inadequate. Simulation of arbitrary (built) designs need further work.

4.15 Chapter Summary

This section has presented:

- simulator major software components,
- the major capabilities,
- the internal operational concepts of FPB,
- the degrees of freedom and
- the outputs of the system.

The next chapter considers to what ends the developed simulator should be used.

this page deliberately left blank

Chapter 5: Methodology

The prior chapter has described the construction of a functional EV on LV simulator. This chapter describes the application of the simulator i.e. to describe the scenarios the simulator is to investigate, and how it is used to do so.

5.1 Statistical Basis of Methodology

The method used is a broad quantitative approach. However the problem (hence, system) includes unfamiliar control and feedback loops so is not known to be linear. There is no knowledge if the system will produce results on a normal distribution, exhibit skewing, some other shape or experience catastrophic or radical changes.

The approach is problem domain exploration by statistical saturation i.e. many runs are performed to identify emergent effects. Note that the complexity of the problem is not clear; charging timings per phase have 1680 * 2^33 combinations. Other loads, departure prioritisations and contributing events such as V2G discharge make it unclear as how to further determine complexity. There are many degrees of freedom which, as they follow heuristics, actively switch in and out. What sample size is then meaningful? There is no clear answer. What is known is that, with c. 1 million feeders, many trials occur simultaneously in the real-world.

The author decided to perform as many simulations as reasonable, arbitrarily estimated as 500 simulations per situation. Variation within the 500 is of trip timings only.

Trip-timings are generated by a Monte Carlo method: random picks from probability-profiles defined by UK National Travel Data and UK MOT data (detailed in 5.2), i.e. the frequency distribution of synthesised trips follows the profile of observed UK trips. The python pseudorandom generator is the Mersenne Twister, which is adequate and repeatable. All trips generated are possible, therefore legal.

The impact of trip timings were assessed by a profiling run of 3,000 random simulations per mpd, with no control. Results were ranked to find trips causing greatest discomfort i.e. severity and frequency of network overload. The most awkward 500 were selected.

There is no certainty these are the most difficult timings; however these do provoke network load problems.

Later meta-analyses uses the simple means of the 500 results. This is perhaps naive; at this stage there is no basis for preferring one assessment route over another. Certainly, electrical systems see means - but factors causing discomfort to drivers (severe undercharging i.e. EV cannot return home) perhaps should be assessed by looking at (say) the 98th percentiles of an area of contention, rather than means.

Spot-checks of result distributions appear plausible with mostly normal distributions seen, some skew distributions and occasional placement into repeating quantised values e.g. charging loads. Checks viewed all result fields; however coverage was limited i.e. not performed for each ply across all simulations. See distribution analyser included with Seq_6.1.2 spreadsheets.

Note each simulation also logs a histogram of high and consecutive peak loads.

5.1.1 Limits to Confidence

Standard error or confidence intervals are often used to indicate relevance of statistical outcomes based on a sample of a population i.e. to show standardised bounds of result.

However the calculation of such a value for FPB can only relate to the last step in a long chain of assessments, i.e. does not bound possible variability of code or input data, which admittedly includes many projections.

For example, the assessment of a parameter: Count of mandatory clamps for the 27mpd, 100 EV ply of a situation vs. a simulation which varied residential load timing only, so “should” be similar: For a 95% confidence on Seq_6.2.2 (of 27mpd with 100 EVs):

- Mean value is 366.31 and n = 500
- Standard error calculated over 500 simulations as 2.227
- t for 95% confidence interval with n = 500: t = 1.9647
- confidence limits (95%) is t x std. error = 4.38 => **362 .. 371**.

Seq_6.2.2.4 is identical other than the residential loads. These are adjusted to have the same throughput energy; only the <u>timing</u> of domestic appliance use varies. The clamp count for the 27mpd by 100 EV ply is: **458**, some 41 standard errors away.

The author contends that confidence limits, in this context, have no meaning. Indeed they offer false confidence by suggesting "the population of results is expected to relate to these bounds". That is not rigorous; such limit marks are therefore omitted.

An alternative is to mark result plots with 100% error bands (which the author has seen).

5.2 Data Sourcing and Preparation

EV data mimics car data which is sourced as follows:

- span of vehicle mpd from RAC Foundation **(RAC, Le Vine, & Polak, 2009)**
- trips as probabilities from JRC Mobility Survey **(Pasaoglu et al., 2012)**, Figs. 3.2, 3.3
- distances travelled as from UK National Travel Survey (NTS, data generated on request) **(HM Government, 2018b)**. Preprocessing is by forming synthetic datasets based on probabilities of:
    - departure time and driven distance
    - return time
- proportion of vehicles "always staying at home" from MOT data (by assessing a count of vehicles driving under 500 miles pa **(DfT, 2017)**). These are included as when connected, they are electrically active
- EV general characteristics improvised from SMMT data **(SMMT, 2018)**
- residential load data is from SSE's New Thames Valley Vision project **(SSEPD & NTVV, 2015)**. This is converted to 6-minute data sets by interpolating randomised values and scaled so the net half-hourly energy in the synthetic data matches the source data; see also Residential Data Sourcing and Preparation,
- PV insolation data is from **(Solar Sheffield, 2018)**.

5.3 Concerning Networks

5.3.1 Network Types: Weak, Typical, Strong

The "Weak, Typical and Strong" designations are for convenience. Other than in this work, these do not describe UK installed networks, which have varied over the last century. Built asset strength data is held by the ENA and EATL, but not available to the author.

Network types are defined as: **Weak: 1.2 kW** design ADMD per house, **Typical: 1.5 kW** and **Strong: 2 kW** per house, each having appropriate transformer and cable ratings.

On occasion other ratings may be used (these are indicated).

5.3.2 Transformers and Distribution Rating

Transformers are made in standard sizes. However, the installed transformer's kVA rating may be under-sized by c. 25 - 30%. This is a common policy to save cost (as transformers can cope with brief overloads) but means sustained throughput capability is below design ADMD. The practice is termed "distribution rating" and is connected to load duty cycles; overheated transformers can cool overnight when they have little or no load.

Transformers are designed for 25 - 40 year life. In practice, many remain serviceable when 60 years old. Most assets are likely viable for decades; there is expectation of piecemeal replacement.

5.3.3 Clamps

The purpose of clamps is to constrain "dumb" EVs which otherwise charge unrepentantly. Again, this term is the author's and means the forced disconnection of the EV from supply via a DNO controlled switch. The switch is in the EVSE, which isolates the EV on command. The method was pioneered in the MEA project **(EA Technology & Roberts, 2016)** and used in EN **(Electric Nation, 2017)**. Such capability is mandated in the UK Automated and Electric Vehicles Act 2018 **(HM Government, 2018)** Section 15 paras 1 and 2, operable by a "prescribed person", to be present in Smart home chargers.

The primary use of clamps is to enforce a load limit, the "hi_limit". A second motive is the "transformer clamp". The same disconnection mechanism is used, only the purpose changes. The need for a transformer clamp arises due to the practice of fitting under-rated substation transformers. The transformer clamp is used to ensure total transformer heating does not exceed the limit implied by transformer nameplate rating. If exceeded, the transformer is cooled by load clamping to avoid damage.

Clamps can only be applied to controlled elements e.g. EVs, not residential loads.

Note optimising systems like MCS, maximising throughput (for 100% asset utilisation) can and will overload distribution-rated transformers. See also Clamping Mode - Transformer Limit Clamp section 4.5.13.2.

5.4 Residential Loads and Feeder Plots

Unless otherwise stated, simulations use a standard residential load dataset, shown in the feeder plot (Figure 5-1) below. All .pdf images may be zoomed-in on.

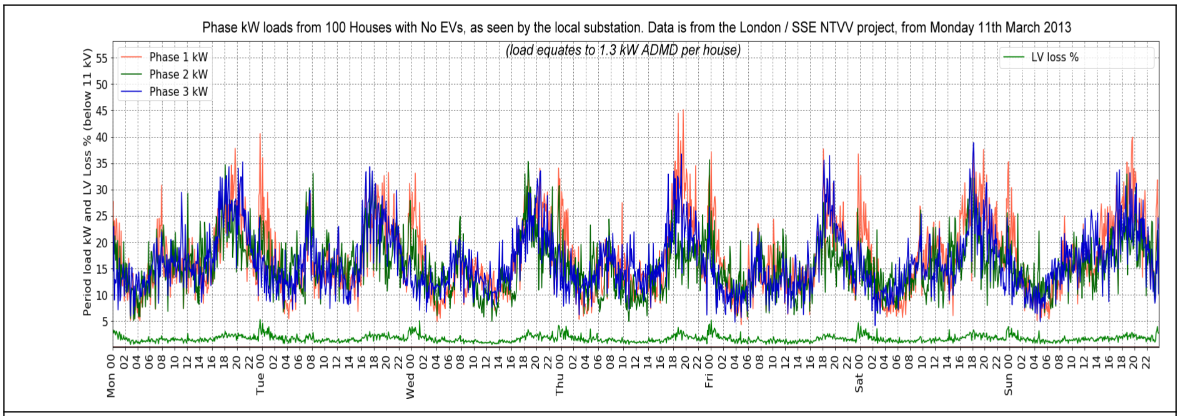


Figure 5-1: A residential load dataset for 100 houses as a feeder load plot

Several datasets are available and selected via the scenario “misc_setup_info.txt” file (the “house_prefix:” parameter). Load data is sourced from the NTVV project as half-hourly household kWh energy consumption. Data for the coldest week of the winter of 2013 (from Monday 11th March 2013) is used, which is pre-processed (see section 4.8.4.1) by a pseudo-random “jitter” into 1/5ths, so:

- output data retains the same half-hourly energy,
- errors from “averaging-away peaks” are reduced **(Urquhart & Thomson, 2015)**
- the data is more plausible i.e. as seen in practice / more “life-like”

giving 10 data points per hour. This base load has been assessed at 1.5 kW ADMD, which may be scaled as needed. The standard scaling gives 1.3 kW; this compensates for the introduction (from c. 2016) of LED lighting, lowering per-room consumption from c. 60 W to c. 8 W. About 6% of homes in the sample use night storage heaters.

The plot shows residential load per phase, as seen by the feeder as it joins the substation busbars. The x-axis is time over a week, with 2-hour period ticks. The y-axis is kW of load or loss %. **Note** that peak residential load (Thursday, c. 19:00) exceeds the standard hi_limit for the Weak network. Such spot peaks are not unknown.

5.4.1 Sample FPB Output Feeder Plot

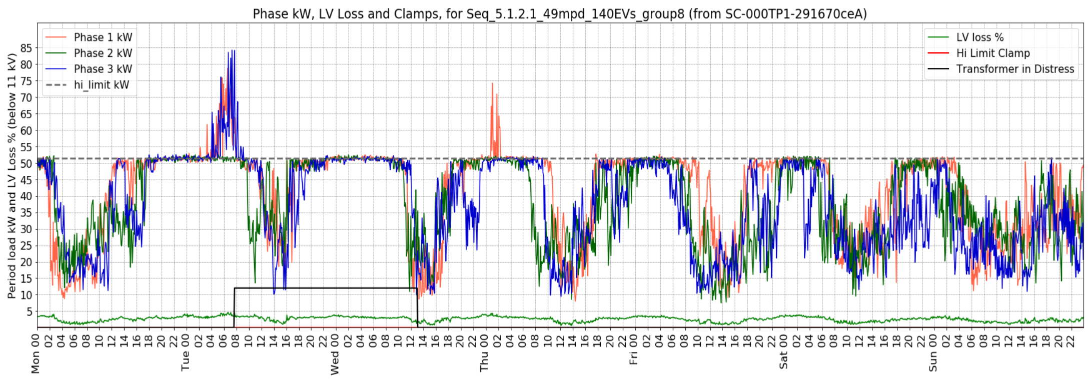


Figure 5-2: Feeder load plot: EVs exceed limits, transformer distress signal

The sample (Figure 5-2) shows phase load (blue, light-red and green) supplied from the substation. Each phase load is the sum of 34, 33 and 33 individual house loads.

Here, the FPB MCS system is striving to limit total load to the hi_limit, yet certain EVs force the issue and ignore MCS instructions, causing overloads.

5.4.1.1 Losses Line

The loss % line (in green, near axis) is from OpenDSS output. This includes losses from all electrical components below 11 kV i.e. substation transformer, feeder and service cable losses. On rare occasions (during OpenDSS solve fails) the loss figure may be calculated at nonsensical values; the loss line is then shown broken and made zero if implausible.

The transformer is modelled as a low-loss Amorphous core type. UK legislation requires all new-fit transformers from 2021 to be of a low-loss type **(Rietveld, Houtzager, & Zhao, 2015)** and **(European Parliament, 2014)**. This is presently not true to life; for decades yet old, non-low-loss units will remain in operation.

5.4.1.2 Other Lines: Hi_Limit line and Clamp lines

The hi_limit (kW set point for the FPB control system) is shown in Figure 5-3 as a broken line. Clamp actions are also shown, as cherry-red and solid black lines at the bottom of the plot. The FPB support two clamp protocols:

- hi_limit clamps (cherry-red) and
- requests for transformer protection (solid-black, see Figure 5-2 during Tuesday).

Both are controlled by MCS.

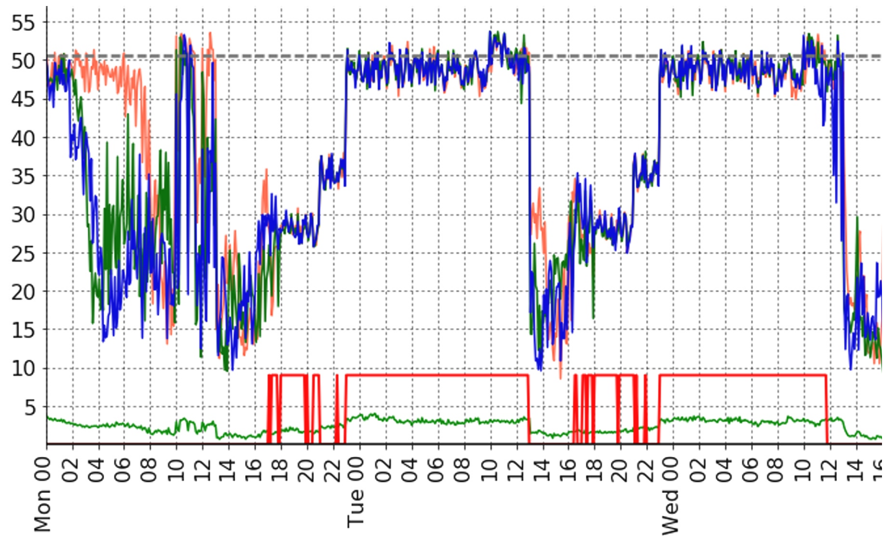


Figure 5-3: Examples of hi_limit clamp with hi_limit modulation

The hi_limit (broken grey) and clamp lines. hi_limit clamp firings are cherry-red.

Figure 5-2 shows transformer distress detection (black line at axis), but no action results for clamping is not turned on. Figure 5-3 has no transformer distress flag, as the load-profile allows transformer the to cool. Clamping is seen aiding DR and FFR by hi_limit modulation (a daily signal), to manage chaotic residential and arbitrary EV charging loads. The deep drop is evening Demand Reduction, and the repetitive notching due to following a Frequency Response command. See also “DR_SunshineSignal” in Section 4.10.2.

5.4.2 Broaching Assessment

Broaching is the author’s term for exceeding asset limits. The intent is to detect excessive cable or transformer loads. Two rules are used:

- kW feeder phase load instantaneously at or over 1.4 x cable rating, or
- transformer load exceeds 1.5 x rating, for 18 minutes or more.

These are upper bounds to emergency asset ratings; exceeding these are “broaches”. Such factors are investigated in **(CLNR & Wang, 2014)** and **(Gao, 2016)**, who finds transformer internal 11 kV to 230 V insulation can fail for sustained operation at x1.5 duty.

5.5 Introduction to Simulation Sequences

Simulation runs are grouped as “Sequences” (Figure 5-4, Figure 5-5); each a variant on a common scenario as defined in .csv files.

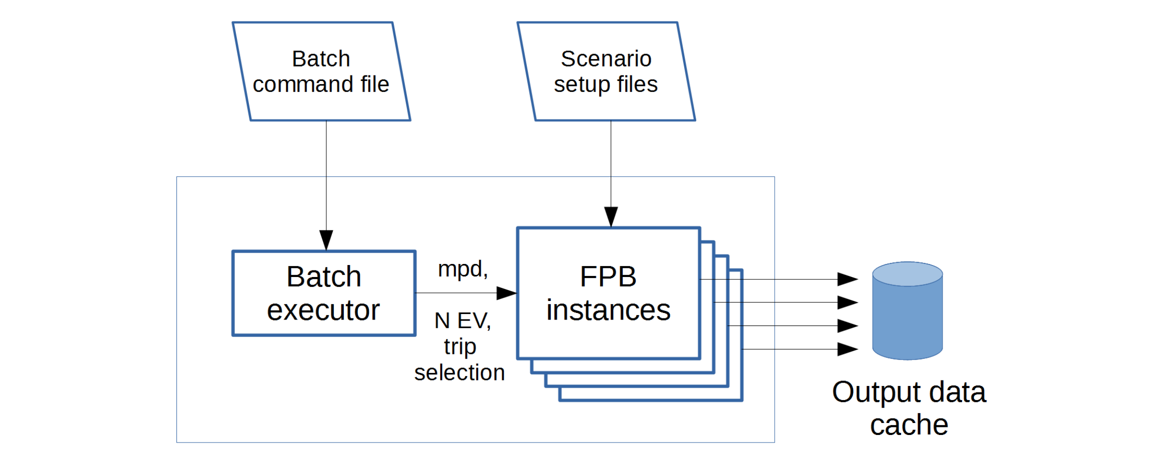


Figure 5-4: Configuring the FPB to run a Sequence

Sequences explore the use of EVs as cars, so trial various population densities and driven distances. This is expressed as 4 mpd bands and 8 N EV bands, giving 32 plies. Any one ply has a selected average “miles per day” (mpd) driven distance and number of EVs per 100 houses studied. Each ply cell contains 500 simulation runs, varying the driving duties only. This allows a statistically significant number of trials for each situation, representing a possible EV density for a feeder, with vehicle use exhibiting the driven miles per day.

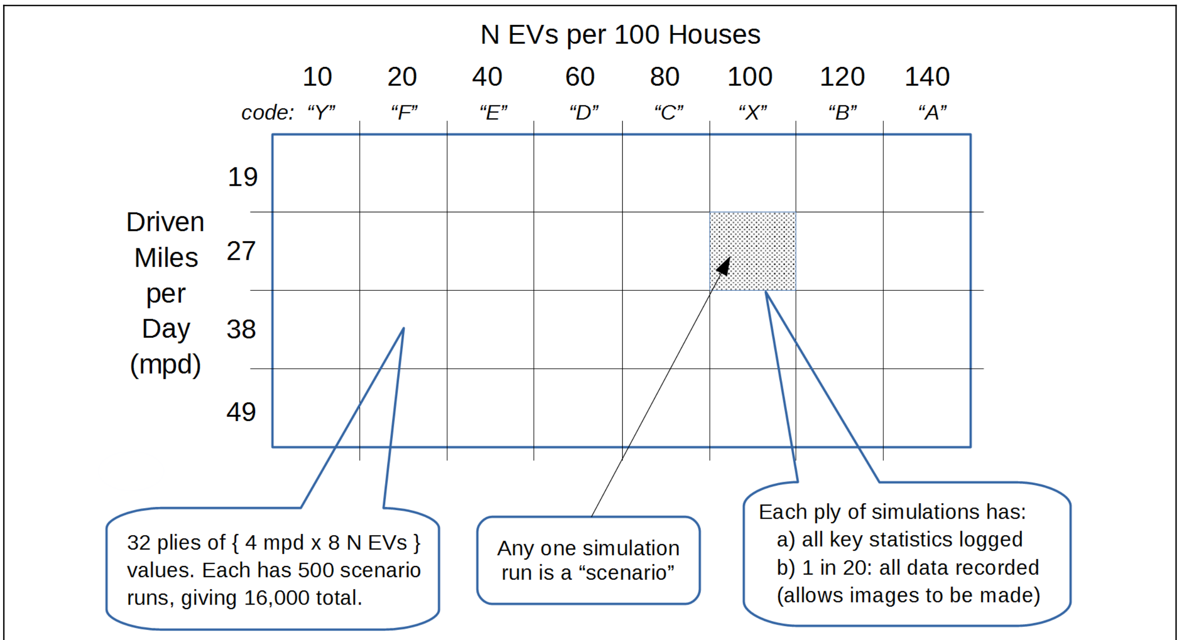


Figure 5-5: A Sequence of 16,000 simulated weeks, each varying the scenario

A complete sequence consists of 32 sets of 500 co-themed simulations i.e. 16,000 individual simulation runs based on a common scenario. The FPB can be fed batched instructions, defining the number of EVs and trips to use in the simulation. The batch is controlled by a command file (a .csv text file); see section 4.4.2.

5.5.1 Overview of Sequence Execution

Sequence intent is determined and the simulator configured:

- the core scenario is defined by amending items of interest as necessary,
- an output data space for results is prepared
- the simulation is run, with the first output checked for plausible operation
    - simulations continue to run until 16,000 complete, taking c. 16 hours;
- output data is collated and zipped into an identified package.

If the output from this process appears valid and has addressed the intent correctly, the run is promoted to be a valid sequence and is forwarded to post-processing.

5.6 Sequences Investigated

Sequences explore the affect of changing a factor, implying a comparison is needed to quantify impact. Most use the Typical network and take (with post run tasks) 2 - 3 days. These are identified as **Seq_** followed by **g. v. n [.x]** (e.g. Seq_2.1.2), meaning:

> **g:** set number, **v:** variant investigated, **n:** network (1:Weak, 2:Typical, 3:Strong)
>
> **x:** (optional sub-variant).

Note: the purpose and configuration of individual sequences is in results Volumes 2 - 4.

5.6.1 Overview of Sequence Sets

Some 7 themed sets of sequences are investigated, each a related group which progress from “no control” to “maximum feasible ICT control” i.e. from basic function to a possible practical system. The Sequences Sets cover:

- **Sequence Set 0**: Residential Loads Only,
- **Sequence Set 1**: Uncontrolled EVs (5 sequences) - Table 5-1:
    - These are detailed explore having no management system i.e. today's networks.
- **Sequence Set 2**: Peak Load Clamped EVs (11 sequences) - Table 5-2:

    - a load setpoint is defined; operating beyond this causes EVs clamping. Clamps reduce charging opportunities so may impact the driver.
- **Sequence Set 3**: Clamped EVs with V2G (2 sequences) - Table 5-3:
    - investigate clamping with V2G charge injection
    - attempt to defer clamps by supplying EVs with pre-stored power; clamps however remain in use.
- **Sequence Set 4**: Remote Aggregator Control (3 sequences) - Table 5-4:
    - Aggregators may assert control over various EVs. Does this impact the local situation; can this substitute for local management?
- **Sequence Set 5**: Managed Charging (no clamps, 11 sequences) - Table 5-5:
    - local ICT working with broadly co-operative EVs strives to minimise network stress without clamps.
- **Sequence Set 6**: Managed Charging (with clamps) - Table 5-6:
    - 24 sequences with MCS and clamping
    - a possible system for deployment in the real-world. As clamps are in use, the DNO LV system is assured to not be under great duress
    - assess: EV undercharging
- **Sequence Set 7**: Special Situations - Table 5-7:
    - for brevity only 7.1.2.1 will be explored. Power Fail with delayed comms recovery has an unexpected outcome.

5.6.1.1 Sequence Set 1: No Control Mechanisms

Table 5-1: Sequence Set 1: No Control Mechanisms

Sequence ID	Purpose
Seq_1.1.1	Baseline: Dumb EVs on the Weak network
Seq_1.1.2	Baseline: Dumb EVs on the Typical network
Seq_1.1.2.1	Dumb EVs on the Typical network **without** residential loads
Seq_1.1.2.2	Baseline: Dumb EVs on the Typical network **In Summer**
Seq_1.1.2.6	*Exploratory sequence used to determine impact of removing BLPs*
Seq_1.1.3	Baseline: Dumb EVs on the Strong network

Note several exploratory sequences exist, but are not detailed. Seq_1.1.2.6 for example assesses removing BLPs, and performed 250 trials per cell (not 500) to speed assessment.

5.6.1.2 Sequence Set 2: Clamp Only Control

Table 5-2: Sequence Set 2: Clamp Only Control

Sequence ID	Purpose
Seq_2.1.2	Dumb EVs plus clamps (similar MEA). Expected to limit overloads. Compare to Seq_1.1.2. Includes DR/FFR signal
Seq_2.1.2.8	As 2.1.2 using an alternative tripset (to detect if differences arise)
Seq_2.1.2.9	As 2.1.2 but no DR/FFR signal
Seq_2.2.2	As Seq_2.1.2 with simplified EV charging priority (mimics MEA closely) but expected to exacerbate EVs undercharging. Compare to Seq_2.1.2
Seq_2.3.2	As 2.1.2.9 but EV drivers always plugin on arriving home
Seq_2.3.2.1	Similar 2.1.2. No V2G EVs, 9 Static Batteries (static V2G), MCS control
Seq_2.3.2.2	Similar 2.1.2. No V2G EVs, 9 Static Batteries (static V2G) with MCS plus remote aggregators
Seq_2.3.2.9	As 2.3.2 but no DR/FFR
Seq_2.4.2	As 2.2.2 with simplified EV charging priority and home perfect plugins
Seq_2.5.2	As 2.1.2.9 with home and away perfect plugins
Seq_2.6.2	As 2.2.2 with home and away perfect plugins

5.6.1.3 Sequence Set 3: Clamps with V2G

Table 5-3: Sequence Set 3: Clamps with V2G

Sequence ID	Purpose
Seq_3.1.2	Clamps plus V2G support; every 4th EV is V2G
Seq_3.2.2	Clamps plus V2G support; 2 periods (12 mins total) per hour of forced V2G, via “blind” aggregator control

5.6.1.4 Sequence Set 4: Remote Aggregator Control

Table 5-4: Sequence Set 4: Remote Aggregator Control

Sequence ID	Purpose
Seq_4.1.2	Aggregation management for Demand Reduction (DR) by imposing timed charging limits. Compare to Seq_3.1.2
Seq_4.2.2	As 4.1.2 with Clamps. Compare to Seq_3.1.2 and Seq_4.1.2
Seq_4.3.2	As 4.2.2 with every 4th EV as V2G under aggregator control. Compare to Seq_3.1.2 and Seq_4.2.2

5.6.1.5 Sequence Set 5: Managed Charging System (no clamps)

Table 5-5: Sequence Set 5: Managed Charging System (no clamps)

Sequence ID	Purpose
Seq_5.1.1	Use FPB's Managed Charging System (MCS). SV1G and V2G vehicles are controlled. Compare to Seq_1.1.1
Seq_5.1.2	Attempt FPB's Managed Charging System (MCS). SV1G and V2G vehicles are controlled. Compare to Seq_1.1.2
Seq_5.1.2.1	As 5.1.2 but residential loads drop 300 W per house (load ADMD = 1 kW). Compare to Seq_5.1.2
Seq_5.1.2.2	As 5.1.2 but residential loads up 300 W per house (load ADMD = 1.6 kW).
Seq_5.1.3	As 5.1.2 but on the Strong network (design ADMD = 2, from 1.5 kW)
Seq_5.2.2	(otherwise as 5.1.2) Attempt a DR/FFR control signal modulating the MCS hi_limit. Compare to Seq_5.1.2
Seq_5.3.2	(otherwise as 5.1.2) Attempt Aggregation management for Demand Reduction (DR) by timed charging limits over all EVs. Quantify by comparing with Seq_5.1.2, 5.2.2
Seq_5.4.2	As 5.2.2 plus extra 9 Static Batteries
Seq_5.5.2	As 5.2.2 plus extra 9 Static Batteries and alternative DR/FFR signal
Seq_5.6.2	As 5.1.2 but V2G EVs replaced by SV1G types (cannot dispatch)
Seq_5.7.2	FPB MCS plus Aggregation management for Demand Reduction (DR) by timed control of 1 in 4 EVs only. Compare to Seq_5.2.2 and Seq_5.3.2

5.6.1.6 Sequence Set 6: Managed Charging System (with clamps)

Table 5-6: Sequence Set 6: Managed Charging System (with clamps)

Sequence ID	Purpose
Seq_6.1.2	(as 5.1.2) with Clamps active. What is the impact of clamps? Compare to

Sequence ID	Purpose
	Seq_5.1.2
Seq_6.1.3	Standard EV mix, DR/FFR, clamps
Seq_6.1.3.1	Standard EV mix, DR/FFR, clamps and 20 houses have Heat Pumps
Seq_6.2.2	(as 5.2.2) with clamps active and DRFFR control signal. Compare to Seq_5.1.2, 6.1.2
Seq_6.2.2.1	(as 6.2.2) V2G supports overloads, not EV charging
Seq_6.2.2.2	(as 6.2.2) with 9 Static Batteries giving local support
Seq_6.2.2.3	(as 6.2.2) trails “BurnSave” intended to limit EV V2G battery duty / costs
Seq_6.2.2.4	(as 6.2.2) with alternative Winter week of residential loads
Seq_6.2.2.5	(as 6.2.2) trial impact of EV battery heaters
Seq_6.2.2.9	(as 6.2.2) adds EV battery heaters and +10% EV “visitors”
Seq_6.3.2	(as 5.3.2) with clamps. Compare to Seq_5.3.2, 6.2.2
Seq_6.3.2.1	(as 6.3.2) set in Summer (ambient = 18°C, Summer residential loads).
Seq_6.3.2.2	(as 6.3.2) set in Summer (ambient = 18°C, Summer residential loads) but no V2G EVs.
Seq_6.3.2.3	(as 6.3.2) set in Summer (ambient = 18°C, Summer residential loads) with FFR only, no DR signal
Seq_6.3.2.4	(as 6.3.2.3) with Agg control applying DR / ToU control
Seq_6.4.2	(as 6.2.2) with Agg attempting ToU control of 1 in 4 EVs
Seq_6.5.2	Withdrawn; (as 5.3.2) with Clamps and a revised (“hybrid”) control strategy. Is this control method more effective? Compare to Seq_6.4.2.
Seq_6.6.2	Withdrawn; (as 5.7.2 i.e. 1 in 4 EVs Aggregator controlled) with Clamps and a “hybrid” control strategy. Does the control method remain effective with a reduced number of controlled EVs? Compare to Seq_6.5.2.
Seq_6.7.2	(as 6.2.2) with without FFR element of DRFFR signal.
Seq_6.8.2	(as 6.1.2) with a static lowered hi_limit (40 kW). Expectation: losses reduced but EVs may go hungry. Compare to Seq_6.1.2.
Seq_6.9.2	Withdrawn as misconfigured. Rerun as 6.9.2.2
Seq_6.9.2.1	Further lowered hi_limit, alternative DR/FFR signal. Pre-Burn V2G OFF
Seq_6.9.2.2	As 6.9.2.1 Pre-Burn V2G mode ON
Seq_6.10.2	As 6.9.2.1 but V2G removed
Seq_6.11.2	As 6.9.2.1, 9 Static Batteries, alternative DR/FFR, hi_limit made 24 kW
Seq_6.12.2	As 6.11.2 with hi_limit made 32 kW

Sequence ID	Purpose
Seq_6.13.2	As 6.11.2 with Winter PV panels, hi_limit 39 kW

5.6.1.7 Set 7: Special Situations

Note all of these have been run, but other than Seq_7.1.2, 7.1.2.1 and 7.2.2.1 are not included in the thesis for the sake of brevity.

Table 5-7: Set 7: Special Situations

Sequence ID	Purpose
Seq_7.1.2	(as 6.1.2) with “Comms Fail” by converting all EVs to dumb for 3 days
Seq_7.1.2.1	(as 6.1.2) Power Fail with Comms Fail; on recovery radically lifting hi_limit for 1hr to mimic delayed comms recovery
Seq_7.2.2.1	“Power Fail 1” with no Clamps, no V2G but DR/FFR modulation of hi_limit. Aggregation commands active. Expectation: system overloads?
Seq_7.2.2.2	“Power Fail 2” (as 7.2.2.1) with Clamps operating. Aggregation commands active. Objective: explore impacts: overloads reduced? Compare to Seq_2.1.2 and Seq_7.2.2.1
Seq_7.2.2.3	“Power Fail 3” (as 7.2.2.1) with Clamps and V2G operating. Expectation: overloads reduced? Compare to Seq_2.1.2 and Seq_7.2.2.1
Seq_7.3.2	“Bias 40” inject a fixed 40 Wh per pd (= 400 W continuous) bias **on phase 1 only**. Otherwise as Seq_6.2.2.
Seq_7.3.2.1	“Bias 40” inject a fixed 40 Wh per pd (= 400 W continuous) bias **on all phases**. Otherwise as Seq_6.2.2.
Seq_7.4.2	“Bias 80” inject a fixed 80 Wh per pd (= 800 W continuous) bias **on phase 1 only**. Otherwise as Seq_6.2.2.
Seq_7.8.2	“Res loads Up” - household demand upscaled to 1.6 kW per home from 1.3 kW. Otherwise as Seq_6.2.2. Objective: explore what happens as household loads increase
Seq_7.9.2	“Res loads Down” - household demand made 1 kW per home from 1.3 kW. Otherwise as Seq_6.2.2. Objective: explore what happens as household loads drop
Seq_7.10.2	“Summer View” - household dataset from Summer 2013; ADMD made 1.1 kW per home. Negative load profile injected to mimic 2 kW PV panels per house (UK PV dataset used). Otherwise as Seq_6.2.2. Objective: DNOs cannot assess their networks in Winter. So, what does a Summer view of the Winter situation look like?
Seq_7.11.2	“Some Heat Pumps” - with Winter residential loads, the Bias system is used to

Sequence ID	Purpose
	inject mock HP preheat and daily top-up heating loads, for 1 in 5 i.e. 20 houses only. Accompanying auxiliary heat loads are mimicked by increasing ADMD to 1.8 kW per home. Objective: Inspect "UK 2040" situation in which HP begins to displace gas for home central heating.
Seq_7.11.2.1	"Less Heat Pumps" - with Winter residential loads, the DR system is used to inject mock HP preheat and daily top-up heating loads, for 12 houses only. Accompanying auxiliary heat loads are mimicked by increasing ADMD to 1.6 kW per home. Objective: Inspect possible "UK 2040" situation in which HP begins to displace gas for home central heating.
Seq_7.11.3	"Some Heat Pumps - on Strong" - a repeat of 7.11.2 but on the Strong network (design ADMD = 2 kW from 1.5 kW)
Seq_7.13.2	"Home Perfect Plugins" - as 6.2.2 where people always plug-in their EVs on returning home. Away from Home plugins remain pseudo-randomised. Inspect impact of peoples habits. Compare to Seq_6.2.2
Seq_7.14.2	"All Opportunity Perfect Plugins" - a version of 7.13.2 in which Away from Home charging also has 100% plugins. Inspect impact of peoples habits. Compare to Seq_6.2.2 and Seq_7.13.2
Seq_7.15.4	NPG new build home rating with EVs using design ADMD of 3.7 kW; Local MCS, Std. EV mix, DRB/FFR, C2CT clamps, 20 HP. Will there be broaches?

5.7 Running a Simulation Sequence

To run a sequence, the operator needs to:

- define a purpose or key characteristic to perform, for these sequences
- construct a scenario to include:
  - required EV characteristics
  - required LV electrical situation including any DR/FFR signal
  - required household load situations (including any bias or phase scaling)
- form a Batch Runner script which defines:
  - the scenario to use
  - the number of EVs to use
  - state flags for any systems e.g. Clamps on / off
  - any timed events e.g. Aggregator signals
  - the frequency of running OpenDSS

    - set reporting management options (clearing data areas, result zip flags etc.)
    - a list of the trip variants to run (list of EV trips with randomisation seed)
- write / edit a python invocation script which calls the Batch Runner N times, which defines a range of number of EVs to employ in the simulations; also sets the start tripset to run from (allows a reruns from a known point if PC crashes etc).
- (by hand, in MSDOS console) Start the synchronisation system “synch_watcher.py” - this interleaves access to common file areas to stop lock and conflict issues
- (by hand, in MSDOS console) Start N instances of the invocation script, adding a code specifying the number of EVs to employ

On successful completion, a set of data exists which has:

- summaries of all output (EV states, Feeder loads etc)
- logging all runs but retaining detailed datasets for OpenDSS runs (1 in 20)
- the logs cite input / setup conditions as well as results.

A quality check is made. If the run is acceptable, it is promoted as a Sequence.

5.8 Analysis / Post Processing

This is an automated process which transposes data from N EV to mpd themed sets, extracts items for later processing and creates the feeder and EV CICD plot images (Figure 5-6) from the OpenDSS runs (500/20 = 25 “groups” per ply). Intermediate data is then compiled into spreadsheets. For a description of plots, see Appendix D.

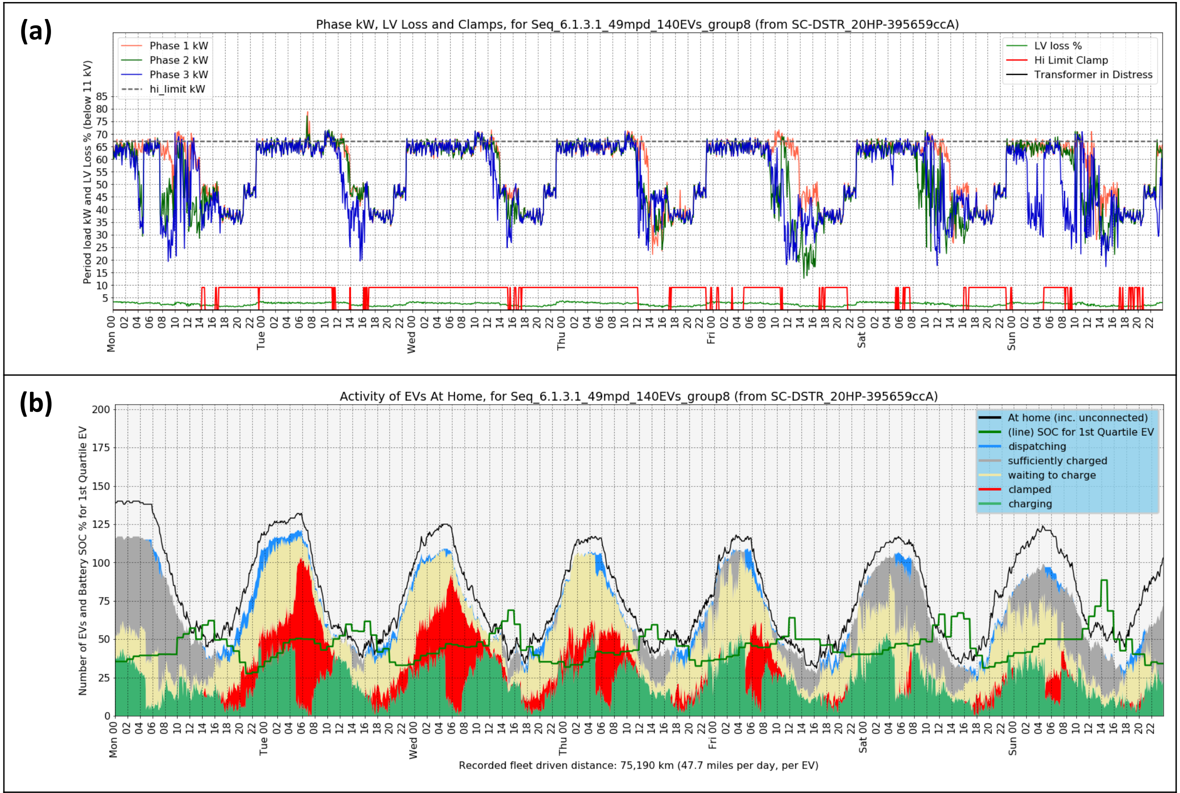


Figure 5-6: Example of auto-generated Feeder and EV CICD plots

The purpose of post-processing is to gain meaning from the data, i.e.:

- understandings of what is happening in specific instances,
- specific aspects (e.g. number of overloads) can be quantified and
- to generate an overview of the entire simulation exercise, so that a synthesis of understanding to be formulated.

The author wrote all tools used. Pearson's r is from numpy, a standard python library.

5.8.1 Post-Processing Workflow

Figure 5-7 and Figure 5-8 below show the post-processing scheme for a sequence. These proceed through several mostly automated stages. Figure 5-7 gives the overview sans plotting; Figure 5-8 shows the points at which plotting occurs. Plotting is mostly by python / matplotlib; on occasion a hand-generated plot (via LibreOffice or Excel) will be constructed. The meta-meta spreadsheets are very informative and show the progression of the parameter of interest as EV duties (mpd x N EV) rise.

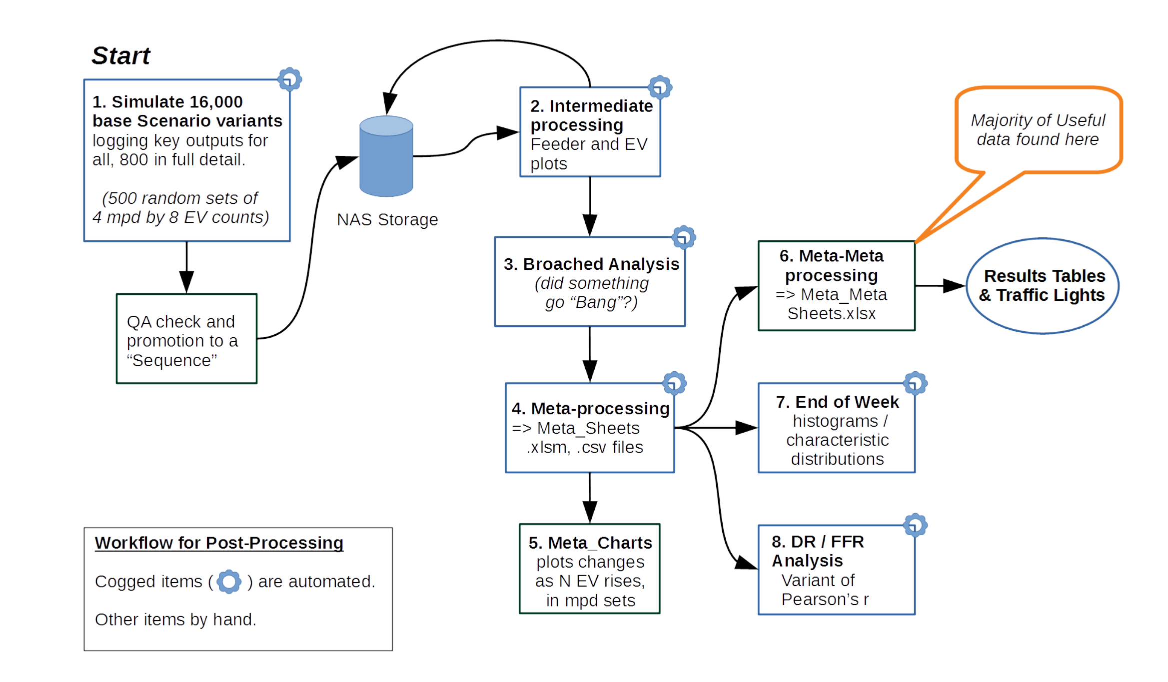


Figure 5-7: Post-processing workflow

The workflow is:

- Intermediate processing stage (stage 2 in Figure 5-7)
    - raw log file data is collated into "by mpd" groups. Each group has a run of N EVs, relating what is experienced as N increases.
    - The intermediate processing routines generate plots for the Feeder and EV: Arrive / Depart, Rolling Fleet kWh totals and the CICD plot (see Figure 5-6 samples)
    - intermediate output is saved in an identified, versioned zip file e.g. *Seq_4.2.2_inter5.zip* and archived.
- the zip is archived then unpacked on a post-processing PC,
- the PC performs a Broached Analysis (stage 3 in Figure 5-7):
    - substations have asset-protection fuses. Whether these logically blow is assessed from per-pd load data, in logfiles. Two criteria are used:

      a) cable overloads (any peak >= 1.4 x cable rating) and

      b) transformer overloads of 1.5 x transformer rating for >= 18 minutes;
    - assessment is performed per simulation run and summed into mpd groups, plied by N EVs (thus "40 EVs driving an average of 27 mpd on this network caused no overloads, whereas under the same circumstances 60 EVs driving 27 mpd caused 12 overloads")

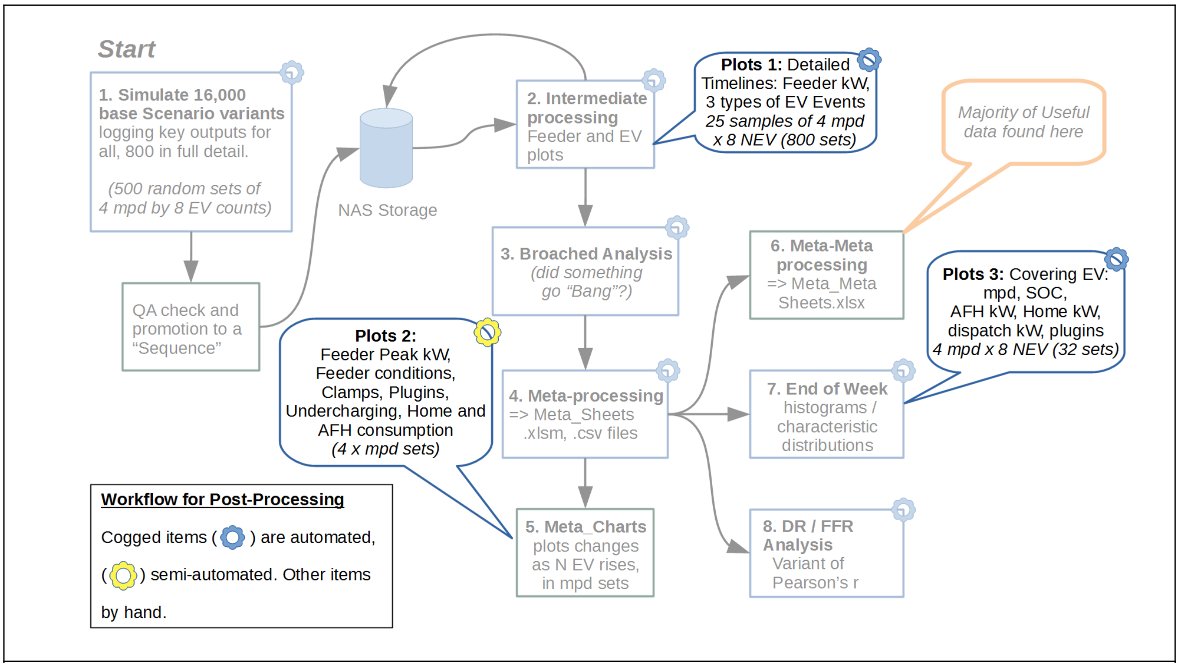


Figure 5-8: Post-processing workflow showing generation of image plots

- ◦ <u>the acceptable count of broaching events is zero</u>.

- Meta-Processing (stage 4 in Figure 5-7):
  - N EV ply groups are summed into a single multi-sheet .xlsm spreadsheet, one per mpd group (automated using python's openpyxl library)
  - a summary page in each spreadsheet is populated by averages of N EV sheets values, forming an overview of the ply for that simulation situation
  - data is now in 4 "per mpd" spreadsheets (Meta_19.xlsm ... Meta_49.xlsm), as detail sheets plus a top-level collation onto a single sheet.
  - End of Week stats and plot generation:

    a) EV data from simulation logs is analysed to form histograms, again split into mpd and N EV groups. These are used to form distribution plots for each group:

    b) EV charging (at home)

    c) EV weekly Away from Home charging

    d) EV weekly V2G dispatch (at home)

    e) EV recorded mileage driven per day

    f) EV Home plugins

    g) EV end-of-week battery SOC %.

- Meta-Charts (stage 5 in Figure 5-7):

  - the top-level collation sheet from the Meta_mpd.xlsm is copied and pasted into another spreadsheet, designed to plot charts, showing how that situation / network is affected by increasing N as EV population rises;
- MetaMeta Spreadsheet (stage 6 in Figure 5-7):
  - top-level sheets for each Meta_mpd.xlsm are copied and pasted to one spreadsheet, forming an overview of the entire simulation.
- quantification of DRFFR response:
  - a list of deltas between each period FFR control signal vs. the prior signal is made, and a second list of deltas of average value of period ply load vs. the prior period load. The two lists are then correlated using Pearson's r method (see 5.8.3). Plausible correlations are counted to form a ply cell % response;
  - this is inserted into the MetaMeta sheet by hand.

The MetaMeta spreadsheet (stage 6) has most useful output, described below.

5.8.2 Generation of Meta Spreadsheets

A python program populates "Meta" spreadsheets with intermediate data. There is a Meta spreadsheet for every mpd; for that distance the spreadsheet holds results sheets for each value of N EV (10, 20, 40 … 140, Figure 5-9) each with 500 rows of results data. Including headings, sheets are 86 columns wide i.e. contain approximately 80 data points from each simulation run e.g. averaged headroom kW, fleet km driven etc. Samples of spreadsheets are in the Data Repository e.g.

4. Final Analysis Output (All sequences)\Meta_Seq_1.1.2.zip\Meta_Seq_1.1.2\

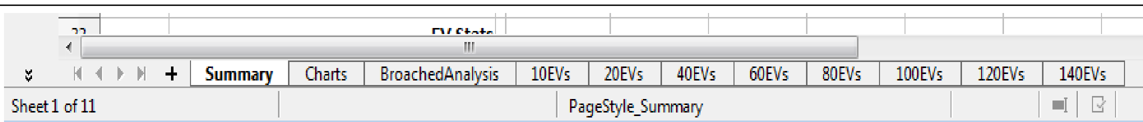


Figure 5-9: Sheets in a Meta_mpd .xls, showing Summary and N EV tabs

Data from the 500 rows are averaged per column on the N EV sheet, and the averages collated into a Summary sheet with the values arrayed per N EV thus (to save width, only N EV of 10 … 60 not 10 … 140 are shown, in Figure 5-10 and Figure 5-11):

27 mpd Seq_1.1.2 using (S_83) NEV_DumbTypical

Trial various numbers of Evs on the Dumb Typical network using the 500 top

In the Week under study, with

N_EVs =	10	20	40	60
hi_lim kW	51.33	51.33	51.33	51.33
Max 98% kW	39.09	42.37	49.16	57.07
Peak kW	60.15	63.26	76.32	90.33
Seq_1.1.2 Sum Broaches for 27 mpd	0	0	2	53
av phase mean_headroom_kW	19.79	19.07	17.69	16.37
av mean_OOB	0.21	0.22	0.23	0.23
weekly av network free / unused kWh	16,980	16,157	14,533	12,912
weekly av network throughput kWh	8,904	9,727	11,351	12,972
av net_losses %	1.10	1.20	1.30	1.55
weekly network loss kWh	97.95	116.72	147.56	201.33
weekly estimated V2G loss kWh	0.00	0.00	0.00	0.00
weekly net system loss inc V2G kWh	97.95	116.72	147.56	201.33
net loss % including V2G losses	1.10	1.20	1.30	1.55
weekly av n events over hl_limit	0.21	0.79	7.86	34.81
est. % feeders over cable rating	0%	0%	0%	0%
max weekly n kW > 1.3 * cable rating	0	0	0	0
est. n_hrs per week undervolts	0.00	0.00	0.00	0.00
est. n_hrs per week overvolts	0.00	0.00	0.00	0.00
av Mand clamps in week	0.00	0.00	0.00	0.00
av Txf_clamps in week	0.00	0.00	0.00	0.00
av Txf_stress in week	0.00	0.00	0.00	0.00

Figure 5-10: Meta sheet for Seq_1.1.2: Meta_27mpd EV stats (part 1 of 2)

These values are cell averages. e.g. weekly av network free / unused kWh for 10 EVs, 16,980 kWh, is the average from 500 simulated weeks.

N_EVs =	10	20	40	60
EV Stats				
av fleet km	3,010	6,237	12,315	18,526
av EV_av_km	300.96	311.83	307.86	308.77
av EV mpd	26.71	27.68	27.33	27.41
av max_plugins	21.41	21.91	22.42	22.65
av av_plugins	16.51	15.49	14.77	14.55
av home_chg_kWh	478	1,000	2,035	3,072
per EV av home kWh	47.8	50.0	50.9	51.2
av AFH_chg_kWh	69	161	311	483
per EV av AFH kWh	6.9	8.1	7.8	8.1
n V2G EVs	0	0	0	0
av home_disp_kWh	0.00	0.00	0.00	0.00
Home Charge %	87.34%	86.13%	86.73%	86.41%
av kWh disp per V2G EV	0.00	0.00	0.00	0.00
estimated V2G losses kWh	0.00	0.00	0.00	0.00
av n EV_undercharged	18.02	37.69	74.37	111.26
90th %tile undercharges	27	52	94	134
av undercharges per EV	1.80	1.88	1.86	1.85
av n EV_must_rechg_to_finish_trip	0.00	0.01	0.03	0.06
av EOW_fleet_holds_kWh	132.3	273.5	557.8	831.8
av EOW_fleet_AFH_kWh	69.2	161.0	311.2	483.1
av EOW_fleet_home_kWh	477.5	1,000.2	2,034.9	3,071.9
av EOW_fleet_disp_kWh	0.00	0.00	0.00	0.00

Figure 5-11: Meta sheet for Seq_1.1.2: Meta_27mpd EV stats (part 2 of 2)

The Meta Summary sheets are now merged into a "MetaMeta" spreadsheet, Figure 5-12. This presents results as a ply-grid, showing parameter progression with:

- number of EVs present
- distances these EVs travel.

For example, Figure 5-12 shows the "Feeder Stats" rows of MetaMeta2.3_Seq_1.1.2.xlsm sheet "CompareMetas". This compares (i.e. overviews) results from all 16,000 simulations in the sequence. **Note** that broach counts (the number of simulations seen to exceed cable or transformer limits) are not averaged, so run from 0 to a maximum of the simulations count per ply (normally 500). Counting halts as soon as a broach is detected i.e. regardless of how many fails a simulation experiences, this is 1 failed week.

	A	B	C	D	E	F	G	H
1								
2		**Meta-Meta Summary**	**Seq_1.1.2 using (S_83) NEV_DumbTypical**					
3								
4		**Feeder Stats ONE**	**N EV**	**10**	**20**	**40**	**60**	**80**
5								
6		hi_lim kW		51.33	51.33	51.33	51.33	51.33
7								
8	19mpd	**Seq_1.1.2 Sum Broaches**	19mpd	**0**	**0**	**0**	**11**	**60**
9	27mpd		27mpd	**0**	**0**	**2**	**53**	**203**
10	38mpd		38mpd	**0**	**0**	**7**	**125**	**357**
11	49mpd		49mpd	**0**	**0**	**10**	**188**	**383**
12								
13	19mpd	**Max 98% kW**	19mpd	39.02	41.28	46.39	52.05	57.57
14	27mpd		27mpd	39.09	42.37	49.16	57.07	62.65
15	38mpd		38mpd	39.42	43.62	52.66	60.91	68.59
16	49mpd		49mpd	40.38	44.35	53.44	62.08	71.59
17			**N EV**	**10**	**20**	**40**	**60**	**80**
18	19mpd	**Peak kW**	19mpd	59.46	68.27	74.11	80.27	89.65
19	27mpd		27mpd	60.15	63.26	76.32	90.33	96.08
20	38mpd		38mpd	61.79	66.87	77.70	96.47	104.90
21	49mpd		49mpd	61.75	71.89	88.48	96.15	112.32
22								
23	19mpd	**av phase mean_headroom_kW**	19mpd	19.92	19.30	18.14	17.02	15.93
24	27mpd		27mpd	19.79	19.07	17.69	16.37	15.13
25	38mpd		38mpd	19.70	18.91	17.33	15.85	14.44
26	49mpd		49mpd	19.63	18.76	17.05	15.47	13.99
27								
28	19mpd	**av mean_OOB**	19mpd	0.21	0.22	0.22	0.22	0.22
29	27mpd		27mpd	0.21	0.22	0.23	0.23	0.23
30	38mpd		38mpd	0.22	0.23	0.24	0.23	0.23

19mpd | 27mpd | 38mpd | 49mpd | **Compare Metas**

Figure 5-12: MetaMeta2.3_Seq_1.1.2 CompareMetas

A sample table of values (each value is an average of 500 simulation runs):

Table 5-8: Sample of parameters gathered per Sequence Ply Cell

N EV	**10**	**20**	**40**	**60**	**80**	**100**	**120**	**140**
19mpd	2,098	4,334	8,689	13,029	17,548	22,092	26,447	30,787
27mpd	3,010	6,237	12,315	18,526	24,904	30,988	37,161	43,054
38mpd	4,169	8,387	17,199	25,951	34,382	43,259	51,673	60,434
49mpd	5,910	11,347	22,343	33,182	43,991	54,964	66,160	77,227

Seq_6.1.2 Weekly Average fleet driven distances in km

The author has found colouring the “parity case” (1 EV per house, driving 27mpd UK average distance) forms a useful visual reference.

The results in MetaMeta sheet CompareMetas are shown in Table 5-9:

Table 5-9: Meta-Meta Chart: Parameters Gathered per Sequence Ply Cell

Row:	Table of:	mpd x N EV Cells contain:
8	Sequence Sum Broaches	N plies having broaches (500 max)
13	Max 98% kW	98th percentile of max kW in 500 sims
18	Peak kW	peak kW seen in 500 simulations
23	av phase mean_headroom_kW	average over 500 sims of mean headroom
28	av mean_OOB	average of 3-phase Out of Balance
33	weekly av network free / unused kWh	average unused kWh
38	weekly av network throughput kWh	average used kWh
43	av net_losses %	average losses as %
48	weekly network loss kWh	average losses as kWh
53	weekly estimated V2G loss kWh	average V2G loss kWh
58	weekly net system loss inc V2G kWh	average all losses kWh
63	net loss % including V2G losses	average all losses as %
68	weekly av n events over hI_limit	average N over hi_limit
73	est. % feeders over cable rating	average % feeders > rating
78	est. n_hrs per week undervolts	average N hrs undervolts
83	est. n_hrs per week overvolts	average N hrs overvolts
88	av Mand clamps in week	average N overload phase clamps
93	av Txf_clamps in week	average N transformer cooling clamps
99	av fleet km	average distance fleet drives
104	av EV_av_km	average distance drives per EV
109	av EV mpd	average mpd per EV
114	av max_plugins	average highest home plugins
119	av av_plugins	average home plugins
124	av home_chg_kWh	average kWh taken @ home
129	per EV av home kWh	(as above per EV)
134	av AFH_chg_kWh	average kWh taken @ Away from Home e.g. public or work chargepoints
139	per EV av AFH kWh	(as above per EV)
144	n V2G EVs	count of observed V2G EVs present
149	av home_disp_kWh	average V2G dispatch @ home

Table 5-9: Meta-Meta Chart: Parameters Gathered per Sequence Ply Cell

154	Home Charge %	percent of home vs total charging
159	av n EV_undercharged	average count of EVs departing with SOC < (target - 5%)
164	90th %tile undercharges	90th percentile of weekly count of EVs departing undercharged over 500 sims
169	av undercharges per EV	(row 159) / N EV
174	av undercharged on disconnect	(row 159) counting only EVs connected
179	av n EV_must_rechg_to_finish_trip	average severely undercharged
184	av EOW_fleet_AFH_kWh	average kWh taken AFH
189	av EOW_fleet_home_kWh	average kWh taken @ home
194	Weekly kWh consumed per EV	average per EV kWh use
199	av EOW_fleet_holds_kWh	average end of week fleet total kWh
204	Av in week “Disconnect & Depart”	average weekly home chg events
209	N AFH charges in week †	average weekly AFH chg events
214	AFH kWh charged in week	average kWh taken AFH
219	kWh per AFH charging †	(row 214) / (row 209)
224	N AFH charges per EV in week	(row 209) / N EV
230	DR % effective hrs in week	See 5.8.3
236	AFH kWh charged per EV in week	(row 214) / N EV
242	Severe Undercharges per EV in Week	(row 179) / N EV
248	V2G per EV	(row 149) / (row 144)

† assumes 1 AFH charge occurred per trip.

Note EVs are animated through varied trip driven distances (some zero, some far) as per probabilities from UK NTS data. Fleet driven distances may vary from goal slightly.

5.8.3 DR/FFR Assessment (PEH)

Demand Response / Fast Frequency Response is assessed in a 2-part process by python programs. These take intermediate data and extract per-pd net and EV load levels, which is then compared to the DR/FFR command signal. The first step is to break the data into whole population, distance and N EV bands by time period. **Note** that as the same week of DR/FFR commands is simulated in several sequences, it is possible to combine these (period to period) to get a view of the response of a region with diverse EV populations.

The next step forms a metric based on Pearson's r, a metric of correlation, here the correlation between changes in command signal vs. resulting electrical load changes.

This is performed using bands of 10 periods (an hour), each of which is the average experience of 500 simulations of EVs. The ratio of periods N to N-1 is produced for both:

a) the DR/FFR signal and
b) the average output load kW.

These are (a) the input, and (b) response which Pearson's r can measure a correlation. However when EVs are away from home, correlation is taken as zero (as there is nothing controllable) - but the net response over a week is needed, hence there is another step.

Every hour with $r > 0.3$ is counted (implying there is a response to some degree). The percentage of this value vs. the hours in the week is found, giving a measure of DR/FFR response over the week: "Percent Effective Hours" (the PEH metric). The measure is arbitrary and only useful for comparisons within this work, for it relates proportional temporal coverage, not degree of response from cause to effect. **Note** that more or less response can be gained by co-opting more or less EVs, however the utility of that effort is being measured. For example, when does a 10% command response become a 50% response, and how does that very with situation? In practice, response would want to be predicted in (say) 1/4 hr availability slots throughout the day.

5.8.4 System Verification

Data to formally verify the simulator are not available. However the action of each input to output can be checked and issues arising explored; FPB was verified by desk-checking in that manner. It was found possible to compare results with My Electric Avenue results; see 4.11.2.

5.9 Chapter Summary

This chapter presented the intended use of the FPB simulator: to perform saturated testing. Figure 5-13 below indicates the broad volume of simulations performed, arising due to the degrees of freedom spread and the statistical saturation approach.

FPB Performed Simulation Statistics	Minimum	Maximum	Average or Total	
Per Simulation				
Number of EVs modelled per 100 houses	10	140	71	
Average number of trips an EV makes in a week			17	
Mileage range of EVs, per day	0	290	33	
Number of EV SOC assessments per week	500	7,000	3,563	*estimated*
Number of discrete events modelled per week	2,524	13,496	7,694	
Per Sequence				
Number of Simulations (of a week) in a Sequence			32,000	*inc. data conditioning run*
Number of discrete events modelled per Sequence			246,192,000	
In Whole Works				
Number of sequences performed which completed			126	
Number of sequences promoted to thesis			82	
Number of individually modelled EV trips across all attempted simulations			4,941,216,000	4.94E+09
Number of discrete events modelled, across all simulations			31,020,192,000	3.10E+10
Number of adjustments made to results			256	*for V2G EVs mimicking Static Batteries: So they are not counted as EVs*
General				
Number of PCs running at once	1	4		
hours simulating			2,016	
hours simulating (including development)			2,416	*estimated*

Figure 5-13: FPB Performed Simulation Statistics

The next chapter reviews simulation results.

this page deliberately left blank

Chapter 6: Results

6.1 Introduction

This chapter presents notable results and findings for each simulation sequence. The following chapters discuss these findings to form conclusions.

Analysis of results cover c. 400 pages; for brevity the analyses are outside the thesis in Volumes 2 - 4 of the data repository (see Figure 6-2 Folder 2. Vols 2 - 4 Results Analyses).

Sequences are grouped into themed Sets as shown in Table 6-1 below. Sequence Set 7 data is available, but not written up.

Table 6-1: Sequence Set Analysis: Results and Findings hotlinks

Set	Re	Text Body	Findings in Précis	Analysis Volume
Seq Set 0	plain residential loads, no EVs	6.2		Vol 2
Seq Set 1	all Dumb EVs on networks (no control)	6.3	Table 6-27	Vol 2
Seq Set 2	Dumb EVs controlled by clamps (charge point disconnectors)	6.4	Table 6-28	Vol 2
Seq Set 3	Dumb EVs with clamps plus local V2G support	6.5	Table 6-29	Vol 3
Seq Set 4	Dumb EVs with Aggregator control (Time of Use services)	6.6	Table 6-30	Vol 3
Seq Set 5	MCS controlling mixes of Smart EVs, no clamps	6.7	Table 6-31	Vol 3
Seq Set 6	MCS controlling mixes of Smart EVs, with clamps	6.8	Table 6-32	Vol 4
Seq Set 7	*(part only: Special Situations, Unbalance, Losses Mitigation, Power / Comms Failures)*	*6.10*	*Table 6-35*	--

Given the purpose of the thesis, what aspects are of interest? Effects or conditions which disrupt network operation, which interfere with use of EVs as cars and anything surprising (i.e. unclear causation).

Assessing results concerning the network:

- broaches (overloads) cannot exceed 0,
- losses must be acceptable i.e. < 5% delivered energy, whole LV system.

Assessing results re the utility of the EV as a car:

- are EVs undercharged when leaving home (can the driver get home), and
- have factors which modify the cost of ownership been optimised?

Finally, there is an Added Value Services/Aggregator view:

- does the method usefully perform DR / FFR services,
- is EV use as a car impeded?
- the PEH command/response coverage metric is assessed on occasion.

6.1.1 Review of Sequence Structure

There are 16,000 simulations per Sequence, structured as in Figure 6-1. Each Sequence has 32 cells of 500 simulated weeks. The scenario investigated is common to all cells, which vary one to another by N EV and distance travelled. Within each cell randomised trips are taken; the random trip picks being profiled to match UK NTS travel survey findings and the fleet target mpd. Each EV travels individual trips.

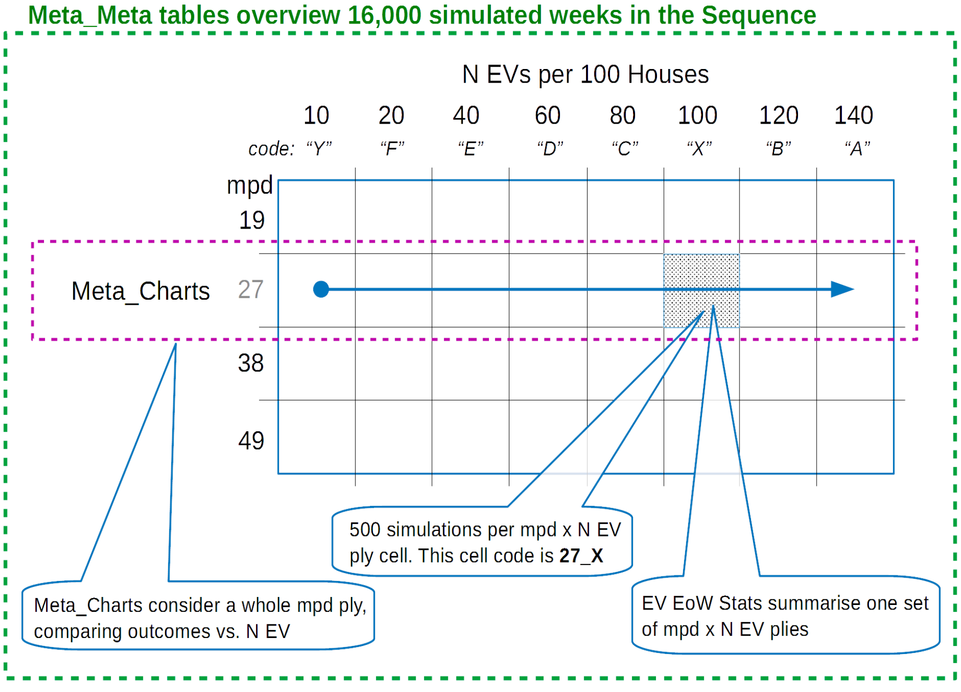


Figure 6-1: Sequences Overview and Relation to Meta Charts

Sequence have an identifier code, being 3 or 4 number groups with the prefix "Seq_", for example Seq_2.1.2.8. The number code meanings in Seq_S1.C2.N3.v4 are:.

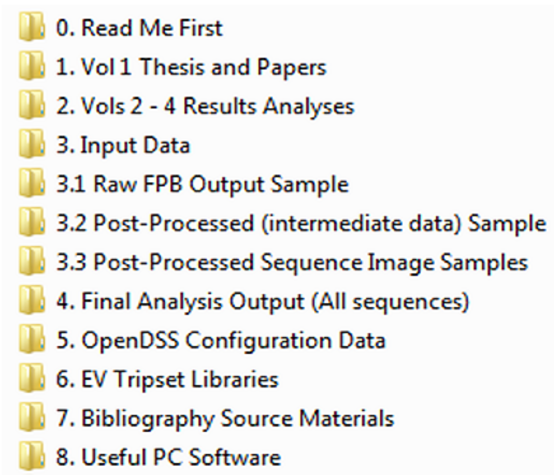
Table 6-2: Sequence Code Numbering

S1	Sequence **Set number** for a theme e.g. Seq_0: Residential Loads (no EVs)
C2	**Scenario Code** (arbitrary, often ascending)
N3	**Network ADMD Strength** (1: Weak 1.2 kW, 2: Typical 1.5 kW, 3: Strong 2 kW, 4: NPG 3.7 kW, 5: Strong Plus 2.5 kW, 6: Strong Xtra Plus 3 kW)
v4	optional variant of an existing scenario; numbers are arbitrary

thus Seq_2.1.2.8 means: Set 2, scenario 1, network type 2, variant code 8. Results are held in meta and meta-meta charts, identified by Sequence ID.

6.1.2 Accessing Results in the Data Repository

The USB memory and online repository Figure 6-2 includes all major items and results:



https://doi.org/10.5258/SOTON/D0716 - Once Final Version Published

Figure 6-2: Overview of results folders (on 16GB USB stick)

6.1.3 Locating Results

Results are available in raw, post-processed (intermediate data form) and final forms:

Simulation Logs: in **Folder 3.2** as intermediate data zips Seq_N.N.N.n_inter5.zips e.g.

Seq_1.1.2_inter5.zip which contain:

Results for OpenDSS Runs: cells results (e.g. 19_A) in Seq_N.N.N.n_inter5.zips for example: Seq_1.1.2_inter5.zip\Seq_1.1.2\BatchResults_ODSS_only\19_A\<N: 1..25>

EV_output.csv EV activity (event log)

EV_Timeline.csv	EV activity (falling timeline)
Feeder_load_output.csv	Network loads, sources of load, V2G etc.

SC-DUMBTPl-117708cGA-FPB_local_log.txt

- Run-time simulator log: setup, warnings, notes on activity, stats

stats1-histo.txt	Stats1: histogram of peak kW seen
stats2-OOB-Headroom.txt	Stats2: out of balance and headroom seen

Image Plots (Feeder and EV image files): zipped in **Folder 3.3** e.g.

Seq_1.1.2\Feeder_images\Pfdr_Seq_1.1.2_19mpd_10EVs_group1.png

Seq_1.1.2\EV_images\P_ArrDep_Seq_1.1.2_19mpd_10EVs_group1.png

Top Level (final) analyses are in **MetaMeta spreadsheets:** Meta_Seq zips e.g.

MetaMeta2.3_Seq_1.1.2.xlsx **(Folder 4)**

Other data is large and is held by the author, available on request.

Note a sample PEH metric dataset is included in the zipfile for Seq_6.2.2.1, Folder 4.

6.1.4 Use of BLPs and OpenDSS

Unless otherwise stated, simulations use mid-century EVs with BLPs. OpenDSS is run every 20th simulation to find electrical currents, losses and point voltages. Commands to OpenDSS are logged. These may be sent to an arbitrary other network:

- the network to use the same element names on the same phase; topology and electricals may be different
- replaying OpenDSS commands will give the effect of EVs on the altered network.

6.1.5 Data Logging

OpenDSS runs have all results data, but summary logs only are retained for others. Summary logging is however comprehensive and captures headline network events, energy use, EV states etc. See Post-Processing Workflow section 5.8.1 for details.

6.1.6 Method of Analysis

The method is presented in Chapter 5. An analysis suite generates holistic views as one spreadsheet per Sequence, so giving a single-sheet view of tracked parameters. Interpretations compare between these overview sheets to see situational variation.

6.2 Sequence Set 0: Residential Load Profiles

These are sourced from SSE's NTVV residential load monitoring project, starting with Figure 6-3 the Standard Winter Week - the coldest week of 2013 (from 11th March 2013):

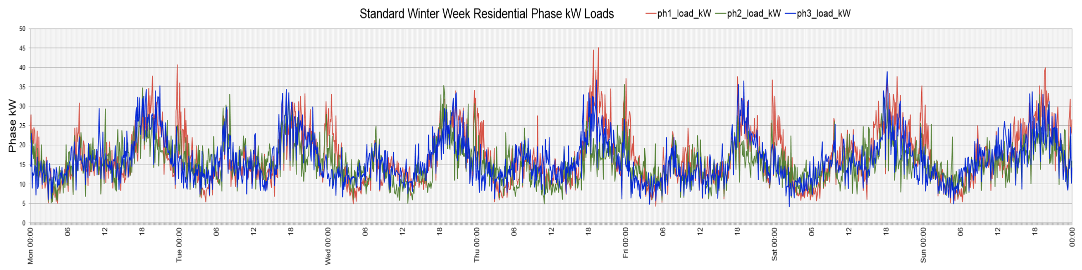


Figure 6-3: The "Standard Winter Week" Residential Loads (2013 coldest week)

Sum of loads for 100 houses (NTVV project, Bracknell). Week used was coldest

The Alt_Winter is the following week (Monday 18th March 2013), Figure 6-4

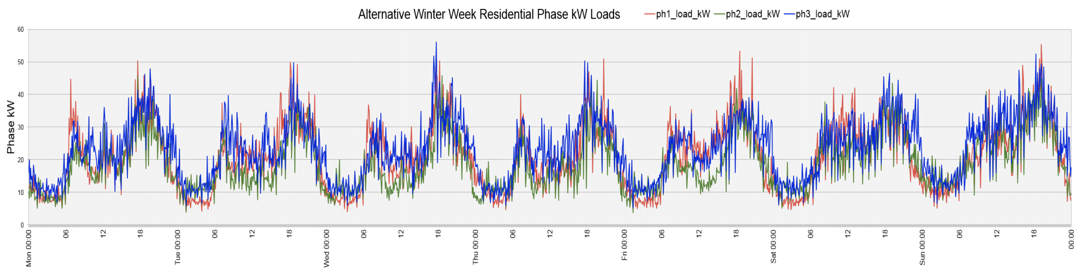


Figure 6-4: The "Alternative Winter Week" Residential Loads

By eye, the alternative week is more demanding load-wise. The author has not been through every week looking for "the worst / most severe"; it was thought that lowest temperature would cause this. How representative then is the standard Winter week? That is unknown. **Note** .pdf images are high-resolution and are zoomable.

The Summer load (Figure 6-5) is for hottest week of 2013 (Monday 15th July 2013):

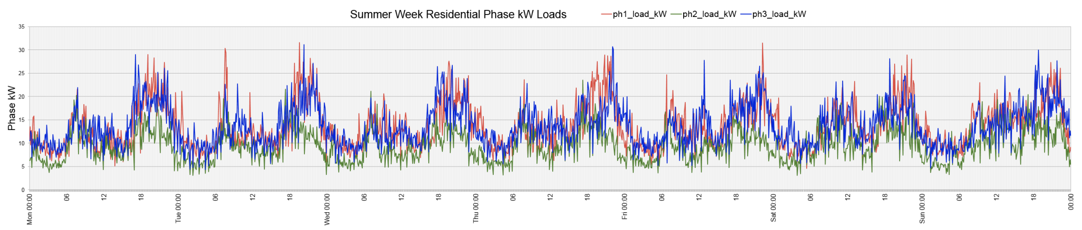


Figure 6-5: The "Summer Week" Residential Loads (2013 hottest week)

***Note** kW scale change: this is 0-35 kW vs. 0-60 kW above. It is unlikely AC was in use*

Data is per individual house from Bracknell, England and has been interpolated so to form 10 data points per hour from half-hourly data, yet retains the 1/2 hr kWh of the originals.

6.3 Sequence Set 1: Uncontrolled EVs

The Sequence inspects the ability of networks to support uncontrolled EVs, which is found a function of: miles driven per day, number of EVs and network capability.

6.3.1 Synthesised Coincidence (ADMD) Plots

Sequence 1.1.2.1 has no residential loads and no control, so can plot vehicle charging coincidence ratio, as N EV rises:

$$Coincidence = Observed\ peak\ load / \left(\sum_{1}^{N} Peak\ charging\ rate\right) \tag{26}$$

Coincidence is the basis of ADMD. Generated data is shown plotted for:

- a single phase,
- maximum kW seen by the whole substation transformer, and
- the 98th percentile of transformer maximum kW:

The single phase plot Figure 6-6 has less EVs, improving resolution for low EV counts. Including that phases adds diversity; the transformer (Figure 6-7 (a, b)) sees lower coincidence, and that synchronised control (e.g. Economy 7 timers) would fix the plot at 1.0 for all N EV. The mpd lines span c. 0.1 coincidence, potentially significant. A transformer expecting a low mpd ratio of 0.2 might be unable to cope if raised mpd gave a ratio of 0.3, perhaps due to local route happenstance (e.g. road closure and diversions). From this, electricals are subject to varied load due to variations in driven distance such as route changes.

A classic example is closure of the Humber Bridge, which normally reduces the driven distance between Hull and Grimsby by about 50 miles. Bridge closure would impact local driven distances, affecting local substations - raised mpd means EVs consume more kWh.

In general, diversions change load. The possibility exists that a network built for 19 mpd will periodically experience greater ADMD coincidence, due to higher driven distances.

This is a new issue and as far as the author has seen, is as yet unreported.

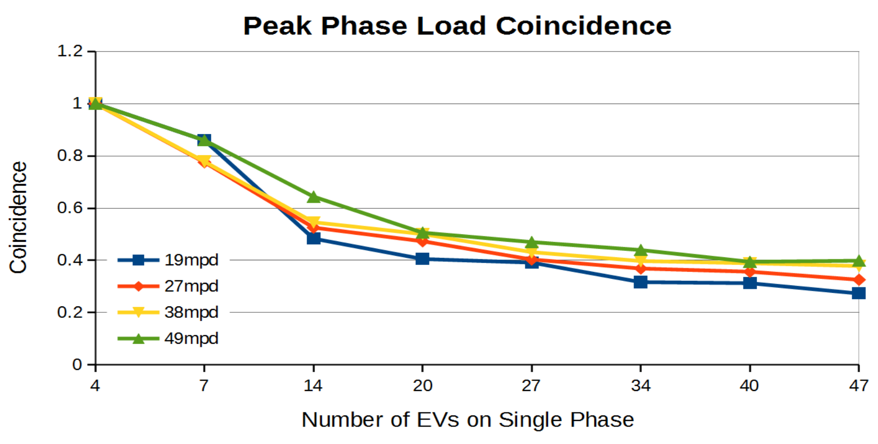


Figure 6-6: Single (most loaded) Phase Synthesised Coincidence plot

Figure 6-7 (a, b) plot 98th percentile and maximum loads and show: Plot (a) maximum to 98th percentile (b) varies x1.5 (0.3 vs. 0.2, 140 EV) to x2 (0.7 vs. 0.36 10 N EV).

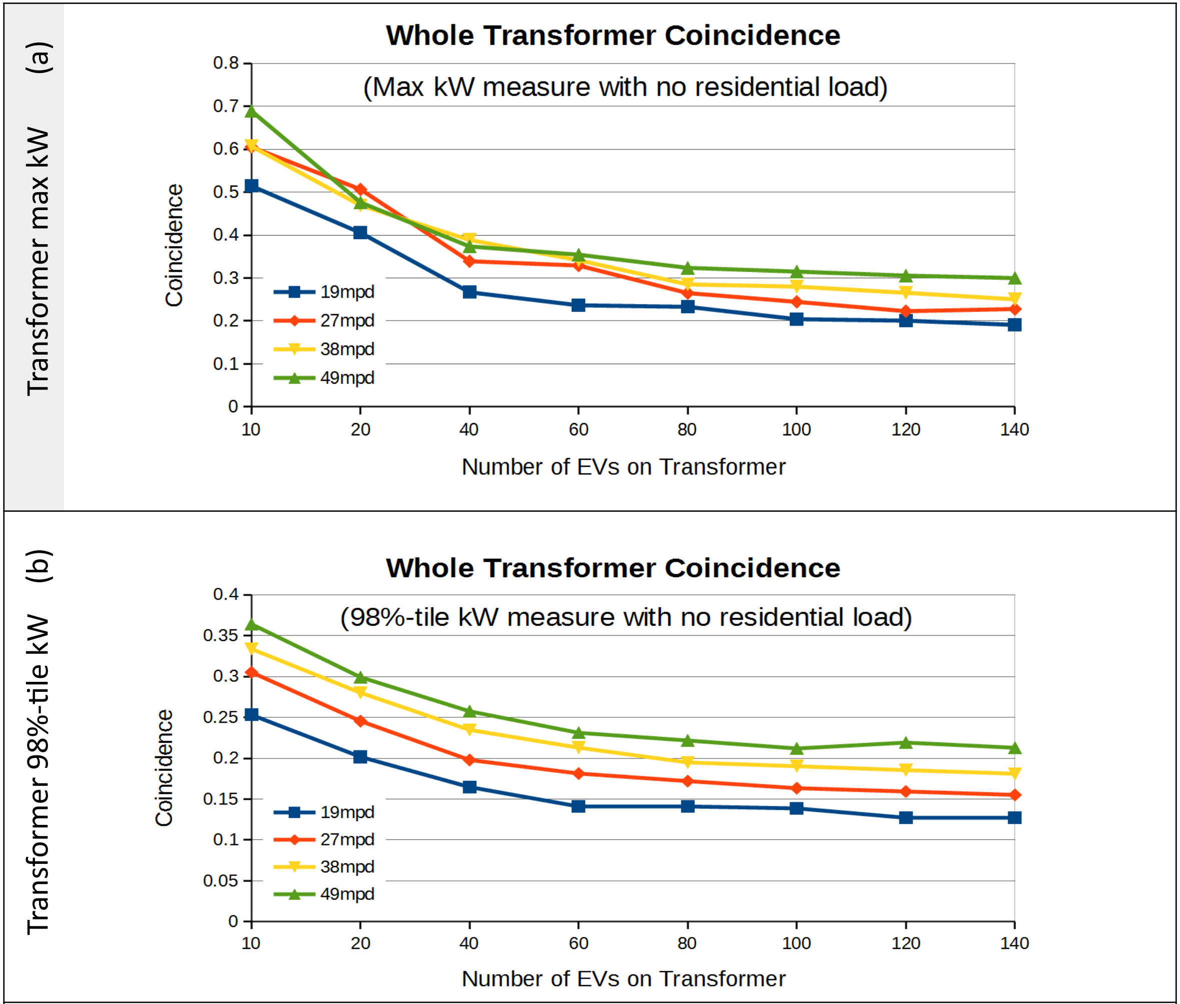


Figure 6-7: Transformer Synthesised Coincidence plot

Which curve then to design to? This underscores need for LV system margin. UKPN **(UKPN & Halsey, 2018)** advise "allow 0.5 x EV peak load". This is sensible if N EV ≥ 20, but for lower N the factor needs be over 0.5. Coincidences for high N EV cited by Halsey (see Figure 2-27 re Electric Nation project) were 0.2 to 0.3. The conditions were not stated.

6.3.2 Sequence Set 1 Broaching Events

Simulation EVs all use BLPs, electrically less demanding than present EVs (has no over-arching EV management). A torrent of broaches (notional fuse blows or transformer duress) occur. Table 6-3 to Table 6-6 below show the number of simulated weeks experiencing broaches, out of 500 simulations:.

Table 6-3: Winter Broaches in 500 simulations: Seq_1.1.1 Weak network (1.2 kW)

DNO fails	N EV	10	20	40	60	80	100	120	140
	19mpd	0	0	74	282	359	449	498	500
	27mpd	0	4	150	339	444	498	500	500
	38mpd	2	20	300	404	497	500	500	500
	49mpd	0	33	339	433	498	500	500	500

Network needs intervention if any broach occurs (limit: 0)

Colourisation: Clear: OK, Red: Fail, Yellow: the Parity case, Grey: maximum mpd and EVs

E.g. for 60 EVs @ 38mpd: Some 404 / 500 = 81% of substations broach in this week.

Scottish Power **(Scottish Power, 2016 Table 4 p.20)** use 1 kW ADMD minimum for a 3-bed semi-detached house. SP have 30,000 substations: www.spenergynetworks.co.uk/pages/our_distribution_network.aspx each serving perhaps 100 homes. If the cell was representative of 10% of SP's stock then 0.81 * 30,000 = 24,300 substations are at risk, i.e. 243,000 homes in difficulty. **Note** ambient temperature driven failures may be simultaneous as a cold front covers a region.

The EV driven mpd is a significant parameter, implying DNOs need mpd data for feeder locations as well as network and N EV statistics.

Next is Sequence 1.1.2, a Typical network for the same conditions, Table 6-4, then repeated (as Seq_1.1.2.2) for **Summer** (Table 6-5): July residential loads and 18° C ambient..

Table 6-4: Winter Broaches in 500 sim'ns: Seq_1.1.2 Typical network (1.5 kW)

DNO fails	N EV	10	20	40	60	80	100	120	140
	19mpd	0	0	0	11	60	249	349	333
	27mpd	0	0	2	53	203	383	358	344
	38mpd	0	0	7	125	357	371	352	380
	49mpd	0	0	10	188	383	360	392	439

Network needs intervention if any broach occurs (limit: 0)

Colourisation: Clear: OK, Red: Fail, Yellow: the Parity case, Grey: maximum mpd and EVs

.

Table 6-5: Summer Broaches in 500 sim'ns: Seq_1.1.2.2 Typical network (1.5 kW)

Summer

DNO fails	N EV	10	20	40	60	80	100	120	140
	19mpd	0	0	0	0	0	0	1	3
	27mpd	0	0	0	0	0	6	22	81
	38mpd	0	0	0	0	13	118	271	410
	49mpd	0	0	0	3	74	319	417	417

Network needs intervention if any broach occurs (limit: 0)

Colourisation: Clear: OK, Red: Fail, Yellow: the Parity case, Grey: maximum mpd and EVs

Summer shows improved results, gaining the lime cells. Next, the Strong (2 kW ADMD) network, for Winter, Table 6-6:

Table 6-6: Winter Broaches in 500 simulations: Seq_1.1.3 Strong network (2 kW)

DNO fails	N EV	10	20	40	60	80	100	120	140
	19mpd	0	0	0	0	0	6	8	30
	27mpd	0	0	0	0	0	19	43	182
	38mpd	0	0	0	0	2	71	192	363
	49mpd	0	0	0	1	17	176	343	379

Network needs intervention if any broach occurs (limit: 0)

Colourisation: Clear: OK, Red: Fail, Yellow: the Parity case, Grey: maximum mpd and EVs

6.3.3 Sequence Set 1 Winter / Summer Plots (Typical network)

Feeder plots Figure 6-8 and CICD plots Figure 6-9 are the parity case (27mpd, 100 EV).

The prevalence of the cream yellow areas in the CICD plot for Winter shows nearly all EVs need charge, whereas in Summer, some do not plug in on arrival home (hence the gap between the black outline and colour, Figure 6-9). Also, Winter SOC (green line) is higher due to battery capacity shrinkage i.e. a given kWh presents as higher SOC. However the green plot line for sample vehicle SOC is very similar.

Winter charging demand is higher than Summer. For the parity case EV, the AFH charge taken throughout the Winter week is 8.3 kWh, falling to 1.4 kWh in Summer.

Note for the same cell group, EVs undertake the same trips Winter and Summer. In Figure 6-9, both are for group 8 (8th plot from 25). This causes the black "at home count" line to be identical e.g. Seq_1.1.2 group 8 line matches Seq_1.1.2.2 and Seq_6.1.2 group 8 etc.

It can be seen that in Winter, many EVs are waiting to charge. If unsuccessful, this need for charge affects the use of Away from Home charging, considered next. Assessments are weekly averages, not peak daily behaviour (daily variations exist e.g. Tuesday vs. Friday). The daily AFH data is available, but not presently analysed.

Table 6-7: Comparative AFH Charging: Winter (Seq_1.1.2) vs. Summer (Seq_1.1.2.2)

Seq_1.1.2	**A Winter per EV AFH kWh**	**N EV**	**10**	**20**	**40**	**60**	**80**	**100**	**120**	**140**
		19mpd	2.7	3.1	3.3	3.3	3.4	3.6	3.6	3.6
		27mpd	6.9	8.0	7.8	8.0	8.4	8.3	8.3	8.1
		38mpd	17.6	17.3	17.9	18.5	18.2	18.5	18.5	18.5
		49mpd	35.5	33.0	31.5	31.3	31.1	30.8	31.2	31.2
Seq_1.1.2.2	**B Summer per EV AFH kWh**	**N EV**	**10**	**20**	**40**	**60**	**80**	**100**	**120**	**140**
		19mpd	0.2	0.3	0.5	0.5	0.4	0.4	0.4	0.4
		27mpd	0.8	1.0	1.2	1.4	1.5	1.4	1.3	1.4
		38mpd	4.0	3.9	4.2	4.6	4.6	4.7	4.6	4.6
		49mpd	10.4	9.8	9.5	9.6	9.4	9.3	9.5	9.5

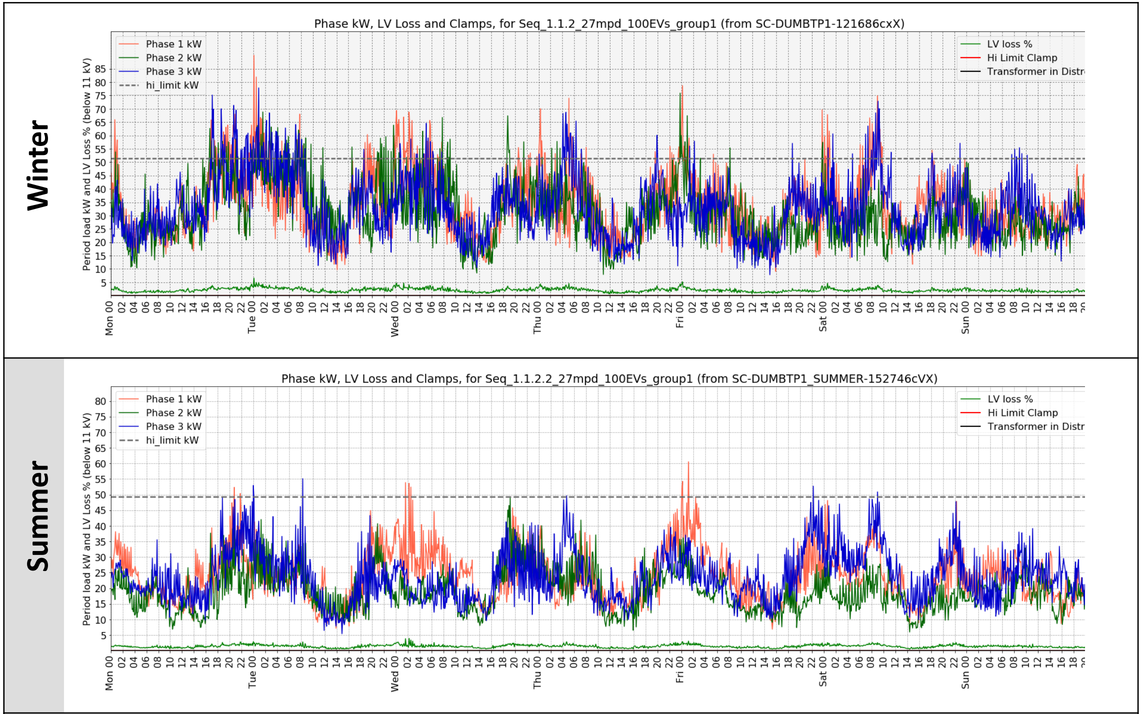


Figure 6-8: Winter (Seq_1.1.2), Summer (Seq_1.1.2.2) Feeder plots, 27mpd 100EVs

During these periods, the EVs experience:

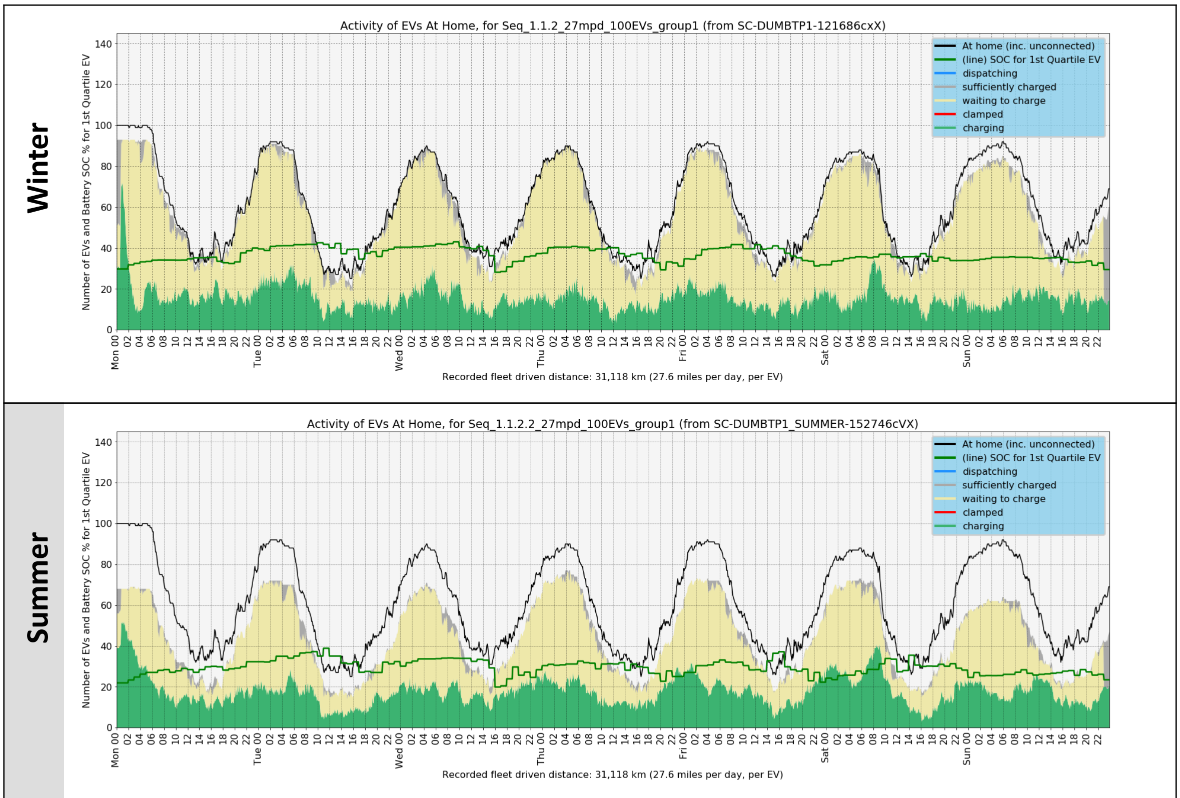


Figure 6-9: Winter (Seq_1.1.2), Summer (Seq_1.1.2.2) CICD plots, 27mpd 100EVs

.

Table 6-8: AFH Charging Visits: Winter (Seq_1.1.2) vs. Summer (Seq_1.1.2.2)

		N EV	10	20	40	60	80	100	120	140
Seq_1.1.2	A Winter per EV N AFH Visits	19mpd	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15
		27mpd	0.30	0.32	0.29	0.30	0.32	0.31	0.31	0.31
		38mpd	0.62	0.60	0.60	0.61	0.61	0.61	0.62	0.62
		49mpd	1.14	1.02	0.95	0.94	0.95	0.94	0.96	0.95
Seq_1.1.2.2	B Summer per EV N AFH Visits	N EV	10	20	40	60	80	100	120	140
		19mpd	0.006	0.008	0.014	0.012	0.012	0.011	0.011	0.013
		27mpd	0.027	0.031	0.033	0.036	0.042	0.039	0.038	0.038
		38mpd	0.105	0.108	0.104	0.114	0.112	0.113	0.114	0.113
		49mpd	0.244	0.221	0.213	0.216	0.218	0.218	0.219	0.218
Ratio A / B	C Ratio Winter to Summer Visits	N EV	10	20	40	60	80	100	120	140
		19mpd	22.31	17.55	9.73	11.83	11.98	13.74	13.36	11.78
		27mpd	11.01	10.31	8.99	8.33	7.72	8.11	8.22	8.14
		38mpd	5.89	5.60	5.79	5.37	5.44	5.43	5.42	5.48
		49mpd	4.66	4.59	4.47	4.37	4.38	4.32	4.37	4.35

A difference in number of AFH charges was noticeable: Winter (Seq_1.1.2, 1° C) vs. Summer (Seq_1.1.2.2, 18° C), Table 6-8. The counts per 100 EV population at parity were:

1. Winter: 31 AFH recharges
2. Summer: 4 AFH recharges.

It is seen <u>EVs AFH charge 4 - 22 times more often in Winter vs. Summer</u> (Table 6-8 C) depending on situation. This was surprising given that EVs drive the same trips. The cause was investigated and found to consist of two parts: EVs consume more overall in Winter (fleet consumption for the parity case being 5.9 MWh vs. Summer's 3.6 MWh), plus <u>EV batteries suffer significant cold thermal shrinkage</u>. Li-ion battery capacity falls with temperature (e.g. a 50 kWh battery may effectively become 35 kWh as ambient drops). EVs needing, say, 40 kWh for intended trips now cannot hold sufficient charge. Departing with insufficient SOC, they must charge Away From Home. This is likely to be at-destination AFH, as the driver will seek charging. Short- and long-range drivers charging patterns are likely unaffected, however mid-range travellers who need no AFH in Summer in Winter must charge, as the batteries cannot hold kWh for desired range. For many, this implies that without charging the EV cannot reach home i.e. stranding likely rises in Winter. There is a solution: put heaters in the battery space, investigated in Seq_6.2.2.5 and now becoming available on some EVs.

Note the impact on short and long-range drivers is: The short don't care and the long normally recharge, so broadly retain prior behaviour. **Also note** it is not known if such seasonality of AFH demand has been seen in the real-world.

These results suggest public charge-points have different seasonal usage rates, with elevated demand in the Winter. This implies need of different charge-point built capacity and a different economic outlook: utilisation rates (so income) varies by season. Such effects impact provision estimates and the economics of public charging points - given that EV batteries remain affected by capacity loss with reduced temperature.

For example, a planner expecting a city population to visit a mall might install 1 EVSE per 100 parking spaces, adequate for Summer (Table 6-8 B, 19mpd row shows about 1% of EVs need charging). However if a housing development was built 10 miles away and the mall attracted visitors from the development, each undertaking a minimum 20 mile trip - then a Winter EVSE provision (Table 6-8 A, 27mpd) might be more apt. But this table shows 30% of EVs charge, not 1%. How many charge points to install? 10 per 1,000 mall car parking spaces - or 300? If miscalculated, the mall may find EV drivers stay away in cold periods, impacting turnover. However forecourt sales (from a filling-station) of charge would rise.

There is a clear difference between city and rural charge-point needs - at the destination, not the home location. However there are caveats:

a) shrinkage is linked to Li-ion battery chemistry (which may change), and/or

b) EVs may not suffer such shrinkage with improved thermal management i.e. overnight heating. This implies further elevated Winter at-home charging load.

c) EVs likely arrive home with a warm battery. How much this offsets the thermal derating behind the issue is not easily determined (a battery thermal model is not included, for key parameters are unknown). However temperatures will tend to ambient standing overnight. Further, temperatures may fall below 1°C used.

It may be useful to revisit this when more is known of EVs and battery characteristics.

However, these results imply the following scenario: A driver leaves home with a low battery, expecting to recharge somewhere whilst away, as per normal habit. Yet today there are no charging points free - so they attempt to return home hoping they can make it. Some are unlucky; stranding rates rise. If there are only enough recharging points for Summer then (in the parity case) 27 EVs per 100 fail to charge in Winter. This is about 4% of EVs per day, so per million vehicles 40,000 risk running out of charge in transit, per day. **Note** while it is common knowledge that EV range falls in winter, the author has not yet seen this phenomena connected to a need for increased AFH charging provision.

Concerning undervolt conditions. These were not prevalent and appeared well past other broaching conditions. For example, in Seq_1.1.1 Weak network for 27mpd, overloads occurred at 10 EVs yet had no voltage problems until 80 EVs. The Typical network for 27mpd suffered undervolts past 120 EV, and the Strong network did not undervolt in any simulation. If the network had a different design, undervolts may be provoked earlier.

6.3.4 Sequence Set 1 Observations:

1. random chance can throw unexpected outcomes. For Seq_1.1.1 (Weak) 38mpd, 10 EVs broach at 38mpd, even though they do not at 49mpd - which has more kWh demand i.e. 500 simulations are insufficient to identify “zero broaches”
2. even a small number of EVs (3) left to their own devices broach Weak networks
3. greater network strength helps, yet the Strong 2 kW ADMD fails for parity-case EVs
4. The time of year makes a difference:
    1) residential loads rise in Winter,
    2) EV consumption also rises in Winter due to increased heating loads, yet
    3) the amount of charge the EV can hold (for Li-ion batteries) drops.
5. Hence network assessments made in Summer need be adjusted for Winter, and
6. there is more network stress hence problems in Winter. A steady growth in EVs may go unnoticed, but provoke clusters of problems in hard Winter weeks
7. DNOs with weak networks are at greater risk, especially being overburdened with multiple simultaneous repair works due to a cold snap;
8. broaches are seen as roughly proportional to mpd (i.e. EV kWh demand) as well as number of EVs. As driven miles per day as well as N EV affects outcome, location

affects outcome. An M4 commuter belt estate will have different charging loads and outcomes vs. an identical estate and EVs, located inside the M25.

9. Networks are impacted by EV charging patterns. FPB's assumptions re EV charging patterns (BLPs) are for mid-Century; if a rapid increase of EV numbers occurred, these vehicles may not yet use BLPs hence loads may be unexpectedly high.
10. The author wondered what kW built per house would allow full operation and used the simulator to chase the 49mpd, 140 EV ply up in kW. Passes begin over 3 kW per house (for BLP type EVs) which confirms NPG's 3.7 kW per house per EV at 100 houses recommendation, seen in **(Northern Power Grid, 2018, p47)**.

6.3.5 Limits for Severe Undercharging

A severe undercharge is: An EV departing home with insufficient charge to return i.e. the immediate trip cannot complete; AFH charging is forced. If unavailable the EV is stranded. Conversations with MEA participants indicated that severe undercharging was for some a repeated issue, causing great upset, likely arising due to unbalanced network load.

An acceptable limit was calculated: a 50:50 chance in 100 Winter weeks (assume 10 very cold weeks a year i.e. even chances of once in 10 years of EV severely undercharged):

solving: $$0.5=(1-x)^{100} \tag{27}$$

gives: $$x=0.007 \tag{28}$$

6.3.6 Traffic Lights Presentation Format

To save space, a Traffic Lights format is introduced. Traffic Lights show both the highest N EV allowable and the cause of failure to progress in braces, illustrated in Table 6-9.

Table 6-9: Sequence Set 1 Traffic Lights results

	Weak Network		Typical Network			Strong Network
	Winter		**Winter**	**Summer**		**Winter**
	Seq_1.1.1		Seq_1.1.2	Seq_1.1.2.2		Seq_1.1.3
19mpd	**20 (B)**		**40 (B)**	**100 (B)**		**80 (B)**
27mpd	**10 (B)**		**20 (B)**	**80 (B)**		**80 (B)**
38mpd	**0 (B)**		**20 (B)**	**60 (B)**		**60 (B)**
49mpd	**10 (B)**		**20 (B)**	**40 (B)**		**40 (B)**

Progress halted due to (B) = broach, (c) = excessive clamps, (S) = severe undercharging

RAG Colourisation: Red: <= 40, Amber: 60 - 80, Green: >= 100

This allows straightforward comparison of results. For instance, the Typical network results for Summer are contrasted with Winter; Seq_1.1.2 at 27mpd could support no more than 20 EVs; any more provoke (B) broaches i.e. some form of overload. On the occasions when there was complete failure, this is shown as either zero or “--”.

The limits of acceptability are:

- broach count = 0 and
- clamp counts < 420 (clamps in week < 2 hours, see 6.4.13) and
- severe undercharging (the EV not being able to complete the trip without a charge) rate < 0.007 per EV per week.

6.4 Sequence Set 2: EVs with Peak Load Clamping

Set 2 explores managing dumb EVs solely by clamps, broadly mimicking the My Electric Avenue (MEA) project), in one of two modes. Results traffic lights are shown in Table 6-10.

Table 6-10: Sequence Set 2 Supportable EVs as Traffic Lights

Typical Network “Just Clamps” (MEA mode, all set in Winter)						
	DRFFR + C2	**DumbTrips**	**DefaultTrips**	**DRFFR + C1**	**HomePP**	**StatBatt + C2**
	Seq_2.1.2	Seq_2.1.2.8	Seq_2.1.2.9	Seq_2.2.2	Seq_2.3.2	Seq_2.3.2.1
19mpd	**20 (c)**	**120 (c)**	**120 (c)**	**20 (c)**	**20 (c)**	**60 (c)**
27mpd	**20 (c)**	**100 (c)**	**100 (c)**	**20 (c)**	**20 (c)**	**60 (c)**
38mpd	**20 (c)**	**80 (c)**	**80 (c)**	**20 (c)**	**20 (c)**	**40 (c)**
49mpd	**-- (S)**	**60 (c)**	**60 (c)**	**-- (S)**	**-- (S)**	**40 (c)**
Typical Network “Just Clamps” (MEA mode, all set in Winter) Ctd.						
	StatBatt + C1	**HomePP - DR**	**HomePP + C1**	**AllPP + C2**	**AllPP + C1**	
	Seq_2.3.2.2	Seq_2.3.2.9	Seq_2.4.2	Seq_2.5.2	Seq_2.6.2	
19mpd	**60 (c)**	**120 (c)**	**20 (c)**	**80 (c)**	**80 (c)**	
27mpd	**60 (c)**	**100 (c)**	**20 (c)**	**60 (c)**	**60 (c)**	
38mpd	**40 (c)**	**80 (c)**	**20 (c)**	**40 (c)**	**40 (c)**	
49mpd	**20 (S)**	**60 (c)**	**-- (S)**	**20 (S)**	**20 (S)**	

A maximum phase load (hi_limit setpoint) is defined; exceeding this causes EVs to be clamped. Clamps reduce charging opportunities, so may provoke EV undercharging. Services (DR and FFR) are injected by hi_limit modulation. EVs are all dumb.

Observation: Clamping works; at no time in Sequence Set 2 did a broach occur. However other problems have arisen. No wholly green “clean sweeps” are present.

6.4.1 Legend Meanings

6.4.1.1 DRFFR:

- Demand Reduction (a reduction lasting hours) and FFR (per-period adjustments of 0% to ± 5%) are applied by hi_limit modulation. See Analysis Samples Seq_2.1.2, 6.9.2 for details. The default DR scheme is DR-B. Options are:
    - an alternative DR-C imposing 1/2 DR-B reduction,
    - with no DR element i.e. FFR only, or
    - "flat" i.e. modulation is 1.0 at all times.
- A metric for DRFFR time-effectivity is calculated: Percent Effective Hours (PEH):

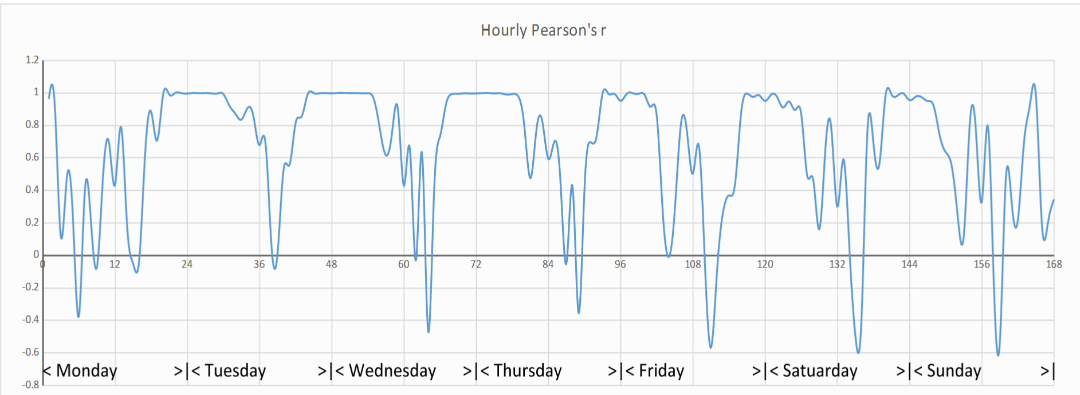


Figure 6-10: Pearson's r plotted for Seq_6.9.2.2, 27 mpd 100 EVs (PEH = 80.4%)

Figure 6-10 plots Pearson's r in each hour (the early afternoon negative correlation has not been investigated), which is the net change in feeder load vs. the DR/FFR signal change. The PEH metric is the % of weekly hours with r > 0.3, calculated as the mean for each ply.

6.4.1.2 C1 / C2: Clamping Prioritisation:

C1: mimics MEA by offering "equal kWh supplied". This is straightforward to arrange and possible by timing only (no Smart Grid communication with EV), but:

- can undersupply EVs needing a high SOC level,
- whilst allocating supply to EVs which do not need more charge.

C2: the FPB "by equitable need" method. EVs are supplied what they state they need; excess SOC may be supplied only if spare/unclaimed power is available.

6.4.1.3 Dumb / Default Trips:

- the tripsets per ply cell used are 500 chosen from a test of 3,000, for maximum kW demanded. Selections were made for all dumb or a fleet of mixed EVs. Changing tripsets i.e. applying the Dumb tripset or Default tripset explores sensitivity to trips driven.

6.4.1.4 Home / Away / All Perfect Plugins

- aka HomePP, AllPP
- investigates forced connections when parking
- otherwise EVs connect when there is clear need or a probability / habit factor

6.4.1.5 Static Batteries:

- aka StatBatt, an approximation of static energy stores on the LV network. Three static V2G EVs are placed on each phase (no trips scheduled) and operated so to charge during the day and support load (other EVs charging) in the evening. This mimics a local energy store. These have standard EV charging and dispatch capabilities plus 150 kWh batteries;
- this is an approximation as the plotting system considers these as EVs, so totals may be 9 out. Tables of numerical results are adjusted; plot images are not.

6.4.2 Sequence 2.1.2: DRFFR with C2 Clamps

Clamps immediately limit overloads (Figure 6-11 (a)).

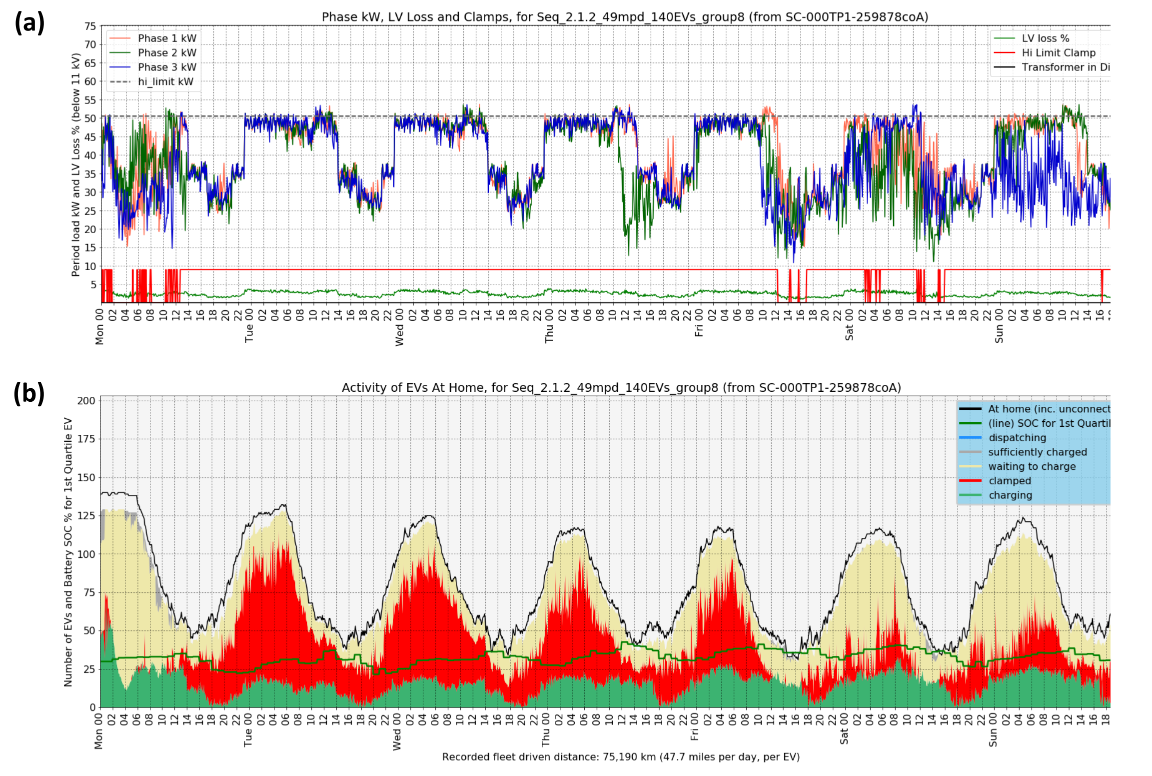


Figure 6-11: Seq_2.1.2 49mpd 140EVs group 8 Feeder (a) and EV CICD (b) plots

However, for the extreme mpd and N EV cases this provokes significant use of clamping (red areas in Figure 6-11 (b)); only 20 EVs are supportable on the Typical network. From the EV viewpoint, this is a regression vs. uncontrolled charging.

The "Percent Effective Hours" (PEH) DRFFR metric was found to track EV numbers and mpd duty, spanning 52% to 83% (parity to maximum EV case) showing variable utility.

The DR element was seen to move charging from the evening to the overnight period.

Observations: Seq_2.1.2 is not practical, due to inadequate EV support capability.

6.4.3 Sequence 2.1.2.8: C2 Clamps Only (Dumb Trips)

This sequence is without DRFFR. An immediate improvement is seen in supportable EVs, reaching the parity case of UK average mpd for 1 EV per home. 2.1.2.8 also looks at the affect of varying the tripset used vs. 2.1.2.9; there is no difference at high level between these. The full datasets show similar results with differences < 3%, often < 1%, with the exception of variability at low EV population counts.

Observations: Seq_2.1.2.8 is practical but cannot support a 1:1 EV:car replacement. Varying tripsets changes outcomes for low N EV counts, but are otherwise comparable.

6.4.4 Sequence 2.1.2.9: C2 Clamps Only (Default Trips)

A near-twin to 2.1.2.8 with alternative tripsets. The purpose of this test was: Does tripset choice make a difference to outcomes?

Observations: High level results match 2.1.2.8; no great sensitivity to tripsets is seen.

6.4.5 Sequence 2.2.2: DRFFR with C1 Clamps

A variation on 2.1.2 using C1 clamping protocol, to mimic the MEA clamping method.

Inspecting detailed results shows C1 clamping degrades (increases) severe undercharging rates, but at the high level view changes do not sway outcomes.

Observations: Seq_2.2.2 is not practical, due to inadequate EV support capability. C1 clamps slightly aggravate severe undercharging counts.

6.4.6 Sequence 2.3.2: Home Perfect Plugins (C2 by default)

A version of 2.1.2; plugins are forced on arriving home. No change vs. 2.1.2 is seen at high level; the root cause being that in Winter most EVs plug in anyhow; making this compulsory brings little advantage. AFH charging is slightly down.

Observations: Seq_2.3.2 is not practical, due to inadequate EV support capability.

6.4.7 Sequence 2.3.2.1: Static Batteries (C2 by default)

This is 2.1.2 plus Static Batteries (supernumerary V2G EVs making no trips). An immediate improvement is seen in ability to support EVs, alongside significant dispatch duties per Static Battery, similar to kWh load of driving. MCS manages the Static Batteries only.

Note that DRB/FFR is used. At parity (1 EV per house, driving average UK distances). PEH responsiveness is 54% - 77% (49mpd and 140 EVs), cf. 2.1.2’s 52% - 83%.

Observations: Seq_2.3.2.1 remains impractical due to inadequate EV support capability, but shows that Static Batteries (hence V2G) can assist at the local level.

6.4.8 Sequence 2.3.2.2: Static Batteries with C1 Clamps

This is 2.2.2 plus Static Batteries (or 2.3.2.1 with C1 clamps). Improvement is evidenced to support EVs, with duties per Static Battery comparable to the kWh load of driving.

It is notable that at 49mpd supportable EVs drops to 20 from 40, caused by onset of severe undercharging. Detailed results show degradation for all EV ranges.

Note that DRBFFR is used.

Observations: Seq_2.3.2.2 remains impractical yet shows Static Batteries (hence V2G) can assist at the local level - but that C1 clamps impose a loss of capability at 49mpd.

6.4.9 Sequence 2.3.2.9: Home PP sans DRFFR

This is 2.3.2 with no DRFFR, so could be viewed as a functional repetition of 2.1.2.9 (as Home Perfect Plugins "do nothing"). The result of 2.1.2.9 is replicated; removal of the DRFFR signal improves ability to support EVs. More kWh become available for charging.

Observations: DRFFR can degrade ability to support EV charging.

6.4.10 Sequence 2.4.2: Home Perfect Plugins with C1

A version of 2.3.2 using protocol C1 not C2. The change makes no high-level difference, although detailed results again show elevated severe undercharging.

Observations: Seq_2.4.2 is impractical, having inadequate EV support capability.

6.4.11 Sequence 2.5.2: All Perfect Plugins (C2 by default)

EVs connect both home and away i.e. 2.3.2 with "away perfect plugins"; DRFFR is present. Improvement is noticeable; not surprising as an away charge point is assumed to have no kW constraint (EVs may charge their fill, greatly reducing Home charging needs).

Observations: Seq_2.5.2 is impractical but shows the ability of away charging to supplement restricted home charging. Contrast with Seq_2.1.2.

6.4.12 Sequence 2.6.2: All Perfect Plugins with C1 Clamps

This is functionally identical to 2.5.2, with C1 clamping replacing C2.

Observations: Seq_2.6.2 is not practical but again shows the benefit of away charging to supplement restricted home charging.

6.4.13 Sequence Set 2 Summary Observations

1. Clamps stop broaches (a noticeable side effect: no under-voltages observed).
2. Sets with DRFFR suffer noticeably degraded capability. It is not yet clear as to why:
   a) the DR element, the FFR element or both, or
   b) an artefact of assessment e.g. the author's expectation for a limit of clamping
   c) or a combination of the two i.e. imposing a DRFFR system provokes clamps.

Note clamp counts are the MCS view i.e. counts of decisions to assert clamps to a phase, not a count of EVs clamped. One clamp may withdraw power from multiple EVs. Thus, in 2.1.2's "MetaMeta2.3_Seq_2.1.2.xlsx sheet CompareMetas" the 27mpd 100 EV average clamp count is 2,211 implying that (if 10 EVs are effected per clamp) 22 k periods (6 minutes each) of suspended EV charging have occurred. That is, across 100 EVs, 2,200 hours of charging are lost (protecting the network) i.e. 22 hours a week per EV; about 3 hours parked at home every night.

It is unknown if this is acceptable. The clamp count limit, 420, intends no more than 2 hours per EV per week. However, this is arbitrary.

3. Static Batteries support home charging.
4. Away from Home charging lifts the count of supportable EVs.
5. The clamping mode (C1 or C2) affects severe undercharging, C2 is better but the difference is negligible. Given <u>C1 has potential to not need of a full ICT comms path to each EV</u> (the MCS times the period the EVSE clamp allows power to flow, rather than dialogues with each EV); the system simplification may have benefit. For instance, removing a comms channel simplifies security.
6. Conversely, using C2 slightly improves (reduces) undercharging rates.
7. A separate analysis of longer-range driving is called for; these EVs may be disproportionately penalised by C1 which offers a similar kWh supply to all.

6.5 Sequence Set 3: Clamps with V2G Support

This Set explores if V2G EVs can reduce use of clamps and improve undercharging rates, shown in Table 6-11. 25% of EVs become V2G. Controller headroom calculations now use a proportionate part of available V2G capability. Clamps are applied if excess load remains. V2G support may reduce the number of clamp firings and reduce undercharging, and is broadly confirmed.

Two methods of V2G control are used:

- FPB MCS, which is aware of the local network load levels and
- remote Aggregator without local load awareness i.e. "blind" control.

DRFFR is not in use; however the most comparable results seen to date are Seq_2.1.2.9.

Table 6-11: Sequence Set 3 Supportable EVs as Traffic Lights (cf 2.1.2.9)

Typical Network		Typical Network (Clamps + V2G, Winter)		
	DefaultTrips		MCS Control	MCS + Agg
	Seq_2.1.2.9		Seq_3.1.2	Seq_3.2.2
19mpd	**120 (c)**	19mpd	**140**	**140**
27mpd	**100 (c)**	27mpd	**140**	**140**
38mpd	**80 (c)**	38mpd	**120 (c)**	**120 (c)**
49mpd	**60 (c)**	49mpd	**100 (c)**	**100 (c)**

Progress halted due to (B) = broach, (c) = excessive clamps, (S) = severe undercharging

RAG Colourisation: Red: <= 40, Amber: 60 - 80, Green: >= 100

There is a subtle difference between Sequence Sets 2 and 3. In Set 2, EVs were 100% dumb. Set 3 introduces V2G EVs which are Smart i.e. dialogue with a controller, including when to start charging. The ability to perform “managed charging” is intrinsically present in this test, so this is a different situation to Set 2’s Static Batteries and dumb EVs (which attempt to charge to their own schedule). MCS manages V2G EV charging, even when V2G is not needed. Detailed results assess the relative contributions of MCS and V2G.

6.5.1 Sequence 3.1.2: V2G with MCS and C2 Clamps

Results show great reductions in clamping and severe undercharging, for increasing V2G duty. Thus the issue arises: are EV batteries being excessively aged by V2G duty?

For the parity case, there is about 2.2 kWh spent over the week per V2G EV, cf. c. 7 kWh used for driving per EV per day, i.e. around 5% extra duty.

If repeated over 10 weeks in a year, then about 22 kWh V2G is performed in the year vs. c. 2,500 kWh for driving so battery life impacts may be estimated as 0.9% reduction pa or about 3 days a year, or 1 month over the 10 year life of an EV battery.

However, the V2G duty raises with mpd and N EV, to c. 19 kWh per EV per week at 49mpd with 140 EVs. This implies about 9 months life shortening; a significant amount.

Conclusion: increased ageing is likely present so needs to be recompensed.

An analysis of the benefit of MCS control vs. V2G is detailed in results Volume 3. This shows merit of MCS : V2G can rise to 10 : 1 i.e. the greater aid is from Managed Charging rather than V2G. From this, managed charging of all vehicles would seem of benefit.

Note in Seq_3.1.2, 75% of EVs are dumb.

Observations: Seq_3.1.2 is deployable; adding 25% locally managed V2G EVs is beneficial.

6.5.2 Sequence 3.2.2: V2G, MCS and Aggregator Intervention

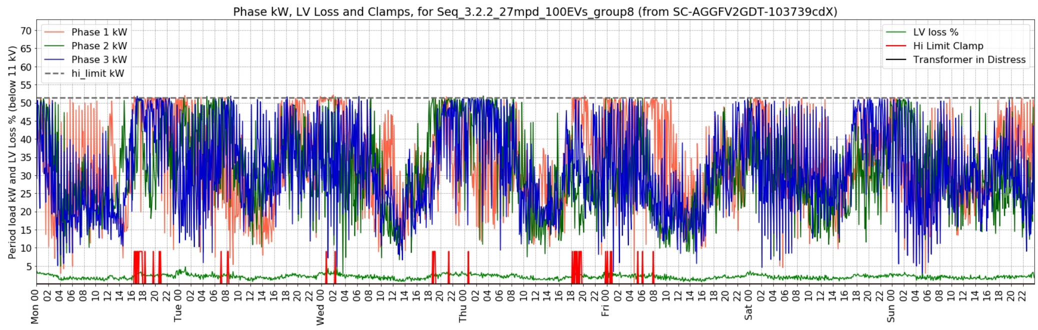
This is a version of 3.1.2 to assess the impact of aggregator control. Every second and sixth period of the hour (i.e. for 6 minutes from HH:06 and HH:36) the remote Aggregator forces V2G EVs to dispatch. At other times, MCS control over V2G continues.

There are no differences between the high-level results for 3.1.2 vs. 3.2.2, which is likely due to the MCS action. The detailed results analysis shows a slight increase in severe undercharging, but a leap in V2G duty, Figure 6-12 (c). All V2G vehicles undertake very high V2G dispatch, being worse at low EV counts. For 27mpd, 61 kWh is dispatched per EV in a 20 EV fleet vs. 28 kWh for a 120 EV fleet. This is likely due to levels of spare SOC; at low EV counts EVs have more chance to charge thus to hold “extra excess SOC” than when EV numbers are high, so are better positioned to dispatch.

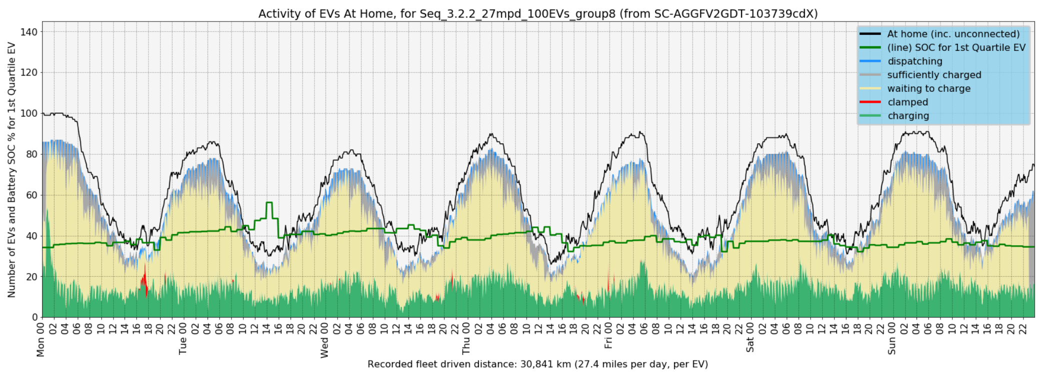
Note that 27 mpd driving duty consumes c. 60 kWh over a week. V2G duty approaching or exceeding driving duty is unacceptable; today’s Li-ion batteries will age rapidly. Also, there is likely “charge circling” going on i.e. an EV is depleted by performing V2G, so must charge thus accepts charge from another V2G EV - which performs an otherwise unnecessary dispatch. However each transaction is very lossy (c. 40% round-trip energy is lost). The EVs trade charge to no good benefit; raised losses mean degraded net efficiency.

Observations: Seq_3.2.2 headlines as if acceptable but “blind” aggregator control is found detrimental to V2G EVs, so is not recommended.

(a)



(b)



(c)

		N_EV=	10	20	40	60	80	100	120	140
19mpd	**V2G per EV**	19mpd	74.2	61.3	59.4	48.2	36.4	29.5	25.4	23.1
27mpd		27mpd	71.9	60.9	60.9	49.2	37.3	31.0	28.1	27.9
38mpd		38mpd	74.1	64.4	64.2	51.8	39.9	35.4	34.8	39.0
49mpd		49mpd	71.0	62.9	63.2	51.6	40.6	38.1	39.7	41.5

Figure 6-12: Seq_3.2.2 Aggregator forced V2G and V2G kWh dispatch

***Note**: (c) represents kWh dispatched per V2G EV present, for fleet N EV and mpd*

6.5.2.1 Aggregation V2G DSR May Not Escape LV Network

In the following plots (Figure 6-13) the Aggregator forced V2G (e.g. Tuesday midnight - 4am) *does not effect net network load*. This is due to the MCS allocating the dispatch to EVs; the V2G dispatched kW is consumed locally to charge other EVs and does not reach the external grid, when local load is high.

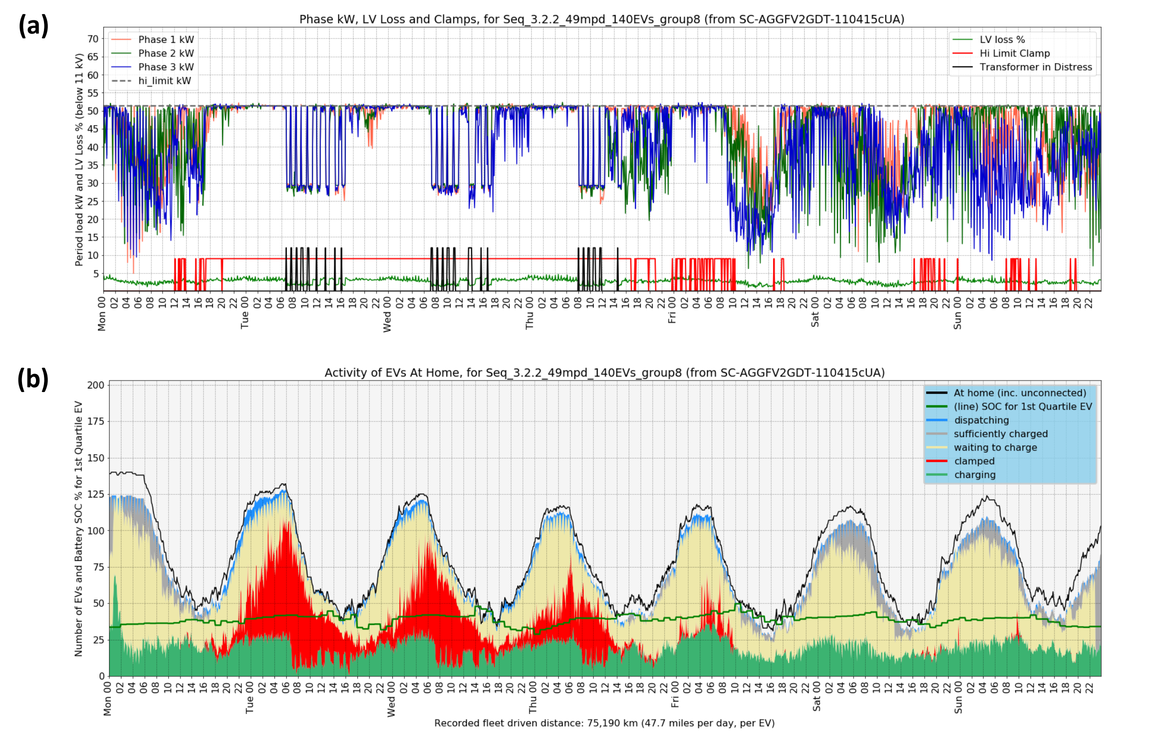


Figure 6-13: Seq_3.2.2 forced V2G impacts network load only if not saturated

Note the black peaks along the bottom of Figure 6-13 (a) are Transformer thermal distress detections, imposing a severe hi_limit reduction forcing the feeder load to drop, so to cool the transformer. The author suspects this may cause flicker of household lighting.

6.5.3 Sequence Set 3 Summary Observations:

1. Clamping continues to work; at no time in Sequence Set 3 did a broach occur
2. MCS is found to have contributed
3. V2G is also found to have contributed (but only at 1/10th the rate of MCS)
4. Aggregator control over V2G has achieved nothing of note at local level, other than expending large amounts of V2G charge, implicitly accelerating battery ageing
5. at times, the MCS consumes Aggregator commanded V2G locally (as extra resource to support local charging). Aggregator intent is frustrated, for what is intended is a drop of net load, not here seen when LV is congested
6. Comparing total weekly feeder kWh for the parity case in Seq_2.1.2.9 (with EVs driven under the same conditions) shows Seq_3.2.2 consumes 330 kWh more over the week with Aggregator control, to no benefit for EVs or the greater network.
7. Without local sensing, it is not clear how remote Aggregator V2G can be improved.

6.6 Sequence Set 4: Remote Aggregator DSR Control

Here, an aggregator is modelled applying peak Demand Side Reduction (DSR), often region-wide. In this work, DSR is a signal and DR the outcome. The intent is to explore how this impacts LV and EV situations, specifically if a remote Aggregator can assist broaches and / or undercharging. This test is similar to Aggregators applying DSR for NGESO as proposed in **(DfT & OLEV, 2019)**. It is assumed that the remote aggregator has no real-time local situational awareness, i.e. issues a DSR command blind. The Aggregator times commands are:

- 1pm - 6pm: no charging or dispatch
- 6pm - 11pm: charging allowed for EVs < 33% SOC (V2G dispatch permitted)
- 11pm on: unconstrained.

Table 6-12: Sequence Set 4 Supportable EVs as Traffic Lights

Typical Network (Agg ToU only, Winter)			
	Agg ToU	**Agg + Clamps C2**	**Agg ToU, Clamps, V2G**
	Seq_4.1.2	Seq_4.2.2	Seq_4.3.2
19mpd	**-- (S)**	**-- (S)**	**-- (S)**
27mpd	**-- (S)**	**-- (S)**	**-- (S)**
38mpd	**-- (S)**	**-- (S)**	**-- (S)**
49mpd	**-- (S)**	**-- (S)**	**-- (S)**

Progress halted due to (B) = broach, (c) = excessive clamps, (S) = severe undercharging

RAG Colourisation: Red: <= 40, Amber: 60 - 80, Green: >= 100

DRFFR is not used and the first sequence (4.1.2) has no clamping. The outcome is disappointing with endemic severe undercharging, Table 6-12.

6.6.1 Sequence 4.1.2: Aggregator Control Sans Clamps

The Aggregator control regime is applied without clamps to 100% dumb EVs. The concept is similar to current intent for DSR peak management. Seq 4.1.2 suffers rapid onset of broaches and endemic severe undercharging.

Observations: This is clearly impractical.

6.6.2 Sequence 4.2.2: Aggregator Control with C2CT Clamps

The Aggregator control regime is applied with clamps to all dumb EVs; however the reduction of kWh available to EVs means there is likely more undercharging (Table 6-13):

Table 6-13: Severe Undercharging per EV (weekly averages) for 4.2.2 vs. 2.1.2.9

3. Sevr. UnChg	N EV	10	20	40	60	80	100	120	140
	19mpd	0.0312	0.0332	0.0355	0.0346	0.0364	0.0382	0.0370	0.0372
	27mpd	0.0734	0.0767	0.0694	0.0647	0.0727	0.0706	0.0730	0.0787
	38mpd	0.1266	0.1395	0.1354	0.1321	0.1320	0.1388	0.1628	0.2231
	49mpd	0.2218	0.1933	0.1920	0.1972	0.1997	0.2274	0.2967	0.3954

(limit: < 0.007)

Light red: failed in 2.1.2.9, deep red: now fails in 4.2.2. These plies show:

- a major rise in severe undercharging; no ply cell is acceptable
- by eye, Table 6-13 shows severe undercharging correlates to mpd, less to N EV
- in general, there is an increase in severe undercharging, yet (from the Arrive / Departs plots) we know departing EVs have similar counts of undercharging hence in general there is a tenancy for undercharging:
  - not to increase in count, but
  - to <u>increase in severity</u> (i.e. SOC shortfall).

The limit of 0.007 is a 50:50 probability of being trailered home once in 10 years. Consider the parity case (highlighted yellow). This is c. probability limit x10, meaning individuals have an even chance of being trailered home once a year; for a fleet of 100 EVs there are about 50 trailered home each year (of 10 Winter weeks) i.e. 5 a week per 100 homes. Although this is likely unacceptable, what is more unacceptable is that the nature of the LV system (especially with unbalances) means that some houses can intrinsically be at low risk, others high. Alas <u>the same individuals may be repeatedly trailered home</u>.

Is the test unreasonable? The test envisions:

- supporting the afternoon peak demand by prohibiting charging
- supporting the evening peak demand by limiting charging (worthy cases allowed)
- allowing overnight charging of 8 hours (before morning 7am commuting depart).

The situation has been provoked by a Time of Use pattern, imposed by a remote Aggregator. Why did this outcome occur? EVs are all dumb. There is no local MCS knowledge or control beyond clamping, so no prioritisation to aid optimise charging.

6.6.3 Sequence 4.3.2: Agg Control, C2CT Clamps, 1 in 4 V2G EVs

Aggregator control with clamps and V2G (EV mix is 75% dumb, 25% V2G). The V2G EVs suffer have Aggregator and MCS control. A petty improvement is seen (Table 6-14):

Table 6-14: Severe Undercharging per EV (weekly averages) for 4.3.2

3. Sevr. UnChg	N EV	10	20	40	60	80	100	120	140
	19mpd	0.0268	0.0256	0.0250	0.0254	0.0268	0.0287	0.0277	0.0274
	27mpd	0.0546	0.0587	0.0512	0.0475	0.0528	0.0507	0.0510	0.0499
	38mpd	0.1068	0.1086	0.1050	0.0999	0.1012	0.1019	0.1044	0.1334
	49mpd	0.1966	0.1486	0.1517	0.1544	0.1520	0.1560	0.1863	0.2662

(limit: < 0.007)

Red: failed in 4.3.2; no ply succeeds. Detailed results show V2G EVs are relatively passive. The author suggests this means: Starved themselves, V2G EVs have little to offer.

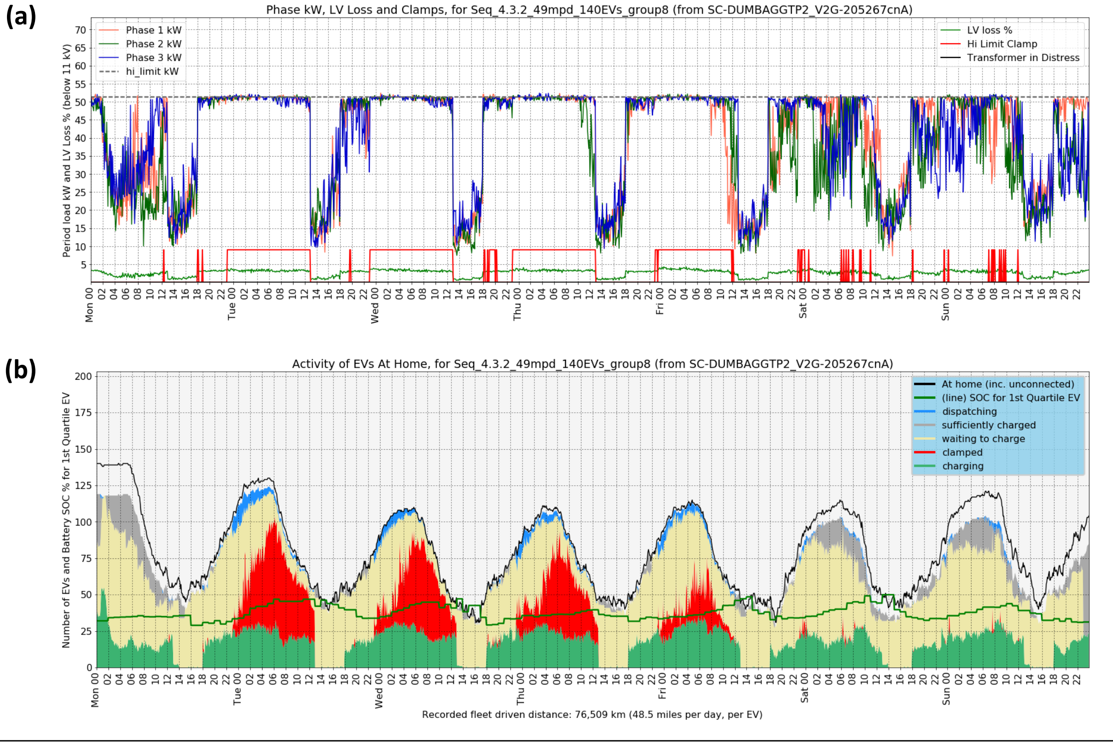


Figure 6-14: Seq_4.3.2 ToU / DR: Afternoon charging prohibited, evening restricted

Furthermore, clamps imposing a hi_limit means any post-DR recovery is frustrated. On recovery, loads demand power together (EVs charge together), area 4 in Figure 6-15.

The red areas in the CICD plot (Figure 6-14 (b)) show this effect.

Observations: The use of remote aggregation control needs knowledge both of EV states, intents and local network state. In the form simulated, the aggregator can modulate demand to notionally assist the greater network, at the discomfort of home charging EVs.

6.6.4 Sequence Set 4 Summary Observations

Aggregator Time of Use (ToU) commands suspend charging, mimicking Demand Reduction (DR, aka DSR). Applied sans local knowledge, undercharging and broaching issues arise.

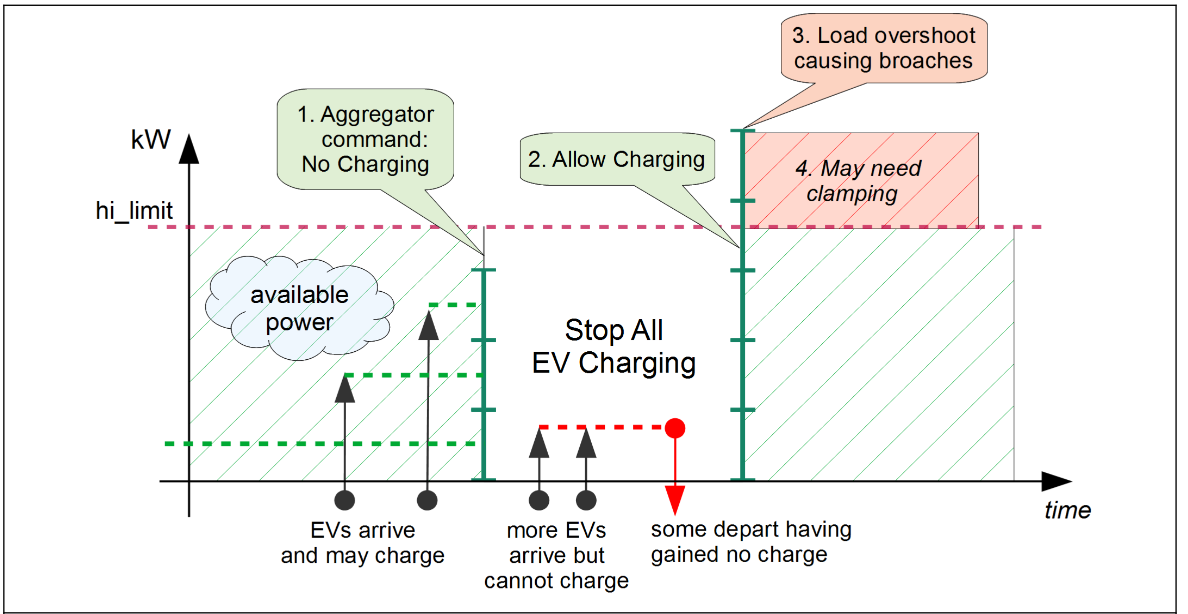


Figure 6-15: Seq_4.3.2 Agg ToU / DR: EVs are not charged ⇒ Demand Backlog

EVs needing to charge in the afternoon could not charge, so flag "undercharged / severely undercharged" on depart. Broaches can arise due to a build-up of demand in DR periods: on DR release, a simultaneous stampede for resource can occur (overshoot balloon 3. in Figure 6-15). In Seq_4.1.2 this provoked broaching.

Note the V2G (blue, above cream) in Figure 6-14 (b). From 11pm Aggregator ToU restraints cease; blue shows V2G supporting a burst of demand as EVs recover kWh not taken, due to periods of charging prohibition.

Although Aggregator control does offer DSR to the overall power system, evidenced by timed dips in Figure 6-14 (a), the resulting undercharging and broaching is unacceptable. The Aggregator system in this form needs some other management scheme.

Although not investigated, roadworks with traffic lights could cause platooning (driving as a group, so EVs arrive and charge together), potentially causing similar overloads.

6.7 Sequence Set 5: Local MCS Control (not clamped)

Purpose: Explore if a local, network-aware Managed Charging System (MCS) can assist broaches and undercharging, without clamps. EV mix is arbitrarily selected as 19% dumb, 48% SV1G, 33% V2G. Dumb EVs represent vehicles not able to dialogue.

Observations: MCS is a great improvement, but still allows occasional broaches.

6.7.1 Sequence 5.1.1: MCS with V2G on the Weak Network

Table 6-15: Sequence Set 5 (Weak Network) Supportable EVs as Traffic Lights

Weak Network (MCS, V2G, Winter)		
	Seq_1.1.1	Seq_5.1.1
19mpd	**20 (B)**	**20 (B)**
27mpd	**10 (B)**	**20 (B)**
38mpd	**0 (B)**	**20 (B)**
49mpd	**10 (B)**	**10 (B)**

Progress halted due to (B) = broach, (c) = excessive clamps, (S) = severe undercharging

RAG Colourisation: Red: <= 40, Amber: 60 - 80, Green: >= 100

Observations: 27 and 38 mpd are lifted (Table 6-15). MCS + V2G offers progress, but remains inadequate; broaches arise (Figure 6-16) as individual EVs force charging e.g. when they must away / time is short.

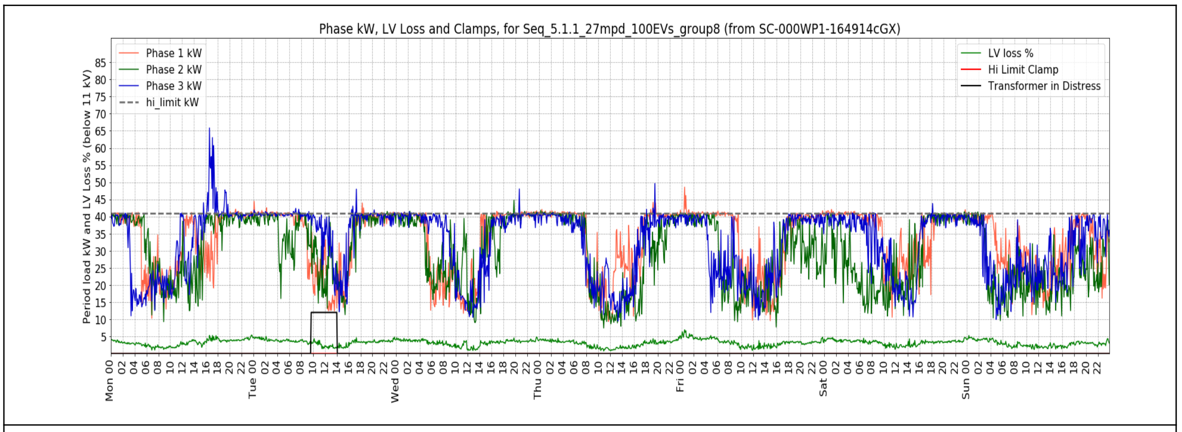


Figure 6-16: Seq_5.1.1 Unclamped EVs ignore MCS and tear-through the hi_limit

6.7.2 Sequence 5.1.2: MCS with V2G on Typical Network

Table 6-16: Sequence Set 5 (Typical Network) Supportable EVs as Traffic Lights

Typical Network (MCS, V2G, Winter)					
			ResLoad Down	**ResLoad Up**	**DRFFR**
	Seq_1.1.2	Seq_5.1.2	Seq_5.1.2.1	Seq_5.1.2.2	Seq_5.2.2
19mpd	**20 (B)**	**80 (B)**	**140**	**40 (B)**	**80 (B)**
27mpd	**10 (B)**	**60 (B)**	**120 (B)**	**40 (B)**	**60 (B)**
38mpd	**0 (B)**	**40 (B)**	**80 (B)**	**20 (B)**	**60 (B)**
49mpd	**10 (B)**	**40 (B)**	**60 (B)**	**10 (B)**	**40 (B)**
	FFR + Agg ToU	**DRBFFR + StatBatt**	**DRCFFR + StatBatt**	**Remove V2G**	**Agg ToU**
	Seq_5.3.2	Seq_5.4.2	Seq_5.5.2	Seq_5.6.2	Seq_5.7.2
19mpd	**-- (S)**	**140**	**140**	**60 (B)**	**80 (B)**
27mpd	**-- (S)**	**80 (B)**	**120 (B)**	**20 (B)**	**60 (B)**
38mpd	**-- (S)**	**80 (B)**	**80 (B)**	**20 (B)**	**10 (S)**
49mpd	**-- (S)**	**60 (B)**	**60 (B)**	**20 (B)**	**10 (S)**

RAG Colourisation: Red: <= 40, Amber: 60 - 80, Green: >= 100

Observations: Seq_5.1.2 in Table 6-16 shows MCS assists at all mpd, but still cannot reach parity. N EV uplifts vs. Seq_1.1.1 are seen, in the range of 60 to 30 EVs.

6.7.3 Sequence 5.1.2.1: As 5.1.2 with Lower Residential Loads

Residential loads are scaled to 1 kW from 1.3 kW per house. This improves N EV substantially, with 19 mpd EVs (city dwellers) fully served.

6.7.4 Sequence 5.1.2.2: As 5.1.2 with Higher Residential Loads

Household loads are raised to 1.6 kW from 1.3 kW; supportable N EV halve.

Observations: 5.1.2.1, 5.1.2.2 together show that headroom limitations are the deciding factor; even modest changes sway supportable EV numbers. This suggests that initiatives to lower household loads would benefit EVs.

Note: Sequence 5.1.3 *is at the end of Set 5, in Section 6.7.11.*

6.7.5 Sequence 5.2.2: As 5.1.2 with DRFFR

The DRFFR signal (as DRB-FFR) is applied, giving a small improvement in N EV which was not expected, for DR reduces weekly (available) kWh. How are more EVs supportable? The spreadsheet “MetaMeta2.3_Seq_5.2.2.xlsx” sheet “Meta-Ref” (which subtracts 5.1.2 values from 5.2.2 values) show that like-for-like V2G activity is higher in 5.2.2. The author suspects a form of “annealing” (injection of random jitter, as in magnetic tape recording and heat-treating) helps. Or, this may be a lacunae of simulation. The “Meta-Ref” sheet shows AFH charging drops, that the network is more loaded, and that early broaches have dropped for 7 plies.

Observations: An unexpected improvement; it is not immediately apparent why.

6.7.6 Sequence 5.3.2: As 5.1.2 with FFR and Agg ToU (DSR)

An Aggregator operating in the blind performs a Demand Reduction role via a Time of Use (ToU) signal i.e. mimics the DR element by commanding EV charging activity:

- 1pm - 6pm: no charging or dispatch
- 6pm - 11pm: charging allowed for EVs < 33% SOC (V2G dispatch permitted)
- 11pm on: unconstrained.

Severe undercharging is provoked, similar to Sequence Set 4. Figure 6-17 broaches at 11pm and on morning departure. Also, in Figure 6-17 below, phase 1 (red) is repeatedly affected showing the existence of repeatable bias arising from a small dataset.

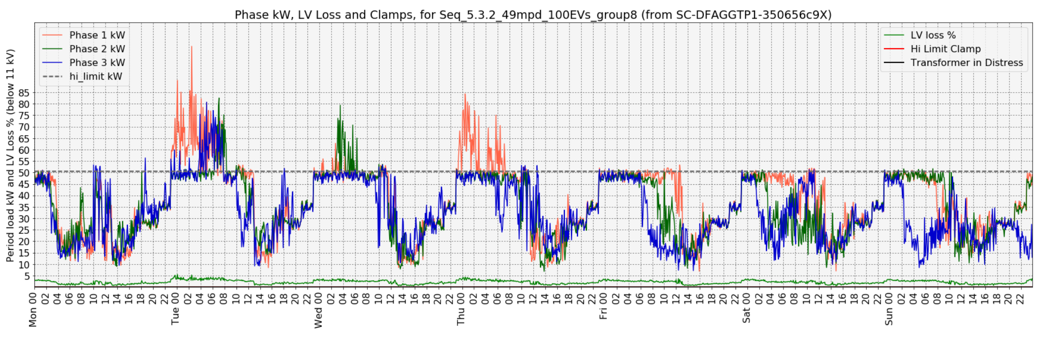


Figure 6-17: Seq_5.3.2 EVs tear-through once Aggregator control lifted @ 11pm

Observations: Again, blind Aggregator control is not useful to EVs.

6.7.7 Sequence 5.4.2: As 5.2.2 with Static Batteries

Three V2G EVs per phase mimic Static Batteries (150 kWh), have no trips and are set to charge last, dispatch first (vs. other EVs). DR-B Demand Reduction is present.

The improvement over 5.2.2 is clear and attributable to the Static Batteries. A spot check shows the Static Batteries delivered an average of 14 kWh per week vs. V2G EVs 11 kWh.

Observations: Static Batteries help plus ease duties on V2G EVs, reducing EV costs.

6.7.8 Sequence 5.5.2: As 5.4.2 with Winter PV

The Bias system injects up to 2 kW per home, following PV Winter insolation for the week.

Observations: N EV was improved for parity, as was undercharging. A small reduction in network losses was seen. PV helps in Winter.

6.7.9 Sequence 5.6.2: As 5.1.2 less V2G

V2G EVs are made SV1G types, so accept MCS commands but cannot dispatch. A loss of c. 20 EVs capability at all mpd occurs.

Observations: V2G is immediately missed hence delivers benefit.

6.7.10 Sequence 5.7.2: As 5.1.2 with 1 in 4 EVs Agg ToU Control

Every 4th EV has blind Aggregator control, using 5.3.2's ToU pattern. There is no DRFFR. As seen for other Aggregator ToU schemes, severe undercharging rises to unacceptable levels, reducing the utility of the method.

Observations: This reiterates severe undercharging threat from Aggregators.

6.7.11 Sequence 5.1.3: MCS with V2G on the Strong Network

A repeat of Seq_5.1.2 but set on the Strong network (2 kW built per house), Table 6-17.

Table 6-17: Sequence Set 5 (Strong Network) Supportable EVs as Traffic Lights

Strong Network in Winter		
		MCS, V2G
	Seq_1.1.3	Seq_5.1.3
19mpd	**80 (B)**	**140**
27mpd	**80 (B)**	**140**
38mpd	**60 (B)**	**140**
49mpd	**40 (B)**	**120 (B)**

Progress halted due to (B) = broach, (c) = excessive clamps, (S) = severe undercharging

RAG Colourisation: Red: <= 40, Amber: 60 - 80, Green: >= 100

Observations: Almost a clean sweep; MCS with V2G is very successful at 2 kW build.

6.7.12 Sequence Set 5 Summary Observations

1. The following were **not useful**:
    - Aggregator ToU commanded actions: lifted severe undercharging (e.g. 5.7.2)
2. and the following **were useful**, in most to least effective order:

  - MCS, especially
  - with added V2G and / or Static Batteries, and
  - added local PV;
  - the FFR component of DRFFR (e.g. 5.2.2)
  - DR-C over DR-B i.e. to use a lowered depth of Demand Reduction.
3. MCS lowers severe undercharging; 5.2.2 vs 2.1.2 shows 1:4 reduction ratio.
4. The system is sensitive to residential loads; 300 W load reduction per house lifting 27mpd N EVs from 60 to 120; an increase of 300 W reduced 27mpd 60 EVs to 40.
5. 5.1.3 suggests reinforcements to lift ADMD to 2 kW is useful.
6. MCS commanding V2G and Smart EVs is near practical; however there are broaches - MCS cannot constrain dumb EVs; clamps are necessary.

6.8 Sequence Set 6: Local MCS Control with Clamps

Set 6 explores a Managed Charging System with clamps to limit broaches, a possible system for real-world deployment. EV mix is 19% dumb, 48% SV1G, 33% V2G and clamps use C2CT priority. Set 6 includes 22 sequences.

In an ideal world:

- all EVs are charged
- DR and FFR services can be offered, and
- the DNO can manage the network to best advantage, meaning the net system:
  - meets network load limits
  - meets voltage limits
  - minimises LV system losses.

In practice, these factors compete. The intent is to discover:

- the impact on EV charging when
- various grid services are active.

Occasionally there are similar sequences with a variable changed, to assess impact. For example, modifying DR changes the kWh EVs can access. Two forms of DR are used, DR-B and DR-C (DR-B is the default). DR-C has half the demand reduction of DR-B.

6.8.1.1 Set 6 Summary Observations

The Strong 2 kW network with MCS scores perfectly, even with MCS DR and FFR services.

For the Typical 1.5 kW built network, Aggregator imposed remote Time of Use commands continue to provoke problems - but in Winter, not Summer. V2G is certainly useful, the best form being PreBurn (which proactively lifts headroom as against retaining V2G to offset overloads), especially aided by Static Batteries paired with local PV panels.

Note that local MCS's DR can effectively mimic Aggregator DSR, while reducing the severe undercharging problems and overload problems of Aggregator DSR.

From this it can be seen, from a DNO view:

- use MCS and clamps
- if network is under 2 kW built, an aid may be Static Batteries and PV,
- yet each built network remains a special case.

If reinforcement of weak sections allows a 2 kW plus per house capability, this is advised.

6.8.2 Simulations in Sequence Set 6

Set 6 looks at variations based around MCS with clamps. The standard configuration has C2 clamping, 19% of fleet as dumb EVs, 48% as SV1G and 33% as V2G units. The variations considered are shown in Table 6-18 below:

Table 6-18: Degrees of Freedom in Sequence Set 6

Degree of Freedom: / Sequence:	6.1.2	6.1.3	6.1.3.1	6.2.2	6.2.2.1	6.2.2.2	6.2.2.3	6.2.2.4	6.2.2.5	6.2.2.9	6.3.2	6.3.2.1	6.3.2.2
EV Mix default is: 19% dumb, 48% SV1G, 33% V2G						allD							SV1
MCS + clamps (CT is standard)	C2	C2	C2	C2	C2	C2	C2	C2	C2	C2	C2	C2	C2
DR mode		B	B	B	B	B	B	B	B	B	B	B	B
FFR		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
V2G mode: PreBurn_V2G, No Preburn, Saver	P	P	P	P	N	P	S	P	P	P	P	P	P
Static Batteries & Agg Control (charging 9:30am - 3pm)						9							
Aggregator Control											Agg		
MCS hi_limit setpoint adjust (default 49 kW)													
Alt residential dataset								Alt					
Summer operation												S	S
Preheat EV									Y	Y			
HP			20%										
PV													
N EV boost										+10%			

Degree of Freedom: / Sequence:	6.3.2.3	6.3.2.4	6.4.2	6.7.2	6.8.2	6.9.2.1	6.9.2.2	6.10.2	6.11.2	6.12.2	6.13.2
EV Mix default is: 19% dumb, 48% SV1G, 33% V2G								SV1			
MCS + clamps (CT is standard)	C2	C2	C2	C2	C2	C2	C2	C2	C2	C2	C2
DR mode			B	B		C	C	C	C	C	C
FFR	Y	Y	Y								
V2G mode: PreBurn_V2G, No Preburn, Saver	P	P	P	P	P	N	P	P	P	P	P
Static Batteries & Agg Control (charging 9:30am - 3pm)									9	9	9_Agg
Aggregator Control		Agg	Agg/4								Agg
MCS hi_limit setpoint adjust (default 49 kW)					39	40	40	40	24	32	39
Alt residential dataset											
Summer operation	S	S									
Preheat EV											
HP											
PV											PV
N EV boost											

Keys:

- **EV mix**: e.g. making all Dumb, converting all V2G to SV1G types
- **DR**: as DR-B, DR-C or none,
- **FFR**: as standard repeating pattern or off,
- **V2G modes**: PreBurn (V2G aid support headroom), No PreBurn (only aids overloads) and Saver mode in which V2G spend is reduced by allowing clamps to operate more often;
- **Static Batteries**: Off, or with PV with a scheme to limit SB charging to daytime only. The count is the number of static batteries: 9 batteries i.e. 3 per phase;

- **Aggregator Control**: none, all vehicles, only 1 in every 4
- **MCS setpoint for hi_limit**: default 49 kW adjusted to 24, 32, 39 or 40 kW
- **Residential dataset**: default is Winter, or Alternative Winter or Summer
- **Preheat EV** (cabin and battery): raises battery temperature to 8°C allowing improved charging at a cost of +300 W load. At 42 minutes before departure cabin heating (400 W) is turned on. NB values are not known real-world, as no data is available.
- **HP/Heat Pumps**: by % of houses (default: 0%)
- **PV panels**: 2kW per home. Insolation follows recorded Sheffield Solar data.
- **N EV boost**: uplifts numbers to mimic visitors; +10% implies 40 EVs are actually 44.

Results traffic-lights are shown in Table 6-19, Table 6-22, Table 6-23, and Table 6-24.

Table 6-19: Sequence Set 6-A (Typical Network) Supportable EVs as Traffic Lights

		DRFFR	V2G PreBurn OFF	StatBatt	BnSv StatBatt
	Seq_6.1.2	**Seq_6.2.2**	**Seq_6.2.2.1**	**Seq_6.2.2.2**	**Seq_6.2.2.3**
19mpd	**140**	**140**	**60 (c)**	**60 (c)**	**80 (c)**
27mpd	**140**	**120 (c)**	**60 (c)**	**40 (c)**	**60 (c)**
38mpd	**140**	**80 (c)**	**40 (c)**	**40 (c)**	**40 (c)**
49mpd	**100 (S)**	**20 (S)**	**40 (c)**	**40 (c)**	**-- (S)**
cf	*primary*	*6.1.2*	*6.2.2*	*6.2.2*	*6.2.2.2*
			DRFFR +	DRFFR +	
	Alt Winter	DRFFR + PreHeat	PreHeat + 10pc	Agg ToU	
	Seq_6.2.2.4	**Seq_6.2.2.5**	**Seq_6.2.2.9**	**Seq_6.3.2**	
19mpd	**140**	**120 (c)**	**100 (c)**	**-- (S)**	
27mpd	**100 (c)**	**80 (c)**	**60 (c)**	**-- (S)**	
38mpd	**60 (c)**	**60 (c)**	**40 (c)**	**-- (S)**	
49mpd	**20 (S)**	**-- (S)**	**-- (S)**	**-- (S)**	
cf	*6.1.2*	*6.2.2*	*6.2.2.5*	*6.2.2*	

Progress halted due to (B) = broach, (c) = excessive clamps, (S) = severe undercharging

RAG Colourisation: Red: <= 40, Amber: 60 - 80, Green: >= 100

6.8.3 Seq_6.1.2: MCS Control With Clamps

This sequence (Table 6-19) adds clamps to 5.1.2.

Observations: 6.1.2 has a near perfect score. Only 49mpd cannot support 140 EVs. This appears to be a practical system.

Note: *6.1.3 Strong network results are placed after Typical results, see 6.8.28.*

6.8.4 Seq_6.2.2: MCS Control, Clamps, DRFFR

Purpose: DRB-FFR is added to 6.1.2 (Table 6-19).

Observations: DRFFR continues to reduce the ability to support EVs from 27mpd and over; see also Seq_6.7.2. Across Set 6 simulations, the PEH DRFFR metric shows capability rising with load, ranging from 74% (parity) to 98% (maximum load, Table 6-20). **Note** that these measure % of week with Pearson's r response > 0.3 (Figure 6-10).

6.8.5 Seq_6.2.2.1: MCS Control, Clamps, DRFFR, No PreBurn

Purpose: V2G mode change: pre-emptive Burn_V2G OFF i.e. V2G only supports overloads.

Observations: Compared to 6.2.2 there is a noticeable loss of ability to support EVs, due to a rise in clamping i.e. EVs are not being charged and are attempting to force the issue, hence clamping increases. In 6.2.2, V2G PreBurn is used to uplift headroom before allocating charging. In 6.2.2.1, V2G only aids control of overloads. This shows the value of V2G: in 6.2.2 with PreBurn, 27mpd N EV is 120 but in 6.2.2.1 only 60 without PreBurn.

Table 6-20: Sequence 6.2.2 PEH metrics

N_EV=	10	20	40	60	80	100	120	140
19mpd	32.7%	35.1%	41.7%	49.4%	57.1%	67.3%	71.4%	78.0%
27mpd	31.5%	35.7%	44.6%	53.6%	66.7%	73.8%	81.0%	88.1%
38mpd	32.1%	36.9%	45.8%	59.5%	72.6%	79.2%	86.9%	94.6%
49mpd	31.5%	36.9%	49.4%	62.5%	75.6%	82.1%	89.9%	98.2%

from MetaMeta2.3_Seq_6.2.2.xlsx "Compare Metas" sheet, rows 229-233

6.8.6 Seq_6.2.2.2: Dumb EVs, MCS, Clamps, DRFFR, Static Bats

Purpose: 3 Static Batteries per phase replace V2G. All EVs are dumb.

Observations: Compared to 2.1.2 there is improvement in clamp counts, severe undercharging and DRFFR response.

6.8.7 Seq_6.2.2.3: MCS, Clamps, DRFFR, V2G Saver

A method to apportion V2G use and clamps (to limit V2G battery damage) was attempted. The method raised N EV for 19mpd but harmed higher mpd.

Observations: Viable in city only; aids 19mpd at expense of 38mpd and on.

6.8.8 Seq_6.2.2.4: MCS, Clamps, DRFFR, Alt_Winter

As 6.2.2 with residential loads for week starting 18th March 2013 (not 11th), adjusted to match weekly kWh consumption of the 11th; only residential load timing is changed.

Observations: Supportable EV numbers over 19mpd dropped drastically. This implies that residential load timings and exact demand levels are factors which impact the number of EVs the network can support.

6.8.9 Seq_6.2.2.5: MCS, Clamps, DRFFR, Winter Pre Heating

EVs batteries are heated to 8°C (giving C = 0.88 *C-rated*, vs. C = 0.57*C-rated* @ 1°C, an uplift of +54% C) when not charging. External ambient is 1°C. The passenger cabin is also preheated before departure.

Note: Data on the prevalence of preheating loads is not available; the author made “reasonable guesses” (battery heater: c. 300 W, cabin heater, 400 W for 3/4 hour).

Observations: Preheating allows EVs to take on more load, which means fewer EVs can be supported. AFH charging instances approximately halve, which impacts the ratio of Winter to Summer AFH chargepoint use:

Table 6-21: Ratio 6.2.2.5 vs. Summer 1.1.2.2 EV AFH N events (weekly averages)

EV N AFH Winter / Summer Ratio	N EV	10	20	40	60	80	100	120	140
	19mpd	6.6	5.8	3.2	3.5	3.7	4.4	4.2	4.2
	27mpd	3.4	3.6	3.1	3.1	3.0	3.3	3.5	5.0
	38mpd	2.6	2.5	2.5	2.4	2.5	2.7	3.3	5.4
	49mpd	2.4	2.3	2.3	2.2	2.3	2.5	3.4	4.7

The ratio has dropped from 8.11 to 3.3 (see Table 6-8) with a worst:least span (19mpd 10 EVs to 49mpd 140 EVs) of: 22.3:4.4. With heated batteries this becomes: 6.6:4.7.

6.8.10 Seq_6.2.2.9: 6.2.2.5 with 10% Uplift in EV Numbers

The author considered the mid-week drop in “overnight stayers at home” to be a problem so trialled a correction: simulate with +10% extra EVs per ply.

Observations: supportable EVs drop c. 20%. This needs further investigation with a simulator able to control overnight stay EV numbers.

6.8.11 Seq_6.3.2: MCS, Clamps, DRFFR, Agg ToU DR

The intent is to replicate DR via Aggregator Time of Use commands (detailed in 6.6).

Observations: Again Aggregator Time of Use control induces severe undercharging.

Note: 6.3.2.1, .2, .3 and .4 are set in Summer. Residential load per week is down c. 1,870 kWh. Assuming 2/3rds of this kWh are available over 10 hours per day, then for 100 houses this adds headroom of 1,200 / 100 / 10 / 7 = 171 W per home.

Over a week, an unregulated 27mpd EV uses 23.5 kWh less from the battery (drawing 27 kWh less from the socket) i.e. 3.9 kWh less a day or about 390 W during a possible connect period. This implies there is c. 560 W extra headroom per home for charging.

Table 6-22: Sequence Set 6-B (Typical Network) Supportable EVs as Traffic Lights

	Summer DRFFR	**Summer DRFFR +**	**Summer FFR**	**Summer FFR**	**DRFFR +**
		No V2G		**Agg ToU**	**Agg ToU 1 in 4**
	Seq_6.3.2.1	Seq_6.3.2.2	Seq_6.3.2.3	Seq_6.3.2.4	Seq_6.4.2
19mpd	**140**	**140**	**140**	**140**	**140**
27mpd	**140**	**140**	**140**	**140**	**120 (cS)**
38mpd	**140**	**120 (c)**	**140**	**60 (S)**	**10 (S)**
49mpd	**140**	**100 (c)**	**120 (S)**	**-- (S)**	**-- (S)**
cf	*primary*	*6.3.2.1*	*6.3.2.4*	*6.3.2.1*	*6.2.2*
			hi_lim 40 kW	**hi_lim 40 kW**	**hi_lim 40 kW**
			DRCFFR	**DRCFFR**	**DRCFFR**
	DR only	**hi_lim 40 kW**	**Pre V2G Off**	**Pre V2G On**	**No V2G**
	Seq_6.7.2	Seq_6.8.2	Seq_6.9.2.1	Seq_6.9.2.2	Seq_6.10.2
19mpd	**140**	**140**	**60 (c)**	**120 (c)**	**60 (c)**
27mpd	**140**	**100 (c)**	**60 (c)**	**80 (c)**	**40 (c)**
38mpd	**100 (c)**	**80 (c)**	**40 (c)**	**60 (c)**	**20 (c)**
49mpd	**80 (c)**	**60 (c)**	**20 (c)**	**40 (c)**	**-- (S)**
cf	*6.2.2*	*6.1.2*	*6.9.2.2*	*6.8.2*	*6.9.2.1*

Summer: Yellow Title Background, Winter: White

6.8.12 Seq_6.3.2.1: Summer MCS, Clamps, DRFFR

These are variants of 6.3.2 set in Summer (Table 6-22). 6.3.2 with Aggregator DSR could not support any EVs due to severe undercharging. 6.3.2.1 supports 140 EVs for all mpd (Figure 6-18).

Observations: With reduced EV and residential demands, severe undercharging moderates and is no longer an issue. This is predominantly a thermal affect.

At face value a 17°C shift mimics a 560 W headroom shift i.e. about 33 W per degree. It is most unlikely that this is linear.

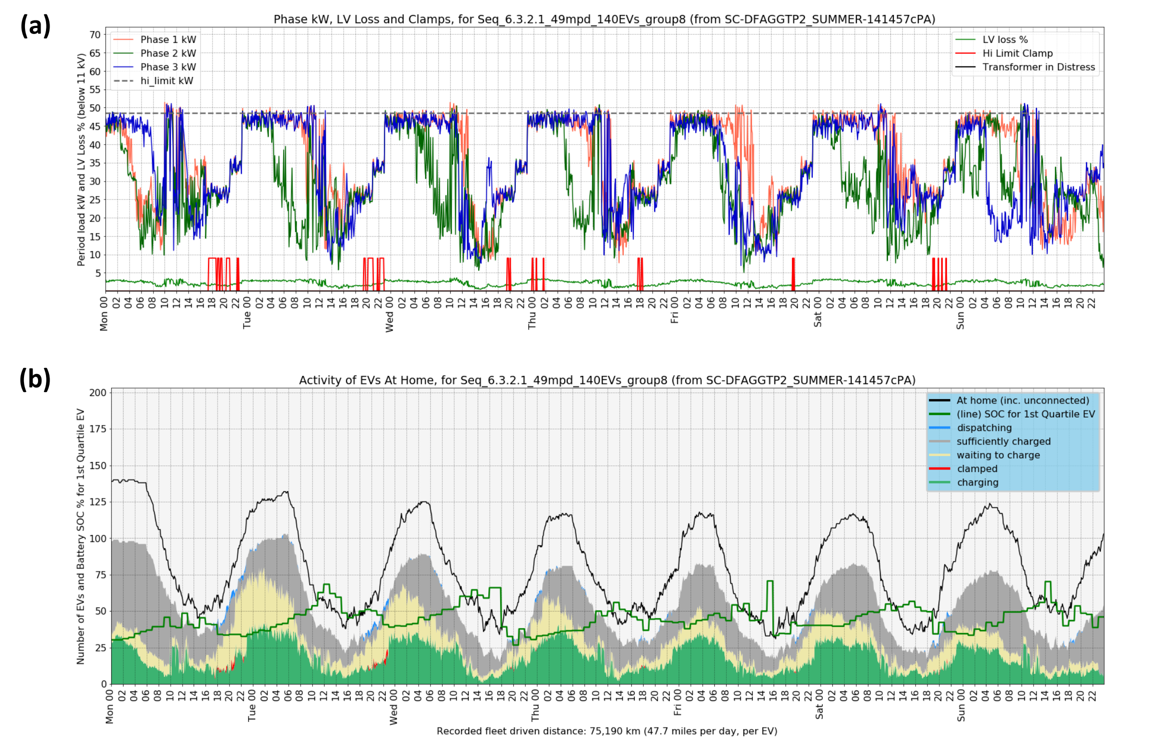


Figure 6-18: Seq_6.3.2.1 Feeder load and EV CICD plots for 49mpd 140 EVs

The issue requires further research with other ambient temperatures being investigated.

6.8.13 Seq_6.3.2.2: MCS, Clamps, No V2G, DRFFR in Summer

Is V2G needed in Summer? Investigate by replacing V2G with SV1G.

Observations: The lack of V2G is felt at 38 and 49mpd, with clamps becoming prevalent from 120 and 100 EVs respectively.

6.8.14 Seq_6.3.2.3: Summer MCS, Clamps, FFR

(out of order: 6.3.2.4 precedes) Remove Aggregator ToU signalling from 6.3.2.4.

Observations: The 38 and 49mpd plies immediately improve sans ToU control.

6.8.15 Seq_6.3.2.4: Summer MCS, Clamps, FFR, Agg ToU

All EVs are Aggregator controlled; hi_limit modulation is by FFR only.

Observations: Again, Aggregator control degrades performance, provoking severe undercharging at the higher mpd’s.

6.8.16 Seq_6.4.2: MCS, Clamps, DRFFR, 1 in 4 Agg DR

This considers every 4th EV being Aggregator controlled. Compare to 6.2.2 and 6.3.2.

Observations: Severe undercharging rises over 27mpd. Individual EVs are being constrained for charge; this includes V2G EVs so others suffer their charge loss.

This sequence highlights that it would be useful to be able to partition or segregate the results analysis, so that Aggregator controlled EVs can be separated from others.

6.8.17 Seq_6.5.2: Withdrawn

6.8.18 Seq_6.6.2: Withdrawn

6.5.2 and 6.6.2 utilised a Hybrid control mode; it is not clear this operated as intended.

6.8.19 Seq_6.7.2: MCS, Clamps, DR-B without FFR

This sequence assesses if the FFR element of DR causes undercharging, the FFR element of control is removed. Compare with 6.2.2.

Observations: System performance is midway between Seq_6.1.2 and 6.2.2. The drop vs. 6.1.2 appears due to the DR element, and rise vs. 6.2.2 due to removing the FFR's -5% offset, necessary to permit a ±5% FFR range.

6.8.20 Seq_6.8.2: MCS, Clamps, 40 kW Hi_limit

Investigate losses reduction strategy: lowered hi_limit (no DRFFR).

Observations: 6.1.2 experienced 345 kWh (347 kWh inc. V2G) parity losses; 6.8.2 losing 328 kWh (406 kWh inc. V2G). Lowering the hi_limit provoked V2G activity. Overall more energy is lost, but DNO sees reduced losses. It is unknown what Ofgem may think of this.

6.8.21 Seq_6.9.2: Withdrawn

Misconfiguration was identified in post processing. Rerun as 6.9.2.2.

6.8.22 Seq_6.9.2.1: DR-CFFR, 40 kW hi, PreBurn V2G Off

(logically Seq_6.9.2.2 precedes) Disable pre-emptive V2G uplift of headroom. V2G now supports mandatory charging EVs when total kW > hi_limit i.e. unclamped mandatories. Beyond this EVs are clamped, not fed V2G as they would be in 6.9.2.2.

Observations: The loss of PreBurn is seen: supportable N EV drops. V2G PreBurn is useful.

6.8.23 Seq_6.9.2.2: DR-CFFR, 40 kW hi, PreBurn V2G On

Purpose: Similar to 6.8.2 but with DR-CFFR. Uses less aggressive DR signal "DR-C".

Observations: Adding DR-CFFR lowers supportable N EV vs. 6.8.2.

6.8.24 Seq_6.10.2: As 6.9.2.2 with V2G Removed

See Table 6-22. SV1G vehicles replace V2G.

Observations: N EV rates halved (ceased for 49mpd), showing V2G has benefits.

Table 6-23: Sequence Set 6-C (Typical Network) Traffic Lights results

	hi_lim 24 kW	hi_lim 32 kW	hi_lim 39 kW
	DRCFFR	DRCFFR	2kW PV DRCFFR
	StatBatts	StatBatts	StatBatts
	Seq_6.11.2	Seq_6.12.2	Seq_6.13.2
19mpd	-- (S)	60 (c)	140
27mpd	-- (S)	60 (c)	140
38mpd	-- (S)	20 (S)	120 (c)
49mpd	-- (S)	20 (S)	100 (c)
cf			*6.1.2*

Progress halted due to (B) = broach, (c) = excessive clamps, (S) = severe undercharging

RAG Colourisation: Red: <= 40, Amber: 60 - 80, Green: >= 100

6.8.25 Seq_6.11.2: MCS, DR-CFFR, 9 SB, 24 kW Hi_limit

Observations: No useful N EV; severe undercharging collapsed all EV use to zero.

6.8.26 Seq_6.12.2: MCS, Clamps, DR-CFFR, 9 SB, 32 kW hi_limit

Observations: Unacceptable reductions in N EV; the hi_limit reduction is too severe.

6.8.27 Seq_6.13.2: Winter PV, DR-CFFR, 9 SB, 39 kW hi_limit

With MCS and clamps. 2kW PV generation per home is added; by themselves these have little impact as the Sun shines when most EVs are away. This sequence adds 3 Static Batteries (SB) per phase with Aggregator control of the SB only. This control restricts the SB in such a way as they may charge as they wish between 9:30am and 4:30pm (i.e. sun-up), at other times they can dispatch but may only charge when below 33% SOC.

Note that the hi_limit is reduced to 39 kW, which allows comparison to 6.9.2.2; also DR-C FFR is available offering network value-added services.

Observations: 6.13.2 is the most capable in overall performance to date, although slightly down from ideal at 38mpd (120 EVs) and 49mpd (100 EVs). A major win has been losses, now at 240 kWh vs. 6.1.2's 345 kWh. V2G duty is high at 150 kWh. However, Static Battery costs may outweigh any advantages.

6.8.28 Seq_6.1.3: MCS Control, Clamps, DRFFR

Table 6-24: Sequence Set 6 (Strong Network) Supportable EVs as Traffic Lights

Strong Network in Winter		
		MCS, V2G
	Seq_1.1.3	Seq_5.1.3
19mpd	**80 (B)**	**140**
27mpd	**80 (B)**	**140**
38mpd	**60 (B)**	**140**
49mpd	**40 (B)**	**120 (B)**

Strong Network (MCS, V2G, Clamps)		
	DRBFFR	DRBFFR + 20% HP
	Seq_6.1.3	Seq_6.1.3.1
19mpd	**140**	**140**
27mpd	**140**	**120 (c)**
38mpd	**140**	**60 (c)**
49mpd	**140**	**-- (S)**

Seq_1.1.3 and 5.1.3 included for reference.

On a 2 kW "Strong" built system, MCS with clamps (Table 6-24) supports all plies while performing DR-B and FFR. The FFR responsiveness for the parity case indicated that FFR control was possible for c. 53% of hours in the week.

Observations: This appears to be a workable system.

6.8.29 Seq_6.1.3.1: MCS Control, Clamps, DRFFR, 20HP

Figure 6-19 below shows Feeder and CICD plots. V2G activity (blue) c. 5 - 7am supports HP. Demand to mimic 20 Heat Pumps (20% houses) and Auxiliary heating are added to 6.1.3. HP loads are timed Bias loads added to each house from c. 3am onwards, plus a raised residential load to mimic kW used for extra water and cooking demand.

Observations: HP compromise ability to support EVs. This may be inverted; LV networks installed for HP heated estates are capable of supporting EVs in high numbers (assuming design ADMD 9 kW+ per house). The MCS "moves EV charging" about non-controllable loads, ensuring EVs are supplied. V2G supports the network and other charging EVs.

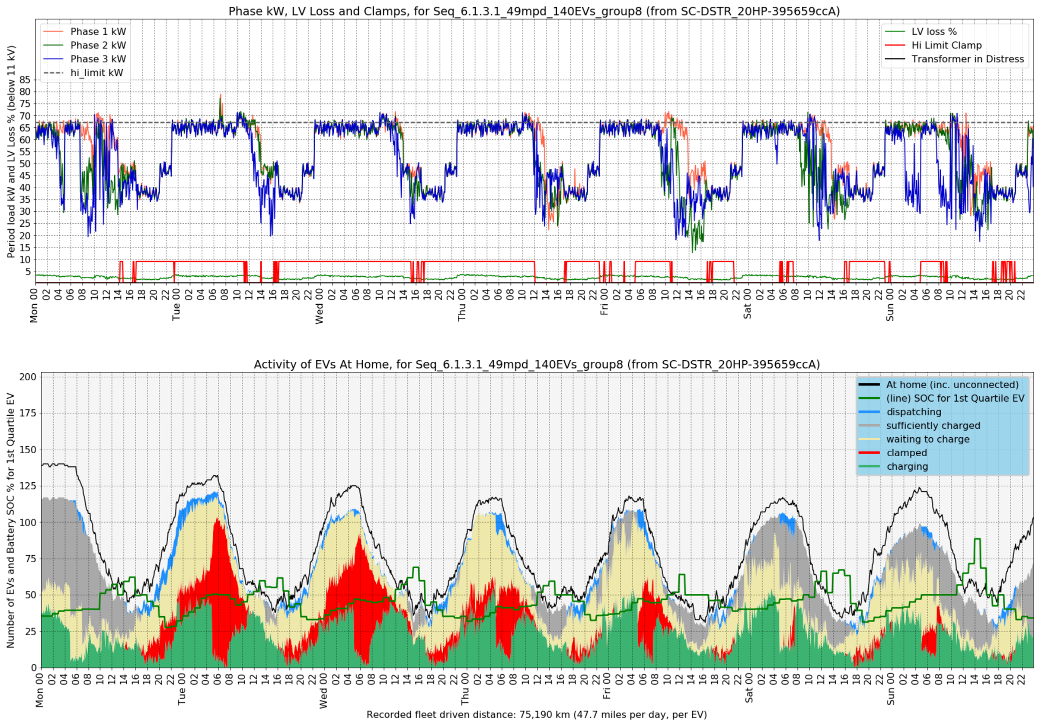


Figure 6-19: Seq_6.1.3.1 Feeder load, EV CICD plots for 49mpd 140 EVs and 20 HP

6.8.30 Sequence Set 6 Summary Observations

Note all sequences possessed at least 18% dumb EVs.

6.8.30.1 Winter Observations

1. The combination of clamps and an MCS is the most practical seen as yet. This is due to:
   - no network issues (broaches or under-volts) as clamps remove excessive loads
   - much improved ability to support N EV for a given situation
   - ability to interwork V2G effectively,
   - especially with Static Batteries paired with PV.
2. Heat Pumps cause problems; they are hardly supportable for the networks studied. However a network designed with kW for HP can support EVs with MCS. The network is sensitive to other forms of load e.g. programmed or commanded DR, with the lower demands of DR-C allowing improved charging vs. pattern DR-B.
3. V2G assists the local network
4. residential loads remain significant; high residential demand may cause EVs to suffer undercharging. This can be inverted; initiatives for home load reduction may aid support charging on a marginal network.

5. Preheating EVs (batteries have a 300 W heater, plus a 400 W cabin heater turned on 42 minutes before departure). These lower N EV (6.2.2.5), however AFH charging is reduced plus a slight rise in severe undercharging. A saturated network expending energy for cabin and battery heating implies less kWh into batteries.
6. Aggregator control (6.4.2) if blind has major disadvantages and no benefits on a constrained network.
7. DR sans FFR in 6.7.2 suggests FFR makes little difference vs the impact of DR-B.
8. Lowered hi_limit reduces DNO attributable losses, yet raises V2G losses (6.8.3).
9. Use of heaters within EV batteries improves the ratio of Winter : Summer AFH (destination) charging, but Winter AFH use may still be x6 greater than Summer.

   This implies that more public charge points remain needed in Winter vs. Summer; without destination charging EVs may become stranded. See 6.8.9.

6.8.30.2 Summer Observations

Clamps with MCS are the most practical combination. This is due to:

10. clamps are needed to halt occasional broaches
11. V2G is still needed
12. the FFR element of DRFFR induces severe undercharging for 140 EV @ 49mpd, with proviso: the unexpected outcome from Seq_6.3.2.4 (6.8.15) is not explained.

6.9 Undercharge to Severe Undercharge Correlation

When departing from home, an EV might be correctly charged, undercharged or severely undercharged. Undercharging means the charging goal was missed at the time of departure, and falls into one of 2 categories:

- undercharged: insufficient charge required for foreseeable trips (to the end of the day), and
- severely undercharged: insufficient charge for the next trip including return home. To get home, the driver <u>must</u> AFH charge. If not possible, the EV will be stranded.

Are there precursors to warn of severe undercharging? The likely candidate is undercharging counts. Data (from the viable sequences) for severe undercharging vs. undercharged-on-depart was gathered and plotted on the x-y scatter plot, Figure 6-20.

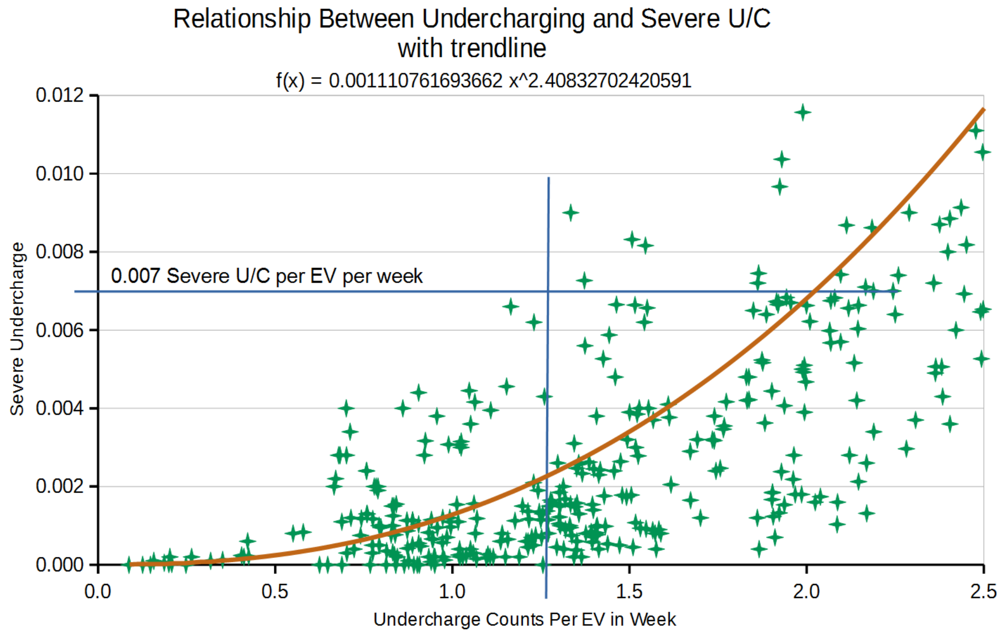


Figure 6-20: Relationship between Undercharging and Severe Undercharging

The intent is to avoid severe undercharging over a 50:50 chance in 10 winters, established as 0.007 severe undercharges per EV per week (section 6.3.5). The vertical blue line, placed by eye, marks a plausible cross-over at 1.25 undercharges per EV per week.

A level is needed for bureaucratic intervention prior to this; a rate of 1 undercharge per EV per week seems reasonable and easy to understand. Other possible precursors are kWh needed for return trip, and departure day and time. However the core data on which an assessment needs be based is not readily available from existing data collections; extra logging is needed of departure EV states vs. trips. The root cause remains: insufficient network available kW. This area needs further consideration.

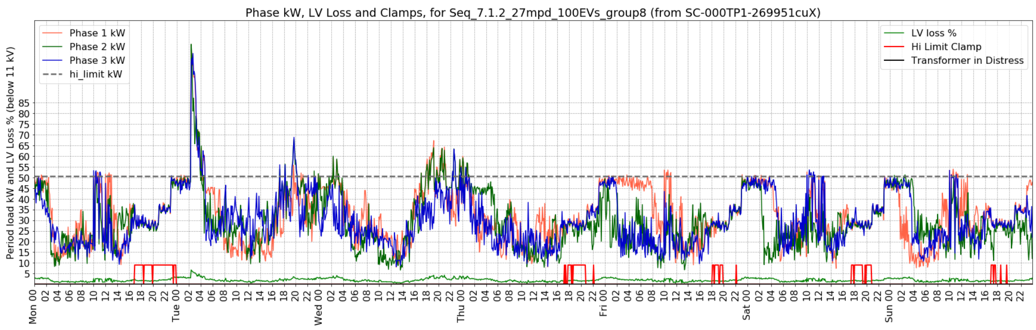
Intervention is suggested for EVs which meet / exceed 1 undercharge per week; perhaps “Get N free AFH charges per week” or discounted charging offer. This could be discovered by data analysis (but who’s data?), the intent being the DNO can discharge their duty to provide a minimum charging capability, by offering recourse to alternative charge sources. The author suggests some form of collaboration with car-park providers. However offering AFH charging (to ease undercharging) likely exacerbates the demands for Winter AFH charging, lifting the challenging ratios seen in Table 6-8.

An alternative is not using the EV (i.e. to work from home) one day a week, to allow the EV to recharge fully through the day.

6.10 Sequence Set 7: Special Situations

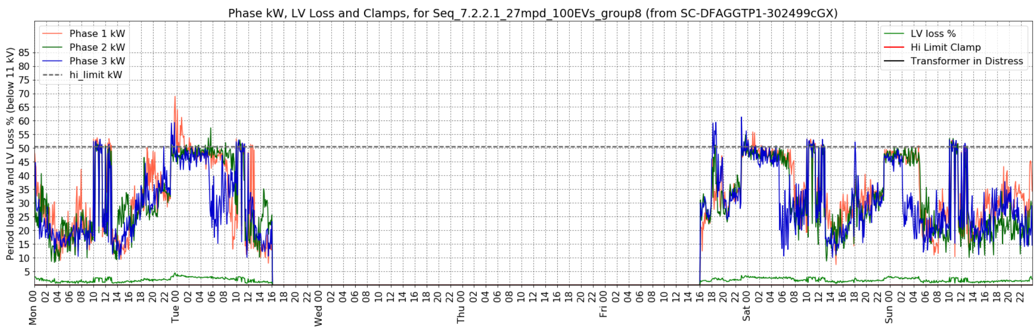
Sequence Set 7 covers situations which are not the norm yet encountered in real life. The author was advised Set 7 was supernumerary for this thesis, yet some results gave concern. Power Fail with Delayed Comms Recovery, Seq_7.1.2.1, (Figure 6-22) exhibits a major (apparently uncontrollable) spike. The scenario is in Winter, with 100 EVs driving 27mpd. Power has failed for an extended period and houses are “cold-soaked”; restart is then a challenge when heat is via Heat Pumps, which likely all go on-load at power restore. Also, EVs are hungry.

(a)



7.1.2 Comms fail Tues 2:24am - Thurs 6:36am. Spike due to no charging constraint

(b)



7.2.2.1 Power fail Tues 4pm - Fri 4pm

Figure 6-21: Comms fail (a) and Power Fail (b) scenarios

The simulations show in Figure 6-21:

(a) an extended communications (comms) failure (Seq_7.1.2)

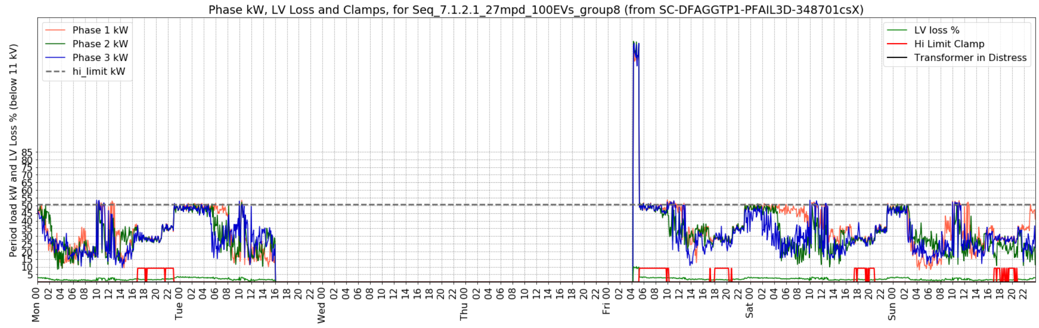
(b) an extended power failure (Seq_7.2.2.1).

The simulations show in Figure 6-22:

(a) power and comms failures together, with the comms networking coming up some time after the power is restored (Seq_7.1.2.1), and

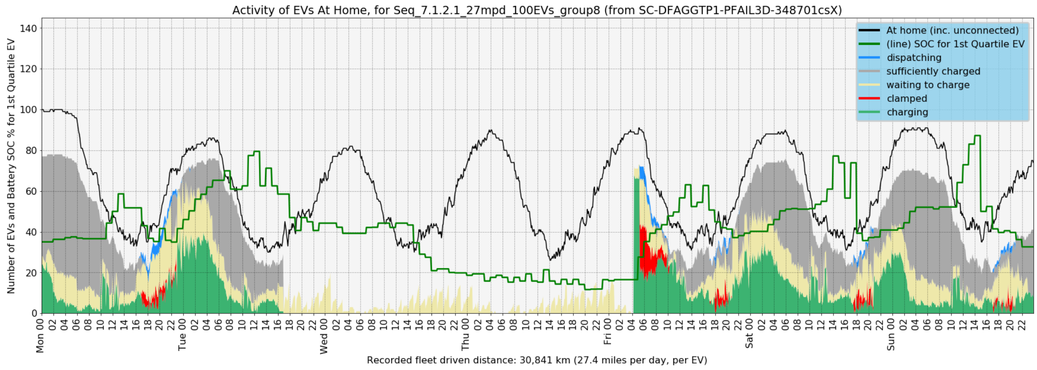
(b) the accompanying EV states for (c) late comms recovery.

(a)



7.1.2.1 Power fail + delayed comms recovery Tues 4pm - power Fri 4:18, comms 5:18am

(b)



CICD plot of EV activity for the above 7.1.2.1 power fail and delayed comms recovery.

Figure 6-22: Power Fail + late comms recovery scenarios

The thinking is comms systems (e.g. cellular telephones) can saturate and may take a period “booting”, so cannot deliver messages. A spike is created, Figure 6-22, (a). As in 7.1.2.1, the EVs charge simultaneously. Seeing power for the first time in days (no doubt the owners have been AFH charging) the EVs crowd-rush the power - there is no comms to say “No”. The situation needs to be managed, as the spike in Figure 6-22 on power-restore will blow fuses and the substation will shut-down.

How might this be managed? Immediately apparent options:

1. no EV charging without comms (some EVSE already do this)
2. EVs may only charge in “limp” mode (e.g. 2 kW) during comms fails
3. reinforce so the transformer can take x4 sustained load rating for many (?) hours
4. fit the substation with a suitable protection system to detect significant overloads, open breakers and reclose (return normal supply) in the region of 1/2 - 1 hour after the event (perhaps interlinked with sensing of comms status).

The first two look like a standards revision; the third is reinforcement.

The fourth option is to fit a protection system, but implies changing the existing (manual) switchgear to a computer controllable unit. While this is cheaper than full BAU reinforcement, it may cost into £10’s k per substation.

The author favours options 2 and or 4 - but neither are the way EVs or the power industry presently work.

Comments from contacts in ENA and EVSE manufacturers indicate that they are aware of the situation above, agree that it is possible and have concern. Further, OLEV concur that comms-less EVSE can offer charge, for to prohibit charging without comms means EVSE cannot operate in comms-less areas e.g. underground, deep rural areas.

6.11 Findings in Précis

Findings are presented as tables, to concisely present a large amount of information.

6.11.1 General

Table 6-25: General Findings - LV Networks

	Description	***Based On***
1.	EV driven mpd effects coincidence, thus ADMD	*Figure 6-6, Figure 6-7*
2.	loadings and EV charging demands differ Winter vs. Summer. Winter is most demanding	*Table 6-4, Table 6-5; Table 6-19, Table 6-22*
3.	⇒ measurements collected in Summer need adjusting to have validity in Winter	*from (2)*
4.	only very strong (NPG now recommend 3.7 kW built per house) systems are likely to cope as-is in Winter	*6.3.4 point 10*
5.	⇒ most LV networks built to deliver under 3.7 kW simultaneously per house need some form of intervention	*from (4)*
6.	broaching can be constrained by EVSE clamps / disconnectors operated from a (data) local MCS	*6.4*
7.	no clamp-less method was free of broaches	
8.	⇒ an MCS with local awareness is needed to manage clamps	*from (6)*
9.	⇒ the same MCS may manage SV1G and V2G i.e. supported "by default" from a suitable MCS controller	*Seq_5: 6.7*
10.	the contribution of the MCS (by time-interleaving EV charging) is c. 10:1 vs. contribution of V2G	*Seq_3: 6.5.1*
11.	V2G assists especially with "PreBurn ON" to lift headroom	*compare 6.9.2.1 vs. 6.9.2.2 in Table 6-22*
12.	LV energy reserves (Static Batteries) assist, esp. with local PV	*cf. Table 6-22 6.9.2.2 vs. Table 6-23 6.13.2*
13.	DR / FFR services by hi_limit modulation is viable (there may be other options). PEH DRFFR metric proportional to EV load;	*Table 6-20*
14.	promoting local load reductions supports the LV network so aids charging	*Table 6-16, 5.1.2, 5.1.2.1, 5.1.2.2*

General Findings - LV Networks ctd.

15.	lowering hi_limit lowers LV losses, but impacts are unclear esp. driving up V2G losses, costs plus unknown Ofgem stance. When N EV is low, a lowered hi_limit may be justified; as EV demands rise the case weakens	*Several in Seq_6 esp. 6.8.27*
16.	LV losses supplying EVs will rise, but an MCS can limit these	*(15)*
17.	comms loss is potentially serious. A form of automated protection with local ICT may be needed at substations	*Figure 6-22, (b)*
18.	a modest population of Heat Pumps (20%) detrimentally affected Strong networks; HP are likely to cause problems on traditional LV systems	*Table 6-24*
19.	⇒ LV systems for HP likely need reinforcement as their loads run for many hours.	*(18)*
20.	Transformer ageing likely accelerated due to increased / sustained peak load profile	*(Scottish Power, 2015, p33)*
21.	Harmonics may need remediation per LV system	*(WPD, 2018d)*

Table 6-26: General Findings - EVs

	Description	***Based On***
1.	Aggregator control applied “blind” can be detrimental	*Table 6-12*
2.	DR regimes may become detrimental: EV capability improved as DR reduced; less Demand Reduction is better from the view of constrained systems	*Table 6-16, Seq_5.4.2 vs. Seq_5.5.2: DRC is less onerous than DRB*
3.	promoting AFH charging reduces EV home need for charge so supports LV networks	*Table 6-10, Seq_2.4.2 vs. 2.5.2, 2.6.2*
4.	severe undercharging may occur; interventions can be applied i.e. a “discounted N full-recharges a week” coupon, issued to EVs experiencing 1 or more undercharges per week	*Section 6.9*
5.	utilisation of AFH (destination) charging is much higher in Winter vs. Summer (x4 to x22); sufficient public charge-points need to be available else EVs are threatened by stranding	*Table 6-8*

6.11.2 Set 1 Findings

Table 6-27: Findings - Set 1 (Uncontrolled)

Network Related

	Description	*Based On*
1.	Broaches proliferate on the Winter Weak 1.2 kW network. No more than 20 EVs @ 19mpd can be supported.	*Table 6-3*
2.	Broaches dominate the Winter Typical 1.5 kW network. The uncontrolled maximums are: 19 mpd: 40, 27 mpd: 20, 39mpd: 20, 49mpd: 20	*Table 6-4*
3.	Summer on Typical network allows 19mpd: 100, 27 mpd: 80, 38 mpd: 60 and 49 mpd: 40 EVs	*Table 6-5*
4.	Supportable N EV is affected by ambient temperature, due to seasonal residential load and EV demand and characteristics changes	*(2, 3)*
5.	The Winter Strong 2 kW network can support 80 EVs up to 27mpd.	*Table 6-6*
6.	Happenstances arise: the Weak network suffered broaches for 10 EVs at 38 mpd but none at 49; randomness is seen	*Table 6-3*
7.	Broaching counts rise with mpd thus location makes a difference: rural areas (longer average mpd) need more kW capacity than city	*(2, 3)*
8.	Variations in fleet (local) mpd due to traffic conditions can impact load	*(7)*
9.	Rural areas suffer before city areas.	*(7)*
10.	Capability assays made in Summer likely need adjusting for Winter	*(2, 3)*
11.	A network useable in December may fail in February i.e. low ambient °C	*(2, 3)*
12.	(11) may be the mechanism discovering a local rise in EV use cf. new car registration plate, 1st March	*(11)*
13.	Cold snaps crossing the country may leave a trail of failed LV systems	*(11)*

EV Related

14.	AFH charging rises in Winter vs. Summer; x 3 .. 8 seen	*Table 6-8*
15.	Gaps below feeder hi_limit kW and load shows EVs are not accessing available network capacity; see Feeder plots and rows 33 - 36 “weekly av. network free / unused kWh” of MetaMeta2.3_Seq_1.1.2.xlsx	*Figure 6-8*

6.11.3 Set 2 Findings

Table 6-28: Findings - Set 2 (Clamps only)

Network Related

	Description	***Based On***
1.	Clamping (in-EVSE disconnectors) stop broaches	*6.4*
2.	Supported EVs now reach 19 mpd: 120, 27 mpd: 100, 39mpd: 80, 49mpd: 60; these are major improvements	*Table 6-10* *Seq_2.1.2.8*
3.	No upper limit to how many clamped EVs can connect; excess remain OFF.	*(1 above)*
4.	clamping + excess vehicles makes undercharging possible (insufficient kWh)	*(3)*
5.	DRFFR degrades capability wiping out all gains *(2.1.2 vs. 2.1.2.8 & 2.1.2.9)*	*Table 6-10*
6.	DRFFR is present in 2.1.2, 2.2.2, 2.3.2, 2.4.2, 2.5.2, 2.6.2 and all suffer from severe undercharging (EV cannot get home next trip) at high mpd. A limit is desired of 50:50 chance of 1 incident per EV in 10 Winters: with 10 Winter weeks pa, limit is 0.007 severe undercharges per EV per week.	*Table 6-10* *6.3.5*
7.	Removing DR element of DRFFR restored the deficit in (5) *(2.3.2.9)*	*Table 6-10*
8.	Weekly clamp counts can run into thousands; at some point customers / Ofgem may object	*6.4.13*
9.	Two hours weekly clamping per phase (clamp count 420) suggested as the limit. N*ote: Clamps counts are MCS view not EV*	*(8)*
10.	Static Batteries support home EV charging *(2.2.2 vs. 2.3.2.2)*	*Table 6-10*
11.	Clamp prioritisation method C2 (by equitable need) marginally better re severe undercharging than C1 (by kW supplied)	*Table 6-10*
12.	C1 has less comms need so simpler to implement than C2	

EV Related

13.	2 hours of clamps on a phase affect an unknown number of EVs (FPB does log statistic)	
14.	Away from Home charging aids home charging (2.4.2 vs. 2.6.2)	*Table 6-10*
15.	suggestion: fight severe undercharging by promoting AFH charging	*(14)*
16.	EVs are not always plugged-in (“Perfect Plugins” - especially AFH - aid charging)	*see CICD plots, Vol 3*

6.11.4 Set 3 Findings

Table 6-29: Findings - *Set 3 (Clamps with V2G)*

Network Related

	Description	*Based On*
1.	No detrimental network impacts (broaches) observed	*Table 6-11*
2.	V2G losses can exceed LV network losses - Ofgem stance? Who has costs?	*6.5.1*
3.	Benefits from Aggregation may be marginal and less effective than modulation of the MCS hi_limit setpoint	*6.5.2.1, (6, 7, 8)*
4.	MCS benefits outperform V2G by c. 10 : 1	*6.5.1*

EV Related

5.	V2G immediately aids EV charging, lifting supported EV counts:	*Table 6-11*
6.	Aggregator remote control with no view of the LV situation expends considerable V2G resource to match the result in (5) with no clear benefit	*6.5.2*
7.	When in hi_limit is managed, the LV system "consumed" the V2G effort (i.e. used power to charge local EVs) with no lowering of load to greater grid	*Figure 6-13* *Tues 02:00*
8.	during periods with many EVs charging, the high-level Aggregation goals (export to greater grid) may not be achievable due to (6)	*(7)*

clamps with	19mpd	27mpd	39mpd	49mpd
no V2G (2.1.2.9)	120	100	80	60
V2G (3.1.2)	140	140	120	100

6.11.5 Set 4 Findings

Table 6-30: Findings - *Set 4 (Aggregator managed)*

Network Related

	Description	*Based On*
1.	The Aggregator is assumed to have no knowledge of instantaneous feeder phase loads at LV level, nor headroom.	
2.	Only the Typical (1.5 kW) network was tested.	

EV Related

3.	Blind Aggregator control caused such high levels of severe undercharging that **no EVs where supportable** i.e. 100% severe undercharging failure rate	*Table 6-12*
4.	metrics show severe undercharging is linked to mpd not N EV	*Note* ***†1***
5.	a V2G case was added; V2G assisted but failed to improve 100% failure rate	*Note* ***†2***
6.	from 3, 4, 5: direct Aggregator control, without local phase situation awareness, is not recommended. Other schemes (e.g. via the MCS rather than direct) may work.	*(3, 4, 5)*

Notes:

†1: see spreadsheet MetaMeta2.3_Seq_4.1.2, “CompareMetas”, rows 242-245

†2: see spreadsheet MetaMeta2.3_Seq_4.3.2, “CompareMetas”, rows 242-245

6.11.6 Set 5 Findings

Table 6-31: Findings - Set 5 (MCS without clamps)

Network Related (Typical network; EV mix 19% dumb, 48% SV1G and 33% V2G)

<table>
<tr><th></th><th>Description</th><th>Based On</th></tr>
<tr><td>1.</td><td>Without clamps, the network suffers broaches from EV charging</td><td>Figure 6-16</td></tr>
<tr><td>2.</td><td><table>
<tr><th>Supportable N EV</th><th>19mpd</th><th>27mpd</th><th>39mpd</th><th>49mpd</th></tr>
<tr><td>no control, 1.1.2</td><td>40</td><td>20</td><td>20</td><td>20</td></tr>
<tr><td>MCS alone, 5.1.2</td><td>80</td><td>60</td><td>40</td><td>40</td></tr>
<tr><td>clamps alone, 2.1.2.9</td><td>120</td><td>100</td><td>80</td><td>60</td></tr>
</table></td><td>Table 6-16</td></tr>
<tr><td>3.</td><td>Residential network loads greatly impact EV charging capability:
increase loads 300 W: halves supportable EV counts (5.1.2.1 vs. 5.1.2)
decrease loads 300 W: doubles supportable EV counts (5.1.2.2 vs. 5.1.2)</td><td>Table 6-16</td></tr>
<tr><td>4.</td><td>DRFFR slightly improves EV numbers, 5.2.2 vs. 5.1.2, 38mpd 60 from 40</td><td>Table 6-16</td></tr>
<tr><td>5.</td><td>Removing V2G (Seq_5.6.2) reduces N EVs by 20 in each mpd</td><td>Table 6-16</td></tr>
<tr><td>6.</td><td>Blind Aggregator control with FFR (Seq_5.3.2) brings such severe undercharging that no EVs at all can be supported</td><td>Table 6-16</td></tr>
<tr><td>7.</td><td>1 in 4 EVs with blind Aggregator control (no DRFFR, Seq_5.7.2) reduces 38 & 49mpd to 10 EVs only (each were 40 in 5.1.2)</td><td>Table 6-16</td></tr>
<tr><td>8.</td><td>Static Batteries aid, lifting EV rates to:
<table>
<tr><th>Supportable N EV</th><th>19mpd</th><th>27mpd</th><th>39mpd</th><th>49mpd</th></tr>
<tr><td>MCS, 5.1.2</td><td>80</td><td>60</td><td>40</td><td>40</td></tr>
<tr><td>MCS, SB, DRB-FFR, 5.4.2</td><td>140</td><td>80</td><td>80</td><td>60</td></tr>
<tr><td>MCS, SB, DR-CFFR, 5.5.2</td><td>140</td><td>120</td><td>80</td><td>60</td></tr>
</table>
NB DRC has half the reduction of Demand Reduction B</td><td>Table 6-16</td></tr>
<tr><td>9.</td><td>The depth of DR affects N EV supportable by a network and loads</td><td>(8)</td></tr>
<tr><td>10.</td><td>The Strong 2 kW network is very successful with a near clean sweep:
MCS alone: 19 mpd: 140, 27 mpd: 140, 39mpd: 140, 49mpd: 120</td><td>Table 6-17</td></tr>
</table>

EV Related

11.	Initiatives to lower residential consumption aid EV charging	*(3)*

6.11.7 Set 6 Findings

Table 6-32: Findings - Set 6 (MCS with clamps)

Network Related (Typical network; EV mix 19% dumb, 48% SV1G and 33% V2G)

<table>
<tr><th></th><th>Description</th><th>Based On</th></tr>
<tr><td>1.</td><td>There are no network broaches, yet the worst case week is unknown:
(a) MCS, clamps, Seq_6.1.2 and (b) MCS, clamps, Alt Winter 6.2.2.4
<table>
<tr><td>(a)</td><td>19mpd: 140</td><td>27mpd: 140</td><td>39mpd: 140</td><td>49mpd: 100</td></tr>
<tr><td>(b)</td><td>19mpd: 140</td><td>27mpd: 100</td><td>39mpd: 60</td><td>49mpd: 20</td></tr>
</table></td><td>Table 6-19
Seq_6.1.2,
Seq_6.2.2.4</td></tr>
<tr><td>2.</td><td>DR and DRFFR degrade N EV supportable:
<table>
<tr><td>Supportable N EV</td><td>19mpd</td><td>27mpd</td><td>39mpd</td><td>49mpd</td></tr>
<tr><td>(a) MCS, clamps, Seq_6.1.2</td><td>140</td><td>140</td><td>140</td><td>100</td></tr>
<tr><td>- (a) + DR only Seq_6.7.2</td><td>140</td><td>140</td><td>100</td><td>80</td></tr>
<tr><td>- (a) + DRFFR Seq_6.2.2</td><td>140</td><td>120</td><td>80</td><td>20</td></tr>
</table></td><td>Table 6-19,
Table 6-22
Seq_6.1.2,
Seq_6.7.2,
Seq_6.2.2</td></tr>
<tr><td>3.</td><td>Comparing 6.2.2.2 to 2.1.2, Static Batteries reduce clamp counts and aid severe undercharging:
<table>
<tr><td>Seq_2.1.2</td><td>19 mpd: 20</td><td>27 mpd: 20</td><td>39mpd: 20</td><td>49mpd: 0</td></tr>
<tr><td>Seq_6.2.2.2</td><td>19 mpd: 60</td><td>27 mpd: 60</td><td>39mpd: 40</td><td>49mpd: 40</td></tr>
</table></td><td>Table 6-19
Seq_2.1.2,
Seq_6.2.2.2</td></tr>
<tr><td>4.</td><td>Blind Aggregator with DRFFR Seq_6.3.2 again suffers severe undercharging to the point that no EVs can be supported.</td><td>Table 6-19
Seq_6.3.2</td></tr>
<tr><td>5.</td><td>If the Aggregator only controls every 4th EV, Seq_6.4.2, (7)’s all-fails improves to: 19mpd: 140, 27mpd: 120, 39mpd: 10, 49mpd: zero</td><td>Table 6-22
Seq_6.4.2</td></tr>
<tr><td>6.</td><td>In Summer, all EV combinations are supported with DRFFR:
<table>
<tr><td>Supportable N EV</td><td>19mpd</td><td>27mpd</td><td>39mpd</td><td>49mpd</td></tr>
<tr><td>Summer Seq_6.3.2.1</td><td>140</td><td>140</td><td>140</td><td>140</td></tr>
<tr><td>Summer, no V2G Seq_6.3.2.2</td><td>140</td><td>140</td><td>120</td><td>100</td></tr>
</table></td><td>Table 6-22
Seq_6.3.2.1,
Seq_6.3.2.2</td></tr>
<tr><td>7.</td><td>Removing V2G support in Summer (6.3.2.2) impacts higher mpd</td><td>(6)</td></tr>
<tr><td>8.</td><td>Removing the DR element gives a slight N EV reduction at 49mpd:
MCS, clamps, FFR: 19mpd: 140, 27mpd: 140, 39mpd: 140, 49md: 120</td><td>Table 6-22
Seq_6.3.2.3</td></tr>
</table>

Table 6-33: Findings - Set 6 ctd. (MCS with clamps)

Network Related ctd. Loss Reduction

<table>
<tr><td>9.</td><td>Adding Agg ToU control degrades further:
MCS, clamps, Agg, FFR: 19mpd: 140, 27md: 140, 39md: 60, 49md: 0</td><td>*Table 6-22*
Seq_6.3.2.4</td></tr>
<tr><td>10.</td><td>hi_limit lowered to reduce losses (no DRFFR):
<table>
<tr><td>**MCS, clamps**</td><td>19mpd: 140</td><td>27mpd: 140</td><td>39mpd: 140</td><td>49mpd: 100</td></tr>
<tr><td>**6.8.2**</td><td>19mpd: 140</td><td>27mpd: 120</td><td>39mpd: 80</td><td>49mpd: 20</td></tr>
</table></td><td>*Table 6-22*
Seq_6.8.2</td></tr>
<tr><td>11.</td><td>With (a) DR-CFFR and 40 kW hi_limit:
<table>
<tr><td>**Supportable N EV**</td><td>19mpd</td><td>27mpd</td><td>39mpd</td><td>49mpd</td></tr>
<tr><td>(a), 6.9.2.2</td><td>120</td><td>80</td><td>60</td><td>40</td></tr>
<tr><td>(a) + V2G PreBurn OFF, 6.9.2.1</td><td>60</td><td>60</td><td>40</td><td>20</td></tr>
<tr><td>(a) + SV1G replace V2G, 6.10.2</td><td>60</td><td>40</td><td>20</td><td>0</td></tr>
</table></td><td>*Table 6-22*
Seq_6.9.2.2
Seq_6.9.2.1
Seq_6.10.2</td></tr>
<tr><td>12.</td><td>Removing V2G PreBurn degrades N EV therefore PreBurn helps</td><td>*(11)*</td></tr>
<tr><td>13.</td><td>Substituting SV1G for V2G N EV therefore V2G helps</td><td>*(11)*</td></tr>
<tr><td>14.</td><td>With (a) MCS, clamps, with DR-CFFR and Static Batteries:
<table>
<tr><td>**Supportable N EV**</td><td>19mpd</td><td>27mpd</td><td>39mpd</td><td>49mpd</td></tr>
<tr><td>(a) + 24 kW hi_limit, 6.11.2</td><td>0 (s)</td><td>0 (s)</td><td>0 (s)</td><td>0 (s)</td></tr>
<tr><td>(a) + 32 kW hi_limit, 6.12.2</td><td>60</td><td>60</td><td>20</td><td>20</td></tr>
<tr><td>(a) + 39 kW hi_limit +PV, 6.13.2</td><td>140</td><td>140</td><td>120</td><td>100</td></tr>
</table></td><td>*Table 6-23*
Seq_6.11.2
Seq_6.12.2
Seq_6.13.2</td></tr>
<tr><td>15.</td><td>Lowring the hi_limit too much (to 24 kW) stops EVs charging</td><td>*(14)*</td></tr>
<tr><td>16.</td><td>Raising hi_limit to 32 kW aids restore N EV</td><td>*(14)*</td></tr>
<tr><td>17.</td><td>PV panels (2 kW) aid lift N EV, lowers losses (default hi_limit is 49 kW)</td><td>*(14)*</td></tr>
</table>

with Strong 2 kW network:

<table>
<tr><td>18.</td><td>**MCS, clamps, DRFFR:**
N EV 19mpd: 140, 27mpd: 140, 39mpd: 140, 49mpd: 140</td><td>*Table 6-24*</td></tr>
<tr><td>19.</td><td>with DRB-FFR and 1 in 5 houses heated by Heat Pumps:
MCS, clamps, DRFFR: 19mpd: 140, 27mpd: 120, 39md: 60, 49md: 0</td><td>*Table 6-24*</td></tr>
</table>

Table 6-34: Findings - Set 6 ctd. (MCS with clamps)

EV Related (Typical network)

20.	Heated EV batteries reduced the destination Winter : Summer AFH charging ratio significantly	*Table 6-21* *vs. Table 6-8* *Seq_6.2.2.5*
21.	Pre-heaters (for battery, cabin) is added to each EV: MCS, clamps, DRFFR: 19mpd: 120, 27m: 80, 39m: 60, 49m: 0	*Table 6-19* *Seq_6.2.2.5*
22.	Pre-heaters and homeostasis adjustment: +10% population to lift overnight stayers: MCS, clamps, DRFFR: 19mpd: 100, 27m: 60, 39m: 40, 49m: 0	*Table 6-19* *Seq_6.2.2.9*

6.11.8 Set 7 Findings

Table 6-35: **Observations** *- Set 7 (part, Special Situations)*

Network Related

1.	Comms failure (ICT to EVSE clamps is lost) permits uncontrolled EV charging	*Figure 6-22*

6.12 Chapter Summary

This chapter has presented findings from Volumes 2, 3, 4 of results analyses, in the data repository (see Accessing Results in the Data Repository). No simulation failures are seen. Coverage has been adequate, but many interesting possibilities are omitted.

In general, results show: Winter is more restrictive than Summer. Anticipated national load control schemes such as Aggregator Time of Use can provoke problems. EV habits and behaviour are significant; once network capacity is met a complex situation arises which broadly follow EV duty stress (N EV, mpd). Effects are dependent on the mix of available capacity and load, with stronger built networks more able to cope. This confirms that spare network headroom is key.

For less able networks, a local MCS, V2G EVs, and LV connected battery store paired to household PV panels demonstrate the best results.

The following chapter discuss findings to form conclusions.

this page deliberately left blank

Chapter 7: Discussion and Conclusion

This chapter discusses findings and reviews the whole project to conclusions. Chapter 8 goes on to form recommendations from the view of the major parties involved.

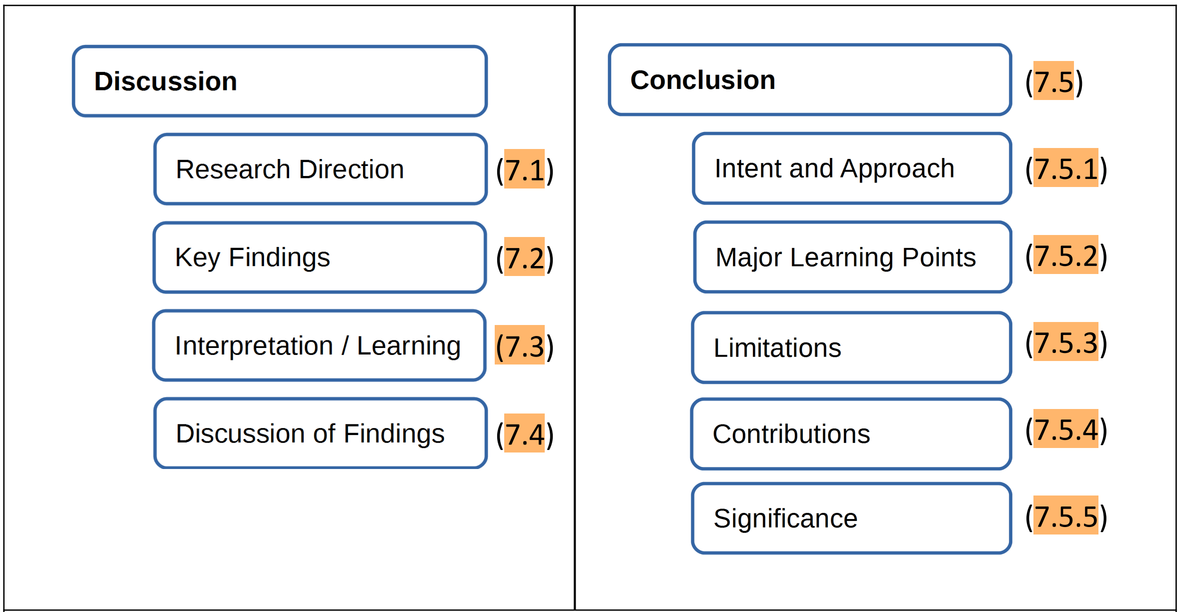


Figure 7-1: Chapter Directory: Discussion and Conclusion chapter

7.1 Research Direction

The work has explored home charging of EVs on UK / EU style 230 V LV power systems, anticipating future Low Carbon Technology (LCT) services: Electric Vehicles and home central heating by Heat Pumps, connected via existing LV systems. Residential LV networks are predominantly built to support 1 - 2 kW for a 3 bed semi-detached house **(Scottish Power, 2016, Table 4 p20)** with c. 10% electrically heated homes up to c. 12 kW per home.

Mass home EV charging and use of HPs is expected to overload many LV systems, which **(EA Technology, 2012, Figure 0.1)** suggests would cost c. £62 bn. to reinforce. This implies replacing up to c. 250,000 local substation transformers and up to 1 million in-road cables. Disruption would be significant. The thesis considered how to model such overloads, using various EV control systems (or none) as proposed and trialled in the UK.

A suitable simulator was developed and configured for Li-ion based EVs. EV profiles attempt to mimic cars sold in the UK. The simulator animated EVs on various journeys based on UK NTS **(HM Government, 2018b)** travel data, driving various distances, on electrical systems with loads based on live UK data **(SSEPD, NTVV. 2015)**. The electrical systems feature various built strength / power capability. A statistical saturation approach was used, with a great range of permutations explored in sets of 500 similar simulations, including:

- increasing daily travel distance (mpd) and number of EVs (N EV),
- using dumb, smart controllable and smart controllable V2G EVs with:
    - no control imposed,
    - My Electric Avenue (MEA) style disconnectors (clamps) to limit excess load,
    - a local Managed Charging System (MCS) coordinating charging activity,
    - MCS plus clamps, and
    - added value services: Demand Reduction (DR aka DSR) and Frequency Response (FFR), to assess the ability to offer services from EVs.

The studied networks experience an EV population density expressed as Number of EVs per 100 houses, swept from 10 to 140. The vehicles in the local fleet drive a defined weekly distance corresponding to 19, 27, 38 or 49 miles per day (mpd).

Simulations are based on the assumptions in section 4.2 (see also Appendix A) and relate to an idealised Low Voltage residential network, typified by the built kW capability per home e.g. 1.5 kW per house (3-bed semi) which is likely more capable (stiff) than many built networks.

No verification of the work vs. real-world EVs has been performed, however when compared to My Electric Avenue **(EA Technology & Roberts, 2016)** projections, the results are very similar (Verification vs. Similar Works). The major uncertainty of the FPB study concerns future EV characteristics; “reasonable projections” have been used. Also see 4.6.7 re simplifications and sources of error.

Data on the capacities of built UK LV networks is not available, thus it is not possible to quantify numbers of networks affected. However LV construction guidelines are available. Only systems intended for overnight storage-heaters (c. 8 - 12 kW, popular c. 1948 - 1970) are clearly fit for today’s residential loads plus EV charging.

As a result, findings concern behaviours of LV systems not intended for EVs. Outcomes may be unexpected.

7.2 Key Findings

Figure 7-2 shows the best-case number of EVs a network strength (kW, coloured) can support in Winter, with mpd de-rated by 10% to correct for errors (see 7.4.1).

When replacing ICE cars one for one, EVs cannot charge without inducing overloads on traditionally built LV networks due to insufficient spare capacity (headroom). A possible exception are networks built for night storage heating. However, where electric storage heaters remain in use, network headroom may be inadequate to allow EV charging.

The key findings are:

- N EV and mpd (miles per day driven, hence location) are major influencers.
- Electrically, Winter is much more demanding than Summer
- when held to network rating, counts of EVs supportable fall significantly in Winter vs. Summer, impeded by inadequate LV network capacity for total demand.
- Heatmaps (Figure 7-2) are shown of built network kW ability to support N EV, keeping in mind:
    - EVs are projected mid-Century BLP types, less demanding than today's EVs;
    - results are for best-case situations, so may exceed real-world outcomes, and
    - will vary (up/down) given setup conditions, options and constraints.
- Given UK possesses c. 1.3 cars per home, no built-to-minimum-capability network has the strength to cope with EVs replacing ICE cars 1:1; yet SSEPD is nearly acceptable (Figure 7-2, c). **Note** actual builds are likely arbitrarily stronger.
- Excess N EV on networks promote outages (substation fuse blows, removing power from many local houses) and possibly low-voltage induced home fires.
- Li-ion battery derating with cold plus higher house consumption causes seasonality of public charging use i.e. Winter vs. Summer chargepoint provision. Provision adequate for Summer charging is not adequate for Winter.

  Under-provision for Winter means **raised numbers of stranded EVs**. This may disrupt traffic flow during adverse conditions and needs further study.
- Addition of remote Aggregation Time of Use / DSR adversely impacts these tables, leading to further EV undercharging and raised likelihood of stranded EVs.
- Local Managed Charging, clamping, V2G and similar can help, however communications reliability is key and not known to "fail safe".

(a)

Number of 2040 Dumb BLP EVs (per 100 houses) by built LV kW

N EV:	10	20	40	60	80	100	120	140
17 mpd:	1.2	1.2	1.5	2	2	2.5	2.5	2.5
24 mpd:	1.2	1.5	2	2	2	2.5	2.5	3
34 mpd:	1.5	1.5	2	2	2.5	2.5	2.5	3
44 mpd:	1.5	1.5	2	2.5	2.5	2.5	3	3.7

(b)

MCS Controlled: N EVs + V2G Supported (per 100 houses) by built LV kW

N EV:	10	20	40	60	80	100	120	140
17 mpd:	1.2	1.2	1.5	1.5	1.5	2	2	2
24 mpd:	1.2	1.2	1.5	1.5	2	2	2	2
34 mpd:	1.2	1.2	1.5	2	2	2	2	2
44 mpd:	1.2	1.5	1.5	2	2	2	2	2.5

(c)

per house	ENW	NPG	SP	SSEPD	UKPN	WPD
kW:	1.1	2.1 (new: 3.7)	1.1	2.4	1.5	1.4

Figure 7-2: FPB Best-Case Winter per Home LV Network Capability Heatmaps

(a) data from Seq_1.1.1, 1.1.2, 1.1.3, 1.1.5, 1.1.6 and 7.15.4. EVs are future ***†2*** *BLP types.*

(b) is a composite of Seq_5.1.1, 5.1.2, 5.1.3 with the 2.5 kW ply being a projection.

(c) minimum ADMD kW each DNO specifies, per gas-heated 3 bed semi-detached house.

Data from DNO tables prior to amendments for EV loads. In 2018 NPG adopted a "with EV" new build ADMD, based on My Electric Avenue data. These are minimum capabilities in kW, per 3-bed semi detached house. Built systems likely exceed these by an arbitrary amount.

Coloured cell values are the lowest kW per house view of either: the transformer (kVA / N houses) or: feeder cable kW capacity (0.23 x ampacity / phase N houses), which must be true for all sections including branches. In operation, heatmaps will use the extra capability.

Notes

1. *Both tables have no EV clamps to stop overloads i.e. is as per present networks, with future EVs, however (b) needs an MCS with V2G EVs to achieve these results.*

†2. *For 2020 style EVs on present networks see Table 1-1.*

3. *DNOs vary built capability by number of houses; see* ***(Northern Power Grid, 2018)*** *A2.2.*

4. *The EV mix in (b) is: 19% dumb, 48% Smart and 33%V2G.*

5. *Other EV mixes, e.g. All dumb, will not likely be able to meet the reported N EV levels*

6*. these are best cases, as network topology can promote far-end volt drop situations*

7*. The tables above assume DNOs wish to retain normal LV operation and asset life.*

Investigated remedial strategies are ranked below by effective utility, with only the 1st choice being a true long-term solution:

(long-term solution)

1st: reinforce network, ideally sufficient for home heating by Heat Pumps,

(temporary stopgaps, may aid support a network until HP arrive)

2nd: addition of a local Managed Charging System, Figure 7-2 (b), to ensure EVs do not charge at the same time,

3rd: (2nd plus) local energy stores (static batteries) and solar PV panels

4th: (3rd plus) inclusion of V2G EVs.

The 1st method is expensive; 2nd on are c. 1/10th to 1/3th the cost yet may be adequate until the coming of Heat Pumps forces LV network reinforcement. Some minor reinforcement may though be needed to get the best from existing networks.

Observation: from Figure 7-2 (b) it is seen 2 kW built capacity is a key point, from which MCS covers the majority of use-cases. Hence **ENW**, **SP**, **UKPN** and **WPD** likely need reinforce their networks for they are, in general, too weak. **NPG** and **SSEPD** enjoy an immediate option to use an MCS. However, networks still need individual assessment.

7.3 Interpretation of Sequences (Learning Points)

This section includes:

7.3.1 Learning: Sequence Set 1,

7.3.2 Learning: Sequence Set 2,

7.3.3 Learning: Sequence Set 3,

7.3.4 Learning: Sequence Set 4,

7.3.5 Learning: Sequence Set 5,

7.3.6 Learning: Sequence Set 6,

7.3.7 Learning: Sequence Set 7,

7.3.8 Collated Learning Points.

7.3.1 Learning: Sequence Set 1

Set 1 explores uncontrolled EV charging; findings are detailed in Table 6-27. Learning points include:

a) Both absolute numbers of EVs and vehicle driven mpd have impact

b) while N EV is more significant than mpd, mpd changes remain a major factor e.g.

   - for 60 EVs: 19mpd had 11 broaches, 38mpd had 125
   - for 120 EVs: 19mpd had 349 broaches, 38mpd had 352 (Seq_1.1.2).

c) The data generated includes Away from Home (AFH) kWh and plugin counts, so can assess the need for public charging points.

In Winter vs. Summer:

- EVs consume more kWh,
- Li-ion batteries de-rate with cold: EVs carry less kWh / cannot fill their want
- thus in Winter, EVs public charging point use is higher

d) EVs are being parked at home but not plugged-in; this means they cannot charge even if there is network capacity. Conversely, when these EVs connect they need more charge than average, so charge for longer periods.

e) Unconnected EVs lower temporal diversity

f) FPB overall is thought optimistic i.e. overstates N EV supportable, due to:

- lack of local homoeostasis (no inbound / visiting EVs) and
- heaters may combat battery low temperature capacity loss, allowing more kWh to be taken on at home, raising coincident load due to heater power plus taking on more charge for EV use
- heaters act to further increase Winter home demand.

Network related learning points include:

g) There is no inherent mechanism to prohibit simultaneous charging, hence simultaneous loads ⇒ overload. A means is needed to diversity charging in time.

h) In Winter, the modelled networks cannot support levels of EVs as common as cars Example (Table 7-1): broach count table in MetaMeta2.3_Seq_1.1.2.xlsx:

- number of overload events, per 500 simulations. Acceptable limit: Zero
- 1 EV per house travelling c. average UK miles per day highlighted in yellow

Table 7-1: Sequence 1.1.2 Broaches on Typical (1.5 kW ADMD) Network

N EV	10	20	40	60	80	100	120	140
19mpd	0	0	0	11	60	249	349	333
27mpd	0	0	2	53	203	383	358	344
38mpd	0	0	7	125	357	371	352	380
49mpd	0	0	10	188	383	360	392	439

from MetaMeta2.3_Seq_1.1.2.xlsx "Compare Metas" sheet, rows 8-11

i) both mpd and N EV affect coincidence profiles: geographic location of residences affects network load as well as number of EVs (rural demanding more than city).

j) Unmanaged, there is unused network capacity which EVs are not accessing

k) Happenstance occurs for unmanaged EVs. Example: broach count table in MetaMeta2.3_Seq_1.1.1.xlsx:

- sheet Compare Metas, rows 8 - 11 “Sum Broaches”:

  no broach at 49mpd when two occurred at 38mpd.

l) Summer N EV charging capabilities are higher, due to:

- household loads are lower, raising available headroom
- EVs use less kWh per km in Summer due to reduced heating needs

m) ⇒ network headroom assessments made in Summer need de-rating for Winter

n) failures may follow cold weather patterns as they cross the UK

o) Car Plate Registrations update 1st March; thus a network acceptable in December might not be in a March cold-snap, given new EVs on a new Plate.

7.3.2 Learning: Sequence Set 2

Set 2 explores MEA-style clamping of EVs (by switch / disconnector aka clamp, in the EVSE); see Table 6-28.

a) a 100% clamp-enabled network halts overloads; no broaches arise

b) network throughput rises to the hi_limit kW setpoint. Transformer cooling clamps occur (transformers assume cyclic duty with overnight cooling, now denied);

c) it appears possible that EVs may be added to a clamped network ad infinitum

d) clamping can reduce net kWh per EV below adequate levels

e) from the driver’s viewpoint, home charging may become inadequate.

f) Away from Home / AFH charging increases due to two factors:

   i. inadequate home charging, and

   ii. EV battery capacity drops due to cold so for some vehicles cannot take on sufficient charge. More destination charging occurs in Winter vs. Summer

g) home perfect plugins marginally assist, but

h) AFH perfect plugins near obviate need for home charging so have major impact

i) the clamping algorithm has minor impact on charging outcomes

j) adding DR/FFR network value added services is possible, but can:

- provoke undercharging and
- elevate use of clamps to high levels (Ofgem pushback?).

k) Adding local PV with static batteries (i.e. local energy stores) raises ability to support EVs, free of severe undercharging (e.g. 6.8.27)

Observations:

i) at some point network constraints diminish home supplied charge causing under-charging and likely customer upset

ii) as a result, customers may home charge via unclamped 13A sockets

iii) in a clamped network a 13A socket has preference, taking kWh otherwise bound for neighbouring EVs.

iv) "Charging wars" are possible with drivers using 13A sockets (provoking LV overloads); those who refrain lose ability to charge.

v) A metric of "what is reasonable undercharging" is needed to forestall the above, a metric which can be used as a forecasting tool thus allowing the planning of appropriate local network upgrades (see 6.9).

vi) AFH charging becomes necessary, to provide charge the home cannot.

vii) Learning: AFH perfect plugins (h) suggests that local networks are assisted by AFH charging. A targeted AFH incentive may aid defer network reinforcement.

7.3.3 Learning: Sequence Set 3

Set 3 (clamps and V2G) investigates whether V2G can offer support, so to:

- reduce clamp counts
- reduce severe undercharging.

See Table 6-29.

a) Table 6-11 indicates V2G reduces severe undercharging in 3 plies vs. Seq_2.1.2.9, so aids the situation. MCS is found to outperform V2G. However,

b) in Seq_3.2.2 the greater V2G effort (raising EV costs) implies a "blind" approach (the remote Aggregator is unaware of local LV situations) does not offer advantage over Seq_3.1.2 to justify the great (c. 700 kWh) V2G spent.

c) From local network and EV view, V2G needs be directed, not repetitive or random

d) yet V2G may achieve a high-level goal, to which the LV view is blind;

e) for this to be true the V2G effort would need to "escape" the LV network i.e. contribute to reducing net external load. Yet it may not, given:

f) V2G likely lowers peak UK load when the network is not EV saturated,

g) when saturated with EVs (Figure 6-13) the V2G effort is consumed locally; V2G supplies local EVs looking to charge, which otherwise would have been clamped (forced to wait). V2G here gives no national kW change.

h) Inspection of network kWh throughput (e.g. in MetaMeta2.3_Seq_3.2.2.xlsx, sheet "Compare Metas" rows 33-36 vs. "Reference" sheet) shows that weekly unused kWh falls i.e. net demand rises with intense Aggregator demands, likely to recharge V2G EVs with kWh replacing V2G round-trip losses (c. 36%)

i) ⇒ V2G is a not a zero-sum exercise; round-trip losses must be supplied

j) ⇒ bulk use of V2G will lift required national kWh generation, due to losses.

The author concludes that V2G should be locally directed, as:

- this minimises needed V2G spend hence cost, and
- does not raise false expectations re benefit for the greater network, given V2G may be consumed locally.

(Return to 7.3 Interpretation of Sequences (Learning Points))

7.3.4 Learning: Sequence Set 4

Set 4 looks at Aggregator Time of Use (ToU) control in afternoon and evening bands (see 6.6 and Table 6-30). The Aggregator uses blind control; the method is unaware of real-time situations at feeder phase level.

a) Aggregator ToU commanded actions shows no evidence of being locally useful, yet

b) cause severe EV undercharging in all cases (6.6.4)

c) ⇒ blind control can be destructive, if applied without local awareness.

However strategies encouraging timed deferral (e.g. Time of Use pricing: 2pm - 10pm £0.40 per kWh, £0.15 thereafter) would promote the same effect; LV overloads at 10pm. The needs of the greater and local networks are not necessarily aligned.

7.3.5 Learning: Sequence Set 5

Set 5 investigates if a local, network aware Managed Charging System (MCS) can assist broaches and undercharging **without clamps**. See Table 6-31.

a) A modest improvement is seen for Weak networks.

b) The Typical network benefits. Average mileage EVs 27mpd, 60 EVs up from 10;

c) the system is sensitive to minor residential load changes; a 300 W per house load drop or uplift doubling or halving N EV capability (for Typical network).

d) DRFFR seems to help at higher mpds. There may be a mechanism behind this reducing severe undercharging, although the modus operandi is not clear.

e) Again, Aggregator ToU brings unacceptable severe undercharging to all mpds,

f) introducing Static Batteries provides useful uplift (27mpd: 120 from 80 EVs), and

g) V2G is seen to assist.

The most successful Typical network sequence was 5.5.2 with Static Batteries, the least Aggregator ToU in 5.3.2. The strong network was almost completely successful with MCS, failing with broaches when exceeding 120 EVs at 49mpd. From this it is seen clamps are needed with MCS, for EVs still follow their own imperatives i.e. driver commands.

7.3.6 Learning: Sequence Set 6

Set 6 investigates how a local, network aware Managed Charging System **with clamps** can assist broaches and undercharging; see Table 6-32. EV mix is 19% dumb, 48% SV1G, 33% V2G. **Note** that clamp counts are subject to a notional "no more than 2 hours a week" limit. Summer is assessed as well as Winter, using the Typical (1.5 kW) network:

a) MCS with Clamps greatly lift performance; 140 EVs can be catered up to 38mpd

b) severe undercharging constrains nearly all simulation 49mpd bands,

c) DRFFR hinders, due to excessive use of clamping (yet assisted in Set 5)

d) Static Batteries reduce clamp counts, severe undercharging and AFH use, while lifting DRFFR response.

e) An Alternative Winter week has degraded performance, which suggests that the default residential load profiles, for coldest week, are not necessarily the most loaded week. However residential kWh in the Alternative week was scaled to be close to the default week (30 kWh error vs. 17,000 kWh in the week), implying that timing of residential loads, not magnitude, is significant.

f) Preheating (battery and cabin pre-departure) was approximated. Preheating was detrimental. 27mpd N EV counts fell from 120 to 80.

g) An attempt at approximating a correction for homeostasis is felt questionable, as it added +10% EVs, with N EV falling by 20 in all bands. This drop is greater than expected. Homeostasis needs further work.

h) Aggregator ToU hinders by provoking severe undercharging in all categories;

i) removing the FFR component from the DRFFR signal reduces clamping (FFR, a random "chatter", likely provokes clamp operation).

j) V2G variants were attempted, which show:

i. **most effective**: V2G PreBurn ON, (uplifts headroom) supports local charging and all overloads, followed by

ii. V2G PreBurn OFF (only acts to defer overloads) and

iii. **least effective**: no V2G.

k) concerning hi_limit reduction to limit LV losses. These:

i. reduce losses, but

ii. reduce supportable N EV for each mpd band, and

iii. may provoke excess V2G activity - which has losses. Ofgem sees merit in lowest system losses. It is moot if DNO activity raising customer losses is acceptable to Ofgem; the author considers this unlikely.

iv. Adding Static Batteries as DNO network assets:

a) allowed useful loss reduction by permitting a lower hi_limit, and

b) transferred V2G costs to the DNO.

c) hi_limit reduction, Static Batteries and local (household) PV was a success, lifting N EV over 100 for all mpd, while operating with DRFFR services.

l) Strong (2 kW built networks) in Winter:

i. had a clean sweep of 140 EVs supportable for all mpd

ii. but could tolerate only 1 in 5 houses with Heat Pumps; N EV rapidly collapses over 27mpd.

Concerning Summer simulations:

m) Summer has a clean sweep of success, and

n) still found V2G support useful from 38mpd; removing V2G from (m) was detrimental, and,

o) with Aggregator ToU DSR suffered severe undercharging from 38mpd.

(Return to 7.3 Interpretation of Sequences (Learning Points))

7.3.7 Learning: Sequence Set 7

a) communications failures which remove ability to clamp EVs may be a great risk to substations especially in a cold-start situation. Loss of ability to clamp EVs risks no ability to restrain “EVs stampede for charge” ⇒ severe peak (c, d) in Figure 6-22.

b) **Some** Smart EVSE, tied by ICT to a specific power retailer, may refuse to charge on comms fails (as billing is uncertain). This is likely arbitrary behaviour;

c) non-Smart EVSE likely charge immediately on power restore. **Note** that in areas persistently without comms, Smart EVSE may default to non-Smart.

d) This area needs further investigation.

7.3.8 Collated Learning Points

1) Without means to explicitly disable EV charging during comms fails, local substations need a protection system with reclosing after comms restore.
2) HP force the situation: networks with built capability of under c. 9 kW per house need reinforcement as HP arrive; likely the great majority of the UK LV systems
3) (sans control) local overloads rise with N EVs and driven miles per day (mpd).
4) mpd is a significant factor and may vary over time,
5) location affects mpd, with in-city the least and rural the most demanding,
6) networks built for under 3 kW per house will have limited Winter EV charging capability Figure 7-2; EV duties exceeding these cause overloads.
7) In order of effectivity and baring reinforcement, networks may be aided by:
    (a) installing an MCS
    (b) MCS + local Static Batteries with PV,
    (c) MCS + local V2G (MCS being c. x10 as effective as V2G).
8) residential load profiles impact how many EVs an LV system can support.
9) Encouraging AFH charging aids how many EVs an LV system can support.
10) Supportable N EVs are likely overstated due to the homeostasis issue 7.4.2,
11) DRFFR services add complexity - sometimes better, sometimes worse
12) “blind” Aggregator ToU services in all cases attempted were detrimental to local charging yet has no utility for the greater grid, due to MCS / local consumption;
13) peak network stress tends to be in the early week
14) EV undercharging may serve as a litmus test for problems, with 1 undercharge per week per EV being a useful precursor.
15) Given an MCS with effective communications,
    (a) networks operated within built kW capability are not seen to suffer from low voltage issues, a boon for public safety
    (b) the use of clamps stops overloads,
    (c) any number of EVs may be supported on a clamped network, but provokes
    (d) the risk of undercharging EVs (need kWh above capabilities ⇒ undercharging)

(e) severe undercharging (EV cannot complete trip i.e. is stranded) rises and at some point becomes lack of provision of sufficient supply;

(f) value added services (DR, FFR) may be added via MCS hi_limit modulation.

16) Winter EV and residential demands are higher than Summer

17) Winter EV battery capacity is less than Summer (NB Li-ion batteries), which may be aided by heating the batteries. But in a constrained system, heating reduces energy flow to the batteries.

18) Winter demonstrates more problems than Summer

19) cold-weather imposes network stress thus faults and failures will be seasonal

20) thus failures may follow weather systems crossing the country.

21) Use of public EV charge points is significantly higher in Winter, impacting provision needs and economics of related businesses (the author would like this verified),

22) known technology improvements to aid Winter EV charging increase load further.

23) There are a range of LV support interventions which aid:

(a) elimination of unbalance issues (high demand on 1 phase of 3),

(b) reduction of local residential loads

(c) promotion of Away from Home charging whenever possible,

(d) provision for extra Winter AFH chargepoints on strong networks and

(e) reinforcement of any weak sections.

24) an MCS allows EVs to “sidestep” other loads. As a result, networks may be built adequate for domestic HP and need no extra capability, assuming a local MCS allows the EVs to charge at times with reduced HP load e.g. 11pm - 3am.

25) Re simulation:

(a) tranches can mimic arbitrary charging profiles including BLPs,

(b) “heuristics of least regret” free the system from a need for forecasts

(c) multi-pass allocation of headroom kW minimises undercharging.

26) Although not investigated in this thesis, two other issues are seen in literature:

(a) EV harmonics back-fed to other customers **(WPD, 2018d)**,

(b) **(Scottish Power, 2015)** implies sustained EV charging duty likely accelerates transformer ageing.

7.4 Discussion of Findings

This section includes:

7.4.1 Sources and Degree of Functional Errors,

7.4.2 Sources of Contextual Errors,

7.4.3 Other Error Sources,

7.4.4 Discussion: Whole Network View,

7.4.5 Discussion: DNO / Local Network Concerns,

7.4.6 Discussion: The EV View,

7.4.8 Discussion: Value Added Services,

7.4.7 Discussion: Destination (AFH) Charging Seasonality,

7.4.9 Discussion: Other Aspects.

7.4.1 Sources and Degree of Functional Errors

Sources of functional (hence numerical) error have been identified, being:

a) simplification of losses and treating kW as if kVA: this lifts apparent N EV capability by c. 3 ... 6% yet offers significant computational speed boost (c. x10),

b) miles per day (mpd) driven is 1 - 4% over intended target. The source is likely the correction for trips discarded due to timing clashes, an uplift applied during trip synthesis. This tends to lower the apparent N EV a network can support.

Error (a) is the more significant, lowering apparent load so overstating the number of EVs the network can support. The author suggests derating N EV or mpd conclusions.

7.4.2 Sources of Contextual Errors

These arise due to the simulation not matching (future) real-world context:

a) EV characteristics are different, e.g. battery losses and thermal derating,

b) EV mix distribution not “2018 UK average”, e.g. more large vs. small EVs,

c) unexpected mpd variance e.g. a change in driving habits caused by diversions,

d) numbers of N EVs overnighting at home during the week varies (drops as days go by e.g. Figure 6-19). This appears valid (weekly commuters) but may vary from place to place (no drop or an increase).

e) Simulations possess no homogeneity / are “set in a desert” with no visiting EVs; no other 3rd party EV charging. This is highly variable and depends on context.

The homogeneity aspect is situational and needs be assessed locally. Impact depends on attractors e.g. a local cinema, a shop sale etc.; in some situations this may be significant.

7.4.3 Other Error Sources

7.4.3.1 Concerning Data Errors

Residential Data: Adequate and available year-long. The dataset covers 2013 for several hundred houses in the Bracknell area; a new dataset may now be due. It is not known which of the datasets are the “worst” or the “most representative”.

Network Data: There is a surfeit of possible network topologies, such that there is no representative network. Many are unique. The author’s approach was to nominate the simplest network possible of known capability and to allow others to apply a correction for their situation.

EV Data: extrapolation for future EV characteristics was necessary. The key items are:

- battery sizing (broadly calculable from practical aspects)
- driving consumption rates (guessable by vehicle size)
- various overheads met during Winter (especially heating)
- EV charging rate; presently 7.2 kW
- over time EV characteristics may diverge from projections e.g. use of steel bodywork which is cheaper but heavier, so less efficient;
- harmonics are ignored. Generated by power converters, these are regarded as also limiting EV deployment. It is supposed that such solutions are deployed (see **(WPD, 2018d)**).

7.4.3.2 Concerning Simulation Errors

FPB was checked during development, yet would benefit from a QA review. Spot checks and whole system (end-to-end) checks were made and issues fixed. These checks inspected intermediate states to identify implausible data.

The most frequent problem was with setup. Some runs were believed configured to do X but performed X’, but may be included if valid and informative.

Most important is to verify output vs. real-world, however may be impossible without:

- knowledge of each household’s actual instantaneous consumption,
- knowledge of the major characteristics / electrical parameters of each EV

- knowledge of the trips (time, distance) each EV takes;
- knowledge of the internal imperatives of the EV Battery Management System, and
- the impact of ambient temperature.

FPB improvements could include:

- per pd ambient temperature,
- longer simulation runs
- reducing task volume e.g. by a sampling system which randomly selects 25 data points in extreme areas to identify limits and tipping points, then bombard areas of value shifts. This offers fast general coverage with focus on transitional areas.
- Assessment and inclusion of non-metered loads (street lamps, services pumping).

A list of improvements is included in 8.6.2 FPB Functionality Enhancements.

7.4.4 Discussion: Whole Network View

It is confirmed that LV systems built closely to historical standards experience overloads, hence failure. That DNO controlled EVSE disconnectors (aka clamps) are needed is clear.

The study found: For unregulated EVs (Seq Set 1), new EV load shifts the residential peak later into the night. The anticipated battery life extension policies (BLPs to cool EV batteries by staggering charging via burst of charging) will ease the experienced peak thus allow more EVs to charge. However Seq Set 1 shows that peaks remain excessive 6.3.2.

An option mimicking ToU timers (aka DSR) to move charging load past the evening period - relocated and accentuated the peak, deferring (accumulating) many EVs waiting to charge. Timed methods synchronise peaks so raise coincidence, and are not recommended. This includes Aggregator DSR and Time of Use signals which synchronise broaching e.g. on releasing a constraint (6.6.4). Local Smart control in the form of a Managed Charging System (MCS) limits broaching - but not as effectively as clamps. MCS alone cannot guarantee a broach-free situation. **(HM Government, 2018)** AEVA 2018 Section 15 clause 2 (a, b) mandate EV charging regulation (which may be used as a clamp) to be present in Smart chargers from mid 2019.

The most effective Smart remediation is a (per-substation) Managed Charging System (MCS), aware of local conditions and co-ordinating EV charging so to not be simultaneous. Once in place, MCS can offer Demand Response (DR) and Frequency Response (FFR) services via MCS hi_limit modulation. The method is likely cheap to free, which may disrupt other market providers. With large numbers of EVs connected, a major control contribution via EV charging modulation becomes available. Given the impact of near-free marketable services via EVs, it might be that other services need be offered financial protection lest EV services collapse the market causing bankruptcies. Such other services remain needed e.g. for balancing during a country-wide black start.

Blind-control (no local knowledge) Aggregator simulations provoke both undercharging and broaching. It is seen better to place this into the hands of the MCS and DNO (who do not need track real-time EV location). **Note** this offers a fortuitous side-effect: EVs away from home plugging into a chargepoint may respond to a local hi_limit control, not a control intended for another region (potentially causing complications).

It is recommended that local sensing controllers are used in preference to blind / remote.

(Return to 7.4 Discussion of Findings)

7.4.5 Discussion: DNO / Local Network Concerns

7.4.5.1 Without a Managed Charging System

The diversity changes anticipated by **(BERR & Arup/Cenex, 2008, Section 6.3)** are born out (Seq Set 1). The observed coincidence curves in 6.3.1 are for projected EVs in Winter.

A major finding is seasonality of EV charging loads, Winter to Summer. Loads are much higher in Winter, due to:

- more EV energy use, for both driving and cabin heating,
- battery characteristics (capacity loss) provoke increased use of AFH charging
- impacting local LV networks and lifting public EVSE use, hence provision needs.

A useful DNO “litmus test” is transformer heating, likely to spike with EV numbers.

Another aspect is the impact of driven miles per day (mpd), which the RAC show is influenced by wealth and location. Drivers from suburbia travel further than in-city drivers; rural drivers even further. Both experience higher net mpd, charge for longer (lowering diversity) hence impose different loads. Coincidence of charging rises with mpd (6.3.1). This suggests clusters of wealthy areas, set away from cities, may form the first hotspots suffering network problems. Reaction to their issues **may set precedent**.

7.4.5.2 With a Managed Charging System

The hi_limit kW control needs to be set at or below the built network capacity. Given that, when the MCS hi_limit is close to the net residential load level the system is sensitive to residential loads shifts, elevating instances of EV undercharging. Clamps are necessary to eliminate broaches and (for correctly designed networks) can limit under-voltages, but provokes undercharging. Away from Home (AFH) charging reduces residential EV loads.

V2G is seen as useful, especially when used to raise local headroom, aiding the "sensitivity to residential load" issue. However, V2G carries costs. Costs are likely born by the EV owner (e.g. bundled within monthly battery financing); DNOs using considerable V2G risks elevating EV costs. Yet a local Static Battery (ESS/ESMU) can mimic V2G, being especially effective paired with Solar PV. This method also places system costs with the DNO.

A managed Static Battery system with PV can aid black start, lower LV losses and (by reducing burden on the transformer) extend transformer life. See Seq_6.13.2 (6.8.27). The DNO may encourage Winter-optimised PV, angled for Winter sunshine. A local energy store might consume excess power, assisting manage daytime PV over-volting, seen on some estates.

There are however major problem areas outstanding:

1) moving residential load profiles from a cyclic pattern to near continuous peak (even at nominal load limit) implies transformer life <u>may be radically shortened</u>;
2) black start with <u>comms failure / late recovery</u> risks <u>uncontrollable spikes</u> (6.10) which may persist for long periods; the substation may need a protection system with reclosing breakers, tied to comms recovery.
3) <u>Heat Pumps force reinforcement</u>; estates built for night storage heaters will possibly cope, anything less will certainly not.

LV reinforcement planning needs be aware of the timescale to HP introduction; if soon the author advises LV network reinforcement ASAP, coupled with an MCS which can "guide" EV charging around HP loads.

Use of an MCS can aid manage major DNO areas of concern, being feeder overcurrent, transformer overheating, losses and voltage drops (usually at end-points). The MCS phase hi_limit kW can be so set that all three areas are acceptable. MCS also outperforms V2G by c. 10:1 without incurring battery degradation costs. Further, as MCS operates the network within intended design limits, volt-drop issues are rarely seen.

However these measures are unlikely to aid future black starts. Given a local power fail of several hours in Winter, reconnecting power to a cold estate with HP implies prolonged HP loads or extensive flow-boiler use (which are x2 HP load). If EVs are present they may attempt charging; in these circumstances MCS control over EVs is useful to manage load, especially if local energy reserves are available to be injected. Comms connection is necessary at this time and is a key vulnerability (6.10).

The alternative is to build for simultaneous black-start load from EVs, HP and residences assuming zero diversity, which may imply 12 - 14 kW capability per home.

Concerning phase load imbalance. In extremis (great load on one phase, none on the next) the MCS strategy is to reduce load on the highly loaded phase. Limiting loads to aid balance will under-provide customers on that phase (i.e. undercharge EVs, even though the network has capacity to supply). This brings no benefit over existing practice and reduces energy throughput. Some alternative approaches include:

- install a phase-load sharing system (e.g. SSE's ESMU unit) as close as possible (or electrically just beyond) the point of imbalance. SSE's study **(SSEPD, 2015)** showed these schemes work, but are expensive vs. other options; or
- install phase-hopping local public chargepoints i.e. which connect to the least-loaded phase, so redistributing EV charging.

Aspects concerning DNOs and local networks:

a) Harmonics are not herein considered, but WPD found cause for concern in **(WPD, 2018d)**. Although an issue which cannot be ignored, this is likely a problem for EV manufacturers (their products are generating harmonics);

b) N EV is expected to grow over time, but at first gather in hotspots. DNO visibility of hotspots can be aided by a local MCS; log data may identify rising EV numbers.

c) Local diversity assumptions are invalidated: Use Figure 6-6, Figure 7-2, or use an MCS.

d) Concerning volt drops: Volt issues may still arise due to excess point-load at the feeder far end; the far reaches will need checking to determine if the low N EV coincidence (see Figure 6-6) can be supplied by that feeder section, given the full feeder run volt-drops. It may be necessary to reinforce a section. However on networks operated within design ADMD limits this is not likely to be a great issue, given that the hi_limit is set correctly (least kW of: the lowest feeder section phase kW capacity or the transformer phase kVA) **and** there is no cluster of far-end loads.

However the author suggests a further investigation: To extend the sample network (so provoking voltage issues) until the previously seen broach condition is met. This would indicate the maximum LV length for which a DNO could expect the results in this thesis to hold true. <u>MCS</u> though <u>limits or eradicates low-volt issues</u>.

e) A mechanism is needed to limit peak demand: EVSE disconnectors / clamps

f) implying need for a form of controlling ICT: an MCS or similar to diversify charging

g) Substation transformer overheating: moderate by reducing MCS hi_limit setpoint,

h) feeder load overcurrent: may be adjusted by reducing the hi_limit.

i) LV system losses rise: will be no more than that implied by the hi_limit but likely above what the DNO desires, as the LV system will spend long periods at maximum load not short bursts.

j) LV network imbalance: imbalances may be limited but not eliminated.

k) Total LV residential load from 2050 may be very flat as MCS maintains an even load, given the proviso re Heat Pumps (an MCS interleaves EV charging about uncontrollable residential loads; there may be benefit to cause EV charging to complete before HP become active i.e. to complete charging by 3am).

l) Various vehicle miles are driven per day in 4 bands; these have different impacts. This implies that city vs. urban vs. rural will exhibit different characteristics

m) undercharging is seen to broadly correlate with rising mpd then rising N EV

n) seasonal patterns show there is a significant Summer / Winter disparity in charging; Winter is more demanding. Networks can support far less EVs (Table 6-9) hence faults and overloads may be provoked simultaneously during a cold snap.

o) EVSE manufacturers are aware of the AVEA 2018 **(HM Government, 2018)**, but from their perspective this is unclear in several areas:

   i) OLEV offers a grant to install Smart EVSE, which has clamps, yet do not grant non-Smart (non-clamping) EVSE. Those who wish may still buy and use non-Smart chargers, likely needed for places without a comms signal.

   ii) The nominated ability to access a control switch within Smart EVSE is written in <u>the singular not plural</u>, with no indication as to whom the controlling party is to be. EVSE manufacturers appear to consider that this is for Aggregator control, not the local DNO. It might be difficult to make this the DNO due to contracts in place and a list of controlling parties limited to 1 entry.

   iii) There is no sense of priority between multiple parties. If a DNO did assert “stop charging” there appears nothing to prohibit an Aggregator to assert "start charging" immediately after. This arises as the number of controllers is written as singular.

iv) There is no defined method of access. Thus cellular systems, wired access, private protocols, Internet / Wifi links etc. arise; there is presently no single method or party by which the DNO can flag "stop charging". It might be any implementable method - perhaps a dozen variants on one street;

v) there is no response time defined, so is likely to be "best endeavour" which might be delayed (cf. circuit breakers which operate in milliseconds). For signalling based about 1/2 hour cycle Smart Meters, many minutes can be expected; this is likely unacceptable and needs a separate study.

p) Finally, DNO networks are threatened by DSR / Time of Use schemes; present schemes have no knowledge of LV constraints. Provoked failures will identify early hotspots, however all that can be done today is to reinforce affected networks.

(Return to 7.4 Discussion of Findings)

7.4.6 Discussion: The EV View

The simulations are of future EVs with invented characteristics. The profiles and deployment of EV types mirrors UK sales (as SMMT reported in 2018) as far as possible.

The number of EVs on a network (N EV) is the major factor, with LV networks designed for (say) 1 kW of power per house potentially saturated at 0.13 EVs per house. Yet over 1.3 cars are seen per house **(ONS, 2016)** in Kent, rising to 1.7 if driven-home small work vehicles (vans, transits) are charged at home (noted but out of scope; see Hart in Hampshire in **(ONS, 2012)** KS404 Numbers).

The daily range (miles per day, mpd) affects the amount the EV wants to charge. Vehicle size (i.e. mass) also affects the amount charged hence observed load diversity.

It is notable that peak charging follows after the weekend, which seems to have less charging than average. It is thought that this is due to EVs enjoying a long charging period hence average charging is low. However the EV forward expectation of kWh use during the week is high. Yet, being well provisioned over the weekend, EVs feel no urgency to AFH charge during early hours of Monday. Overnight Monday → Tuesday they must charge a lot; noticeable in many plots. If allowed, this causes a burst of overloads.

Clearly these follow social patterns, but suggest an alternative tactic: pre-emptively charge to c. 95% at weekends, to ease weekday charging burdens. This has not been investigated.

The primary method explored is to use ICT (a local MCS) to stagger charging. However as N EV rises, network limits are met and clamps are needed to stop overloads. But excessive clamping leads to undercharging (departing below sought SOC) and severe undercharging (the EV departs unable to complete the trip and return; if more charge is unavailable, the EV is stranded).

Severe undercharging can be anticipated using undercharging as a precursor, discussed in 6.9. The author suggests the DNO offers drivers experiencing one or more undercharges a week a coupon for assured AFH charging; this both aids the EV situation and reduces LV local load. Due to network unbalances tending to “favour” one phase, the same drivers may experience repeated undercharging. This may cause fraught customer relations and perhaps force reinforcement. Smart EVs (SV1G and V2G types) working with a local MCS assist, as does V2G. Yet there is lack of clarity re battery damage and kWh recharge costs. Static Batteries (6.8.27) assist, and moves V2G costs from EV to DNO.

Concerning the trips simulated. These are based about reported UK NTS datasets which would need amendment for other countries. **Note** all trips are legal and that energy use (implied in driven miles per day) is logically independent of EV travel timing.

7.4.7 Discussion: Destination (AFH) Charging Seasonality

The marked seasonality (x4 to x22) of destination charging encountered in 6.3.3 is very concerning as the effect impacts capital send and profitability:

- significantly raised need for Winter provision implies more spend if built - yet at other times of the year the extra chargepoints are unused and bring no profit;
- provision adequate only for Summer is inadequate for Winter, which
- likely increases EVs being stranded / running out of charge on the drive home.

The problem is due to EV cold battery shrinkage and kWh use to heat the cabin. This is likely intractable, given present Li-ion characteristics and cold conditions (so not likely amenable to DNO interventions). The author sees no straightforward solution, and would like to see this effect replicated by other parties.

City dwellers are affected the most. **Note** the model does not mimic people commuting into a town to work; this would exacerbate the problem. This impacts planning (so to not strand EV drivers) and the economics of charging forecourt and commercial AFH / chargepoint providers.

No Battery Heating *Copy of (Table 6-8) C: Ratio Winter to Summer AFH Charging*

Ratio A / B	C Ratio Winter to Summer	N EV	10	20	40	60	80	100	120	140
		19mpd	22.31	17.55	9.73	11.83	11.98	13.74	13.36	11.78
		27mpd	11.01	10.31	8.99	8.33	7.72	8.11	8.22	8.14
		38mpd	5.89	5.60	5.79	5.37	5.44	5.43	5.42	5.48
		49mpd	4.66	4.59	4.47	4.37	4.38	4.32	4.37	4.35

Assisted by EV battery heaters, the Winter to Summer AFH use ratios become:

With Battery Heating *Copy of (Table 6-21) C: Ratio Winter to Summer AFH Charging*

Ratio A / B	C Ratio Winter to Summer	N EV	10	20	40	60	80	100	120	140
		19mpd	6.6	5.8	3.2	3.5	3.7	4.4	4.2	4.2
		27mpd	3.4	3.6	3.1	3.1	3.0	3.3	3.5	5.0
		38mpd	2.6	2.5	2.5	2.4	2.5	2.7	3.3	5.4
		49mpd	2.4	2.3	2.3	2.2	2.3	2.5	3.4	4.7

Note caveats concerning this matter (see discussion following Table 6-8), and also that FPB does not include recharging visitors to houses. However visitors are likely during the day.

It is noticeable EV drivers do not always plug-in their vehicles on arriving home, especially when SOC is higher than next needed (this mimics the Electric Nation (EN) project experience, a change vs. the range anxiety in My Electric Avenue project). If not plugged in, EVs cannot pre-emptively charge or participate in Value Added Services or V2G schemes. If the DNO feels the loss it may be useful to encourage people to always plug in. However this may be futile as the limiting factor is the network; Winter CICD plots show most EVs already connect on arriving home (so gains no further advantage in Winter).

Other EVs aspects:

a) home charging: 7.2 kW is the standard per phase
b) V2G and battery costs: with Li-ion there may be margin for order-of-magnitude cost savings; for any more a change of technology is likely needed. At this time (for

the UK, for massed numbers of EVs) V2G ROI appears negative as costs swamp plausible income from available revenue sources;

c) it is questionable if there will be a market desiring the sheer volume of services EVs can offer mid-Century (see Value Added Services below).

d) Away from Home (AFH) charging is encouraged and may be used as a means to offset / reduce undercharging

e) local forecasting is difficult to intractable, so is not used by the developed MCS.

(Return to 7.4 Discussion of Findings)

7.4.8 Discussion: Value Added Services

The primary services are Demand Reduction (DR) to limit peak load and Frequency Response (FFR), to assist balance the National Grid. Two methods are considered:

a) via Aggregators: 3rd party businesses trading power to fulfil contracts, able to send commands to individual EVs. Aggregators are assumed:

   1. not to know the local network conditions, and

   2. not to know each EV's SOC needs and intents (target SOC, depart time), and

   3. not aware of other Aggregators dynamic intent;

b) via a local MCS which sets local load to a hi_limit maximum value: modulating the hi_limit set-point causes local peak load to move up or down.

There are two methods to cause a desired net load reduction:

c) to turn things off: Often free, with no energy losses, or

d) to inject V2G into the grid: Not free, high losses.

and to raise load:

e) either reschedule loads (to bring future loads forward) or to

f) drive allowed peak load levels up.

Other VAS related aspects:

g) V2G local use is of value; the author is not clear if a local market can sell this as a service. However kWh volumes are low and plausible losses c. 30 - 40%

h) costs: DR via (b) is very near free, so should easily out-compete others

i) local Managed Charging System (MCS):

   1. needed to co-ordinate the local situation OR

   2. perhaps not needed as a remote Aggregator may initially be effective, but brings major drawbacks in traditional forms

j) FFR has been successfully demonstrated but may not always be effective, as EVs are away or fully charged.

k) In general, FFR responsiveness is proportional to network load (Table 6-20).

l) The author sees no benefits for a classic Aggregator; they cannot offer the functionality the DNO controls via an MCS. This does not prohibit an Aggregator working with a DNO by substation block, although this removes local connected customer choice to being “in” or “out” of the local scheme.

m) Finally, the stance “markets can do anything / everything” to the author is questionable. Electricity is not fungible as energy dissipates on each transfer.

The simulations show for constrained local networks:

i. Aggregators (and Time of Use schemes applied en-masse) which cause EVs to defer charging, then to charge together in the same timeframe exacerbates LV overloads, so may be impractical on specific networks.

ii. Aggregators can impact EV charging goals, exacerbating undercharging. This occurs as: For any DR scheme, there will be EVs trips effected by DR charging prohibition, causing instances of undercharging.

iii. When suffering LV constraint, V2G has merit supporting local loads, but no clear merit for other loads. Even with large V2G spend, the external grid saw no benefit (V2G energy was consumed locally by other charging EVs, who otherwise would have waited).

iv. Modulating the MCS hi_limit can achieve both DR / FFR goals, and has no V2G-like side effects (costs, delayed use of EV as a car recharging V2G spent energy), and

v. impacts from DR and FFR services may depend on local conditions.

The author recommends offering VAS by modulating the MCS hi_limit set-point. There may be alternatives to inform more appropriate Aggregator control, but these imply considerable processing of bulk data in near real-time. This data will be difficult to gather as it is scattered amongst many retailers. Control in this form the author sees as ultimately technically doable, but implausible in the short-term (capability buy-in and ICT with comms links need be established for all retailers). MCS appears the more practical, simple and achievable.

Note DSR imposed by remote Aggregators risks random Winter LV network failures, once EV counts exceed local limitations. Alas there is no high-level designator able to direct the Aggregator re commanding which EVs provokes the effect where; the system is blind.

7.4.9 Discussion: Other Aspects

Other than MEA, there are no similar other works with which to compare FPB results. In areas where FPB and MEA overlap there is no perceived disparity. The novel features of FPB however presently mean there are no peers for comparison.

EVs on LV network dynamics are complex with many degrees of freedom, and here based about extrapolated future behaviour and EV characteristics. Results should be seen as:

- indicative rather than absolute,
- FPB simulations are ideally compared one to another to view impacts of changes.

There are opportunities to use an FPB derivative simulator to:

- perform LV network assessments / form recommendations to direct policy
- gain insights into public chargepoint provision.

However, to plausibly rely on FPB outputs then the following are needed:

- correct (not projected) EV characteristics including vehicle dynamics and heating consumption i.e. a good per EV marque model;
- modifications to permit branching networks to be included,
- known network samples with EVs to allow verification.

It must be reiterated that FPB outputs are believed to be best cases, as they study an ideal network. Applying results to any one real-world network implies a need to study the network for weaknesses, such as reduced capacity on sub-branches or long cable runs (which would need an end-point study to check for excessive volt-drops).

(Return to 7.4 Discussion of Findings)

7.5 Conclusion

The conclusions of the work include:

7.5.1 Intent and Approach,

7.5.2 Major Findings,

7.5.3 Limitations of Approach,

7.5.4 Contributions,

7.5.5 Significance.

7.5.1 Intent and Approach

Simple numerical analysis and past trials show problems can occur when charging EVs on existing UK residential 230 V LV networks, of which there are c. 1 million supplied by c. 330,000 substation transformers. Many LV systems appear inadequate and cannot simultaneously supply existing loads and charge multiple EVs, given they replace cars. EV charging can overload these networks or cause volts to drop below regulation.

This EngD explored and evaluated EV charging on these constrained networks. The work built a suitable simulator, which was used to investigate the ability of known built network strengths to support EVs, mapping limitations and exploring means to support limitations. The primary optimisation method maximised network throughput via coordinated EV charging, such that EVs did not charge simultaneously. Mechanisms included remote and local ICT control with EVSE disconnectors and V2G.

The simulator modelled both networks and individual EVs, with EV management capability. Saturation simulation of future EVs used as cars was then performed. These EVs mimic cars of types reflecting today's sales mixes, driven in NTS surveyed manners, placing the simulation in a UK context. The simulations focus on feasible worst-case situations which place maximum stress on assets; typically this is in Winter.

7.5.2 Major Findings

The simulations found:

a) UK LV networks built to long-standing regulations for gas-heated houses cannot support EVs replacing cars 1:1 (see Figure 7-2 (a) for EV limits by built network). EVs invalidate historic design assumptions.

b) Winter residential loads plus EV charging can cause local overloads,

c) the point of failure depends on the exact mix of: number of EVs, driven distances, local temperatures, built residential network strength and any EV charging control imposed.

d) Seasonality of Away from Home charging which rises markedly in Winter,

e) DNOs are presently blind and not well served by the Smart Grid or Meters.

f) By descending utility, the most useful local interventions are:
   - a local Managed Charging System, fully aware of local situations, then
   - residential PV operating with a local energy store (Static Batteries), then
   - V2G to inject electricity to the local network.

g) The above steps allow a markedly higher EV density to be supported on existing built networks, see Figure 7-2 (b),

h) a “top-drop” Aggregator DSR / Time of Use signal greatly exacerbates local overload problems i.e. degrades network capability to support EV charging,

i) however a local MCS via DR can duplicate the benefits of DSR from the whole grid view, whilst limiting overloads.

j) Heat Pumps overwhelm the local network and force reinforcement. MCS still has a role under these circumstances, but cannot forestall reinforcement which is needed when converting gas-heated properties to Heat Pumps.

As FPB’s results reflect the best case capabilities of an idealised network, a downwards revision of expectations is very likely when considering a specific network.

The simulations focussed on likely worst case situations, which arise in Winter. Given the number of trials full EV deployment brings (potentially 10’s millions each day) worst cases will happen. The only competent methods found to control such worst cases were:

i. make use of EV clamping (disconnectors) managed by a local MCS; a method which may have limited utility as EV numbers rise, or to

ii. reinforce (rebuild) networks.

The effects of failing to implement either route is local network blackouts (blown substation fuses), with associated risk of under-voltage domestic appliance fires if overloads are allowed to persist (e.g. by fitting bigger fuses).

The author also observes the UK Smart Grid/Smart Meter system being deployed makes a regressive contribution i.e. further degrades already inadequate performance, for it proposes use of DSR, (h) above. This seems intrinsic to the design; the Smart Grid appears unaware that many LV systems are not able to cope. LV system managers (Distribution Network Operators) are not directly aided by the Smart Grid in managing their LV networks. Features and working practice to offer aid are not included, indeed appear actively frustrated so to enforce data confidentiality.

This situation stands in the way of implementing UK Low Carbon / Zero Carbon aims which, without network reinforcement, cannot be realised. A means to permit the desired electrification revolves about equipping the UK with a new LV system an order of magnitude more capable (reinforcing LV network capability to c. 10 kW per home, from c. 1 kW per home). Costing is difficult but likely nearer £100 bn. then £10 bn. The **(EA Technology, 2012)** study suggests £62 bn.

This thesis does show that MCS local control allows intermediate strength LV systems (from 1.5 kW built per house) to accommodate EVs, depending on situation, but not Heat Pumps. These force large-scale reinforcement of transformers and in-road cabling.

7.5.3 Limitations of Approach

The author asserts FPB needs a full QA review of data and code-base; given the size of the endeavour it would be exceptional for no issues (defects) to remain. However, the work does broadly replicate My Electric Avenue trial findings. There are though limitations:

a) EV characteristics can change over time (characteristics of simulated EVs are projections),

b) the study included private vehicles only, i.e. precludes company vans or taxis which choose to charge at home and likely raise loadings,

c) data on UK built network strengths is confidential and not available to the author†

d) analysis of simulation errors and assumptions suggest, on balance, FPB is overly optimistic i.e. tends to overstate the ability of a network to support EVs.

† Note My Electric Avenue had access to built network data and from that suggested, for 70% EV penetration, c. 100,000 LV networks need upgrading. However there are caveats:

- EVs in the 2014 trial were small, entry-level vehicles. Contemporary vehicles charge at higher rates and drive further thus electrically are more demanding, and
- Heat Pumps were not included in My Electric Avenue.

The network used by FPB was simplified for pragmatic reasons and likely less prone to volt-drop issues, compared to some built networks. Not all possible networks have been tested as there is a surfeit of permutations with no one typical type.

Not all possible EV use cases have been tested e.g. use as autonomous taxis, charging of commercial LCVs at home, often heavier and driving greater distances than private cars. Uplifting N EV to 180 vehicles may be needed.

Also, FPB does not simulate inbound visitors i.e. is “set in desert” with no local attractors such as shops or entertainment venues. No visitors implies under-representing total numbers of EVs likely present. This may cause an under-representation of load.

7.5.4 Contributions

The major contributions of this work include the developed simulator, seen as broadly successful given FPB mimics outcomes from other works. This shows there is no means to stop the eventual arrival of Heat Pumps from overwhelming the studied networks, so will force reinforcement. However without HP, the simulations found:

- ability of sample networks to support various EV populations, and
- interim solutions using a local MCS are viable, plus
- encouraging AFH helps
- especially in Winter, the most electrically demanding period, with
- insights into frequency of AFH charging,
- allowing construction of the capability heatmap (Figure 7-1) which may form a simplified assessment system,

given provisos re harmonics and accelerated substation transformer ageing.

The novel elements of the simulator are:

- fine-grain timing giving improved visibility of peak load events,
- EVs are individuals with memory, able to log both home and way charging,
- the tranche system, able to mimic EV charging patterns (The Tranche-based EV Intent Model section 4.5.9),
- forecasts are substituted by a real-time least-regret heuristic method, and
- the integrated system, as a whole.

(Return to Figure 7-1: Chapter Directory)

7.5.5 Significance

There are two significant outcomes: Influencing policy direction and cost savings. This work, plus the availability of a tool to assess EVs on LV network situations, are of importance to HM Government, Distribution Network Operators and research groups studying the subject. Furthermore, some of the techniques developed for the simulator can form the basis of a novel local controller, notionally able to defer remedial works.

7.5.5.1 Potential for Influencing Policy Direction

A summary of the work has been passed to HMG (Department of Transport) as **(Broderick, S. 2019)** in response to their request for feedback on proposed policy for Electric Vehicle Smart Charging, **(DfT & OLEV, 2019)**.

It is apparent from Electric Vehicle Smart Charging that Government policies assume no LV limitations. The thesis may influence such understanding, so may affect policy decisions.

7.5.5.2 Potential for Cost Savings

Schemes similar to the developed MCS may enable cost savings for the UK over the next 30 years. **(EA Technology, 2012, Fig. 0.1)** estimates "Business As Usual" distribution LV refurbishment / reinforcement costs at c. £62 bn. and suggests that a Smart solution could assist lower costs to c. £18 bn. i.e. save c. £44 bn.

The work of this thesis has developed methods to realise such a solution, by steps of:

- assessing the impact of EVs on individual networks, so
- determining the limits of what a given network may support, hence
- needs for intervention, based on
- the capabilities of various approaches.

Projections from My Electric Avenue of c. 1/3rd of UK local network stock needing upgrades via reinforcement, and assuming cost of £1,000 per home can be estimated as c. £1,000 x 30 million / 3 = £10 bn., which would be financed at say 6%, costing roughly £6 bn. over a decade. The author estimates an MCS as likely costing c. 10% of reinforcement, with running costs of the same over 10 years, implying savings of c.

£6 bn. - 2 x 0.1 x £10 bn. = £4 bn. saved per decade.

Stated as per annum per house this is: £4 bn. / 10 million / 10 = £40. Thus, a DNO with 1 million affected customers using an MCS with a 20 year life, might release a value of:

£40 x 1 million x 20 = £800 million, per million customers over the MCS lifetime.

The work has international relevance. European networks are similar, thus the total pool of homes which may benefit is c. 100 - 200 million across the EU. Such deferral at c. £40 per home per annum is worth £4 - 8 bn. pa across Europe. Deferral may be effective for say 15 years, limiting spend by c. £60 - 120 bn.

Other nations may also find benefit.

7.6 Summary

This chapter has inspected results to draw general and specific conclusions. Some useful charts have been proffered and major outcomes have been stated.

The FPB system does need be verified vs. real-life measurements. Until that is done, the output of FPB has to be qualified. However both the utility of the method and ability to manage EVs on a constrained supply have been demonstrated.

Per-substation local Managed Charging Systems have been shown able to defer major spend for years perhaps decades; potentially the methods developed for the FPB MCS can aid realise such a system. Yet from the DNO viewpoint, LV network reinforcement for Heat Pumps is clearly necessary as loadings are so high; this is not a question of “will reinforcement be needed?”, rather “when will reinforcement be needed?”.

The author hopes the outcomes raise awareness of the UK Government (Ofgem, Dept. for Transport) to aid their policies. Present plans **(DfT & OLEV, 2019)** show intent to use the Smart Grid for blind Aggregator control via Demand Side Response, which for constrained networks is shown detrimental (see section 6.6). These insights will hopefully prompt updates and/or local MCS control, which can aid rather than impede LCT rollout.

The next chapter looks at future forward actions, based on the work so far.

(Return to Figure 7-1: Chapter Directory)

Chapter 8: Recommendations and Further Work

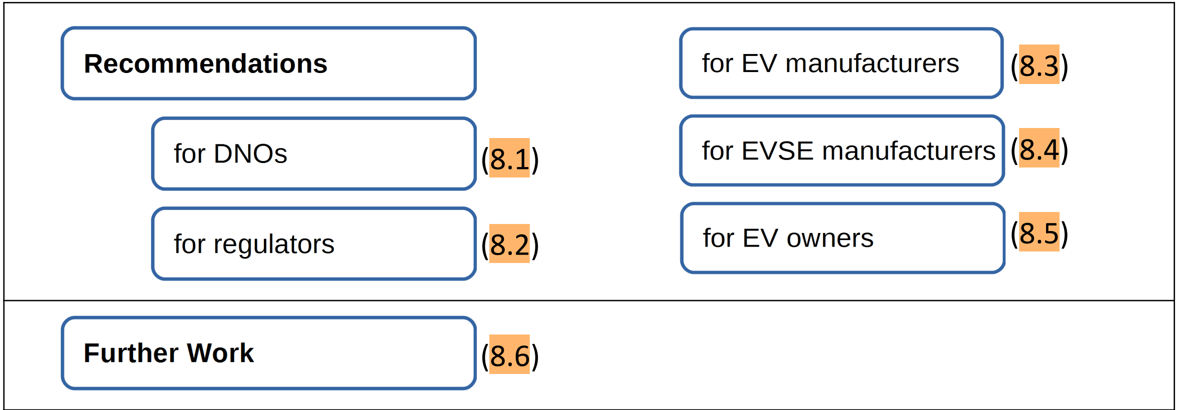


Figure 8-1: Chapter Directory: Recommendations chapter

This chapter suggests forward actions for industry as Recommendations, and possible FPB project continuation/development as Further Work.

8.1 Recommendations for DNOs

This section includes the following:

- 8.1.1 General Concerns,
- 8.1.2 Awareness of EV Characteristics and Use,
- 8.1.3 Suggested Actions,
- 8.1.4 Accelerated Asset Ageing,
- 8.1.5 Unclear Ofgem Stance re Clamping / Undercharging,
- 8.1.6 Using an MCS to Defer Reinforcement.

8.1.1 General Concerns

The simulations presented are near best-case. The test feeder modelled is one which would show no problems in normal use; a built marginal feeder would fail earlier. The 1.5 kW ADMD test network supplying only residential loads had a worst-case volts drop (LV busbars to endpoint) of 246 V to 235 V i.e. 3.1% during the Winter week. There are installed systems which suffer higher voltage drops.

The DNO first task is to determine which networks need intervention. This is potentially a time-consuming task, as each network needs individual assessment. Smart Meter load data may aid retrospective analysis.

The planning situation is dominated by the introduction of Heat Pumps. Provision for HPs implies reinforcing all affected LV systems built to less than 9 kVA per 3-bed semi (includes c. 3 kW HP, auxiliary heating e.g. flow boiler, normal residential load and a modest "cold-start" capability). A 7 kW EV is not included, but when controlled by MCS can charge in low-load times. With no MCS, the ADMD of the EV needs to be found for the feeder section and added to the net load (see 6.3.1 or add UKPN's suggestion of 0.5 coincidence) giving c. 13 kW ADMD for the same property.

Reinforcement may remain necessary without HP. The built ADMD LV capability heatmaps (Figure 7-2) are best-case scenarios which have the provisos:

- the EVs considered use BLPs, electrically less demanding than 2019 types, and
- a real-world network may fall short, due to:
    - feeder tapering (using cheaper, less capable cable to the end of feeders),
    - excess feeder length
    - clustering of high loads at a far-end,
    - together provoking volt-drop issues not seen in these studies, and / or
    - inadequate transformer capability.

However, a major concern is the power-fail with delayed comms recovery scenario (6.10).

The substation must deal with power-fail and recovery. On power restoration it is possible that EVs access supply, yet the comms system may need time to restore connections to manage charging. A comms fail is a non-specific period from minutes to hours. Some EVSE brands may halt EV charging during comms fails, but this is not assured. A mechanism is needed to prohibit EVs from charging, for sans comms they are not managed or the substation needs a protection system which disconnects LV from the estate until comms recovers. A protection system implies replacing the 11 kW disconnector / isolator (16) with automated switchgear and controller; the author suspects works may exceed £10 k per installation.

As an alternative: Use the investment to bring forward the day of reinforcement (for HP) and fit a transformer able to ride out the high demand following power restoration.

A 13 kW ADMD per house rating for HP + ancillary loads is recommended, so able to cope with black-start. With this in place, there need be less emphasis on ICT / Smart solutions.

The author's sponsor has asked **if EVs can correct for phase load unbalance**. The answer to that is: **Not in a useful manner**. Although possible, it is at the expense of not charging EVs on the more loaded phase. This is likely unacceptable and may provoke requests for reinforcement; there is no long-term gain.

However early phase-hopping (auto-connect to the least loaded phase) studies, applied to public chargepoints, found the method effective and worthy of future investigation.

8.1.2 Awareness of EV Characteristics and Use

DNOs need awareness of EVs in terms of **location**, **numbers**, **driven mpd** and **type**. It is possible that some networks have no V2G EVs, or all dumb EVs.

Networks are also affected by EV charging patterns including BLPs where deployed. Rapid uptake of EVs in the early 2020s without BLPs raise loads higher than shown in Figure 7-2. It would aid DNOs for EV manufacturers to adopt BLPs (see 4.2.1.2).

Also it may help if ENA encouraged DfT to release "mpd maps" based on EVs known registered address, to aid planning. These may be anonymised. It it not known how else a DNO can estimate the mpd on any given feeder. A practical way would be to monitor substation demand and correlate vs. physical surveys of parked EVs.

8.1.3 Suggested Actions

An EV characteristics summary and population map, perhaps issued every 2 years by ENA. The concept of "Technical Administration" for congested networks. Here, the DNO gains sole authority to manage; their instructions cannot be gainsaid by 3rd parties e.g. retailers or Aggregators. This would likely need amendments to SEC regulations.

Communications need be certified for reliability and response time, and liability attributable so damage to DNO assets (possibly running into multiple £100 k) caused by comms failures can be financially compensated by the communications provider. DNOs need log comms functions in real-time (to support any legal case).

DNO networks need be assessed individually e.g. by rerunning OpenDSS with the target network replacing FPB's network, "replaying" FPB residential and EV loads. Failure symptoms include transformer and feeder overload or feeder endpoint low-voltage. The transformer duty-cycle seen may indicate accelerated transformer ageing.

Key factors for DNO assessment of networks include:

- time in hand until HP arrive,
- feeder and spur section ratings,
- the number of EVs likely to be present,
- local residential load profiles and whether these allow overnight EV charging.

With this data, consider (cost):

- if HP inclusion is in the near timeframe (< 5 years) reinforce immediately to c. 9-13 kVA per home (perhaps 3-ph at 4.5 kVA phase rating to each home)
    - once reinforced, until HPs arrive MCS is not needed;
    - when HPs arrive, MCS may be needed to provide interleaved charging
- otherwise (HP is not due soon):
    - Assess maximum number of EVs possible and mpd / distance to conurbations;
    - from these determine an appropriate design ADMD;
- if necessary, reinforce the LV system to support the revised net load implied
- if there are many lower-specification spurs on the feeder cable, consider:
    - if the limbs can cope with the new design ADMD
    - reinforcing as needed to the new specification (allows use of µMCS, 8.6.7), or
    - defer reinforcement. Deploy a system to manage each limb individually
    - If complex, such reinforcement may approach HP reinforcement costs and so justifying immediate implementation of an HP capable solution, covering at least the feeder (transformers being easier to replace).

The DNO also needs consider the following:

- prior to MCS installation, use substation data loggers to monitor load. It is suggested that when N EV on the most loaded phase reach a limit (e.g. max EV - 20%) then an MCS is fitted. A suitable data logger can flag this occurring.
- When N EVs might harm the substation transformer, network protection needs be in place for recovery from power fail with comms outage.
- Substation logs can track heat (implied by duty) and use the data to detect:

- ageing due to peaks (log a running integral of i^2 over a week, Figure 8-2);
- indications of rising MCS duty: “spare capacity window” shrinks (log times over 90% hi_limit to sense if mark to space ratio is shrinking), as in Figure 8-3.

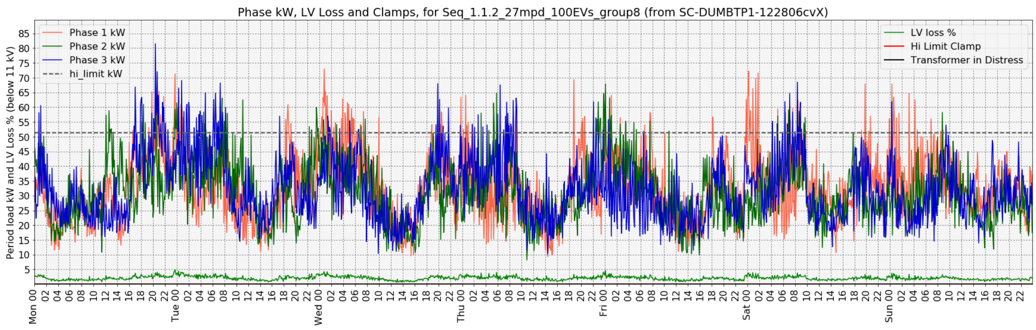


Figure 8-2: Use monitoring to log a running total of (i^2) of spikes over a limit

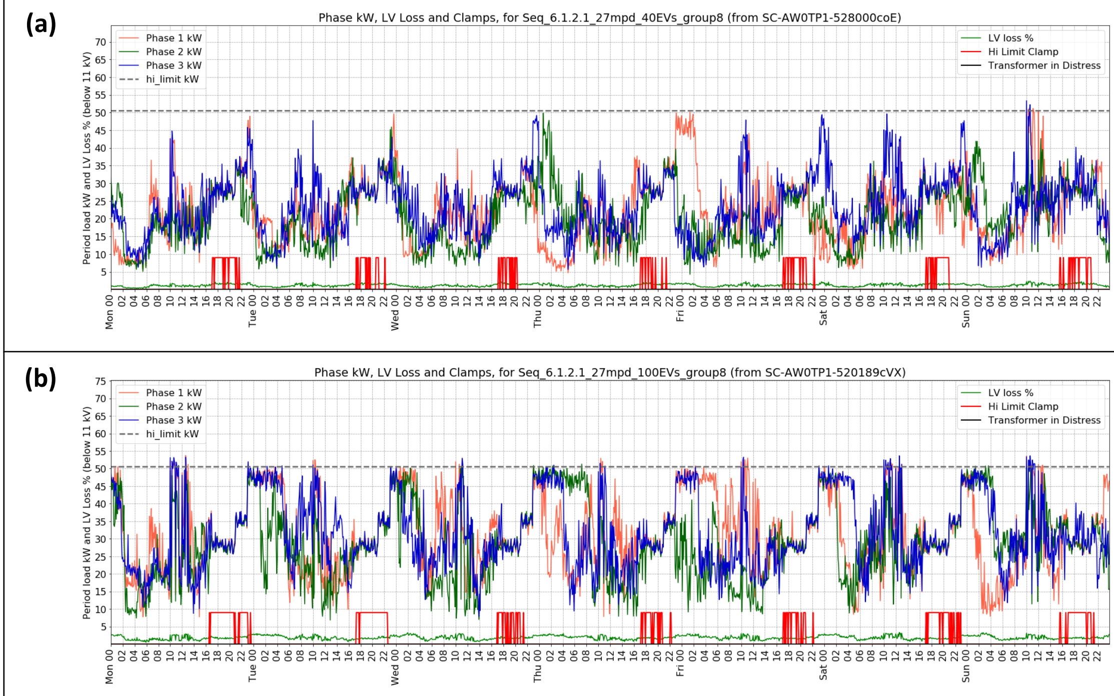


Figure 8-3: Mark/space ratio: Mark fills space as N EV rises 40 (a) ⇒ 100 (b)

- The Primary and 11 kV systems also need review as loads rise.
- The DNO cannot control the phase EV loads appear on. An unbalance may cause early broaches on that phase. This suggests public EVSE (roadside, standard power charging) need be multi-phase and to auto-connect to the least-loaded phase;
- The local shopping, entertainment area car parks etc. should have chargers able to support Winter AFH use; likely higher than at other times
- DNOs might promote use of AFH charging plus Winter residential load reductions,

- those houses with 3-phase available should be encouraged (mandated?) to use a 3-phase EV charger, ideally with phase-hopping capability e.g. when charging at 7.2 kW or below, to take load from the phase with the highest voltage.
- Changed driving patterns (diversions) can affect experienced diversity (see 6.3.1), potentially greatly e.g. closure of Humber Bridge can add 50 miles to trip legs.
- A possible income stream from DR and FFR services via MCS hi_limit modulation
- Static Batteries (local energy stores) plus PV panels optimised for Winter insolation may prove usefully and are to be encouraged.
- EV drivers experiencing undercharging (suggested: from 1 per week) should be encouraged to AFH charge e.g. by giving a free-charging coupon / allowance.

Finally, it is suggested that 3-phase is taken to all new-build properties.

8.1.4 Accelerated Asset Ageing

With an MCS, transformer loads tend to be level not cyclic. If the MCS hi_limit is over the transformer rating (typical when distribution ratings are used) sustained high loads are likely, ageing the asset faster. To limit this either fit a larger unit or lower the hi_limit.

Note FPB logging has retained all the necessary data to assess these ageing effects.

8.1.5 Unclear Ofgem Stance re Clamping / Undercharging

Use of the EVSE disconnector/clamp was envisioned for exceptional situations, not rote. Yet as soon as headroom limits are met, clamps must be used; operation may become endemic as EV numbers rise. Regular use may be frowned on by Ofgem and reinforcement mandated. Yet clamping rates are lower with MCS, thus a possible means to limit clamp counts without reinforcing is to use an MCS with FPB-like scheduling. Clamps remain and can be used on the reluctant EVs, but are no longer rote for well-behaved Smart EVs.

Also the author anticipates that Ofgem will eventually be pressed (by EV owners) to not allow vehicles to fail to charge, especially if power from an EVSE is less than might have been gained from a 13A socket, due to network management.

The author suggests a limit of severe undercharging (0.007 per EV per week, see 6.3.5); this may be too restrictive or too lax. What Ofgem may opine is unknown. However the author suggests that DNOs record a log of interventions including **why** the intervention occurred **NB** Aggregators may provoke undercharging, for which the DNO is blamed.

8.1.6 Using an MCS to Defer Reinforcement

Given the intended LCT rollout of Heat Pumps, the great majority of LV networks will ultimately need reinforcement. However an MCS can defer spend on reinforcement, suggested to be c. £40 per house per annum for at-risk networks. A DNO with 3 million domestic customers with 1 million at risk, this may defer spend of £40 million pa. as a rough estimate.

This is wise not only economically, but deferring reinforcement in the early years allows a better view of EV and HP uptake to be formed. Thus when reinforcement occurs it can be based on observations not projections (as would be needed today). However this is likely a temporary measure as Heat Pumps eventually force local network upgrades. From that viewpoint, deferring work may create a backlog to complete against vanishing timescales.

8.1.6.1 Other MCS Benefits for DNOs

LCT devices such as EVs will uplift LV system losses; MCS can aid manage these. Further, the effect of MCS to limit an LV network to design load levels means (for well designed networks) end-point low voltage issues are minimised / eliminated. This aids public safety by removing conditions promoting home appliance fires. MCS can also offer DR and FFR services, provide data logging functions and aid assess transformer ageing impacts.

8.2 Recommendations for Regulators

The home charging of EVs is targeted by proposed policy (= new law) by the Department for Transport to implement a DSR (power regulation) regime, to lower national peak load in the evenings, **(DfT & OLEV, 2019)**. Yet LV network issues are still in flux; presently there is no consensus. There is risk that a premature policy affects LV systems, bringing forward need to spend £10's bn. on reinforcement. This thesis shows remote control over charging (such as a DSR scheme, 6.6.4) provokes local overload problems. The submitted response document (7.5.5) describes the issues, and is written for the lay reader.

Ofgem needs be aware that DNO targeted network upgrades and initiatives to assess real-time load patterns are justified, for EV use monitoring. At some point network upgrades will be forced. The author sees DNO programmes to plan and cost these works are necessary, suggested as mandated forward plans under a RIIO price control scheme (perhaps similar to Ofgem's required DNO Losses Strategy requirements of 2016-17).

Regulators also need to take A Potential Dependency Trap into consideration.

8.3 Recommendations for EV Manufacturers

These consist of:

- charge batteries to the level needed, not to as much as they might hold
- incorporate BLPs to extend battery life, and
- provide basic electrical data to aid EV modelling e.g.:
    - usable battery kWh,
    - losses in inverter, battery, on-board ICT and draw when idle but connected
    - auxiliary appliance consumption including battery and cabin heating / cooling
    - electrical efficiency by journey distance and ambient temperature
    - any other aspect which would impact an electrical model.

Harmonics are a real issue for LV networks. Regulations re harmonic injection were written assuming they addressed a rare single generator, not dozens on the same network. This may result in tightening of harmonic injection regulations at some point.

8.4 Recommendations for EVSE Manufacturers

Please be aware:

- DNOs need timely high-priority interventions
- which override existing Aggregator commands, and
- retain precedence above Aggregator inputs until the DNO releases command hold.
- Regulations may be volatile, due to DNO needs not yet in legislation.
- Consider a phasing hopping variant:
    - changing EV supply phase on remote command, or
    - selecting and charging from the phase with the highest voltage.
- Consider multi-charging, section 8.6.6, to aid the Winter/Summer AFH ratio issue.

8.5 Recommendations for EV Owners

It is suggested EV owners:

a) have a Smart (remotely controllable) car,

b) users of vehicles > 150 mile range suffer less range anxiety;

c) for the owner, V2G is not necessary but benefits neighbours;

d) pedantically plug the EV in, especially in Winter;

e) keep under cover (reduces morning preheating),

f) expect range to near halve in cold conditions,

g) join a local charging control scheme (MCS or similar),

h) avoid Aggregator schemes which have no local insight

i) during cold weather, run SOC to a high level on Sunday e.g. near 100%.

8.6 Further Work (FPB Development)

Further work may develop FPB:

- as a useful network with EVs assessment tool for DNOs
- as a local data-logger at a substation, upgradable to be
- a local controller, either
    - a fully capable Smart Grid interfacing system, or
    - a chargepoint controller allowing 1 chargepoint to service multiple EVs
    - the µMCS implemented as a cut-down basic controller
- existing FPB generated output data may be repurposed to support other works e.g. transformer life impact assessment.

The most pressing tasks are:

- an exercise to raise confidence (see QA below), and
- to port FPB to python 3.5, as python 2.7 reaches end-of-life in January 2020.

8.6.1 Quality Assurance

Other than output plots, no aspect of system implementation (philosophy of operation, design, programming or input data) has been subject to informed 3rd party scrutiny or oversight. This means the following need reviewing:

- assumptions walk through
- design level walk through,
- code walk through

- input data walk through of residential loads and EV characteristics,
- refactoring as necessary together with
- regression and revalidation tests for each major module,
- integration and system validation tests and
- improved documentation.

This is months of work and must involve others. The effort spent on constructing FPB is c. 4,000 hours, which frankly is insufficient. The author has been involved on a smaller project working to professional standards, taking 6 staff a year (about 12,000+ hours).

8.6.2 FPB Functionality Enhancements

Functional improvements to FPB considered useful include:

1. implement a strategy to reduce errors (re losses and kW / kVA simplifications), or speed up OpenDSS interface and use that only
2. “point limits” on feeders joints to provide a “branch limit”
    a) to impose a kW limit where a feeder limb joins the main feeder, so to mimic a smaller cable branching / en route to further loads
    b) this is needed to detect and manage bunched loads at the far end of a feeder branch (as in a branching root system), allowing the feeder to taper
    c) at present sub-branches are monitored by OpenDSS, but not managed for a reduced load limit
3. a means to allow visitor ingress i.e. load representing EVs visiting “points of interest” e.g. a car-park beside a local restaurant, theatre etc.
4. include non-residential loads e.g. street lighting, utility pumps (gas, water)
5. per EV level reporting of clamp activity
6. clamp “applied kW draw” to be settable e.g. 0, 0.14 kW (true disconnect vs. idle)
7. per EV AFH charging probability, so individual EVs can be flagged to do more AFH. This to allow targeting of:
    a) drivers who suffer from excessive undercharging
    b) high kWh using (high mileage) drivers
    c) V2G drivers, so they bring AFH charge to the home network
8. potentially including a by-use-pattern (individual EV) tranche selector, so a taxi / LCV can be modelled as distinct from private vehicles

9. more sophisticated library of tranches
10. alternative battery C de-rating curves with temperature
11. multiple Aggregators “tied” to EVs, so they respond to those only
12. ability to generate logfile output by phase as well as a whole feeder view (better analysis of bias effects, impacts on EVs on a given phase)
13. a return of phase-hopping, if 3-phase is deployed for widespread domestic use
14. inclusion of phase power bridges (low load phases send power to adjacent high-load phases) which can be arbitrarily located along the feeder. Note: the ability to add one fixed-placement bridge is in the FPB;
15. longer profiling runs e.g. 6 weeks
16. ability to delay departure until there is enough SOC for trip
17. ability to add a distance multiplier so some vehicles mimic LGV (vans, white goods Transits which are driven home and charge as if cars).
18. add spontaneous use capability i.e. driver departs on an unexpected trip. Suggested implementation: “hide” a scheduled trip from the tranche constructor so the run-time assessor is “taken by surprise”. This maintains trip fidelity between scenarios allowing comparisons to be made, but charging is compromised
19. ability to bias 2nd EV use i.e. ability to declare EV_1 as the main car and EV_2 as a car which does less mpd e.g. the small runabout, the occasional special use car
20. provision for dedicated Static Batteries with independent control, such that more complex simulations can be performed e.g. investigation of Black Start methods, especially with Heat Pumps where large loads may be present for c. 12 hours. The batteries to be limited to a different hi_limit (not to suffer clamping)
21. better graphing of static battery and V2G EVs load/dispatch over time
22. add per EV type minimum ON and OFF times
23. per EV Event: EV time and duration parked, of charging and dispatching events
24. per period EV state summaries
25. maximum precharge flag (over weekends EVs to charge to near 100%)
26. 3-phase charging
27. provision for soft-set (in Houses_ID.csv) indicators for voltage monitor points
28. add completed trips in day, km in day to EV summary logfile. Also fleet trips completed per day, trips completed per week (post-processing can yield this)
29. per-EV V2G kWh per day / week budget to limit battery life impacts for the vehicle

30. per EV type heater profiles and battery cold temperature curves
31. per EV overnight sheltering / garaging
32. merge: Away stats e.g. list the times when, duration, distance and kWh taken on plus logging of frustrated attempts and any tow-homes
33. merge: battery ageing data collection: rainflow-counting algorithm i.e. log individual charge / discharge depth on reversal i.e. [Home/Away], time, start SOC kWh, end SOC kWh, time connected
34. revise tranches: In cold weather EVs immediately charge on return home to a new SOC representing next trip kWh + margin (this may make no difference to stranding as the network is the limit to charging)
35. per EV probability of finding an AFH charging point (allows failures…)
36. OR built AFH availability; failure to find Away from Home charging is now allowed
37. logging of depart undercharge state: time, SOC, kWh, [status flag]
38. add post-process code to find voltage imbalance at midpoint and far end of feeder
39. implement a means to simulate µMCS (see 8.6.7) - likely a separate project,
40. ability to analyse sets of EVs e.g. those Agg controlled, those dumb etc.
41. logging on EV departure of under charge state (weekly totals? Post-process for this from existing EV movements data?)
42. minimum mileage charging: EV charges so to be fit ASAP to drive a minimum mileage e.g. an unscheduled trip to a hospital. Charging beyond this uses BLPs;
43. re tomorrow's needed charging; "don't know: default to [80% | 100% SOC]"
44. perfect batteries (very low losses, no thermal degradation with cold) vs. marginal (cheap) batteries with very high losses.

Other enhancements may be considered.

8.6.3 Further Use as a Simulator

Even as is, FPB has unexplored potential. For instance charging from public on-road parking may be explored. On EV connection, a public chargepoint may be simulated connecting to the least-loaded phase. FPB as-is can be used to analyse LV networks in the UK, EU or other countries and also car-parks and HGV charging.

The author suggests a further investigation: To extend the sample network (so provoking voltage issues) until the previously seen broach condition is met. This would indicate the maximum LV length for which a DNO could expect the results to hold true. It would be possible to explore this just using OpenDSS. The method would be to replay logged simulations to OpenDSS, for a set of problematic scenarios (all OpenDSS commands are logged). Each run adjusts the inter-house gap until under-voltage conditions are met.

8.6.4 Construction of a LV System Assessor

A version of FPB could be developed which accepts network-specific real-world LV electrical characteristics, producing a localised analysis per simulation sequence.

This would need modest changes to the general FPB - but would need effort to convert real-world electrical data to OpenDSS-format. Methods to do this were developed in **(Quiros-Tortos, 2015)**. A simplified approach may be feasible e.g. from a library of basic feeders, with customised lengths and characteristics. Pragmatic simplifications may be possible e.g. identify and analyse the weakest network element, knowing other elements have better capability. Such an approach would greatly speed assessment.

However, if an existing network was used in FPB the simulation may trial proposed enhancements e.g. PV, Static Batteries, phase balancing bridges etc.

Other areas suggested as meriting further study include:

- EV stranding in Winter due to severe undercharging,
- the homeostasis (set in a desert) issue and means to correct,
- study of phase-hopping chargepoints
- study up to 180 EVs including works LCVs, business and taxis.

8.6.5 Reuse of FPB Generated Data

A DNO concern is likely transformer impacts, which may be assessed using FPB log data.

(Scottish Power, 2015) presented a transformer ageing plot (see Distribution (Cyclic) Rating section 2.1.6.2). The report suggested this is not a problem, for the transformer duty-cycle shown meant ageing was suffered briefly. Yet a throughput maximiser such as the FPB / MCS lifts duty cycle to near 100%. By eye and ruler, the area shown in orange, Figure 2-13 is c. 10% of the daily area. This implies ageing rates when EV charging (sustaining the transformer at the peak) are c. x10 of usual i.e. a transformer expected to last 4 decades needs replacing after 4 years. How much this is a year-around effect is presently not known; this is a major concern and needs be revisited, for it suggests that throughput maximised distribution transformers need de-rating or early replacement.

However, FPB logs per-period transformer load. This suggests applying the data with transformer ageing equations as in the Scottish Power paper or **(Qian, Zhou, & Yuan, 2015)**. FPB logs contains the transformer load data on the line marked by "Key stats C5d" in any logfile e.g. the post-processed intermediate data zip, in "Recent Logfiles" directory. This logs observed total LV load in kW, for each pd (6-minute period):

> *20180829:2107:SC-TP_9STATBATS-281920csA:0116:M8A:19_30_188:*
> *~Key stats C5d Rep 2 Net feeder load kW per pd with default_hi_limit,*
> *per pd load_kW:153.98,147.32,145.90,141.64,141.08,141.60 … … …*

The transformer kW load data (per pd, starting at pd 0) follows the value highlighted in green. There are 500 such data sets per ply.

8.6.6 Possibility of Multiplexing / Multi-Charging

EVs often spend longer parked then charging, likely common in commuter car-parks. Given 100 spaces, does the owner provide 100 chargepoints, or 33 each being a "multi-charger" providing power to (say) 3 EVs? The key point here is that most EVs which stand for a day only need charge for a few hours. Once charging is complete the EVSE presently remains connected doing nothing - and notionally unavailable to other EVs.

The proposal is to multiplex one EVSE output so 3 EVs can connect. The advantage (for single unit @ £4 k vs. £5 k for a multi-head) being £4 k x 100 vs. £5 k x 33, some £240 k saving per 100 powered parking bays.

The MCS element of FPB would be placed in a chargepoint which allows 3 EVs to connect via 3 cables and manages charging. It is likely the EVs need either dialogue with the EVs re SOC and departure time, or use a form of the micro-MCS, next described (8.6.7).

Note this method aids the Winter / Summer AFH charging problem seen in (Table 6-8).

8.6.7 Possibility of µMCS - a Simple MCS

The internal operation of FPB MCS employs one control signal path per phase. This may be broadcast. Then, given feeder uniformity (or non-uniform with end-point voltage sensing), and:

a) EVs are “mostly honest”,

b) EVs can determine a common ranking index, as used within FPB, and

c) EVs can access a web-page of data and

d) the µMCS sees feeder currents (so can observe the effect of commands),

a “micro-MCS” or µMCS is possible. This publishes a rank (one per phase) on the web; (Figure 8-4). The intent is: Only those EVs of given rank or higher may charge (V2G may though be more complex). The complexities of FPB’s equitable ranking method can be processed in the EV (which has all necessary data to hand), thus “by need” charging performed. Computation on the electrical side would then be low; a Raspberry-Pi per substation likely being adequate.

The µMCS has little to do other then find an appropriate rank value to publish, perhaps using an iterative method. Low endpoint volts would cause the hi_limit setpoint to be lowered. **Note** such updates are minutes apart and apply to the phase, not individual EVs; however EV and EVSE manufacturers would need cooperate.

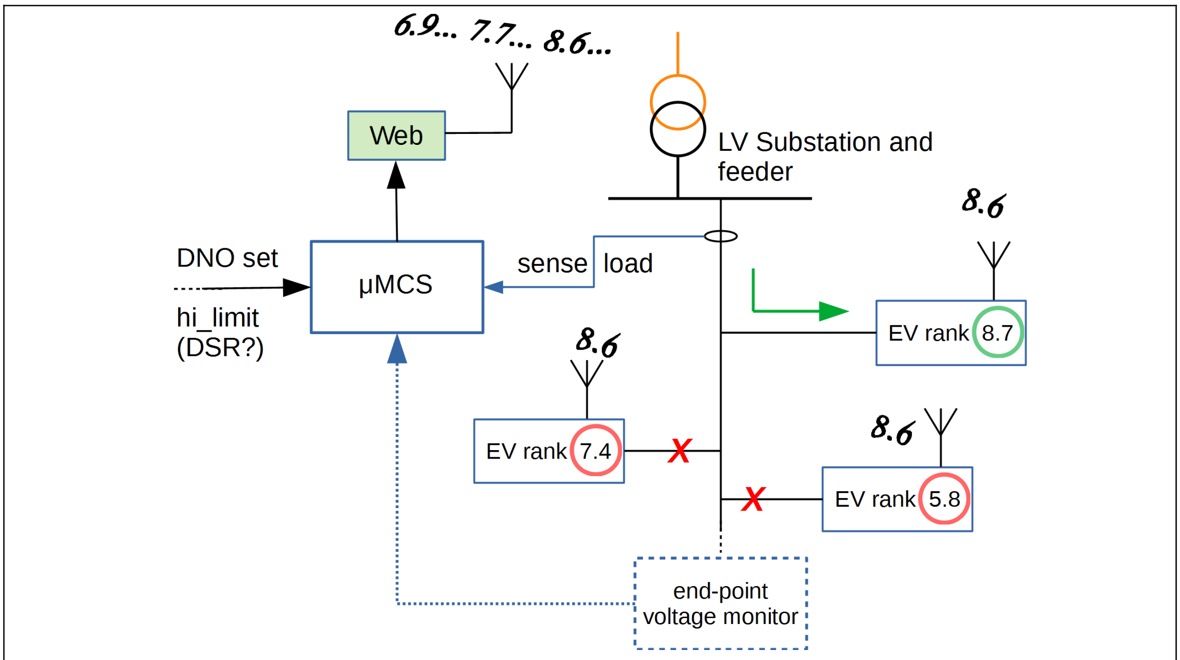


Figure 8-4: µMCS concept of operation: Only ranks >= 8.6 can charge

The appeals of such a simple system are:

- the method may be <u>fully anonymous</u>: an anonymous web-reader and resulting anonymous impact on feeder load,

- security issues are no more than presently faced by websites i.e. existing solutions may be employed. No SG comms layer is used; only website reads, not dialogues
- driver interventions or unusual rankings ("emergency charge") can be easily offered via the EV; this will cause brief overloads automatically corrected by turning other EVs down. This implies need for a setpoint kW margin;
- residential loads etc. are tracked and sidestepped as per FPB, as these influence the cable load hence are seen by the load sensor.

Operation would likely be more sporadic, but worth prototyping.

8.6.8 Other Applications

The immediate application is deploying the MCS element of FPB, so to:

- manage local residential LV systems
- manage car parks equipped with charge points.

As N EV rises in the general population, any destination car parks built to service the initial apparent need (e.g. as seen in 2025) will need to offer more charging. From the heatmaps (Figure 7-2) it can be seen a 2.5 kW installation per chargepoint, with an MCS, allows charging of all EVs vs. 3.7 kW installation otherwise needed. This implies near 50% growth on the same asset base by using an MCS. Clearly this can be rearranged so that an existing 3.7 kW build supports 50% more EVs.

In this manner existing assets may be retrofitted with an MCS to boost numbers of available charging points, without reinforcing the cabling or transformer. Also, the MCS offers DR and FFR as revenue generating services. These features would likely interest providers of large car-parks, e.g. at railway stations and airports. **Note** provisos about vulnerability to communications failure still apply.

The core of the MCS method is a resource allocator, apportioning a limited commodity:

- to uncontrolled consumers "as much as they like"
- to controlled 3rd party consumers by a priority method
- including sharing from 3rd parties with temporary excess of resource.

Exactly where else such a system is needed (dispensing feed in automated farming, dispensing drugs to hospitals?) is not known.

8.7 Beyond Mid-Century

This work has considered EVs on constrained LV systems. With uptake of Heat Pumps, UK LV networks will likely be reinforced, potentially making MCS redundant. However large car parks (of EVs) may find benefit using an MCS. Large freight and works vehicles are likely to be electric by then, presenting a new round of challenges.

The work in this thesis may remain relevant to locations with constrained networks.

< end of thesis main text - thank you for your patience in reading thus far>

this page deliberately left blank

Chapter 9: List of References

Notes:

1. Papers have titles in plain text, Reports and other works have italic titles.
2. The http links are clickable and live at the time of this thesis.

Aberdare Cables. (2008). *Cables Facts and Figures*.

Acha, S., Green, T. C., & Shah, N. (2011). Optimal charging strategies of electric vehicles in the UK power market. *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES*, 1–8. https://doi.org/10.1109/ISGT.2011.5759128

Acosta, J., Higgins, C., Hughes, M., & Manolopoulos, T. (2017). Innovative approaches to identification and reduction of distribution network losses. *CIRED - Open Access Proceedings Journal*, *2017*(1), 2383–2386. https://doi.org/10.1049/oap-cired.2017.1260

Al-karakchi, A. A. A., Lacey, G., & Putrus, G. (2015). *A method of electric vehicle charging to improve battery life*. 1–3.

Anaconda. (2016). *Anaconda Python Data Science Platform*. https://www.anaconda.com

Anon, & Broderick, S. R. (2018). *Author amended Low-voltage_network, with permission https://creativecommons.org/licenses/by-sa/4.0/*. https://en.wikipedia.org/wiki/Low-voltage_network

Apostolaki-Iosifidou, E., Codani, P., & Kempton, W. (2017). Measurement of power loss during electric vehicle charging and discharging. *Energy*, *127*, 730–742. https://doi.org/10.1016/j.energy.2017.03.015

Ardakanian, O., Rosenberg, C., & Keshav, S. (2013). *Distributed control of electric vehicle charging*. 101–112.

BEIS. (2017). *Clean Growth Strategy Leading the way to a low carbon future*. https://www.gov.uk/government/publications/clean-growth-strategy

BEIS, & MacLeay, I. (2016). *Digest of United Kingdom Energy Statistics*. https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes

BERR, & Arup/Cenex. (2008). *Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plugin Hybrid Vehicles*. BERR, DfT.

Blythe, P., Hill, D. G., Huebner, D. Y., Suresh, V., Austin, J., Gray, L., & Wardle, J. (2012). The north east england electric vehicle and infrastructure trials. *World Electric Vehicle Journal*, *5*(4), 856–865.

Boait, P., Ardestani, B. M., & Snape, J. R. (2013). Accommodating renewable generation through an aggregator-focused method for inducing demand side response from electricity consumers. *IET Renewable Power Generation*, *7*(6), 689–699.

Bouhouras, A. S., Athanasiou, A., Christoforidis, G. C., Tsiakalos, A., & Roumeliotis, M. (2017). Analysis of high penetration of electric vehicles and photovoltaics on a greek low-voltage network. *2017 52nd International Universities Power Engineering Conference (UPEC)*, 1–6. https://doi.org/10.1109/UPEC.2017.8231987

Broderick, S. (2018). *The FPB Manual*.

Broderick, S. (2019). *Response to UK Department of Transport Open consultation: Electric Vehicle Smart Charging*.

Broderick, Stephen, Cruden, A., Sharkh, S., & Bessant, N. (2016). An improved network simulator for EV/V2G studies. *IET CIRED Workshop 2016 Proceedings*.

Broderick, Stephen, Cruden, A., Sharkh, S., & Bessant, N. (2017). Technique to interconnect and control co-simulation systems. *IET Generation, Transmission & Distribution*, *11*(12), 3115–3124.

BSI. (2010). *BS EN 50160:2010 Voltage characteristics of electricity supplied by public electricity networks*. BSI.

Castro, M., Yellen, D., Hollingworth, D., Mukherjee, R., Barteczko-Hibbert, C., & Wardle, R. (2014). *Review of the Distribution Network Planning and Design Standards for the Future Low Carbon Electricity System*. www.networkrevolution.co.uk\wp-content\uploads\2014\10\CLNR-L185.pdf

Catapult. (2018). *Preparing UK Electricity Networks for Electric Vehicles*. https://es.catapult.org.uk/publications/preparing-uk-electricity-networks-for-electric-vehicles/

CEN-CENELEC E-Mobility Coordination Group (M/468), & CEN-CENELEC-ETSI Smart Grid Coordination Group (M/490). (2015). *E-Mobility Smart Charging*.

Christenson, B., Marinelli, M., Andersen, P. B., & Amtrup, C. (2017). *Nikola Final Report*. Technical University Of Denmark. https://www.energiteknologi.dk/sites/energiteknologi.dk/files/slutrapporter/12088_nikola_final_report.pdf

CLNR, & Wang, Y. (2014). *Lessons Learned Report Real Time Thermal Rating*.

Committee on Climate Change. (2019a). *Net Zero The UK's contribution to stopping global warming*. https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf

Committee on Climate Change. (2019b). *UK housing: Fit for the future?* https://www.theccc.org.uk/publication/uk-housing-fit-for-the-future

Cross, J. (2015). *My Electric Avenue An assessment of how much headroom an Esprit type solution would yield*. http://myelectricavenue.info/downloads/my-electric-avenue-i2ev-sdrc-98-assessment-how-much-headroom-esprit-type-solution-would

CRS, & Sissine, F. (2007). *Energy Independence and Security Act of 2007: A Summary of Major Provisions*. Library of Congress Washington DC Congressional Research Service.

DasGupta, A. (2005). The matching, birthday and the strong birthday problem: a contemporary review. *Journal of Statistical Planning and Inference*, *130*(1–2), 377–389.

DECC. (2013). *Smart Metering Equipment Technical Specifications Version 2*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/68898/smart_meters_equipment_technical_spec_version_2.pdf

DECC. (2014). *Seasonal Variations in Eelectricity Demand*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/295225/Seasonal_variations_in_electricity_demand.pdf

DEFRA, DfT, & UK Government. (2017). *UK plan for tackling roadside nitrogen dioxide concentrations (The NO2 Plan)*. https://www.gov.uk/government/publications/air-quality-plan-for-nitrogen-dioxide-no2-in-uk-2017

DfT. (2017). *Anonymised MOT tests and results*. Department for Transport; UK Government Department for Transport. https://data.gov.uk/search?q=MOT+Data&filters%5Bpublisher%5D=Department+for+Transport&filters%5Btopic%5D=&filters%5Bformat%5D=&sort=best

DfT, & OLEV. (2019). *Electric Vehicle Smart Charging*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/817107/electric-vehicle-smart-charging.pdf

Dowling, A. (2015). The Dowling review of business-university research collaborations. *London, UK*. https://www.raeng.org.uk/policy/engineering-policy-areas/research-and-innovation-policy/dowling-review

DRAKA. (2011). *The cable and table handbook*.

Dubarry, M. (2017). Electric Vehicle Battery Durability and Reliability Under Electric Utility Grid Operations. *University of Central Florida. Electric Vehicle Transportation Center (EVTC)*.

Dubarry, M., & Devie, A. (2018). Battery durability and reliability under electric utility grid operations: Representative usage aging and calendar aging. *Journal of Energy Storage*, *18*, 185–195. https://doi.org/10.1016/j.est.2018.04.004

Dugan, R. C., & McDermott, T. E. (2011). *An open source platform for collaborating on smart grid research*. 2011 IEEE Power and Energy Society General Meeting. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6039829

EA Technology. (2012). *Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks* (No. 82530; Smart Grids Forum – Work Stream 3). EA Technology Ltd. https://www.ofgem.gov.uk/publications-and-updates/assessing-impact-low-carbon-technologies-great-britains-power-distribution-networks

EA Technology Ltd. (2016). *UK and International Charging Options*. https://www.lowcvp.org.uk/search/results.htm?q="UK%20and%20International%20Charging%20Options"

EA Technology Ltd., & Roberts, D. (2016). *Project Close-Down Report SSET205 – My Electric Avenue (I2EV)*. http://myelectricavenue.info/sites/default/files/My%20Electric%20Avenue%20(I2EV)%20Close-Down%20Report.pdf

Electric Nation. (2017). *Electric Nation Project Website Main Page*. https://www.westernpower.co.uk/innovation/projects/electric-nation

ENA. (1981). *ACE Report No. 49 (1981) Statistical Method for Calculating Demands and Voltage Regulations on LV Radial Distribution Systems*. Energy Networks Association.

ENA. (2013). *ENA Engineering Recommendation G84*. ENA. http://www.ena-eng.org/ENA-Docs/D0C3XTRACT/ENA_EREC_G84_Extract_180902050535.pdf

ENA. (2017). *DCODE - Distribution Code Summary*. www.dcode.org.uk/assets/uploads/DCode_Summary-May_2017.pdf

EON. (2006). *EON Network Design Manual*.

EPRI. (2012). *Simulation Tool – OpenDSS*. http://smartgrid.epri.com/SimulationTool.aspx

European Commission. (2016). *DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on common rules for the internal market in electricity*. http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_864.pdf

Implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to small, medium and large power transformers, 548/2014 (2014). http://ec.europa.eu/smart-regulation/impact/ia_carried_out/docs/ia_2014/swd_2014_0161_en.pdf

FleetCarma. (2018). *Electric Range For The Nissan Leaf & Chevrolet Volt In Cold Weather*. fleetcarma. https://www.fleetcarma.com/nissan-leaf-chevrolet-volt-cold-weather-range-loss-electric-vehicle/

Gao, Y. (2016). *Assessment of Future Adaptability of Distribution Transformer Population Under EV Scenarios*. Doctoral Dissertation, University of Manchester.

Good, N., Zhang, L., Navarro-Espinosa, A., & Mancarella, P. (2015). High resolution modelling of multi-energy domestic demand profiles. *Applied Energy*, *137*, 193–210. https://doi.org/10.1016/j.apenergy.2014.10.028

Green, R. C., Wang, L., & Alam, M. (2011). The impact of plug-in hybrid electric vehicles on distribution networks: A review and outlook. *Renewable and Sustainable Energy Reviews*, *15*(1), 544–553. http://www.sciencedirect.com/science/article/pii/S1364032110002674

Greve, T., Teng, F., Pollitt, M., & Strbac, G. (2017). A system operator's utility function for the frequency response market. *Applied Energy*, *231*, 562–569.

GridKey. (2018). *Electric Nation Functional Requirements Document and Close Down Report*. https://www.westernpower.co.uk/downloads/1963

Guarnieri, M. (2012). Looking back to electric cars. *2012 Third IEEE History of Electro-Technology Conference (HISTELCON)*, 1–6. https://doi.org/10.1109/HISTELCON.2012.6487583

Haque, A., M. Nijhuis, Ye, G., Nguyen, P. H., Bliek, F. W., & Slootweg, J. G. (2017). Integrating Direct and Indirect Load Control for Congestion Management in LV Networks. *IEEE Transactions on Smart Grid*, 1–1. https://doi.org/10.1109/TSG.2017.2751743

Hayes, B. P., Gruber, J. K., & Prodanovic, M. (2018). Multi-nodal short-term energy forecasting using smart meter data. *IET Generation, Transmission & Distribution*, *12*(12), 2988–2994. https://doi.org/10.1049/iet-gtd.2017.1599

The Climate Change Act 2008, (2008) (testimony of HM Government). http://www.legislation.gov.uk/ukpga/2008/27/contents

Automated and Electric Vehicles Act, (2018) (testimony of HM Government). http://www.legislation.gov.uk/ukpga/2018/18/contents/enacted

HM Government. (2018a). *Automated and Electric Vehicles Act 2018*. http://www.legislation.gov.uk/ukpga/2018/18/contents/enacted/data.htm

HM Government. (2018b). *SN: 5340 National Travel Survey, 2002-2015*. National Travel Survey team (DfT). In first instance email NATIONAL.TRAVELSURVEY@dft.gsi.gov.uk

HM Government. (2018c). *The Road to Zero*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/739460/road-to-zero.pdf

HM Government, & DECC. (2011). *The Carbon Plan: Delivering our low carbon future*. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47613/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf

HSE. (2017). *ESQCR Electricity Safety, Quality and Continuity Regulations FAQs*. http://www.hse.gov.uk/esqcr/index.htm

Huang, S., & Infield, D. (2011). *Demand side management for domestic plug-in electric vehicles in power distribution system operation*. *Paper 0701*.

Jiang, T., Putrus, G., Gao, Z., Conti, M., McDonald, S., & Lacey, G. (2014). Development of a decentralized smart charge controller for electric vehicles. *International Journal of Electrical Power & Energy Systems*, *61*(0), 355–370. https://doi.org/10.1016/j.ijepes.2014.03.023

Kalesar, B. (2016). Customers Swapping Between Phases For Loss Reduction Considering Daily Load Profile Model in Smart Grid. *IET CIRED Workshop 2016 Proceedings*, *No. 0321*.

Kempton, W., & Letendre, S. E. (1997). Electric vehicles as a new power source for electric utilities. *Transportation Research Part D: Transport and Environment*, *2*(3), 157–175.

Kempton, W., Udo, V., Huber, K., Komara, K., Letendre, S., Baker, S., Brunner, D., & Pearre, N. (2008). A test of vehicle-to-grid (V2G) for energy storage and frequency regulation in the PJM system. *Results from an Industry-University Research Partnership*, *32*.

King, J., ENA, & Parsons Brinckerhoff. (2016). *DS2030 Stages 4 & 5: Project Results*.

Konstantelos, I., Sun, M., & Strbac, G. (2014). *Quantifying demand diversity of households*. Imperial College London.

Kuenzel, S., Kunjumuhammed, L. P., & Pal, B. C. (2013). Frequency response capability of the GB system in 2030. *Energynautics GmbH*, *3981387074*.

Liscouski, B., & Elliot, W. (2004). *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and recommendations.* (U.S.-Canada Power System Outage Task Force, p. 86). U.S.-Canada Power System Outage Task Force.

MacKay, D. J. (1998). Introduction to Monte Carlo methods. In *Learning in graphical models* (pp. 175–204). Springer.

Mahmud, K., & Town, G. E. (2016). A review of computer tools for modeling electric vehicle energy requirements and their impact on power distribution networks. *Applied Energy*, *172*, 337–359. https://doi.org/10.1016/j.apenergy.2016.03.100

Mogles, N., Walker, I., Ramallo-González, A. P., Lee, J., Natarajan, S., Padget, J., Gabe-Thomas, E., Lovett, T., Ren, G., Hyniewska, S., O'Neill, E., Hourizi, R., & Coley, D. (2017). How smart do smart meters need to be? *Building and Environment*, *125*(Supplement C), 439–450. https://doi.org/10.1016/j.buildenv.2017.09.008

Mouli, G. R. C., Venugopal, P., & Bauer, P. (2017). *Future of electric vehicle charging*. 1–7.

Navarro, A., Ochoa, L. F., & Mancarella, P. (2012). Learning from residential load data: Impacts on LV network planning and operation. *Transmission and Distribution: Latin America Conference and Exposition (T&D-LA), 2012 Sixth IEEE/PES*, 1–8. https://doi.org/10.1109/TDC-LA.2012.6319101

Navarro-Espinosa, A., & Mancarella, P. (2014). Probabilistic modeling and assessment of the impact of electric heat pumps on low voltage distribution networks. *Applied Energy*, *127*, 249–266. https://doi.org/10.1016/j.apenergy.2014.04.026

Neaimeh, M., Hill, G., Blythe, P., Wardle, R., Yi, J., & Taylor, P. (2013). *Integrating smart meter and electric vehicle charging data to predict distribution network impacts*. 1–5.

NGET. (2017). *National Electricity Transmission System Performance Report 2016 – 2017*. https://www.nationalgrid.com/sites/default/files/documents/National%20Electricity%20Transmission%20System%20Performance%20Report%202016-2017.pdf

NGET-Ricardo. (2011). *Bucks for balancing: Can plug-in vehicles of the future extract cash*. http://www.ricardo.com/en-GB/News--Media/Press-releases/News-releases1/2011/Report-shows-how-future-electric-vehicles-can-make-money-from-the-power-grid/Personal-Details/vehicles-of-the-future/

Northern Power Grid. (2018). *Code of Practice for the Economic Development of the LV System* (IMP/001/911). www.northernpowergrid.com\asset\0\document\109.pdf

Northern Power Grid, & Sidebotham, L. (2015). *Customer-Led Network Revolution Project Closedown Report* (CLNR-G026). http://www.networkrevolution.co.uk/project-library/project-closedown-report-2/

Ofgem. (2010). *DNO Electricity Distribution Loss Percentages by Distribution Network Operator (DNO) Area*. www.ofgem.gov.uk/ofgem-publications/43516/distribution-units-and-loss-percentages-summarypdf

Olivella-Rosell, P., Villafafila-Robles, R., Sumper, A., & Bergas-Jane, J. (2015). Probabilistic agent-based model of electric vehicle charging demand to analyse the impact on distribution networks. *Energies*, *8*(5), 4160–4187.

ONS. (2012). *2011 Census: Key Statistics for England and Wales, March 2011*. https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/2011censuskeystatisticsforenglandandwales/2012-12-11

ONS. (2016). *Percentage of households with durable goods by countries and regions, UK: Table A48*. https://www.ons.gov.uk/peoplepopulationandcommunity/personalandhouseholdfinances/expenditure/datasets/percentageofhouseholdswithdurablegoodsbycountriesandregionsuktablea48

Papadopoulos, P., Cipcigan, L. M., Jenkins, N., & Grau, I. (2009). Distribution networks with Electric Vehicles. *2009 44th International Universities Power Engineering Conference (UPEC)*, 1–5.

Pasaoglu, G., Fiorello, D., Martino, A., Scarcella, G., Alemanno, A., Zubaryeva, A., & Thiel, C. (2012). Driving and parking patterns of European car drivers --- a mobility survey. *Luxembourg: European Commission Joint Research Centre*.

Pipattanasomporn, M., Kuzlu, M., Rahman, S., & Teklu, Y. (2014). Load Profiles of Selected Major Household Appliances and Their Demand Response Opportunities. *IEEE Transactions on Smart Grid*, *5*(2), 742–750. https://doi.org/10.1109/TSG.2013.2268664

Poursharif, G., Brint, A., Black, M., & Marshall, M. (2017). Analysing the ability of smart meter data to provide accurate information to the UK DNOs. *CIRED-Open Access Proceedings Journal*, *2017*(1), 2078–2081.

Prince, D. C. (1925). The Inverter. *GE Review*, *28*(10), 676–681.

Procopiou, A. T., Quirós-Tortós, J., & Ochoa, L. F. (2017). HPC-Based Probabilistic Analysis of LV Networks With EVs: Impacts and Control. *IEEE Transactions on Smart Grid*, *8*(3), 1479–1487. https://doi.org/10.1109/TSG.2016.2604245

Python Software Foundation. (2018). *Python 2.7.15*. https://www.python.org

Qian, K., Zhou, C., Allan, M., & Yuan, Y. (2011). Modeling of load demand due to EV battery charging in distribution systems. *IEEE Transactions on Power Systems*, *26*(2), 802–810.

Qian, K., Zhou, C., & Yuan, Y. (2015). Impacts of High Penetration Level of Fully Electric Vehicles Charging Loads on The Thermal Ageing of Power Transformers. *International Journal of Electrical Power & Energy Systems*, *65*(Supplement C), 102–112. https://doi.org/10.1016/j.ijepes.2014.09.040

Quirós-Tortós, J. (2015). *Model Validation and Data Analysis (My Electric Avenue)*. https://www.researchgate.net/publication/283569615_Work_Activity_3_Model_validation_and_data_analysis

Quirós-Tortós, J., Ochoa, L. F., Alnaser, S. W., & Butler, T. (2016). Control of EV Charging Points for Thermal and Voltage Management of LV Networks. *IEEE Transactions on Power Systems*, *31*(4), 3028–3039. https://doi.org/10.1109/TPWRS.2015.2468062

Quirós-Tortós, J., Ochoa, L., & Lees, B. (2015). A Statistical Analysis of EV Charging Behavior in the UK. *Innovative Smart Grid Technologies Latin America (ISGT LATAM), 2015 IEEE PES*, 445–449.

RAC, Le Vine, S., & Polak, J. (2009). *The Car in British Society*. https://www.racfoundation.org/assets/rac_foundation/content/downloadables/

car%20in%20british%20society%20-%20lucas%20et%20al%20-%20170409%20-%20national%20travel%20survey%20wp1.pdf

REA, & WPD. (2018). *The feasibility, costs and benefits of three phase power supplies in new homes*. http://www.r-e-a.net/upload/rea_ev_three_phase_report_final-pdf-01-08-18-hi-res.pdf

Richardson, I., Thomson, M., Infield, D., & Clifford, C. (2010). Domestic electricity use: A high-resolution energy demand model. *Energy and Buildings*, *42*(10), 1878–1887. https://doi.org/10.1016/j.enbuild.2010.05.023

Rietveld, G., Houtzager, E., & Zhao, D. (2015). *Impact of The Ecodesign Directive on Traceability in Power Transformer Loss Measurements*.

Rivera, J., & Jacobsen, H. (2017). *On the Effects of Distributed Electric Vehicle Network Utility Maximization in Low Voltage Feeders*.

Rotaru, D. (2013). The UK electricity market evolution during the liberalization process. *Centre for European Studies (CES) Working Papers*, *5(2)*.

Scottish Power. (2015). *Enhanced Transformer Ratings Tool - Application Guide*. www.spenergynetworks.co.uk/userfiles/file/EnhancedTransformerRatingsTool_DesignandApplicationGuide28.pdf

Scottish Power. (2016). *Framework For Design & Planning OF LV Housing Developments, Including U/G Networks And Associated HV/LV S/S*. https://www.spenergynetworks.co.uk/userfiles/file/ESDD-02-012.pdf

Scrosati, B. (2011). History of lithium batteries. *Journal of Solid State Electrochemistry*, *15*(7), 1623–1630. https://doi.org/10.1007/s10008-011-1386-8

SEC, & Hartshorn, R. (2018). *SECMP0046 Allow DNOs to control Electric Vehicle chargers connected to Smart Meter infrastructure*. https://smartenergycodecompany.co.uk/modifications/allow-dnos-to-control-electric-vehicle-chargers-connected-to-smart-meter-infrastructure/

SECCo. (2017). *The Smart Energy Code*. https://smartenergycodecompany.co.uk

Shen, K., & Dunn, R. (2013). The prediction of flexible load demand in the UK in 2050. *Power and Energy Society General Meeting (PES), 2013 IEEE*, 1–5. https://doi.org/10.1109/PESMG.2013.6672457

Shirazi, Y. A., & Sachs, D. L. (2018). Comments on "Measurement of power loss during electric vehicle charging and discharging" – Notable findings for V2G economics. *Energy*, *142*, 1139–1141. https://doi.org/10.1016/j.energy.2017.10.081

Simmonds, G. (2002). *Regulation of the UK electricity industry. (Vol. 73)*. University of Bath School of Management.

SMMT. (2018). *SMMT VEHICLE DATA Car Registrations*. https://www.smmt.co.uk/vehicle-data/car-registrations/

Sohn. (2009). *Electricity Distribution Systems Losses*.

Solar Sheffield. (2018). *Historic PV Insolation Data*. https://www.solar.sheffield.ac.uk/pvlive/

SSEPD. (2015a). *LV Network Storage – ESMU Trials*. www.thamesvalleyvision.co.uk\wp-content\uploads\2017\05\NTVV-Learning-Outcome-Report-LV-Network-Storage-ESMU-Trials.pdf

SSEPD. (2015b). *RIIO-ED1 Losses Strategy*. /www.ssepd.co.uk/WorkArea/DownloadAsset.aspx?id=5385

SSEPD, & NTVV. (2015). *The New Thames Valley Vision Project*. SSEPD. www.thamesvalleyvision.co.uk

Strbac, G., Gan, C. K., Aunedi, M., Stanojevic, V., Djapic, P., Dejvises, J., Mancarella, P., Hawkes, A., Pudjianto, D., & Le Vine, S. (2010). Benefits of advanced smart metering for demand response based control of distribution networks. *ENA/SEDG/ Imperial College Report on Benefits of Advanced Smart Metering (Version 2.0) (Energy Networks Association, London, 2010)*.

Tao, L., Ma, J., Cheng, Y., Noktehdan, A., Chong, J., & Lu, C. (2017). A review of stochastic battery models and health management. *Renewable and Sustainable Energy Reviews*, *80*, 716–732. https://doi.org/10.1016/j.rser.2017.05.127

TheCapitol.Net. (2009). *Government Series: Smart Grid*. The Capitol.Net. https://www.thecapitol.net/Publications/GovernmentSeries/1626_SmartGrid.html

TNEI, & NPG. (2019). *Final Report Smart Network Design Methodologies*. https://www.northernpowergrid.com/asset/0/document/4918.pdf

Uddin, K., Jackson, T., Widanage, W. D., Chouchelamane, G., Jennings, P. A., & Marco, J. (2017). On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system. *Energy*, *133*, 710–722. https://doi.org/10.1016/j.energy.2017.04.116

Ujvarosi, A. (2016). Evolution of SCADA Systems. *Bulletin of the Transilvania University of Brasov. Engineering Sciences. Series I*, *9*(1), 63.

UK Power Networks, & Low Carbon London Learning Lab. (2014). *DNO Guide to Future Smart Management of Distribution Networks Summary Report*. https://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Low-Carbon-London-(LCL)/Project-Documents/LCL Learning Report - SR - Summary Report - DNO Guide to Future Smart Management of Distribution Networks.pdf

UKERC. (2014). *Synthesis Report Scenarios for the Development of Smart Grids in the UK*. http://www.ukerc.ac.uk/publications/scenarios-for-the-development-of-smart-grids-in-the-uk.html

UKPN. (2014). *Design and Planning Framework for underground networks in UK Power Networks*.

UKPN. (2015a). *Impact of Electric Vehicle and Heat Pump loads on network demand profiles*.

UKPN. (2015b). *Impact of Low Voltage connected LCT on network utilisation*. http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Low-Carbon-London-(LCL)/Project-Documents/LCL%20Learning%20Report%20-%20B4%20-%20Impact%20of%20Low%20Voltage%20%E2%80%93%20connected%20low%20carbon%20technologies%20on%20network%20utilisation.pdf

UKPN. (2017). *UK Power Networks response to A smart, flexible energy system*. https://www.ukpowernetworks.co.uk/internet/en/about-us/documents/UK%20Power%20Networks%20_A_Smart_Flexible_Energy_system_A_call_for_evidence_response_%20final.pdf

UKPN, & Halsey, S. (2018). *Electric Vehicles Workshop* [Slides]. https://www.ukpowernetworks.co.uk/internet/en/have-your-say/documents/EV_WORKSHOP.pdf

Urquhart, A. J., & Thomson, M. (2015). Impacts of Demand Data Time Resolution on Estimates of Distribution System Energy Losses. *IEEE Transactions on Power Systems*, *30*(3), 1483–1491. https://doi.org/10.1109/TPWRS.2014.2349157

Wang, Y., Huang, S., & Infield, D. (2014). Investigation of the potential for electric vehicles to support the domestic peak load. *Electric Vehicle Conference (IEVC), 2014 IEEE International*, 1–8. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7056124

Wardle, R., Capova, K. A., Matthews, P., Bell, S., Powells, G., & Bulkeley, H. (2015). *Insight Report Electric Vehicles*. http://www.networkrevolution.co.uk/wp-content/uploads/2015/01/CLNR-L092-Insight-Report-Electric-Vehicles.pdf

Wilson Power Solutions. (2017). *SUPER LOW LOSS AMORPHOUS TRANSFORMERS*. https://www.wilsonpowersolutions.co.uk/wp-content/uploads/2017/05/Wilson-e2-Brochure-October-2017-For-Web-1.pdf

WPD. (2017a). *Customer Research and Trial Update Report (October 2017) - Electric Nation*. https://www.westernpower.co.uk/downloads/2095

WPD. (2017b). *Western Power Distribution Losses Strategy*.

WPD. (2018a). *Electric Nation Customer Research and Trial Update Report*. https://www.westernpower.co.uk/downloads/13523

WPD. (2018b). *Electric Nation Network Assessment Tool: Interim Development Report*. https://www.westernpower.co.uk/downloads/13529

WPD. (2018c). *Electric Nation The Real-World Smart Charging Trial - What We've Learnt So Far*. http://www.electricnation.org.uk/resources/

WPD. (2018d). *Electric Vehicle Charging Monitoring & Analysis*. https://www.westernpower.co.uk/downloads/1957

Appendix A: FPB Design Assumptions

A.1 Concerning EVs

These include:

a) EV trips mimic trips driven by ICE cars (permitting UK NTS trip data to be used)

b) trips exhibit no Time of Year seasonality i.e. Trips in Winter = Trips in Summer

c) if two EVs are resident at a house, each is driven as per usual (one is not for "occasional" use)

d) Away from Home (AFH) charging points are always available to the EV

e) no homes are 3-phase

f) none are fast DC chargers in-situ

g) the timeframe is a week

h) battery ageing is not modelled

i) EV inverters can do fractional charging at any point in the 1.5 - 7.2 kW range, but other than idle do not operate below 1.5 kW

j) no EVSE can phase-hop (move from phase 1 to phase 2)

k) (depreciated, optional) dumb EVs default to maximum charging rate, even if there is plenty of time

l) on parking, drivers tell the EV of next departure time, likely miles the next day

m) kWh consumption anticipated for trips includes internal cabin heating

n) EVSE based disconnectors cut power to the EV not "tell it to idle"

o) errors from "not immediately commencing charging mid-pd" are trivial / ignored

p) self-discharge (plus ICT devices) c. 0.1 .. 0.4 % per day drop are ignored

q) it is reasonable to "frog-march" EVs about trips even when SOC is too low as the driver will actively seek out and use AFH chargepoints

r) EV inverter c. 200 W leading VAr is approximated to power factor 1.0 in FPB

s) EVs exhibit a constant kW characteristic i.e. are not resistive loads, thus if local volts drop the EV inverter draws more current so to keep the same inbound kW

t) home EV arrival plug-ins are limited by a count, in the week, unless the driver performs lazy plug-ins (asserting: "there is enough SOC for tomorrow... so don't bother to plug it in"). This is based on EN reported driver behaviour **(WPD., 2017)**.

u) batteries charge at the same rate regardless of temperature (i.e. model ignores ambient and need to reduce charging rate - not true under 1° C).

v) battery capacity C kWh falls as per Li-ion temperature curves **(FleetCarma, 2018)**

w) other factors: weather, terrain, "heaviness of the driver's foot" are not modelled

x) Battery Life Policies (BLP) are in use i.e. manufacturers are aware of strategies to optimise battery life **(Al-karakchi, Lacey, & Putrus, 2015)** and **(Dubarry, 2017)**

y) the included BLP's are reasonable (SOC bands, battery temperature lowering)

z) battery charging over long periods are modelled as willingly reduced by the EV

aa) the projected characteristics of EVs are reasonable e.g. losses, internal kWh use

ab) the kWh consumption due to driving is fixed for all speeds and conditions

ac) short-trip EV efficiency loss is not modelled (see 0-4 mile trips on https://evstatus.com/graphs.php)

ad) FPB defers to the EV and driver; their wishes normally come first

ae) not considering deeply negative temperatures; this are possible but EVs (with Li-ion based systems, if the battery under c. -5° C) refuse to operate as:

- batteries perform badly and can deliver only low current, and
- if forced damage is likely; the EV Battery Management Unit halts operation.

That said, some countries (Norway) do experience deep negative temperatures and it is worthwhile researching Norwegian methods further;

af) most studies assume perfect knowledge of future events + perfect control. This study inverts that: It is assumed that there is no overall prior knowledge or control. Although future data is held in FPB memory, the MCS element has no view or foreknowledge of this i.e. the MCS makes decisions based on instantaneous data

A.2 Concerning Drivers, Homes and Utilisation

a) It is reasonable to NOT characterise homes by type e.g. OAP, young family etc. as the author's view is based on network asset life of multiple decades. The occupants of an area (and their behaviour) may change faster;

b) in the limit 140% EV penetration is reasonable as UK data **(ONS, 2016)** states that there are c. 1.2 cars per home in the UK. Presently, on-road cars do not have access to charging; it is likely that this will somehow be provided

c) driving is not synchronised i.e. cars do not arrive and depart in platoons; in general cars travel as individuals NB traffic conditions can affect this

d) the novelty of cheap driving does not encourage a burst of driving-for-pleasure. **Note** Tesla report customers do x2 in their EVs vs. usual cars

e) EVs are plugged-in on arrival or not at all i.e. drivers do not go out at random times to plug in their EV (some people will do this...).

A.3 Concerning Power and Data Networks

a) UK LV ("mains" 0-230 V) systems are studied; these are the networks which distribute power to low-rise residences (bungalows and houses)

b) the substation transformer is configured in an industry standard manner, being a tap setting for 246 V on the local LV busbar

c) it is assumed that a rapid, bidirectional digital communication path exists between the controller and each EV. Rapid here means "response well inside a 6 minute control-loop window"; likely sub-minute

d) the power network is considered in isolation i.e. there are no variations of input 11 kV supply due to any external situations.

A.4 General Settings

These refer to built-in stances or interpretations; some are hard-coded, others can be changed via configuration files.

- "modern" EVs perform 2 forms of BLP (see 4.2.1.2):
  a) apply battery cooling strategies by spreading charging over the time parked
  b) reduce ageing effects by minimising time outside SOC mid-band
- net outcome:
  - cool down on arrival (don't charge)
  - charge in stages to a SOC in mid-band range
  - add final charge just before departure

  The older dumb EVs charge to 100% as fast as possible. This simulation assumes EVs are mature so use BLPs, however a non-BLP dumb model is available within the simulation. Old dumb types impose higher network load than modern dumb using BLPs.
- EVs are characterised by parameters which
  - mimic current SMMT characterisation categories as UK sales
  - in the proportion of categories that SMMT report,

- the residential load is scaled from 1.5 kW to 1.3 kW ADMD per house as LED lighting has become widespread since 2015 (source: industry)
- unless otherwise stated:
    - DR/FFR mechanisms are OFF
    - clamping mechanisms are OFF
- the scenario is a high-stress situation set in Winter, with an average temperature of +1°C. This:
    - slightly increases the transformer hi_limit and
    - reduces EV battery capacity by c. 40% (Li-ion batteries assumed)
    - adds auxiliary loads in EVs (e.g. cabin heating using a Heat Pump)
    - is a sustained residential load worst-case situation
- simulates 1 logical week from Monday 00:00, and
- at Midnight Sunday (Monday 00:00 hours) all EVs are at home
- the simulator performs 2 “repetitions” per run to resolve battery SOC:
    - initialise each battery SOC to 50% and perform a 1-week conditioning simulation, producing a run-log not a full results set
    - repeat simulation resetting all parameters except SOC and the transformer heating i.e. SOC values and thermal loads from the first repetition are retained (this broadly stabilises SOC and heating to an “in use” value)
- simulations are set post 2021 so use an Amorphous core (low-loss) transformer.

Appendix B: The UK Power Industry

The participants, jargon and concerns which drive the industry are overviewed here. For more depth see **(Simmonds, 2002)** and **(Rotaru, 2013)**.

B.1 General Organisation

The UK electricity (aka "power") system has three main parts:

- generation (the production of electricity)
- transmission (the transfer of electricity around the country),
- distribution, undertaken by builders / maintainers of local networks supplying industry and homes.

The system formed from c. 1890 as regional generators and was nationalised in stages, becoming in 1957 the Central Electricity Generating Board (CEGB).

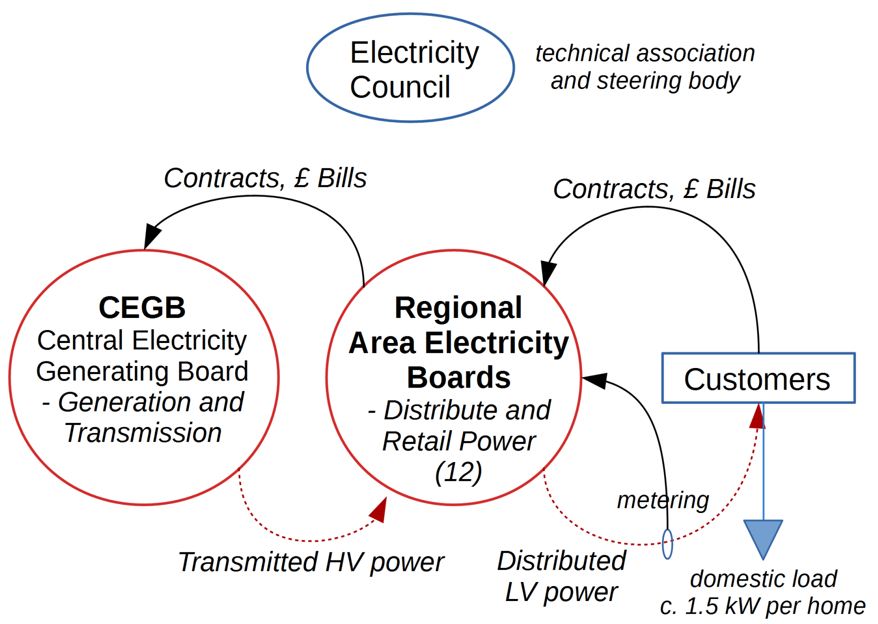


Figure B-1: Organisation of UK power industry under CEGB, 1957 - 1989

Privatisation occurred c. 1990. The CEGB was broken up and the industry reformed thus:

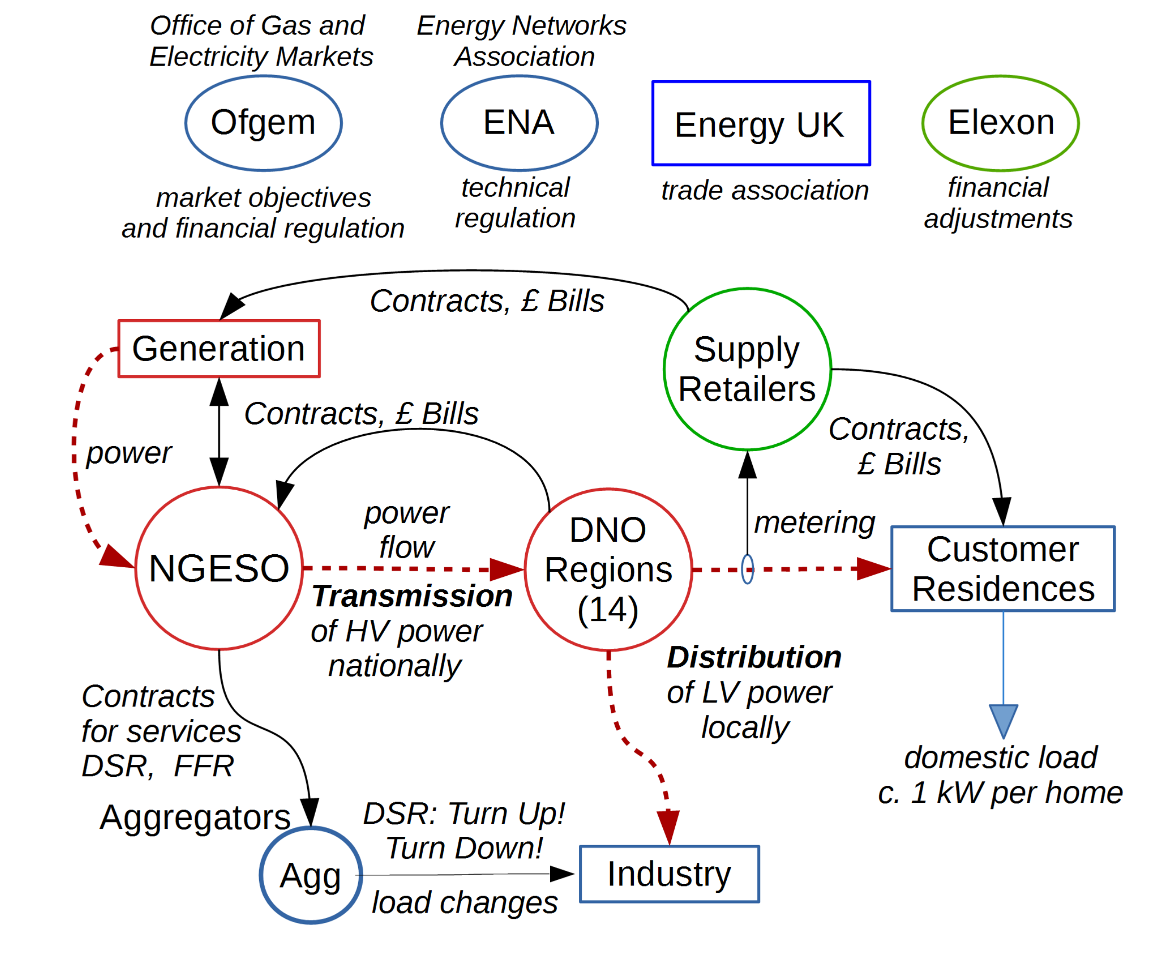


Figure B-2: Organisation of UK power industry from 1990

The responsibilities of the parties after privatisation became:

- the Office of Gas and Electricity Markets (Ofgem), an independent National Regulatory Authority managing markets and financing,
- the Energy Networks Association (ENA, with technical authority and responsibility)
- power generation is performed by 3rd party generation companies
- National Grid Electricity System Operator plc (NGESO, ex National Grid Electricity Transmission, NGET) manage:
    - the purchase of electricity and
    - transmission,
- the old Regional Areas are broken into:
    - Distribution Network Operators aka DNOs (who maintain the local assets) and
    - Retailers (who sell electricity to customers but may arrange purchase).

B.2 Ofgem and Market Regulation

Power supply is a natural monopoly. Ofgem controls price gouging by regulating market profits. The intent is to limit customer bills; Ofgem acts on behalf of the customer and has and will impose penalties. See for example: https://www.telegraph.co.uk/business/2018/03/07/ofgem-threatens-toughest-ever-blow-energy-network-profits/.

B.3 The Energy Networks Association (ENA)

UK technical standards are set by ENA, effectively the technical arm of Ofgem. A quango.

B.4 National Grid Electricity System Operator

NGESO are responsible for purchasing power from generators, regulating the system frequency and transmitting power between regions. **Note** up to April 2019 was NGET.

B.5 DNO Regions and Licenses

DNOs are licensed to own and manage the assets of a region for profit. Licensees can change. Ofgem controls licenses. DNOs do not retail power so have no relationship with consumers. Without contracts, Ofgem requires DNOs to follow regulations which impose responsibilities to supplied premises (ENA, 2017). These are also set in EU legislation **(EuropeanCommission, 2016)**. Presently there are 14 licenses issued to 6 companies (see https://www.ofgem.gov.uk/electricity/distribution-networks/gb-electricity-distribution-network).

B.6 Network Balancing Services

Several ancillary services are needed to manage the network in real-time. Ofgem encourages competitive markets to provide these services. These relate to occasional bulk delivery of power and delivery of either power or demand reduction for various purposes; some need sub-second action and are automated. Any party with suitable grid connected equipment can supply “Balancing Services”.

The act of injecting power or reducing existing load may provide power for use elsewhere. At the highest level, these are interchangeable; however the method used is constrained by the capabilities of local equipment and the ability to communicate and control diverse (small) assets in a timely manner.

NGESO nominates several markets to exist. Contracts are struck by “reverse auctions”. These markets are able to supply within a response frame (e.g. 100 MW in under 10 seconds) for a period (minutes to hours) and are broadly:

- fast acting response (used for frequency control) broken into sub-markets by scale, response time and response duration (part-seconds to tens of minutes) and
- peak support / long duration supply (minutes into hours)
- peak shaving / long duration demand reduction (minutes to hours).

Services are supplied by power generators or 3rd parties called “aggregators”.

Note that in recent times auctions have been over-subscribed; prices have fallen.

B.6.1 Demand Reduction / Demand Response (DR, DSR)

When load experiences a long-term rise (typically, part of a daily or seasonal cycle) extra supply is needed. Keeping a power-station to hand for intermittent use is expensive. One strategy to avoid this is by signalling consumers to turn down demand, so limiting load peaks. This is variously called “curtailment”, “peak shaving”, Demand Reduction or Demand Side Reduction (DR / DSR). ICT can directly command customer loads; this is called Automated Demand Response or ADR. Switches to do this are included in Smart Meters operated via the Smart Grid; the SMETS2 design offering 5 controllable devices.

B.6.2 Frequency Balancing / Frequency Response (FR, FFR)

The UK power system is designed for 50 Hz. Operating outside of this by a few percent causes system efficiency to drop; losses rise.

Power system supply and demand is dynamically balanced in real-time. If demand falls, mechanical (rotating) generators express excess energy as increased angular momentum - they turn faster; system frequency rises. Faced with sudden demand energy moves out of rotation and frequency drops. Storing energy in rotation is referred to as “inertia” although electronic replication (“synthetic inertia”) is possible. Frequency correction is performed by adjusting generated power or net load. See also **(Greve, Teng, Pollitt, & Strbac, 2017)**.

Note power generators are obliged to accept NGESO frequency regulation commands (Mandatory Response).

B.7 Aggregators

An aggregator is a business which co-ordinates many small generation assets to form a command group. Aggregators can then trade power services. The assets are often:

- industrial generation units which can connect to the grid to supply power, or
- industrial processes which can be briefly suspended, so reducing demand.

Aggregators hold contracts with NGESO to supply power on call / as needed.

B.8 Losses, Voltages and Current

The power received by customers is less than supplied by generators. This discrepancy is called "losses". Losses are often technical and caused by the physical characteristics of the supply system. Non-technical losses (theft) also occur, a relatively minor problem. Lost energy is expressed as heat; transformers and cables heat-up. The causes are:

- conductor / cable resistance, and
- the energy spent in re-magnetising transformer cores at 100 changes per second
- radiated energy, primarily as corona discharge from very high voltage systems.

However whilst power flow is:

$$P = I * V \tag{29}$$

resistive losses are:

$$Loss = I^2 * R \qquad \textit{R is resistive impedance of the lossy element} \tag{30}$$

i.e. losses are proportional to the square of current (I). This gives rise to the strategy of using a high voltage (V) to minimise current, which lowers losses by a square law. Hence the transmission system uses c. 400 kV to move power around the country. This voltage needs be lowered before reaching customers. These voltage manipulations are performed by transformers.

DNOs typically accept power at 400 kV and step-down via a cascade of transformers:

- Main station: 400 kV to 66 or 33 kV,

- Primary station: 66 or 33 kV to 11 kV (large customers may take power at 11 kV),
- Substation: 11 kV to 400 V (phase to phase; 230 V phase to Earth i.e. LV).

Networks are arranged in a branching / bifurcating topology, typically following a geographic route to consumers.

Note that some countries have 3-phase routinely taken to houses; most UK homes receive single phase 230 V, although 3-phase is available on request.

Appendix C: Output .csv File Samples

Only the two major files are shown; for the OpenDSS files and other files see the FPB Manual. Also explore the contents of a .zip file "Batch_Results_ODSS" which contains a snapshot of all key files (including logs, Feeder and EV .csv files) held in the data area.

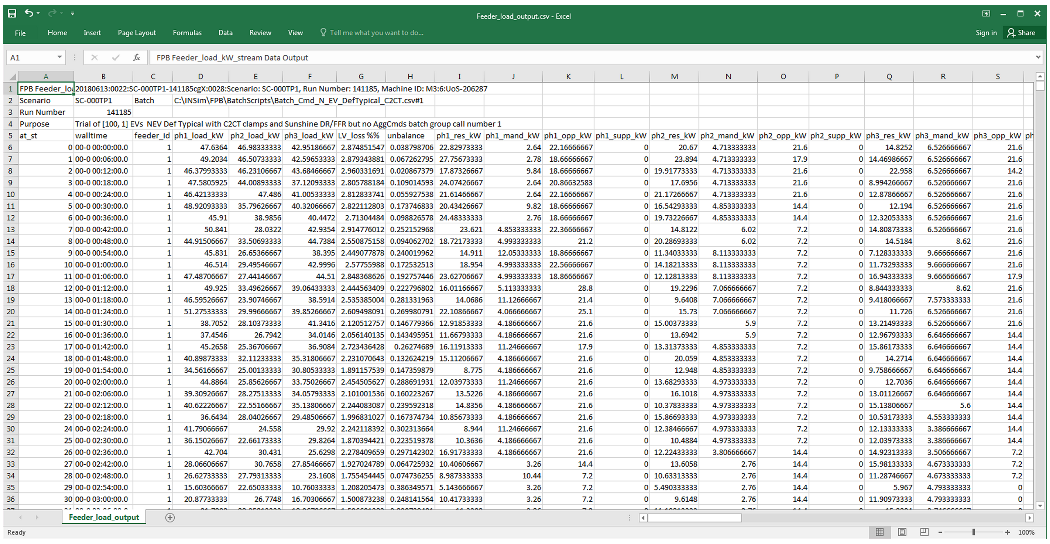
See also the contents of data repository:

> SR Broderick Thesis and Data Repository > 3.1 Raw FPB Output Sample
>
> > (S_AR) DefTyp_DRFFR_C2CT_DRFFR_9StatBats > BatchResults_ODSS > (any zip file)

C.1 Feeder_load_output.csv

The purpose of this file is to record the feeder situations and to delineate the causes of those situations e.g. which EVs are charging. FPB does two weekly passes; the first pass is for system conditioning and is not shown (only pass 2 being retained).

The file reports timed phase loads on the feeder(s) and what is contributing to the load. This file is used to create the phase kW plots. Please zoom-in on this image in the .pdf.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	FPB Feeder_lo	20180613:0022:SC-000TP1-141185cgX:0028:Scenario: SC-000TP1, Run Number: 141185, Machine ID: M3:6:UoS-206287																	
2	Scenario	SC-000TP1	Batch	C:\INSim\FPB\BatchScripts\Batch_Cmd_N_EV_DefTypical_C2CT.csv#1															
3	Run Number	141185																	
4	Purpose	Trial of [100, 1] EVs NEV Def Typical with C2CT clamps and Sunshine DR/FFR but no AggCmds batch group call number 1																	
5	at_st	walltime	feeder_id	ph1_load_kW	ph2_load_kW	ph3_load_kW	LV_loss %%	unbalance	ph1_res_kW	ph1_mand_kW	ph1_opp_kW	ph1_supp_kW	ph2_res_kW	ph2_mand_kW	ph2_opp_kW	ph2_supp_kW	ph3_res_kW	ph3_mand_kW	ph3_opp_kW
6	0	00-0 00:00:00.0	1	47.6364	46.98333333	42.95186667	2.874851547	0.038798706	22.82973333	2.64	22.16666667	0	20.67	4.713333333	21.6	0	14.8252	6.526666667	21.6
7	1	00-0 00:06:00.0	1	49.2034	46.50733333	42.59653333	2.879343881	0.067262795	27.75673333	2.78	18.66666667	0	23.894	4.713333333	17.9	0	14.46986667	6.526666667	21.6
8	2	00-0 00:12:00.0	1	46.37993333	46.23106667	43.68466667	2.960331691	0.020867379	17.87326667	9.84	18.66666667	0	19.91773333	4.713333333	21.6	0	22.958	6.526666667	14.2
9	3	00-0 00:18:00.0	1	47.5805925	44.00893333	37.12093333	2.805788184	0.109014593	24.07426667	2.64	20.86632583	0	17.6956	4.713333333	21.6	0	8.994266667	6.526666667	21.6
10	4	00-0 00:24:00.0	1	46.42133333	47.486	41.00533333	2.812833741	0.055927538	21.61466667	2.64	22.16666667	0	21.17266667	4.713333333	21.6	0	12.87866667	6.526666667	21.6
11	5	00-0 00:30:00.0	1	48.92093333	35.79626667	40.32066667	2.822112803	0.173746833	20.43426667	9.82	18.66666667	0	16.54293333	4.853333333	14.4	0	12.194	6.526666667	21.6
12	6	00-0 00:36:00.0	1	45.91	38.9856	40.4472	2.71304484	0.098826578	24.48333333	2.76	18.66666667	0	19.73226667	4.853333333	14.4	0	12.32053333	6.526666667	21.6
13	7	00-0 00:42:00.0	1	50.841	28.0322	42.9354	2.914776012	0.252152968	23.621	4.853333333	22.36666667	0	14.8122	6.02	7.2	0	14.80873333	6.526666667	21.6
14	8	00-0 00:48:00.0	1	44.91506667	33.50693333	44.7384	2.550875158	0.094062702	18.72173333	4.993333333	21.2	0	20.28693333	6.02	7.2	0	14.5184	8.62	21.6
15	9	00-0 00:54:00.0	1	45.831	26.65366667	38.395	2.449077878	0.240019962	14.911	12.05333333	18.86666667	0	11.34033333	8.113333333	7.2	0	7.128333333	9.666666667	21.6
16	10	00-0 01:00:00.0	1	46.514	29.49546667	42.9996	2.57755988	0.172532513	18.954	4.993333333	22.56666667	0	14.18213333	8.113333333	7.2	0	11.73293333	9.666666667	21.6
17	11	00-0 01:06:00.0	1	47.48706667	27.44146667	44.51	2.848368626	0.192757446	23.62706667	4.993333333	18.86666667	0	12.12813333	8.113333333	7.2	0	16.94333333	9.666666667	17.9
18	12	00-0 01:12:00.0	1	49.925	33.49626667	39.06433333	2.444563409	0.222796802	16.01166667	5.113333333	28.8	0	19.2296	7.066666667	7.2	0	8.844333333	8.62	21.6
19	13	00-0 01:18:00.0	1	46.59526667	23.90746667	38.5914	2.535385004	0.281331963	14.0686	11.12666667	21.4	0	9.6408	7.066666667	7.2	0	9.418066667	7.573333333	21.6
20	14	00-0 01:24:00.0	1	51.27533333	29.99666667	39.85266667	2.609498091	0.269980791	22.10866667	4.066666667	25.1	0	15.73	7.066666667	7.2	0	11.726	6.526666667	21.6
21	15	00-0 01:30:00.0	1	38.7052	28.10373333	41.3416	2.120512757	0.146779366	12.91853333	4.186666667	21.6	0	15.00373333	5.9	7.2	0	13.21493333	6.526666667	21.6
22	16	00-0 01:36:00.0	1	37.4546	26.7942	34.0146	2.056140135	0.143495951	11.66793333	4.186666667	21.6	0	13.6942	5.9	7.2	0	12.96793333	6.646666667	14.4
23	17	00-0 01:42:00.0	1	45.2658	25.36706667	36.9084	2.723436428	0.26274689	16.11913333	11.24666667	17.9	0	13.31373333	4.853333333	7.2	0	15.86173333	6.646666667	14.4
24	18	00-0 01:48:00.0	1	40.89873333	32.11233333	35.31806667	2.231070643	0.132624219	15.11206667	4.186666667	21.6	0	20.059	4.853333333	7.2	0	14.2714	6.646666667	14.4
25	19	00-0 01:54:00.0	1	34.56166667	25.00133333	30.80533333	1.891157539	0.147359879	8.775	4.186666667	21.6	0	12.948	4.853333333	7.2	0	9.758666667	6.646666667	14.4
26	20	00-0 02:00:00.0	1	44.8864	25.85626667	33.75026667	2.454505627	0.288691931	12.03973333	11.24666667	21.6	0	13.68293333	4.973333333	7.2	0	12.7036	6.646666667	14.4
27	21	00-0 02:06:00.0	1	39.30926667	28.27513333	34.05793333	2.101001536	0.160223267	13.5226	4.186666667	21.6	0	16.1018	4.973333333	7.2	0	13.01126667	6.646666667	14.4
28	22	00-0 02:12:00.0	1	40.62226667	22.55166667	35.13806667	2.244083087	0.239592318	14.8356	4.186666667	21.6	0	10.37833333	4.973333333	7.2	0	15.13806667	5.6	14.4
29	23	00-0 02:18:00.0	1	36.6434	28.04026667	29.48506667	1.996831027	0.167374734	10.85673333	4.186666667	21.6	0	15.86693333	4.973333333	7.2	0	10.53173333	4.553333333	14.4
30	24	00-0 02:24:00.0	1	41.79066667	24.558	29.92	2.242118392	0.302313664	8.944	11.24666667	21.6	0	12.38466667	4.973333333	7.2	0	12.13333333	3.386666667	14.4
31	25	00-0 02:30:00.0	1	36.15026667	22.66173333	29.8264	1.870394421	0.223519378	10.3636	4.186666667	21.6	0	10.4884	4.973333333	7.2	0	12.03973333	3.386666667	14.4
32	26	00-0 02:36:00.0	1	42.704	30.431	25.6298	2.278409659	0.297142302	16.91733333	4.186666667	21.6	0	12.22433333	3.806666667	14.4	0	14.92313333	3.506666667	7.2
33	27	00-0 02:42:00.0	1	28.06606667	30.7658	27.85466667	1.927024789	0.064725932	10.40606667	3.26	14.4	0	13.6058	2.76	14.4	0	15.98133333	4.673333333	7.2
34	28	00-0 02:48:00.0	1	26.62733333	27.79313333	23.1608	1.755454445	0.074736255	8.987333333	10.44	7.2	0	10.63313333	2.76	14.4	0	11.28746667	4.673333333	7.2
35	29	00-0 02:54:00.0	1	15.60366667	22.65033333	10.76033333	1.208205473	0.386349571	5.143666667	3.26	7.2	0	5.490333333	2.76	14.4	0	5.967	4.793333333	0
36	30	00-0 03:00:00.0	1	20.87733333	26.7748	16.70306667	1.500873238	0.248141564	10.41733333	3.26	7.2	0	9.6148	2.76	14.4	0	11.90973333	4.793333333	0

Figure C-1: Sample of Feeder_load_output.csv seen in spreadsheet

Data fields are are follows. **Note** the .csv contains fields across the page, not down the page as used in Table C-1 below:

Table C-1: Example of Feeder Load Output .csv file

Field name	Sample Contents	Comments
at_st	205	internal simulation time (10 per hour)
walltime	00-0 20:30:00.0	st as: WW-D HH:MM:SS.S i.e. data is for week 00-day 0 8:30pm. Day 0 is Monday
feeder_id	1	Most transformers have c. 5 feeders
ph1_load_kW	26.264	
ph2_load_kW	24.5115	
ph3_load_kW	29.812	
LV_loss %	2.306687574	sum of LV losses from 11 kV busbar
unbalance	0.109799907	as per DNO method (smaller is better)
ph1_res_kW	28.924	residential (household) load
ph1_mand_kW	0.84	mandatory (must charge) EV load
ph1_opp_kW	0	"use spare headroom" opportunistic EV charging
ph1_supp_kW	-3.5	V2G support injection
ph2_res_kW on: repeats as **ph1_**res_kW thru **ph1**_supp_kW		
ph3_res_kW on: repeats as **ph1_**res_kW thru **ph1**_supp_kW		
ph_clamped_kW	[24.059, 29.69149999, 22.8109999999]	per phase applied clamp level for [phase1, 2, 3]
N feeder mand EVs	8	N mandatory chargers
N feeder opp EVs	32	N opportunistic chargers
N feeder disc EVs	21	N candidate discretionary dispatch (support) V2G EVS
ph1_EVs[m][o][s]	[['EV_39', 'EV_45', 'EV_75'], ['EV_15', 'EV_21', 'EV_60', 'EV_122', 'EV_78', 'EV_87', 'EV_90', 'EV_110', 'EV_99'], ['EV_42', 'EV_131',	[[mandatory EVs on phase 1], [opportunistic EVs on phase 1], [support EVs on phase 1]]

	'EV_84', 'EV_107', 'EV_101']]	
ph2_EVs[m][o][s] repeats as above for **ph1**_EVs[m][o][s]		
ph3_EVs[m][o][s] repeats as above for **ph1**_EVs[m][o][s]		
ph1_unused V2G kW	0	“surplus to need” V2G on phase 1
ph2_unused V2G kW	-3.5	
ph3_unused V2G kW	0	
pd drops_kW	-3.930833333	sum of load reductions
pd rises_kW	7.32	sum of load increases
n_ph1 concurrent chargers	0	count of in-progress / actual chargers, phase 1
n_ph2 concurrent chargers	1	
n_ph3 concurrent chargers	0	
notes (system autogenerated)	Repetition 2, hi_limit 24.51	system generated observations (hints, faults and warnings)

C.2 EV_output.csv

This file records the EV related event and to express the causes, both as events occur and as hourly / nightly / weekly snapshots. Please inspect image in the .pdf.

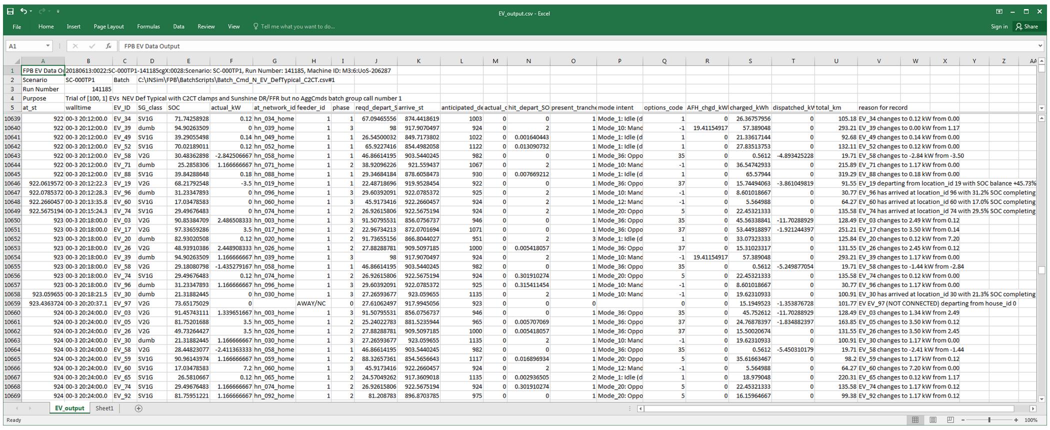


Figure C-2: Sample of EV_output.csv seen in spreadsheet

The fields within the file are described in Table C-2 below:

Table C-2: Example of EV Output .csv file

Field name	Sample Contents	Comments
at_st	1570	
walltime	00-6 13:00:00.0	**WW-D HH:MM:SS**
EV_ID	EV_93	
SG_class	SV1G	
SOC	58.31	**%**
actual_kW	7.2	**the socket load**
at_network_id	hn_093_home	**location**
feeder_id	1	
phase	3	
reqd_depart_SOC	72	**min SOC for 24hrs**
arrive_st	1569.612788	
anticipated_depart_st	1780	
actual_depart_st	0	
hit_depart_SOC_ratio	0	**internal use**
present_tranche	2	**tranche # 1..N**
mode_intent	Mode_20: Opportunistic (ph not high) charge	**text description of goal of mode**
options_code	37	**binary pattern for charge / dispatch options**
AFH_chgd_kWh	0	**AFH in Scenario**
charged_kWh	95.02104816	**home charged in Scenario**
dispatched_kWh	0	**home dispatch in Scenario**
total_km	239.53	**km travelled in Scenario**
reason for record	EV_93 changes kW to 7.0 from 0.14	**description and run-time notes**

this page deliberately left blank

Appendix D: Post Processing and Plots

D.1 Sequence Workflow - From Simulation to Analysis

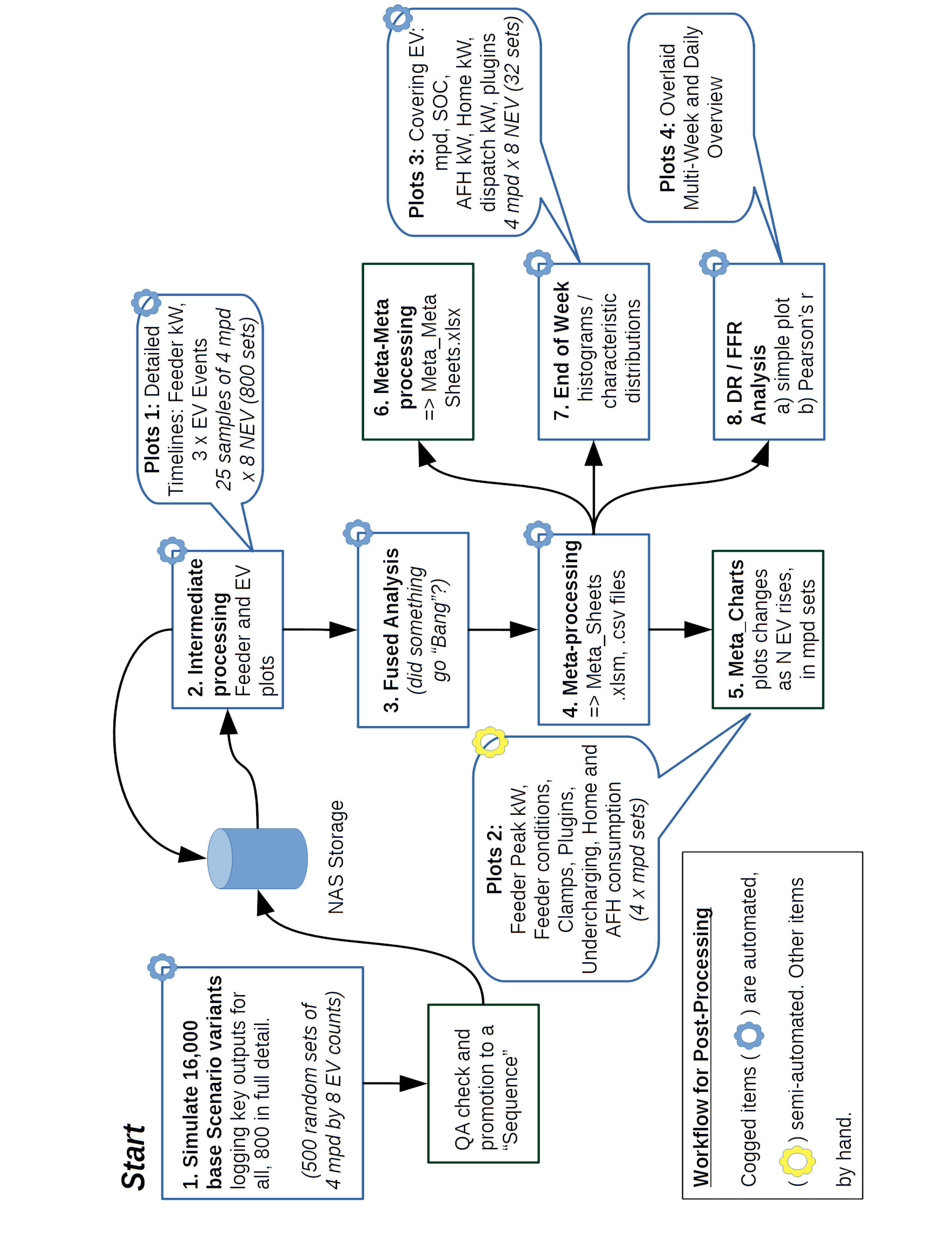


Figure D-1: Post Processing Workflow (large)

D.2 Sample Timeline Detail Plots

These are programmed using python's matplotlib and plotted automatically as part of the intermediate post-processing suite, each Sequence taking c. 4 hours to process. See also data repository Folder 3.3 Post-Processed Sequence Image Samples.

D.2.1 Feeder kW Loading (per pd for a week)

Datasets for 800 Feeder kW loading plots are retained from 16,000 simulations per sequence. Two samples (zoomable in .pdf) are shown below:

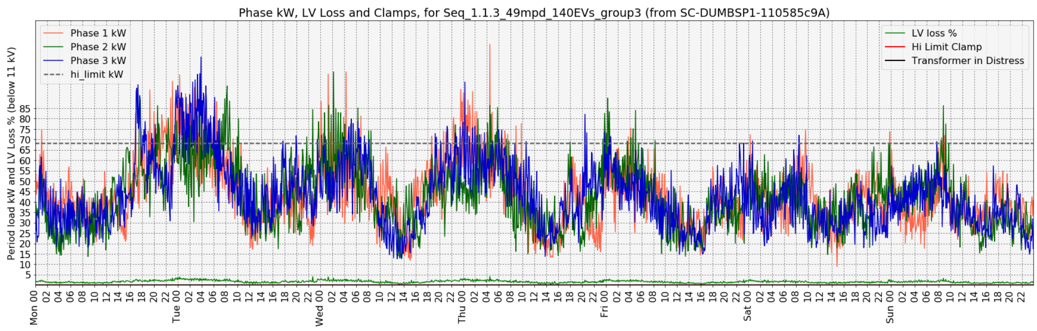


Figure D-2: Uncontrolled network with 140 EVs

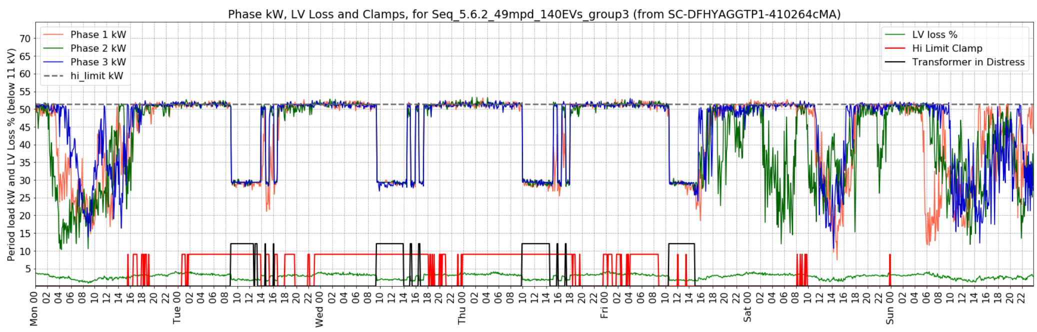


Figure D-3: A simulated MCS controlled network in load saturation with clamps

Clamps in "mandatory" (cherry red) and "transformer" (black line) modes.

D.2.2 EV Arrive / Depart Plot (per pd for a week)

These plots are histograms showing hourly arrivals and departures. Pink / red are departing, sky blue / green are arrivals. The darker colourised tip is a count of EVs which depart undercharged (red tip, of size = EV count) or arrive having taken on charge "Away from Home" (from a 3rd party supply, shown as a dark green tip of size = EV count).

Undercharging is a problem associated with active management; by being constrained EVs may receive insufficient charge, meaning: missed depart SOC charging goal.

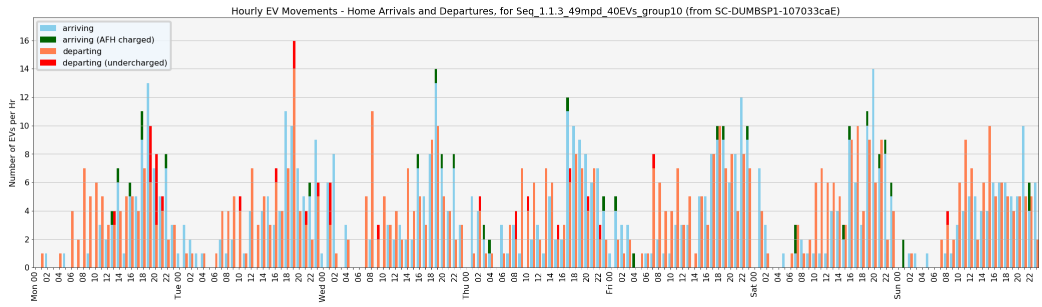


Figure D-4: EV Arrivals / Departures plot

Bar height = N in hour. Tip colours indicate: Red: departing undercharged, Green: arriving with Away from Home kWh

D.2.3 EV CICD Plot (per pd for a week)

Displays home EV activity (i.e. what they are doing). Shows Clamped, Idle, Charging and Dispatching (CICD) status of EVs by colourising a per-pd population bar.

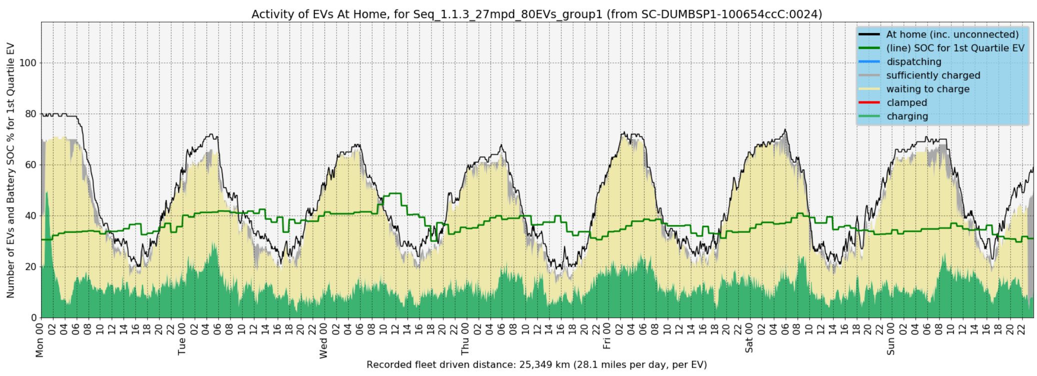


Figure D-5: Colourised EV CICD plot showing number of EVs in a State

Number at home (black line), estimated EV activity (colours) and an SOC % indication (green line). Clear gap below black (N EV at home) line: Not plugged-in

The colours vertically count the number of EVs parked at home as a **black outline** filled by:

- **clear**: parked at home, not connected to supply
- **green**: charging,
- **red**: clamped (EVSE disconnected),
- **cream**: waiting to charge,
- **grey**: finished charging waiting to depart,

- **blue**: V2G dispatch which might lift green counts of EVs charging
- **black** number at home, plus
- a **wandering green line** which shows the 25th percentile EV's SOC, i.e. the SOC of the ranked 1st Quartile (25th out of 100 in ascending rank order).

Monitoring this indicates group SOC change / charging progress.

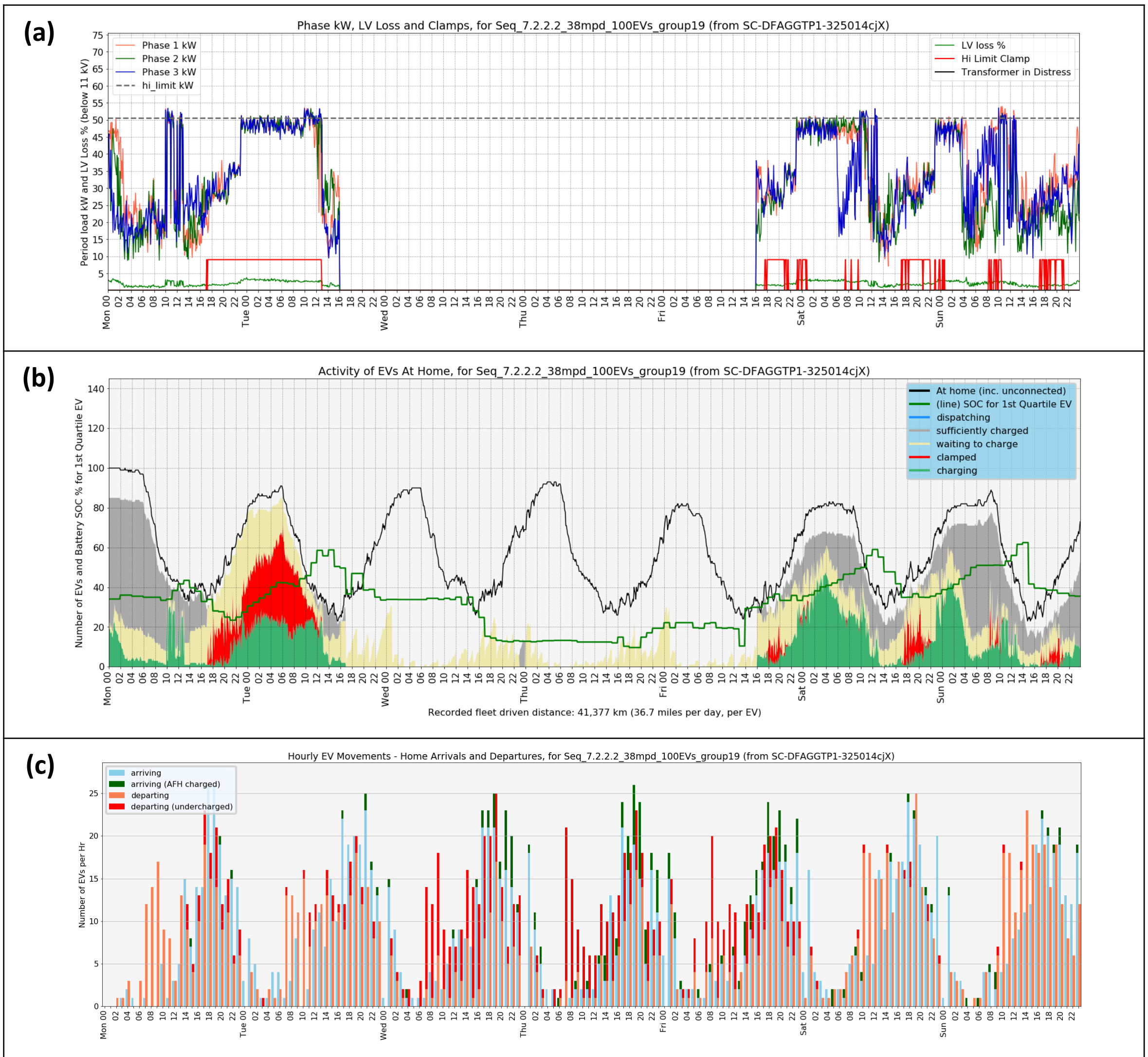


Figure D-6: Timeline plots for a "Power-Fail"

CICD plot shows clamped EVs in red. The SOC line (CICD plot, in green) drops during the outage. EVs loose ground SOC wise; on the Arrive/Depart plot "starving" EVs depart with insufficient charge (red tips); increased AFH charging is occurring (green tips).

Mass EV undercharging is likely to cause customer distress and politics.

Note the CICD colourisation is a close approximation. The plotting "activity - interpolator" may abruptly change levels (occasional notches in the colourised bars). This effects CICD plots only. Correcting the issue requires substantial revisions (to explicitly record each EV's state per pd) and was not progressed as this is a marginal problem.

Figure D-6 illustrates these plots together. Weekly Feeder, CICD and Arrive / Depart plots are married time-wise and show how EVs respond to a power-fail event.

D.2.4 Sample EV Rolling Fleet Energy / Distance Plot (per pd)

Simple running totals for kWh taken on at home, Away from Home (dark green), the total driven distance and any dispatch (negative, in blue).

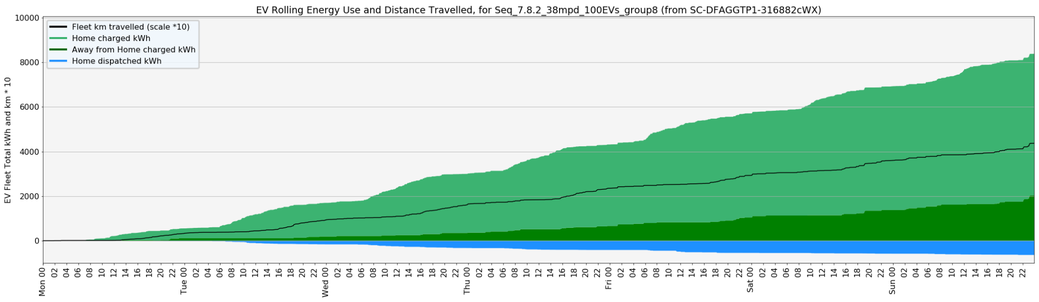


Figure D-7: A typical Rolling Fleet plot showing sources of EV charge

Showing At Home charging (soft green), Away From Home charging (dark green) and V2G dispatch (negative blue)

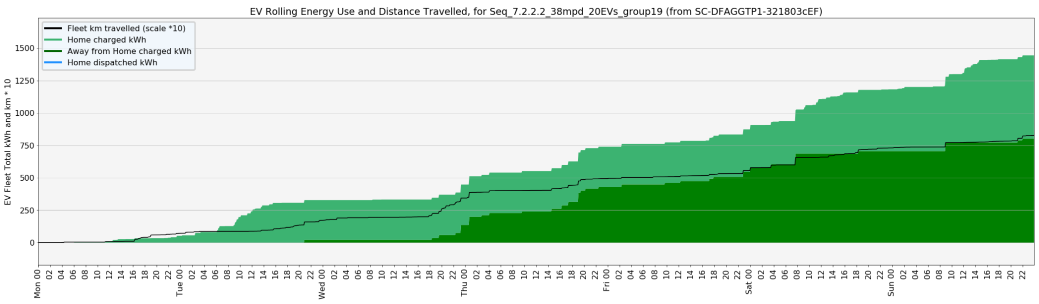


Figure D-8: A Rolling Fleet for "starving" EVs

60% of all driven kWh obtained via Away from Home charging; starving EVs have less excess charge to offer for V2G

These plots are replaced with summary totals, so to save space.

D.3 Samples of Meta_mpd Charts

These are summaries of the 4 mpd bands (4,000 simulations in each) showing how the simulation reacts as N EV increases. This may be visualised as "going across the cells" shown in Figure D-9 (sequence overview diagram).

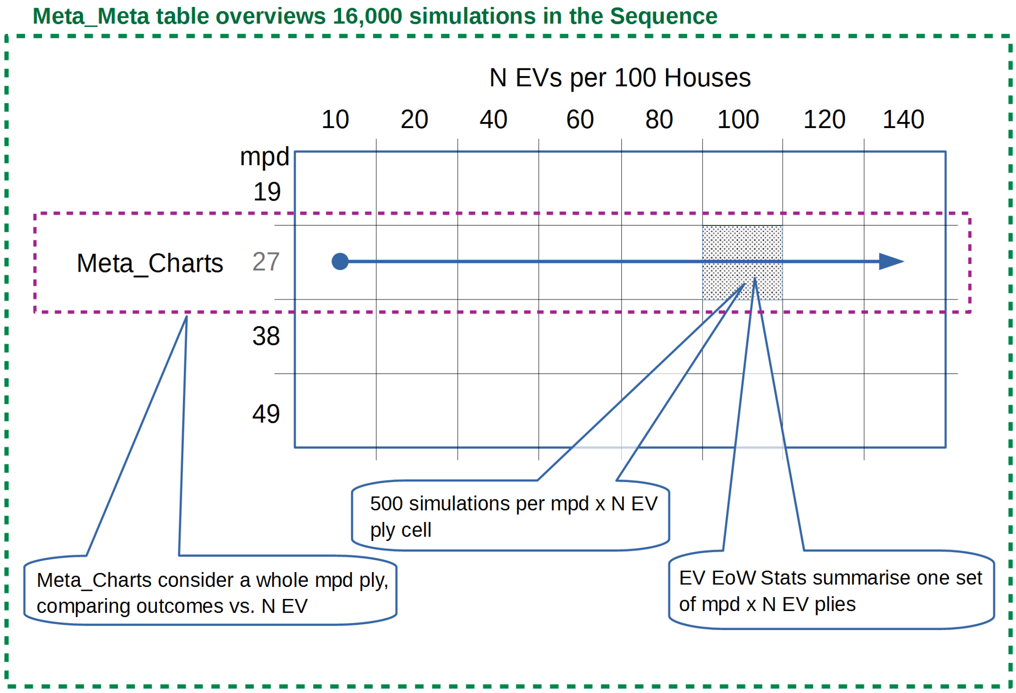


Figure D-9: Recap of Ply Cells in a Sequence

Each red-outline mpd band has a “Meta” spreadsheet, filled by a python post-processor with intermediate processed data. There is a sheet for each value of N EV, each holding results from 500 sets of simulations for that number of EVs. Field averages are then taken, collated onto a summary page and plotted.

These plots are generated by the Meta_Chart system and is performed manually in LibreOffice Calc. Calc is an indifferent plotter but adequate.

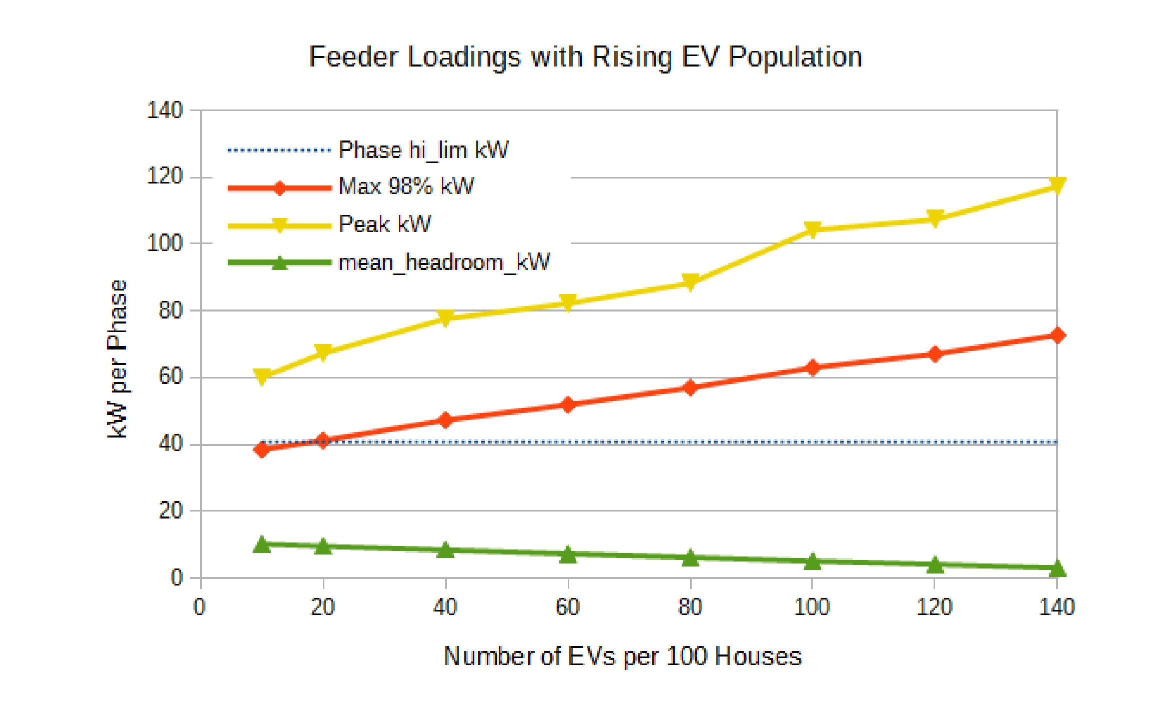


Figure D-10: MetaChart plot of Feeder loadings with Rising N EV

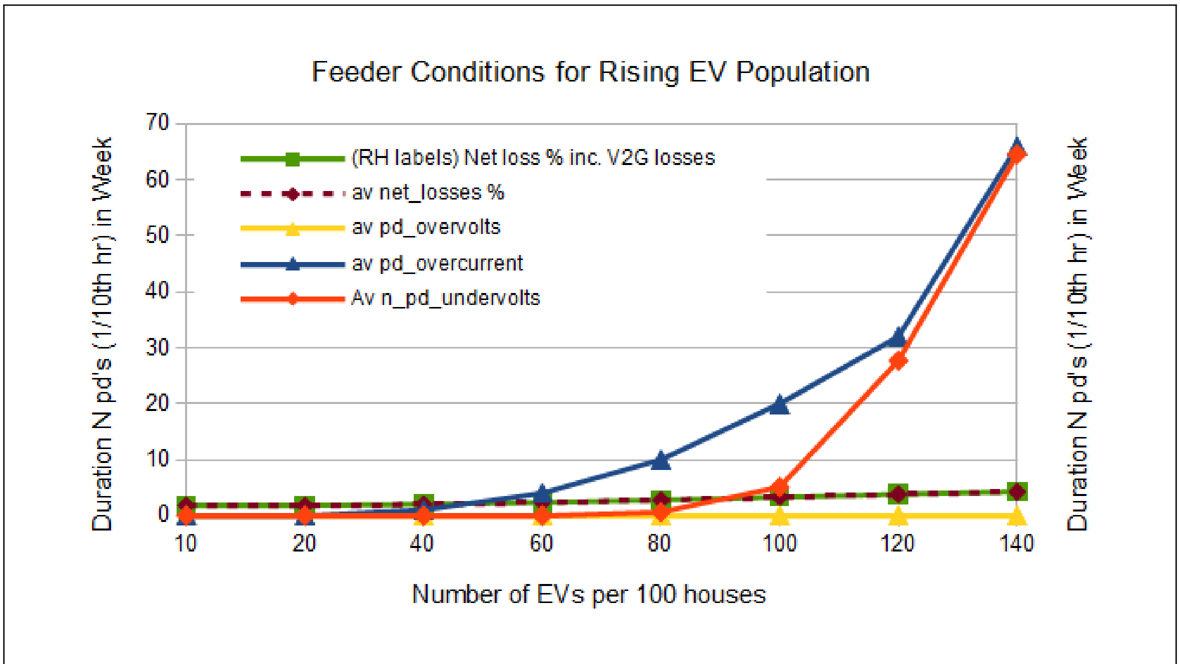


Figure D-11: MetaChart plot of Feeder conditions with Rising N EV

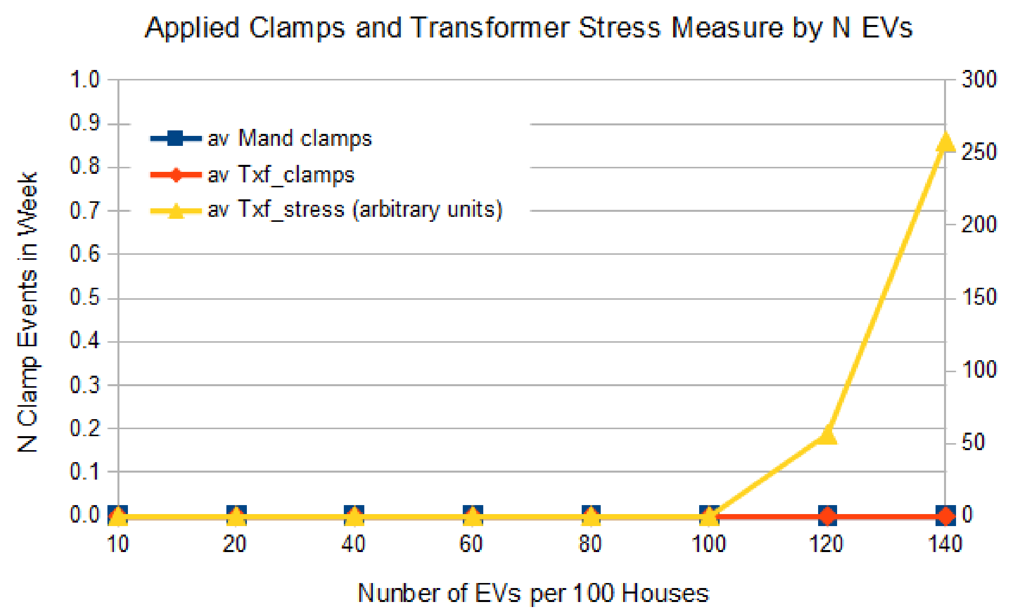


Figure D-12: MetaChart plot of Clamping Events with Rising N EV

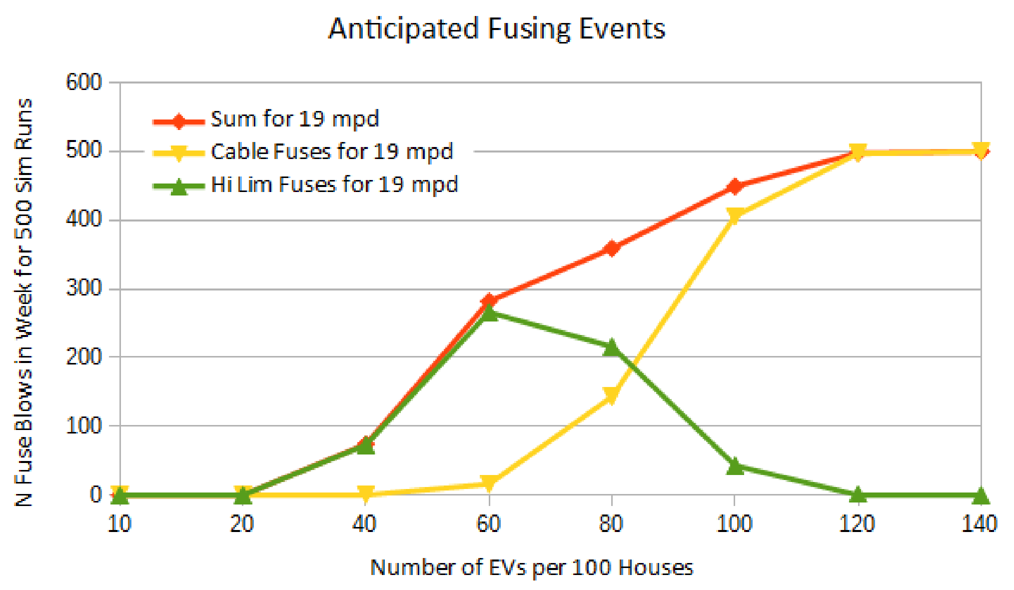


Figure D-13: MetaChart plot of Fusing / Broaches Events with Rising N EV

Note: "Whoever broaches a limit first - wins"; cable limit broaches inhibit transformer (sustained hi_limit) fusing detection.

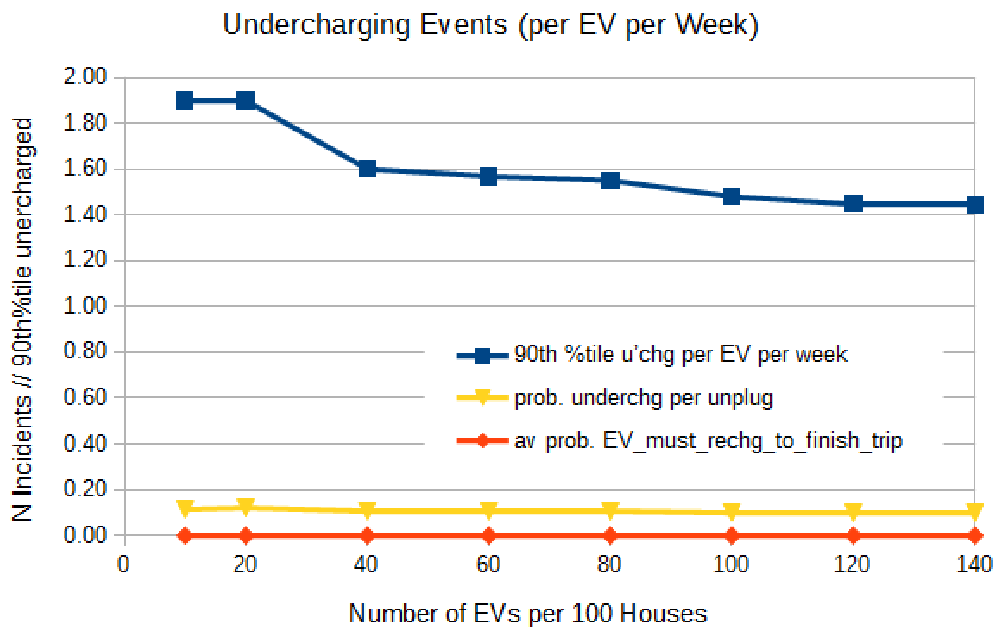


Figure D-14: MetaChart plot of Undercharging Events with Rising N EV

Note: As use of clamps proliferates, EV undercharging is like to rise

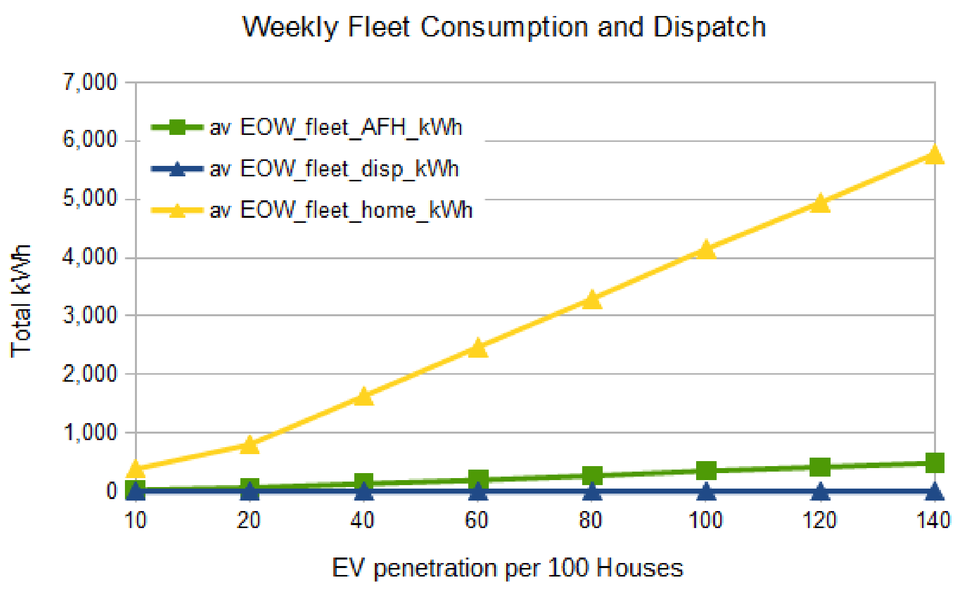


Figure D-15: MetaChart plot of EV Power Sourcing

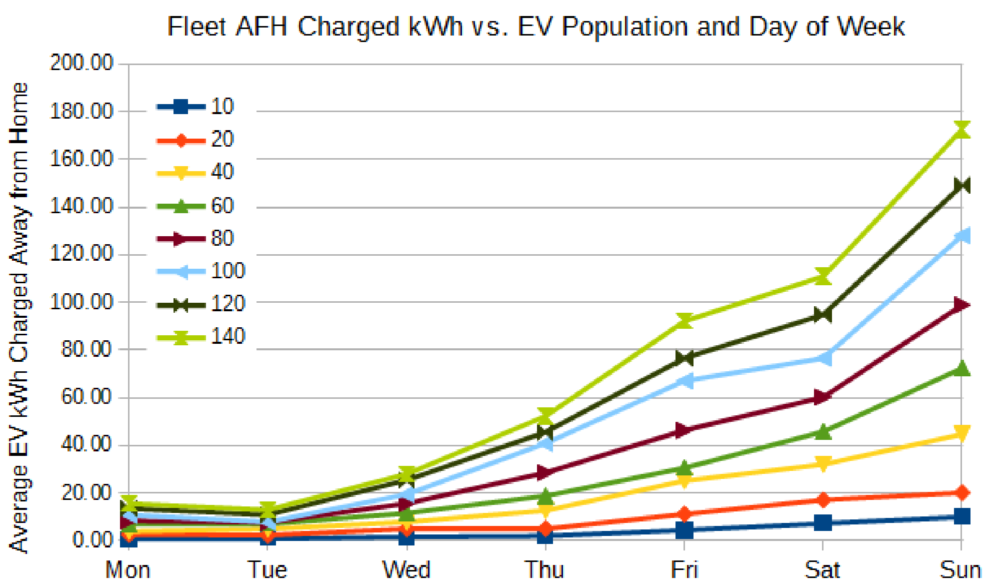


Figure D-16: MetaChart: Cumulative plot of Fleet AFH Charging

Another consequence of clamps: EV use of AFH charging is like to rise

D.4 Samples of End of Week Histograms

These are histograms of results from each mpd x N EV cell, to produce a distribution of the week-ending states. Up to 70,000 individually modelled EVs are in a plot; as a result some columns are tall and removed for clarity. These plots are produced using python / matplotlib. Colours match those used on the CICD plot.

Plots are made for End of Week:

- home charging kWh,
- home dispatch kWh
- away from home charging kWh
- average mpd driven,
- number of plug-ins and
- EV SOD.

Each sequence has 32 sets of these plots. These are formed into a contact sheet of 32 mpd x N EV images, to assist view images en-masse. The examples in Figure D-17 on show plots for Seq_1.1.2 End of Week Home charging, each of which summarises 500 simulation runs (each of the 500 vary by randomiser seed only).

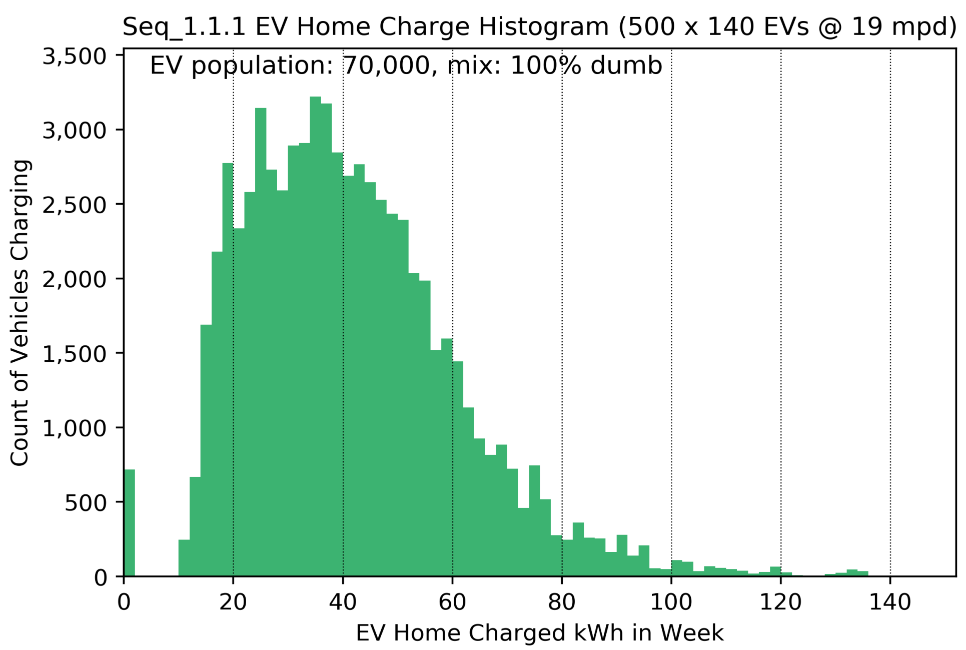


Figure D-17: EoW Histogram: EV Home kWh Charged in Week

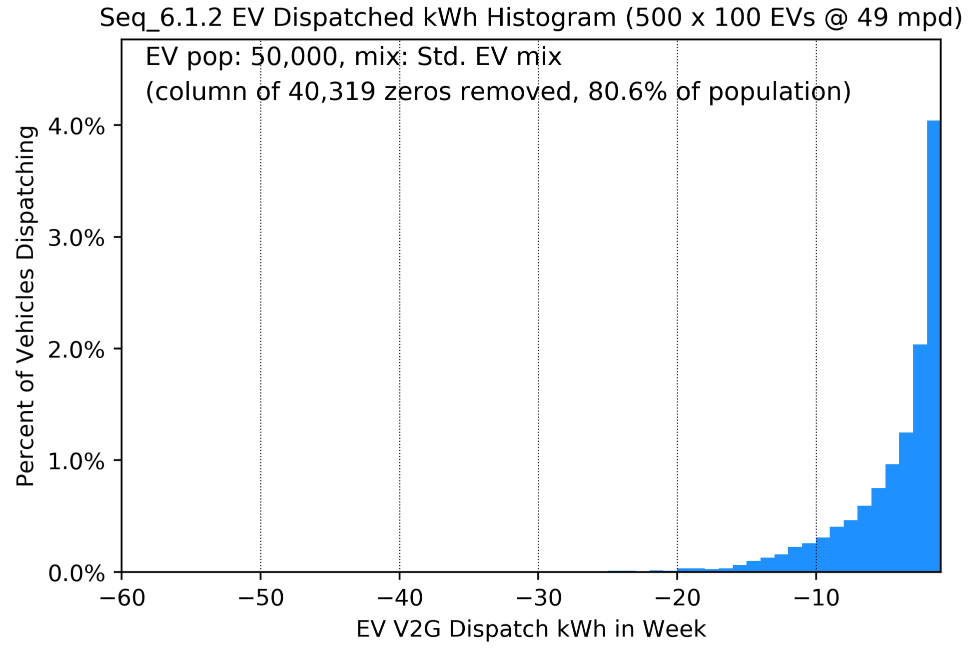


Figure D-18: EoW Histogram: EV Home kWh Dispatched (V2G) in Week

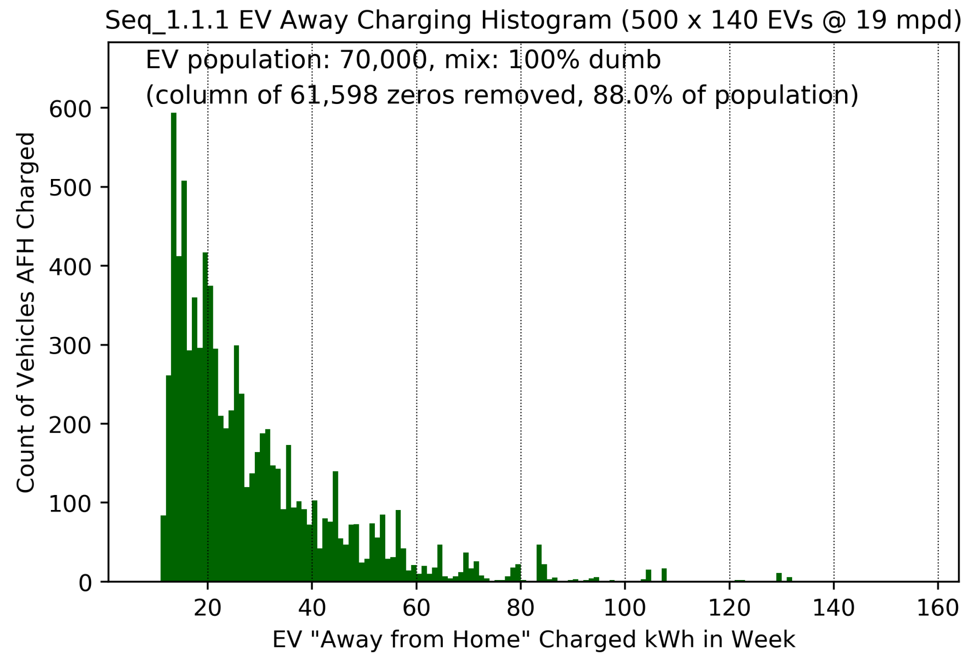


Figure D-19: EoW Histogram: EV AFH kWh Charged in Week

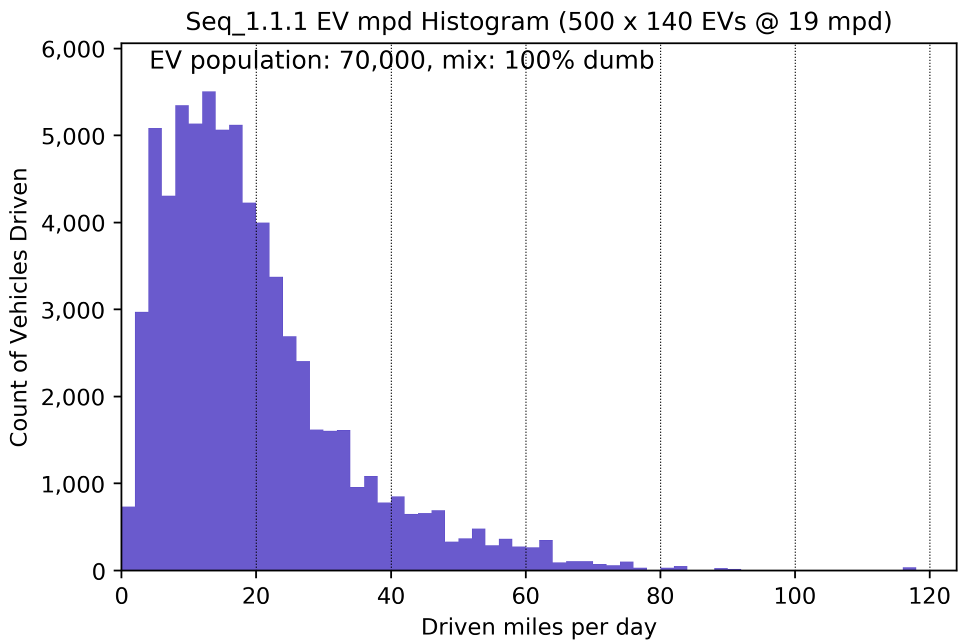


Figure D-20: EoW Histogram: EV Driven Miles per Day in Week

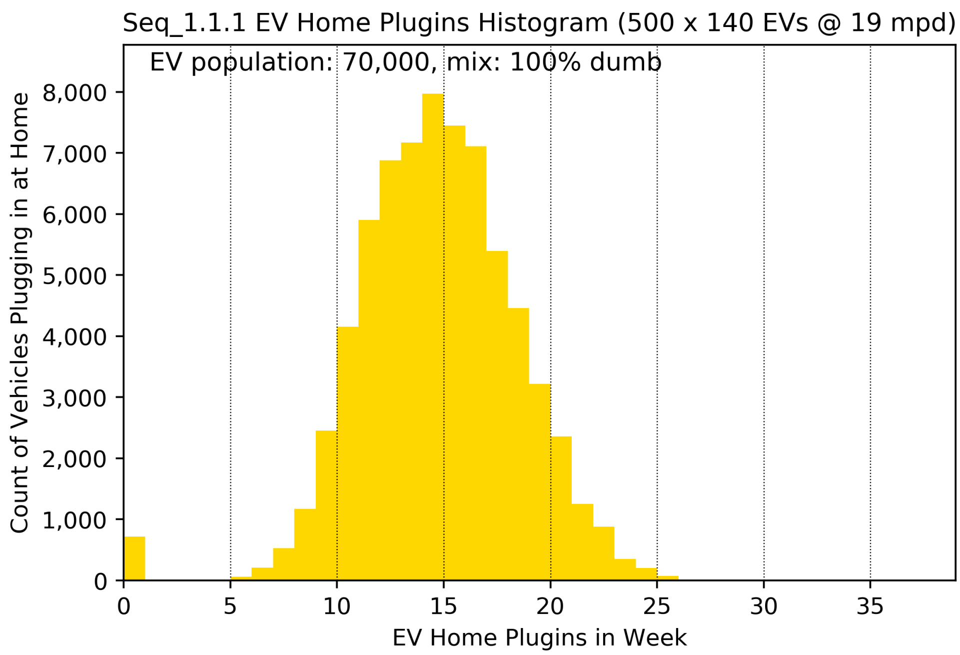


Figure D-21: EoW Histogram: EV Home Plugins in Week

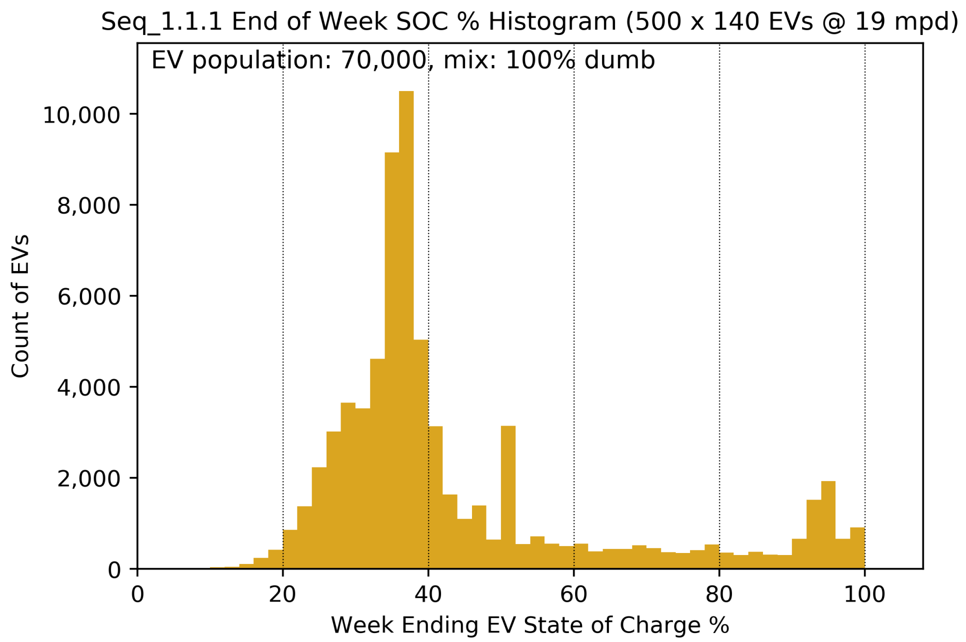


Figure D-22: EoW Histogram: EV SOC Held at end of Week

D.5 Sample of Data Distribution Inspection

This shows the data distribution (for any field of data collected) across the 500 simulations in a Sequence cell (i.e. contents of an mpd x N EV ply). The viewer has 4 spreadsheets for Meta_19, Meta_27, Meta_38 and Meta_49 held in data repository Folder 4, e.g.

> 4. Final Analysis Output (All sequences) >
> Meta_38_distribution_analyser_via_Excel.xlsx

Instructions for use are in the accompanying README in Folder 4.

Each spreadsheet for mpd has a sheet for N EV. The image Figure D-23 is “Re 100EVs” in Meta_38, and shows a view of data column 84 (the AFH kWh the fleet has charged on Saturday). The system defaults to 20 frequency bins.

The user can amend the column number from 84 to some other (a key to columns is provided), causing the plot to show the distribution of data for the new field.

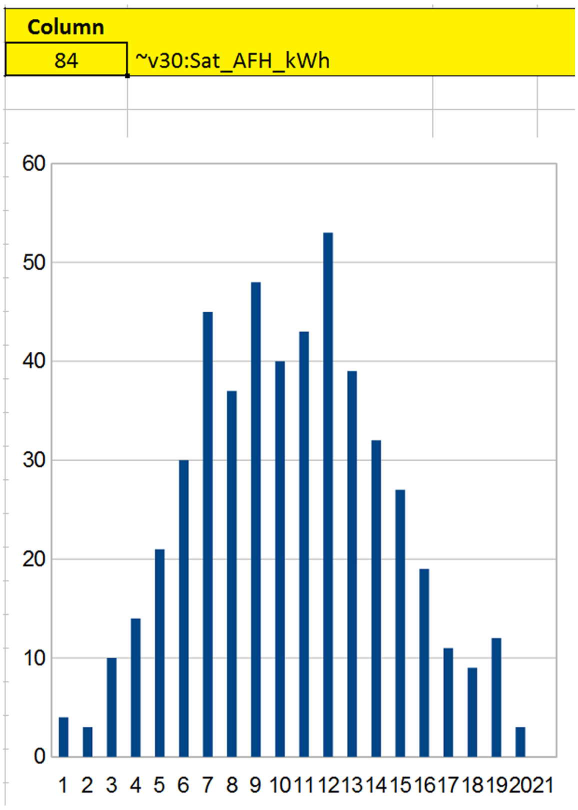


Figure D-23: Distribution diagram for fleet AFH charging on Saturday

The purpose is to discover any unusual distributions, which may indicate a fault.

this page deliberately left blank

Appendix E: Analysis Samples

These are included to give appreciation of what is in the online data and analysis repository. The full set of analyses are large so are not included in the thesis.

E.1 Sequence 2.1.2

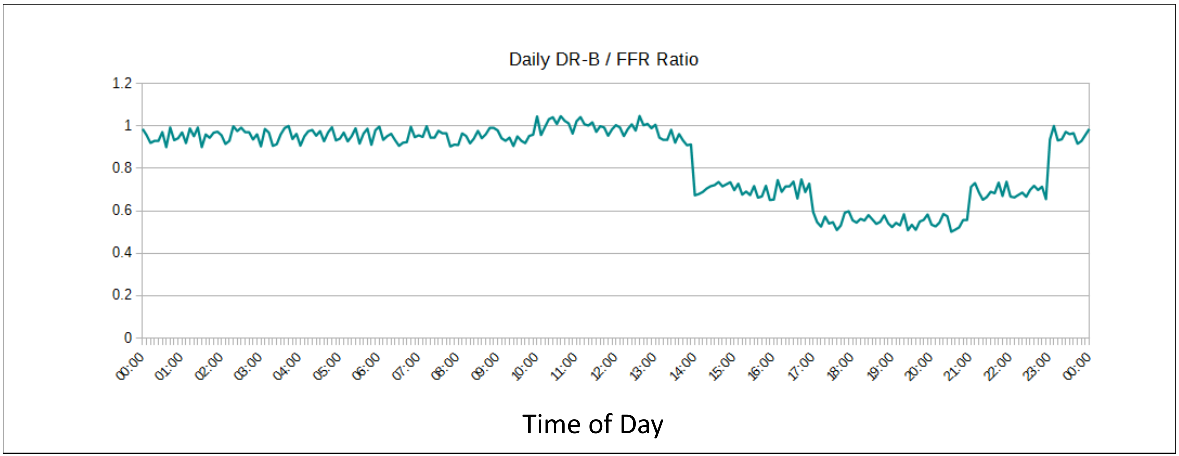
Sequence	**Simulation ID**	**Description**
Seq_2.1.2 BASELINE	(S_AC)	Winter, NEV, mpd sets, all dumb EVs, clamps ON (2), pre-burn_V2G OFF, hi_limit 51.3 kW, control modulation via hi_limit using pattern "DR-B / FFR", normal plugin regime

The simulation uses mode 2 clamping strategy: "by ranked need". Note that "pre-burn V2G" is off; reduction will be employed before using V2G (but there are no V2G EVs).

The DR-B / FFR pattern is repeated daily, with Demand Reduction as follows:

Table E-1: Demand Reduction regime for DR-B with plot of DR-B plus FFR

	Time of Day	**Applied Ratio**	**Rationale**
	each ratio +/- 0.05		*the FFR signal*
	10am to 1pm	variation about 1.0	values > 1 are "Sunshine Signal"
	1pm to 2pm	variation about 0.95	default
	2pm to 5pm	variation about 0.7	afternoon load limiting
	5pm to 9pm	variation about 0.55	evening peak load mitigation
	9pm to 11pm	variation about 0.7	late evening load limiting
	11pm to 10am	variation about 0.95	default



This signal is used to modulate the hi_limit every day. Note that the FFR component is contrived to sum to zero.

Data is viewable in: MetaMeta2.3_Seq_2.1.2.xlsx.

E.1.1 Seq_2.1.2 in Précis

Clear ply cells are acceptable, however the dark red ply is a loss vs. Seq_1.1.2, due to "excessive use of clamps". Broaching is however avoided; assets are secured from risk of damage or power outages following a substation fuse-blow, yet EVs become undercharged as numbers rise.

Table E-2: 2.1.2 Overall Usable EV Bands

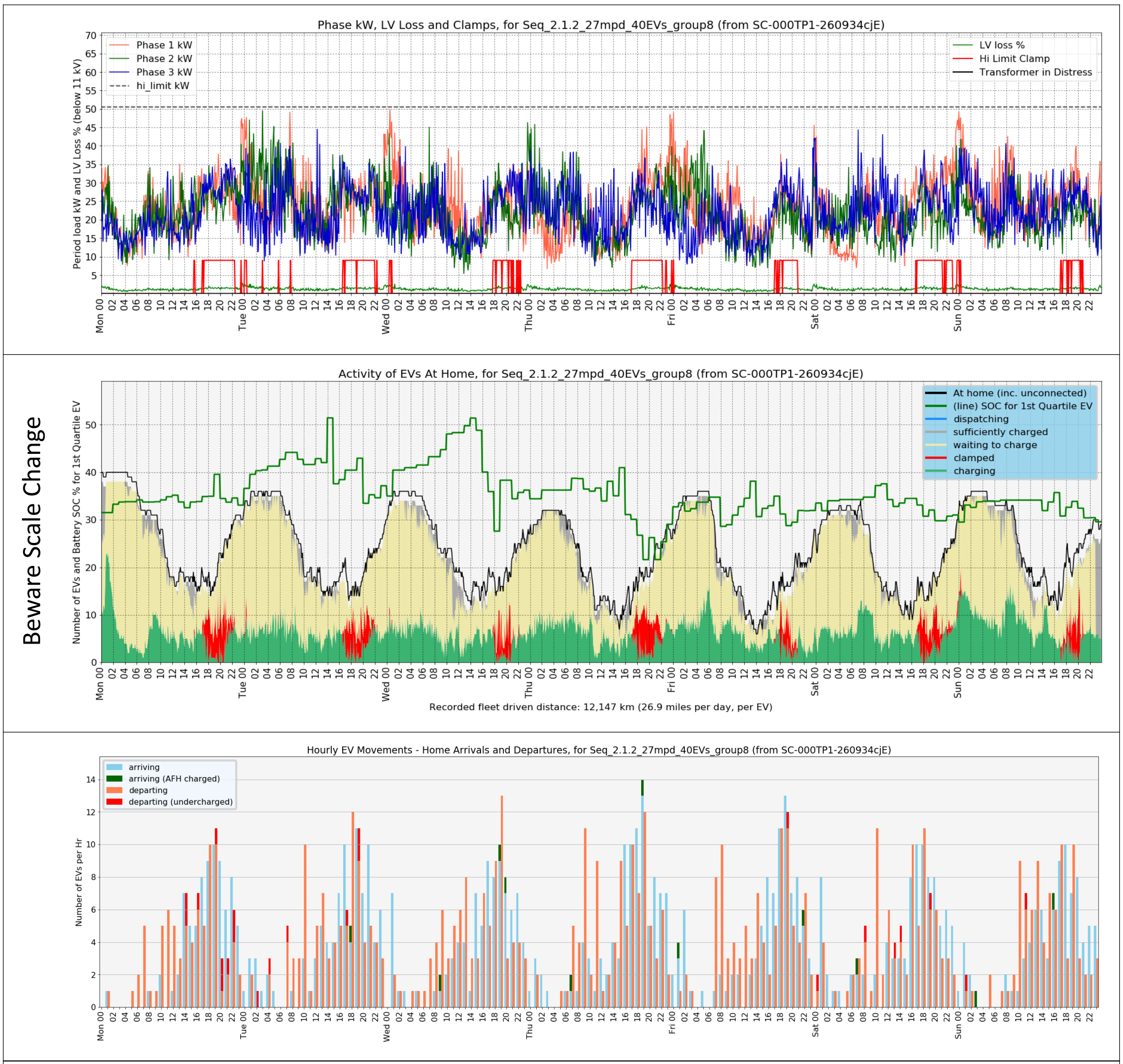
0. Overall Usable Plies	N EV	10	20	40	60	80	100	120	140
	19mpd			C	C	C	C	C	C
	27mpd			C	C	C	C	C	**CS**
	38mpd			**CS**	**CS**	**CS**	**CS**	**CS**	**CS**
	49mpd			**CS**	**CS**	**CS**	**CS**	**CS**	**CS**

C: clamping limit exceeded; S: severe undercharging encountered.

The DR regime is shown to move the EV charging demand from early evening into the overnight period, at the expense of underchared EVs.

E.1.2 Seq_2.1.2: Feeder and EV Plots

E.1.2.1 Seq_2.1.2: 27mpd 40EVs



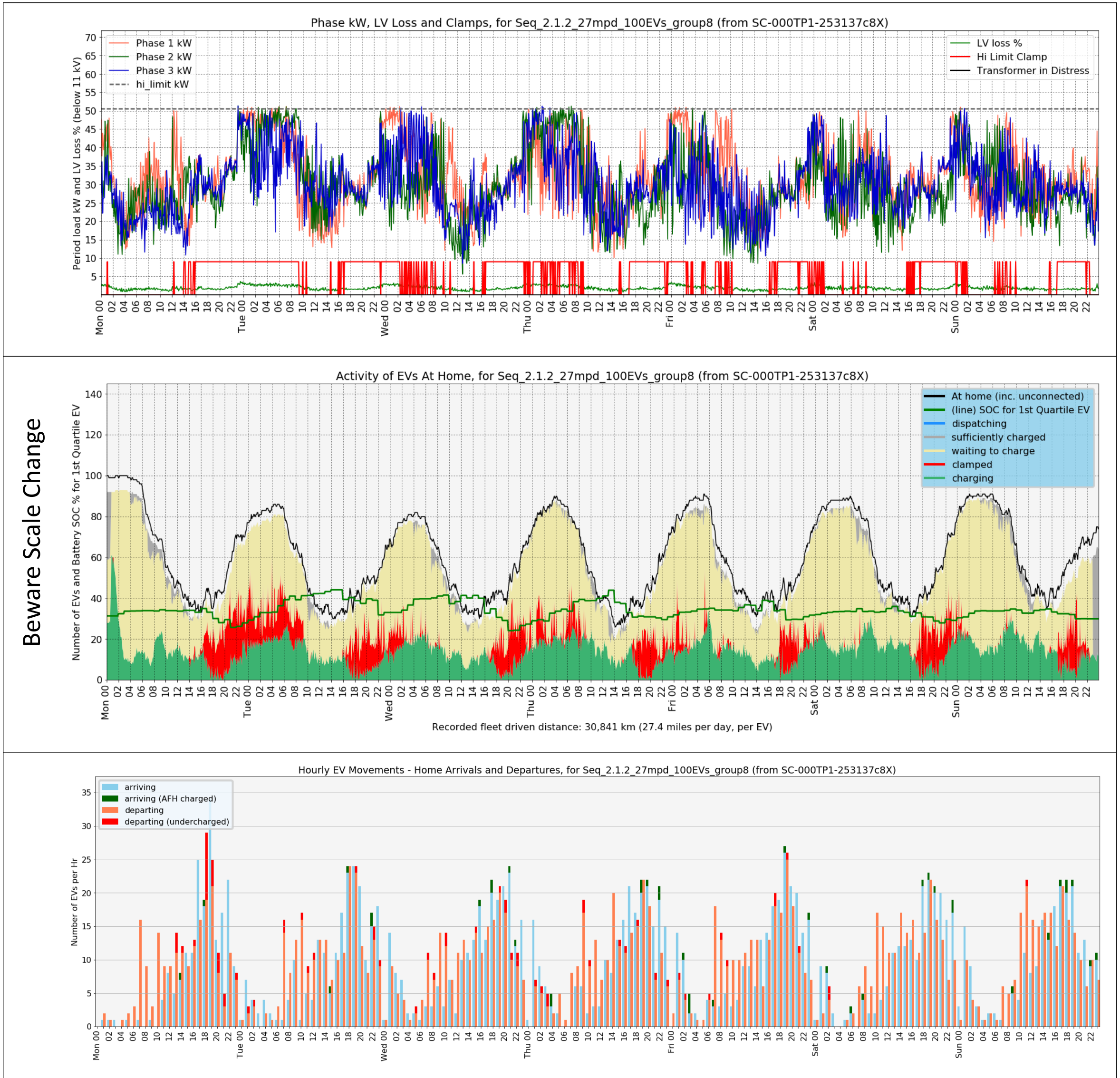
EoW stats: kWh[b]	EV total: 2,334	Home: 2,010	AFH: 324	V2G: 0

Figure E-1: Seq_2.1.2 27mpd 40 EVs group 8 plots. Weekly fleet km: 12,212

Notes re above plots:

- (Feeder) the hi_limit lowered by DR (2pm - 10pm) is causing clamp firings
- (CICD) there is little sign of grey (EVs finished charging) but red marking clamps are seen; EV SOC is good, in the 30 - 50% range. Most EVs are being plugged in implying they do not have enough SOC for the next day
- (Arrive/Depart) there are rare departs undercharged and AFH charging.

E.1.2.2 Seq_2.1.2: 27mpd 100EVs



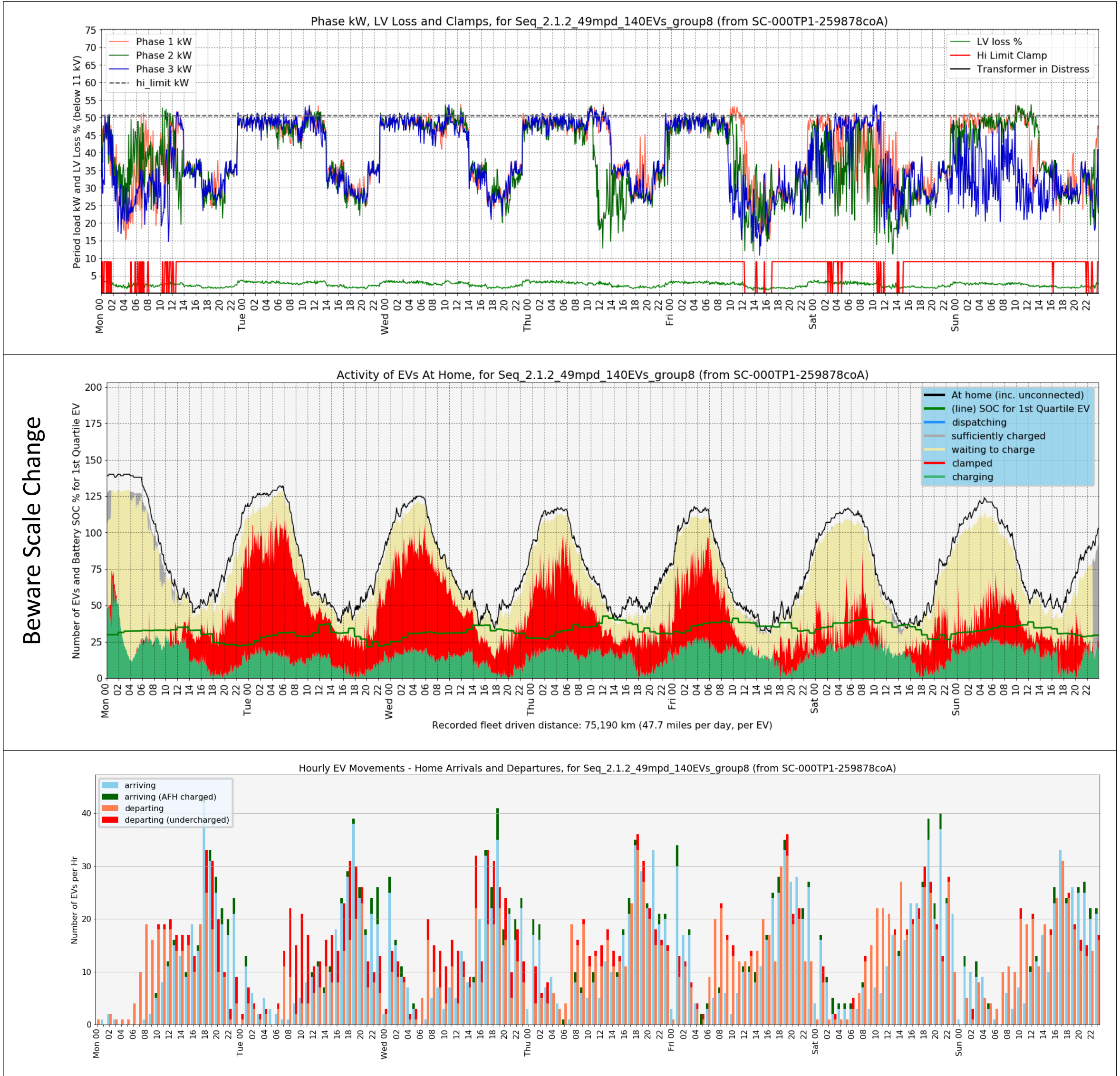
EoW stats: kWh[b] EV total: 5,912 Home: 5,014 AFH: 898 V2G: 0

Figure E-2: Seq_2.1.2 27mpd 100 EVs group 8 plots. Weekly fleet km: 30,876

Notes re above plots:

- (Feeder) clamps succeed in limiting any broaches; the load curve is just under the hi_limit implying the standing 5% FFR decrement is being applied
- (CICD) EV SOC appears down with more frequent clamps
- (Arrive/Depart) there are more departs undercharged and AFH charging.

E.1.2.3 Seq_2.1.2: 49mpd 140EVs



EoW stats: kWh[b]	EV total: 13,543	Home: 8,224	AFH: 5,320	V2G: 0

Figure E-3: Seq_2.1.2 49mpd 140EVs group 8 plots. Weekly fleet km: 77,327

Notes re above plots:

- (Feeder) clamps are used continually for days; the DR/FFR signal is apparent
- (CICD) EV SOCs are subdued; clamping is extensive, reaching 4 of 5 EVs clamped on Tuesday
- (Arrive/Depart) departing undercharged is common as is AFH charging.

E.1.3 Data Tables Seq_2.1.2

The parity case (average mpd with 1:1 household EV penetration) is in yellow and the lower RH corner being grey, as visual references. Red indicates a fail for some reason.

Table E-3: 2.1.2 Unused kWh (weekly averages)

1. Unused kWh	N EV	10	20	40	60	80	100	120	140
	19mpd	19,196	18,752	17,913	17,035	16,186	15,341	14,483	13,730
	27mpd	19,059	18,433	17,277	16,080	14,944	**13,806**	12,645	11,582
	38mpd	18,923	18,168	16,645	15,104	13,676	12,161	10,728	9,259
	49mpd	18,753	17,864	16,071	14,294	12,590	10,815	9,101	7,363

No broaches are detected.; the clamps are limiting overloads.

(Tables reordered due to page layout)

Table E-4: 2.1.2 Difference: Per EV AFH N events (weekly average of away connects)

Difference 2.1.2 - 1.1.2	3. Diff EV N AFH	N EV	10	20	40	60	80	100	120	140
		19mpd	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01
		27mpd	0.01	0.01	0.0	0.0	0.0	0.0	0.03	0.04
		38mpd	0.04	0.05	0.04	0.04	0.05	0.06	0.07	0.14
		49mpd	0.07	0.06	0.06	0.06	0.06	0.10	0.16	0.28

These counts show the driver is not noticeably plugging in AFH more often, when experiencing clamps.

Table E-5: 2.1.2 Counts of Undercharging events per EV (weekly averages)

4. EV UnChg	N EV	10	20	40	60	80	100	120	140
	19mpd	1.4	1.5	1.5	1.5	1.5	1.6	1.6	1.6
	27mpd	2.1	2.1	2.2	2.1	2.2	2.2	2.3	2.6
	38mpd	2.7	2.8	2.9	2.9	2.9	3.1	3.5	4.6
	49mpd	3.3	3.4	3.5	3.5	3.5	4.0	4.9	6.3

Here, an undercharge is any EV departing with SOC < (depart target SOC - 5%).

Table E-6: 2.1.2 Dumb vs Dumb+Clamped per EV AFH kWh (weekly averages)

		N EV	10	20	40	60	80	100	120	140
Seq_1.1.2	2. A Dumb AFH kWh	19mpd	2.7	3.1	3.3	3.3	3.4	3.6	3.6	3.6
		27mpd	6.9	8.0	7.8	8.0	8.4	8.3	8.3	8.1
		38mpd	17.6	17.3	17.9	18.5	18.2	18.5	18.5	18.5
		49mpd	35.5	33.0	31.5	31.3	31.1	30.8	31.2	31.2
Seq_2.1.2	B Clampd AFH kWh	N EV	10	20	40	60	80	100	120	140
		19mpd	2.9	3.5	3.5	3.5	3.6	3.9	3.8	3.8
		27mpd	7.0	8.2	8.1	8.5	8.9	9.0	8.9	8.9
		38mpd	18.1	18.3	18.7	19.2	19.1	19.8	20.0	21.5
		49mpd	36.8	34.4	32.9	32.8	32.6	33.1	35.0	38.0
Difference B - A	C Diff B - A	N EV	10	20	40	60	80	100	120	140
		19mpd	0.13	0.37	0.23	0.20	0.15	0.30	0.22	0.23
		27mpd	0.08	0.14	0.3	0.4	0.5	0.7	0.59	0.86
		38mpd	0.50	0.95	0.87	0.75	0.92	1.32	1.53	3.06
		49mpd	1.23	1.32	1.36	1.45	1.43	2.31	3.81	6.79

Average AFH charging Winter Seq_2.1.2 (top, A) vs. Summer Seq_2.1.2 (middle, B)

The EVs are acquiring more AFH charge as they cannot obtain kWh at home.

Table E-7: 2.1.2 Counts of Severely Undercharged EVs in Week, per EV

5. EV Severe UnChg	N EV	10	20	40	60	80	100	120	140
	19mpd	0.0004	0.0005	0.0010	0.0007	0.0009	0.0013	0.0013	0.0013
	27mpd	0.0008	0.0010	0.0030	0.0038	0.0039	0.0039	0.0051	0.0104
	38mpd	0.0044	0.0053	0.0099	0.0101	0.0096	0.0168	0.0333	0.0979
	49mpd	0.0076	0.0064	0.0109	0.0113	0.0164	0.0437	0.1148	0.2430

(limit: < 0.007) being 50:50 chance of Once in a Decade

This is the downside of clamping; by being able to add more and more EVs, at some point undercharging and severe undercharging occur. Red highlights unacceptable values.

A severe undercharge is an EV departing knowing the trip cannot be completed e.g. "pushed home", including "pushed out of driveway". These (occurred in MEA) are known to cause vociferous upset and blowback, especially as they tend to be prompted by network conditions hence may unfortunately affect the same drivers repeatedly.

A "50:50 chanced of 1 severe undercharge per EV, per decade" was calculated (for 10 Winter weeks pa) and found the probability as 0.007; this is taken as a limiting value beyond which driver distress might be incurred. Red highlights unacceptable values.

Table E-8: 2.1.2 MCS Clamps (weekly averages)

6. MCS Clamps	N EV	10	20	40	60	80	100	120	140
	19mpd	239.7	344.7	541.1	742.4	977.0	1,278.7	1,630.7	2,089.8
	27mpd	246.7	370.6	591.8	855.7	1,199.3	1,659.6	2,211.8	2,866.7
	38mpd	254.7	389.1	655.8	1,010.4	1,495.7	2,138.8	2,816.1	3,499.8
	49mpd	260.7	401.5	697.6	1,132.3	1,726.2	2,472.4	3,166.9	3,787.1

(limit: < 420)

Clamping raises another problem; excessive use to manage levels rather than limit an emergency. It is thought likely (but no decision is reached) that Ofgem will penalise this; DNOs are to supply not curtail supply to customers. An arbitrary limit of roughly 2 hours a phase clamped a week over say 2.5 EVs gives about 420 clamp event limits (note this is an approximation and FPB in its present form cannot assess these stats easily).

This highlights a concern: How to rank clamps. Is this:

- per worst-case week (i.e. winter), or
- spread over the year, or
- a nominal “average rate” with a cap of say x2 per week, for winter?

This suggests that clamping is perhaps both more complex and potentially contentious (as clamps deny charge, which can cause undercharging) than suspected. The author suggests “worst case week” as this is simple to understand.

Table E-9: 2.1.2 DRFFR Percent Effective Hours (weekly averages)

7. DRFFR %	N EV	10	20	40	60	80	100	120	140
	19mpd	29.2%	30.4%	29.8%	33.9%	38.1%	42.3%	52.4%	62.5%
	27mpd	27.4%	28.6%	31.5%	36.9%	41.1%	52.4%	62.5%	73.2%
	38mpd	28.0%	31.0%	32.7%	40.5%	50.0%	58.3%	70.8%	81.5%
	49mpd	28.6%	30.4%	35.1%	42.3%	51.2%	63.1%	77.4%	82.7%

6.2.2 span: [73.8%] => [98.2%]

The measure here is Parson’s r comparing the {rate of change between periods} of the DR/FFR signal vs. the observed change of the output. A score of 25% implies random. DR/FFR does though appear to operate well for the parity case and over.

Table E-10: 2.1.2 Difference in LV Losses kWh (weekly averages)

Difference 2.1.2 - 1.1.2	8. Diff Losses kWh	N EV	10	20	40	60	80	100	120	140
		19mpd	-0.1	-3.3	-2.4	-8.1	-7.2	-19.4	-26.9	-44.0
		27mpd	-0.2	-1.9	-0.9	-8.6	-12.8	-28.9	-48.4	-81.0
		38mpd	-0.1	-0.4	-8.9	-7.5	-18.6	-38.5	-72.9	-137.8
		49mpd	-0.3	-0.6	-9.2	-15.4	-25.3	-59.7	-108.5	-196.2

The peak loss on this network equates to 2.6% at 520 kWh for 49mpd x 140 EVs. Losses are down compared to Seq_1.1.2.

E.1.3 Seq_2.1.2 Summary

The distinction of Seq_2.1.2 from earlier sequences is the use of clamps. Clamps will stop overloads, and are shown to be able to allow any number of EVs to be connected to a feeder. However as more are connected, the net energy available drops and more AFH charging results due to EVs leaving with insufficient charge.

Without further study into the measurement, use and acceptability of clamps to Ofgem all that can be stated is that:

a) as EV numbers and mpd duty rise, the number of clamps rise
b) as clamps rise undercharging rises.

The net feeder load for 2.1.2 control is shown in Figure E-4. This compares total network load vs. rolling averaged load for the parity case; each curve is an average of the ply's 500 simulations, which is then smoothed by applying a 1 hour rolling average i.e. for all periods from $pd = 10$ and up, the plots show values:

$$load_{hr} = 0.1 * \sum_{n=pd-10}^{n=pd} load_n \tag{31}$$

Loads are shown compared to 5.1.2 results, with MCS but no DRFFR signal. To reduce visual clutter, Monday - Friday only are plotted for the parity (27mpd, 100 EVs) case.

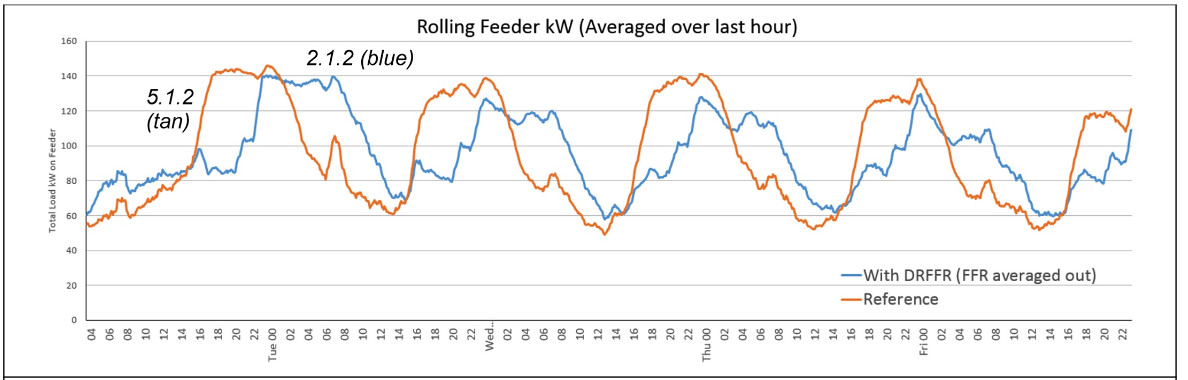


Figure E-4: DRFFR defers Evening Charging to Overnight

DR steps and a resulting load timeshift are seen (tan plot is the reference, the blue plot is shifted later), with imposed DR outline becoming clearer for higher loads.

Note that by successfully removing incipient overloads, the clamp system has both protected the local network and provided a mechanism to offer DR/FFR.

Yet by using a control level set below the point of risk to assets, and <u>then applying</u> a DR/FFR regime, might this be viewed as an abuse of a protection system?

Further, by protecting its networks the DNO has introduced constraints on EV use.

It is likely that Ofgem will address these issues at some time.

E.3 Sequence 2.1.2.9

Sequence	**Simulation ID**	**Description**
Seq_2.1.2.9	(S_93r)	Winter, NEV, mpd sets, all dumb EVs, clamps ON (2), pre-burn_V2G OFF, hi_limit 51.3 kW, normal plugin regime
Baseline: *2.1.2*		*Difference vs. Baseline: 2.1.2.9 has no DR/FFR*

The simulation again uses mode 2 clamping strategy: “by ranked need”.

This sequence investigates: Does DR/FFR affect clamps? The clamping system remains active but the hi_limit modulation by DR/FFR is removed.

E.3.1 Seq_2.1.2.9 in Précis

Table E-11: 2.1.2.9 Overall Usable EV Bands

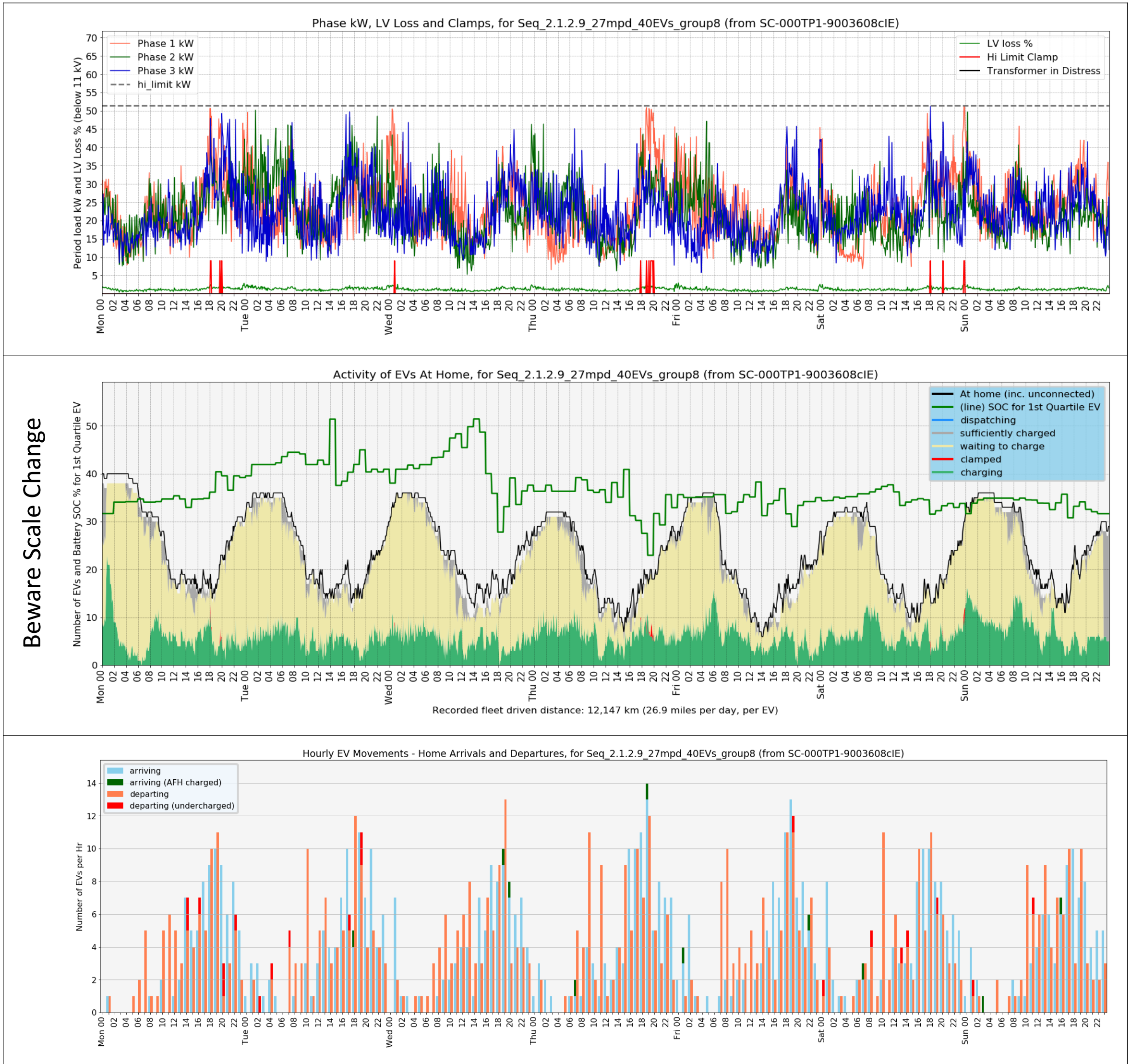
7. Overall Usable	**N EV**	**10**	**20**	**40**	**60**	**80**	**100**	**120**	**140**
	19mpd								
	27mpd								
	38mpd								
	49mpd								

Light green shows plies available in 2.1.2.9 which were not in 2.1.2. The message coming from this is that DR/FFR raises both EV severe undercharging and clamp counts, with the primary cause likely being the DR element.

However it has been demonstrated that DR can reduce total load.

E.3.2 Seq_2.1.2.9: Feeder and EV Plots

E.3.2.1 Seq_2.1.2.9: 27mpd 40EVs



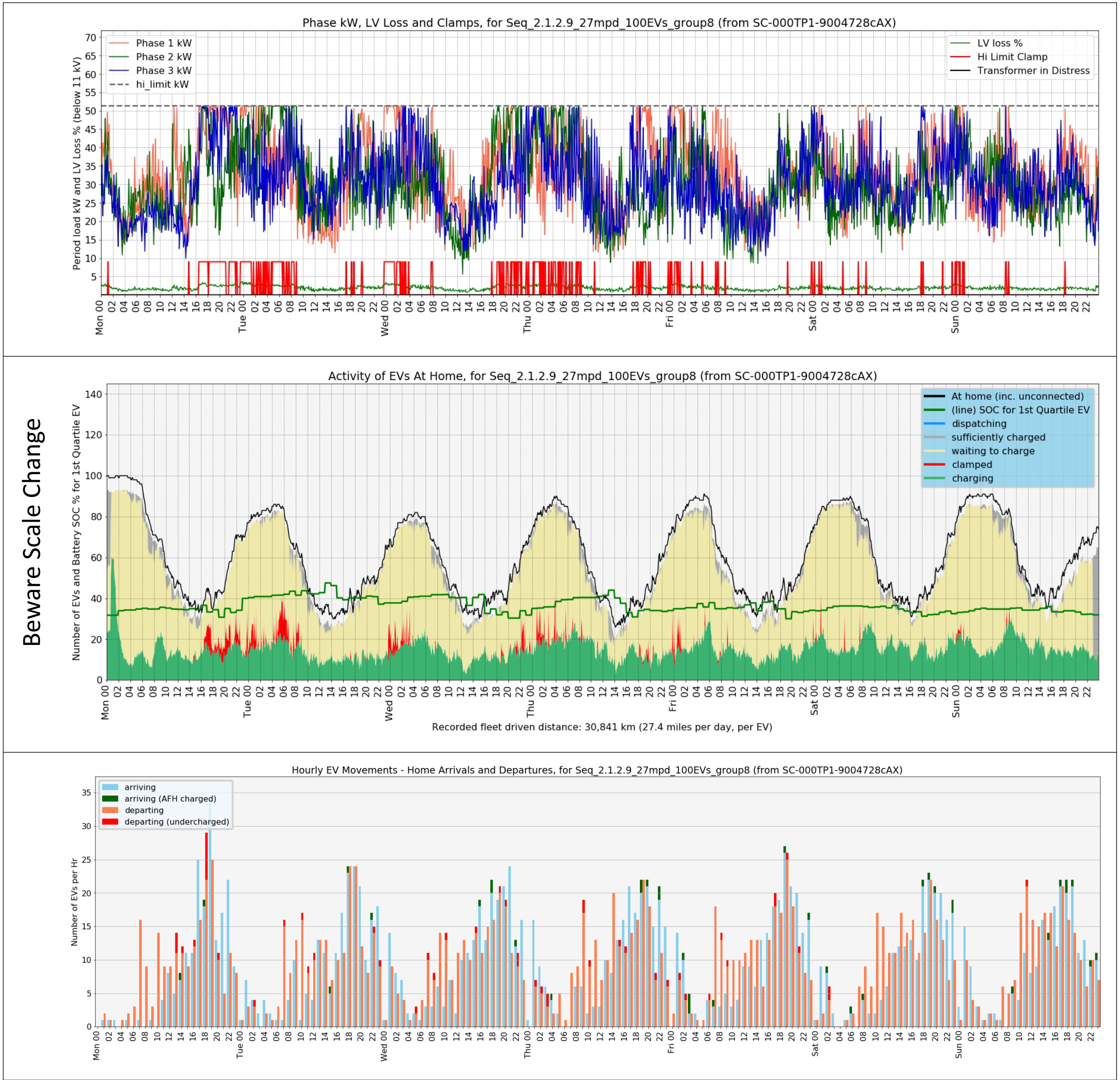
EoW stats: kWh[b] EV total: 2,330 Home: 2,023 AFH: 307 V2G: 0

Figure E-5: Seq_2.1.2.9 27mpd 40 EVs group 8 plots. Weekly fleet km: 12,212

Notes re above plots:

- (Feeder) there is clearly much less clamping occurring
- (CICD) there is little sign of grey (EVs finished charging)
- (Arrive/Depart) there are occasional departs undercharged and use of AFH.

E.3.2.2 Seq_2.1.2.9: 27mpd 100EVs



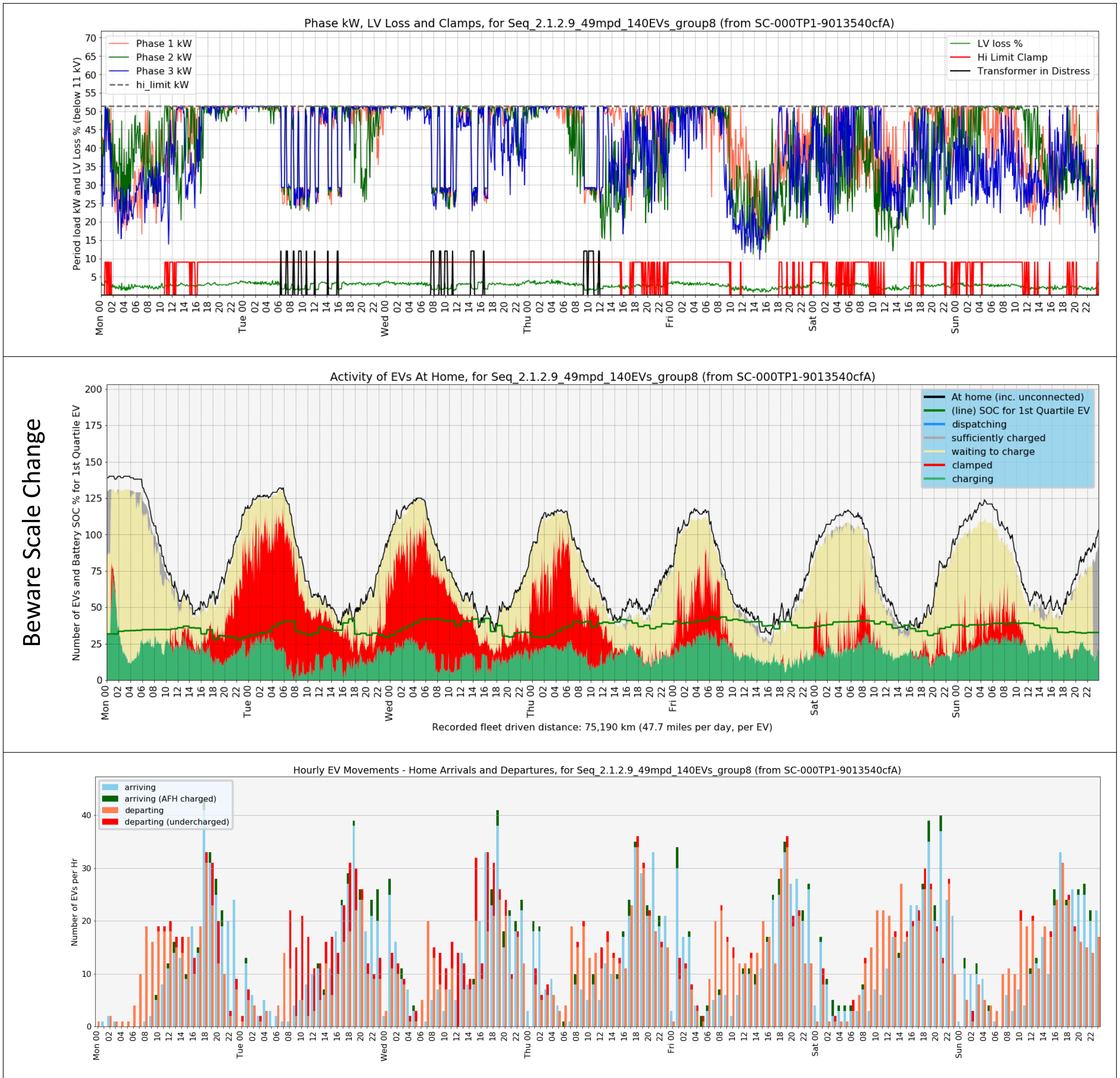
EoW stats: kWh[b]	EV total: 5,902	Home: 5,058	AFH: 844	V2G: 0

Figure E-6: Seq_2.1.2.9 27mpd 100 EVs group 8 plots. Weekly fleet km: 30,876

Notes re above plots:

- (Feeder) there appears potential for broaches but these are clamped
- (CICD) EV SOC appears slightly down; clamps are beginning to appear
- (Arrive/Depart) increasing numbers of EVs depart undercharged

E.3.2.3 Seq_2.1.2.9: 49mpd 140EVs



EoW stats: kWh[b]	EV total: 9,457	Home: 8,118	AFH: 1,339	V2G: 0

Figure E-7: Seq_2.1.2.9 49mpd 140 EVs group 8 plots. Weekly fleet km: 77,276

Notes re above plots:

- (Feeder) clamps (both hi_limit and transformer) are now endemic
- (CICD) EV SOCs remain similar; there are many clamps
- (Arrive/Depart) there is a noticeable rise in departs undercharging and AFH.

E.3.3 Data Tables Seq_2.1.2.9

The parity case (average mpd with 1:1 household EV penetration) is in yellow and the lower RH corner being grey, as visual references. Red indicates a fail for some reason.

Table E-12: 2.1.2.9 Unused kWh (weekly averages)

1. Unused kWh	N EV	10	20	40	60	80	100	120	140
	19mpd	17,094	16,401	15,017	13,637	12,285	10,938	9,661	8,338
	27mpd	16,983	16,161	14,546	12,931	11,392	9,865	8,380	3,135
	38mpd	16,893	15,986	14,144	12,315	10,579	8,833	1,848	*0*
	49mpd	16,814	15,836	13,827	11,864	10,022	5,801	14	*0*

Note: Transformer clamping creates periods in which recorded kWh is not sensible; such plies have ***italic red text***.

Table E-13: 2.1.2.9 EV AFH kWh Uptake (weekly averages)

2. EV AFH kWh	N EV	10	20	40	60	80	100	120	140
	19mpd	2.7	3.3	3.3	3.3	3.4	3.6	3.5	3.5
	27mpd	6.6	7.7	7.7	8.0	8.4	8.4	8.3	8.2
	38mpd	17.3	17.5	17.8	18.4	18.2	18.6	18.5	19.1
	49mpd	35.5	33.2	31.7	31.5	31.1	31.1	32.2	34.1

Inspecting “Meta - Ref” sheet in MetaMeta2.3_Seq_2.1.2.9.xlsx” shows that these values are down on 2.1.2 AFH kWh.

Table E-14: 2.1.2.9 Per EV N AFH (count of away connects, weekly averages)

3. EV N AFH	N EV	10	20	40	60	80	100	120	140
	19mpd	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15
	27mpd	0.29	0.30	0.29	0.30	0.32	0.32	0.31	0.31
	38mpd	0.62	0.61	0.60	0.61	0.61	0.62	0.62	0.65
	49mpd	1.14	1.03	0.96	0.95	0.95	0.95	0.99	1.06

These counts are down vs. 2.1.2, by about 10% in the parity case.

How many charge points are needed? 10 per 1,000 car parking spaces - or 300? If this is miscalculated the mall may find EV drivers stay away in cold periods, impacting turnover.

Note that there is a clear difference between city and rural charge-point needs.

Table E-15: 2.1.2.9 Counts of Undercharging events per EV (weekly averages)

4. EV UnChg	N EV	10	20	40	60	80	100	120	140
	19mpd	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3
	27mpd	1.8	1.8	1.9	1.8	1.8	1.8	1.8	1.9
	38mpd	2.3	2.4	2.4	2.4	2.4	2.4	2.5	3.1
	49mpd	2.9	2.9	2.9	2.9	2.9	2.9	3.4	4.7

An undercharge is defined as any EV departing with SOC < (depart target SOC - 5%).

Table E-16: 2.1.2.9 Counts of Severely Undercharged EVs in Week, per EV

5. EV Severe UnChg	N EV	10	20	40	60	80	100	120	140
	19mpd	0.0002	0.0003	0.0003	0.0002	0.0002	0.0001	0.0003	0.0003
	27mpd	0.0002	0.0006	0.0006	0.0011	0.0013	0.0011	0.0010	0.0012
	38mpd	0.0006	0.0021	0.0028	0.0034	0.0026	0.0034	0.0067	0.0325
	49mpd	0.0032	0.0027	0.0050	0.0042	0.0053	0.0079	0.0396	0.1372

(limit: < 0.007)

These values are substantively down vs. 2.1.2, with 9 light green indicating improved plies vs. 2.1.2. Red highlights unacceptable values.

It is noticeable that the DR element of the control modulation in 2.1.2 27mpd 40 EVs (Figure E-1) was provoking clamps, whereas clamps were less prominent in the same figure for 2.1.2.9.

Table E-17: 6.2.2.2 MCS Clamps (weekly averages)

6. MCS Clamps	N EV	10	20	40	60	80	100	120	140
	19mpd	0.3	1.0	6.1	23.6	72.6	180.6	335.3	590.8
	27mpd	0.3	1.5	12.2	53.6	161.4	380.0	703.6	1,222.8
	38mpd	0.4	1.9	22.0	100.9	299.5	702.4	1,265.5	2,074.7
	49mpd	0.5	2.6	30.1	150.8	449.8	1,004.7	1,760.4	2,651.9

2.1.2 span: [1,660] => [3,787] (limit: < 420)

Clamps are down vs. 2.1.2, with 14 overall extra plies usable. Light green indicates improved plies. Red highlights unacceptable values.

E.3.3 Seq_2.1.2.9 Summary

Sequence 2.1.2.9 is an improvement in all areas vs. 2.1.2, indicating that DRFFR imposes a handicap on operation.

E.4 Sequence 6.9.2 (Later Withdrawn)

Misconfiguration was identified in post processing and the sequence was rerun as 6.9.2.2.

This sequence is presented as it reviews and illustrates DR/FFR using DR-B and DR-C.

Sequence	Simulation ID	Description
Seq_6.9.2	(S_Ai)	Variation vs. Seq_6.2.2 and Seq_6.8.2: DR/FFR "C" is in use with hi_limit reduced to 40 kW from 49 kW per phase. Clamp are active in mode 2. EVs are **75% dumb and 25% V2G. Pre-burn V2G is OFF**
Baseline Seq	***Description***	
Seq_6.2.2	*Typical network, Winter, std. EV mix of 19% dumb, 48% SV1G and 33% V2G, clamps ON (2), pre-burn_V2G ON, hi_limit 51.3 kW*	

This sequence explores operation with different EV population conditions and DR/FFR "C" hi_limit modulation. "C" has less aggressive DR than "B", and retains the FFR pattern.

The DR value is a static amount over a long period (hours), whereas FFR typically changes from moment to moment. The net DR/FFR value forms a ratio applied to hi_limit e.g a net DR_Sunshine signal of 0.96 applied to a 40 kW hi_limit modifies it to become 38.4 kW.

From Time of Day	DR "B"	DR "C"	Purpose
Midnight	1.0	1.0	normal operation
10am	1.05	1.05	Sunshine (charge now) signal
1:06pm	1.0	1.0	normal operation
2pm	0.75	0.9	early afternoon DR
5pm	0.6	0.72	late afternoon DR
9pm	0.75	0.9	late evening DR
11pm	1.0	1.0	normal operation

These are presented in Figure E-8 below:

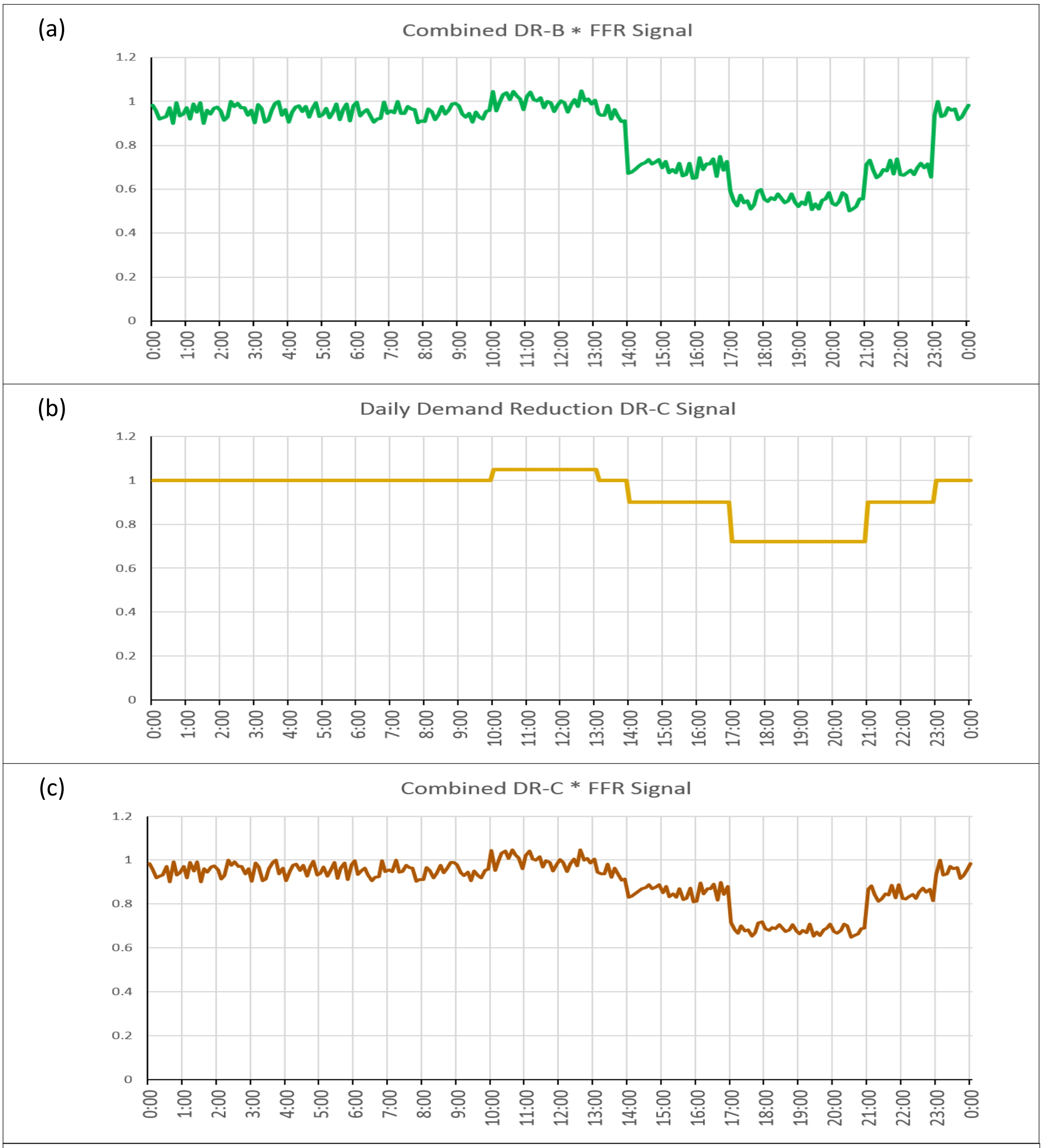


Figure E-8: Prior DR-B / FFR Signal (top), DR-C, Combined DR-C and FFR

Data originate from MetaMeta spreadsheets for Seq_6.9.2. Note that:

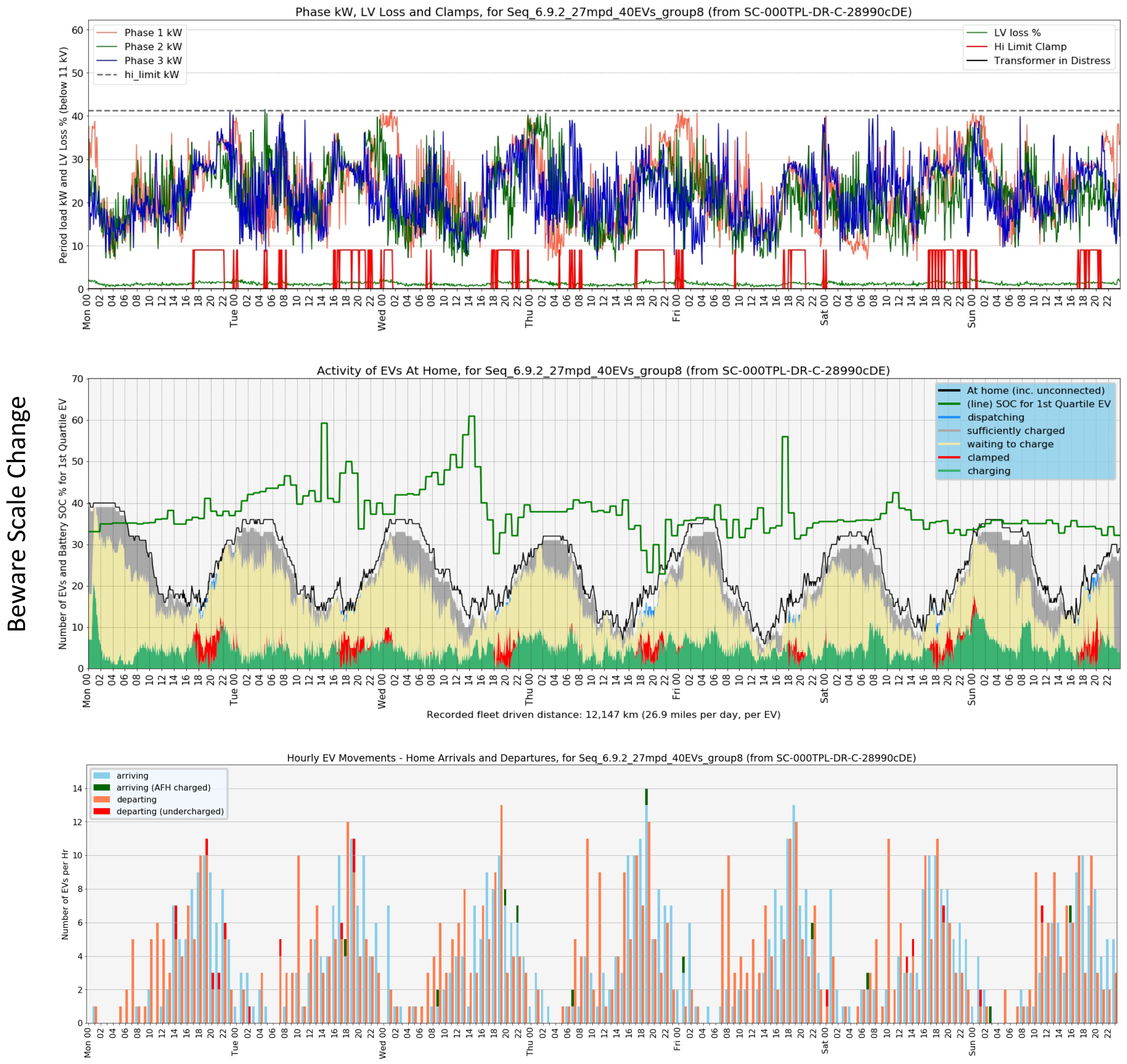
- 6.2.2 has no Aggregation control,
- 6.3.2 has 100% of EVs under Aggregation control,
- 6.9.2 has no EVs under Aggregation control.

E.4.2 Seq_6.9.2: Outcomes

The method shows residential spikes. Losses are improved but undercharging is raised.

E.4.3 Seq_6.9.2 Feeder and EV Plots

E.4.3.1 Seq_6.9.2: 27mpd 40EVs



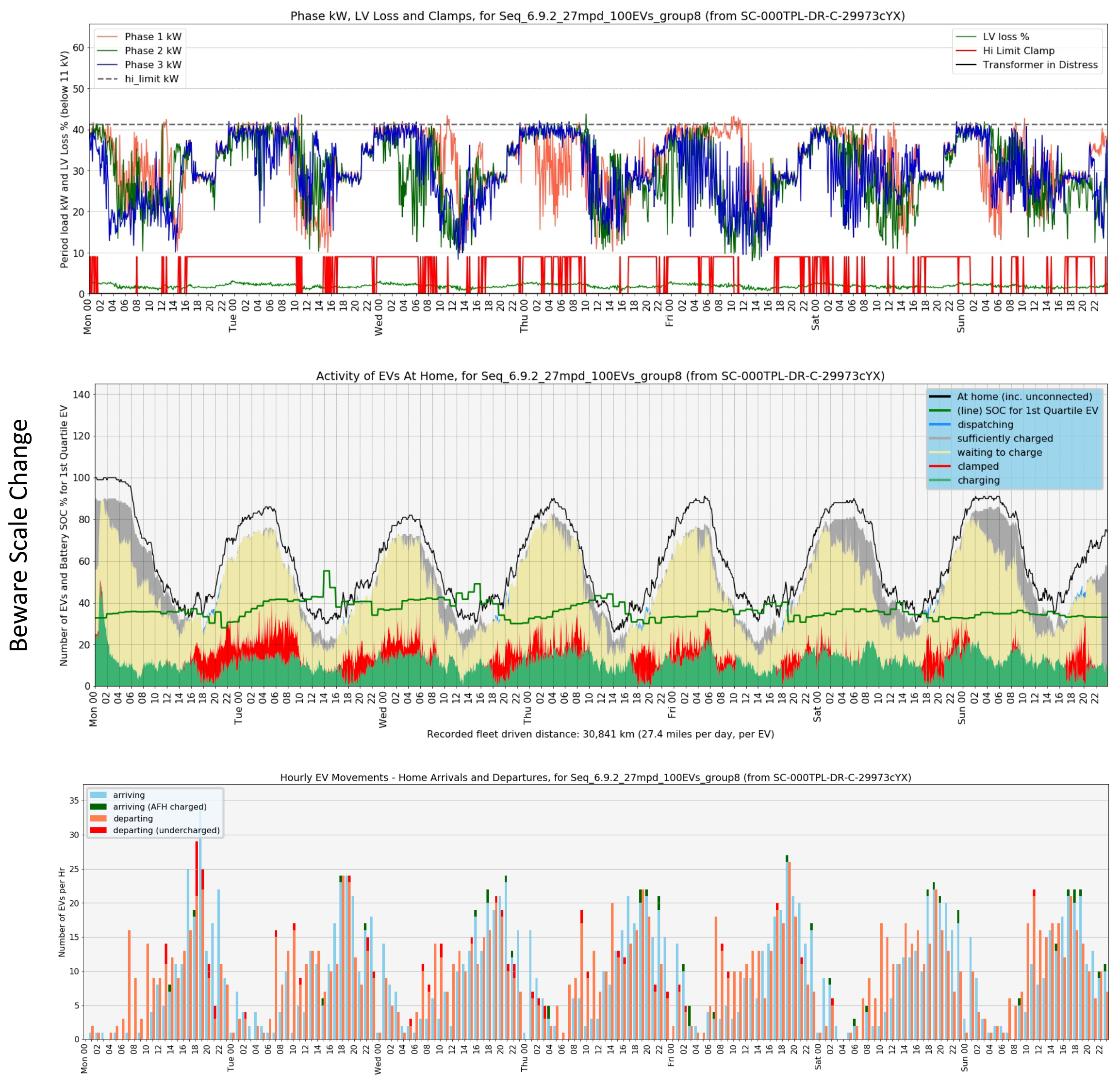
EoW stats: kWh[b] EV total: 2,363 Home: 2,052 AFH: 311 V2G: 41

Figure E-9: Seq_6.9.2 27mpd 40EVs group 8 plots. Weekly km: 12,212

Notes re above plots:

- the Feeder plot shows clamps and the lowered hi_limit
- (CICD) EVs have good SOC but relatively few are ready to depart. Some V2G
- (Arrive/Depart) there are few undercharged; AFH charging is rare.

E.4.3.2 Seq_6.9.2: 27mpd 100EVs



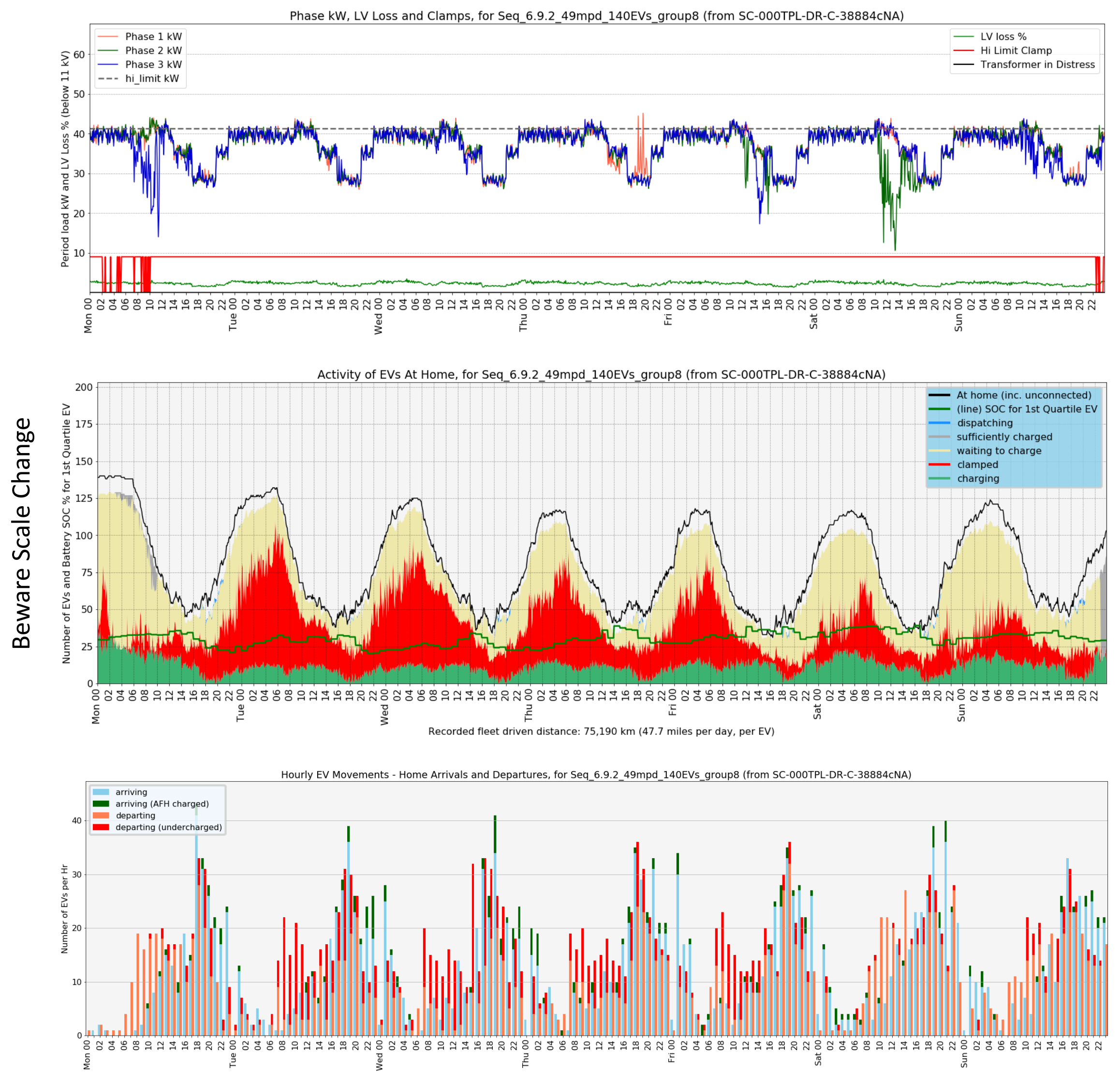
EoW stats: kWh[b] EV total: 5,966 Home: 5,101 AFH: 865 V2G: 63

Figure E-10: Seq_6.9.2 27mpd 100EVs group 8 plots. Weekly km: 30,876

Notes re above plots:

- the Feeder plot shows many clamps but is unremarkable
- (CICD) SOC is similar with significant numbers of EVs ready to depart; some V2G
- (Arrive/Depart) has more undercharged departs; AFH charging has increased. However both are low.

E.4.3.3 Seq_6.9.2: 49mpd 140EVs



EoW stats: kWh[b] EV total: 13,515 Home: 7,328 AFH: 6,187 V2G: 69

Figure E-11: Seq_6.9.2 49mpd 140EVs group 8 plots. Fleet drives 77,327 km

Notes re above plots:

- the Feeder plot shows the DR/FFR signal well, also the residential load “bursting through” c. Thursday 9pm
- (CICD) clamps dominate. Very few EVs seem ready to depart
- undercharging and AFH charging has risen to likely unacceptable levels.

E.4.4 Data Tables Seq_6.9.2

Table E-18: 6.9.2 Unused kWh (weekly averages)

1. Unused kWh	N EV	10	20	40	60	80	100	120	140
	19mpd	12,348	11,687	10,378	9,068	7,798	6,545	5,345	4,167
	27mpd	12,240	11,451	9,908	8,367	6,902	5,474	4,112	2,957
	38mpd	12,150	11,275	9,510	7,746	6,105	4,541	3,305	2,607
	49mpd	12,073	11,129	9,190	7,294	5,579	4,054	3,016	2,568

6.2.2 span: [10,098] => [4,763] and 6.3.2: [10,239] => [5,747]

Note that the reduced hi_limit has lowered all values by c. 4,700 kWh. It can then be seen the span here would be: [10,174] => [7,268] which implies that the DR/FFR signal is less restricting the upper load ranges.

Table E-19: 6.9.2 Per EV AFH kWh Uptake (weekly averages)

2. EV AFH kWh	N EV	10	20	40	60	80	100	120	140
	19mpd	2.6	3.2	3.3	3.3	3.4	3.7	3.6	3.6
	27mpd	6.8	7.9	7.8	8.1	8.5	8.6	8.7	9.4
	38mpd	17.4	17.6	18.1	18.6	18.6	19.6	21.1	25.6
	49mpd	35.6	33.4	31.9	31.8	31.8	33.8	38.0	44.2

6.2.2 span: [8.0] => [34.2] and 6.3.2: [8.7] => [39.2]

AFH kWh taken is slightly up.

Table E-20: 6.9.2 Per EV AFH N events (count of away connects, weekly averages)

3. EV N AFH	N EV	10	20	40	60	80	100	120	140
	19mpd	0.12	0.14	0.14	0.14	0.14	0.16	0.15	0.15
	27mpd	0.30	0.31	0.30	0.31	0.33	0.33	0.34	0.37
	38mpd	0.62	0.62	0.62	0.62	0.63	0.67	0.73	0.92
	49mpd	1.14	1.04	0.97	0.96	0.98	1.05	1.21	1.45

6.2.2 span: [0.3] => [1.05] and 6.3.2: [0.34] => [1.26]

Clearly there are more AFH connections, however for the parity case these are modest.

Table E-21: 6.9.2 Counts of Undercharging events per EV (weekly averages)

4. EV UnChg	N EV	10	20	40	60	80	100	120	140
	19mpd	1.0	1.2	1.2	1.2	1.3	1.3	1.3	1.4
	27mpd	1.6	1.7	1.8	1.8	1.8	1.9	2.1	3.3
	38mpd	2.3	2.4	2.5	2.5	2.6	3.2	4.5	7.2
	49mpd	3.0	3.0	3.1	3.2	3.4	4.7	6.6	9.0

6.2.2: [1.4] => [5.0] and 6.3.2: [2.0] => [6.6]

Undercharging has risen overall.

Table E-22: 6.9.2 Counts of Severely Undercharged EVs in Week, per EV

5. EV Severe UnChg	N EV	10	20	40	60	80	100	120	140
	19mpd	0.0030	0.0021	0.0015	0.0014	0.0014	0.0017	0.0015	0.0016
	27mpd	0.0010	0.0008	0.0024	0.0035	0.0036	0.0042	0.0097	0.0433
	38mpd	0.0042	0.0045	0.0090	0.0091	0.0106	0.0325	0.1102	0.2973
	49mpd	0.0070	0.0063	0.0103	0.0099	0.0271	0.1204	0.2799	0.5229

6.2.2 span: [0.0015] => [0.1631] and 6.3.2: [0.0209] => [0.3175] (limit: < 0.007)

Severe undercharging is up; the blue being for 6.2.2.

Table E-23: 6.9.2 MCS Clamps (weekly averages)

6. MCS Clamps	N EV	10	20	40	60	80	100	120	140
	19mpd	183	282	442	627	885	1,238	1,648	2,191
	27mpd	189	305	500	766	1,166	1,738	2,468	3,449
	38mpd	199	329	584	979	1,588	2,476	3,378	4,202
	49mpd	210	345	649	1,162	1,950	2,941	3,757	4,440

6.2.2 span: [366] => [2,985] and 6.3.2: [244] => [2,370] (limit: < 420)

Perhaps an unfair comparison, as we are managing 75% dumb EVs and 25% V2G EVs.

Table E-24: 6.9.2 V2G kWh dispatch per EV (weekly averages)

7. V2G kWh	N EV	10	20	40	60	80	100	120	140
	19mpd	7.1	5.2	4.3	3.6	2.9	2.5	2.2	2.0
	27mpd	6.8	5.2	4.1	3.6	2.9	2.5	2.3	2.1
	38mpd	6.7	5.2	4.3	3.6	2.9	2.5	2.3	2.1
	49mpd	6.1	4.5	4.0	3.4	2.8	2.5	2.2	2.0

6.2.2: [7.9] => [27.0] and 6.3.2: [5.5] => [21.9]

V2G EVs have surprisingly low duty; this is likely as Pre-Burn is OFF.

Table E-25: 6.9.2 Average LV Losses Comparison

		N EV	10	20	40	60	80	100	120	140
Seq_6.2.2	8. A	19mpd	96.6	112.9	138.5	178.7	230.6	292.8	357.9	420.6
		27mpd	97.8	116.0	150.2	200.8	261.8	335.9	420.7	502.2
		38mpd	98.9	118.3	162.3	221.9	294.2	389.0	486.5	570.4
		49mpd	99.8	120.3	167.8	236.2	317.4	418.7	518.7	591.4
Seq_6.9.2	B	N EV	10	20	40	60	80	100	120	140
		19mpd	96.6	109.2	138.1	171.8	217.6	274.2	325.8	373.9
		27mpd	97.8	115.8	145.9	191.5	241.9	307.5	371.0	418.7
		38mpd	98.8	118.3	151.1	209.3	270.5	341.7	401.4	437.9
		49mpd	99.6	120.0	157.6	219.7	283.0	358.6	413.7	438.8
Difference B - A	C	N EV	10	20	40	60	80	100	120	140
		19mpd	0.1	-3.7	-0.4	-6.9	-13.0	-18.6	-32.1	-46.7
		27mpd	0.0	-0.2	-4.3	-9.3	-19.9	-28.4	-49.7	-83.5
		38mpd	-0.1	0.0	-11.2	-12.6	-23.7	-47.3	-85.1	-132.5
		49mpd	-0.2	-0.3	-10.2	-16.5	-34.4	-60.1	-104.9	-152.6

Average LV Losses kWh: Seq_6.9.2 (B) vs. Baseline 6.2.2 (A)

This is a good loss reduction of 100 % * (28 / 336) = 8.33 %, at £385 k per 1% reduction yielding c. £3.2 m over Winter.

Table E-26: 6.9.2 DRFFR Percent Effective Hours (weekly averages)

9. DRFFR %	N EV	10	20	40	60	80	100	120	140
	19mpd	32.7%	35.7%	42.3%	48.8%	57.1%	65.5%	70.8%	76.8%
	27mpd	32.1%	36.3%	43.5%	54.2%	66.7%	72.6%	81.0%	86.9%
	38mpd	31.5%	36.9%	46.4%	57.7%	71.4%	78.0%	86.3%	94.6%
	49mpd	31.5%	36.9%	48.8%	61.3%	73.8%	82.1%	90.5%	95.8%

6.2.2 span: [73.8%] => [98.2%] and 6.3.2: [68.5%] => [85.1%]

Hi_limit modulation PEH results are noted.

9.1 Seq_6.9.2 Results Summary

The author was concerned about the spikes seen on the 49mpd 140EV feeder plot which occur Thursday c. 18:00 - 20:00. These appeared anomalous and potentially a defect.

Investigations show the observed peaks are in the core residential load dataset, but usually hidden by:

- hi_limit exceeding the peak value, and
- V2G support.

Note “idle” EVs draw 140 W each; a full set taking 4.6 kW occasionally lifting the peaks.

<document ends>

this page deliberately left blank

DISCARD DISCARD

DISCARD - DISCARD

DISCARD - DISCARD

NB hidden para of definitions formats below in Master

Figure_Coincidence

General_Intelligent_EV

Capability_Heatmaps

Broaching

Ageing_Spike

Transformer_Limit_Clamp

Post-Processing_Workflow

Halsey_UKPN

bursts_of_charging

Tranches

Dependency_Trap

Verification_vs_Similar Works

Further_Work

Cable_pics

MEA

Traditional_Passive_Substation

Residential_Data Sourcing_and_Preparation

Apdx_E_Analysis_Samples

Periodicity_Error

Battery_Life_Policies

EA_Fig_0.1

Impact_MEA_UK_Charging_Policy

UKPN_ADMD_Table