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Spatial context matters: Assessing how future renewable energy pathways will impact nature and society

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ABSTRACT

Pathways to decarbonisation are commonly explored by government and industry through the use of energy system models. However, such models rarely consider where new energy infrastructure might be located. This is problematic as the spatial context of new renewable energy infrastructure will determine, in part, the environmental, social, and technical impacts of the energy transition. This paper presents the ADVENT-NEV model which brings together innovations in energy and natural capital modelling to identify the optimal locations of multiple renewable energy technologies at a national scale and high spatial resolution. Using Great Britain as a case study, the results show how the spatial distribution of renewable energy technologies changes when a natural capital approach is taken. In particular, the least-cost locations for onshore wind farms and bioenergy crops are highly influenced by the value of carbon sequestration, or emissions associated with their land use change. Siting using a natural capital approach produced appreciable ecosystem service benefits, such that the overall welfare gain to society was estimated at nearly £25 B. Overall, this paper demonstrates that understanding the geospatial context of the energy transition is essential to identifying which renewable energy pathways are consistent with decarbonisation and environmental objectives.

1. Introduction

The decarbonisation of global energy systems is critical to limit global warming [1–3]. Decision makers use energy systems models to explore the merits of different energy pathways to transition to a low carbon future ([4] [3]). These models optimise the energy system to minimise total financial costs under technology, emissions, and policy constraints [5]. One limitation of such models is that they are often poorly spatially resolved [6]. Yet spatial information is critical as, due to its distributed nature and land footprint, the location of new renewable energy infrastructure influences its financial costs, environmental impacts, and socio-political acceptability [7–11].

Energy models can typically be categorised into: energy systems models, spatial energy systems models, and energy location models. Energy systems models are usually aspatial and exclude environmental impacts barring greenhouse gas (GHG) emissions [5,12,13]. As energy systems become more decentralised, the aspatial nature of most energy systems models mean they are unable to consider the 'on the ground' implications of different energy pathways. Governments are faced with multiple policy challenges relating to the environment such as biodiversity loss and deteriorating water resources. It is essential that decarbonisation is not pursued without evaluating the trade-offs between renewable energy expansion and ecosystem services (ES) [14–16]. Indeed, it is possible that models are creating energy pathways which will prove difficult to implement due to their land use and environmental implications [17]. In contrast spatial energy systems models depict countries as multiple regions, and energy location models determine the optimal location(s) for new energy infrastructure at a

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local or regional scale. Table 1 summarises the differences between the modelling approaches, highlighting how spatially resolved models consider broader environmental implications.

In this paper, we use the spatially-explicit ADVENT-NEV cost-minimisation model to assess an existing future energy pathway. The model determines the optimal locations of the pathway's solar farms, onshore wind farms, bioenergy power stations and their bioenergy crops, considering both market and non-market costs. Our approach is underpinned by the natural capital paradigm, a framework that considers the value of the natural environment by including the stocks of natural assets and the flows of ES they provide and how these alter when an intervention occurs [25–27]. This type of analysis has proved valuable in other contexts (e.g. Ref. [28]) by identifying the implications of land use changes to ES including flooding, greenhouse gas emissions, and recreation.

Limited research has been undertaken using the natural capital approach to consider the impacts of energy technologies on society and ES ([29] [30]). Drechsler et al. [31] was one of the first studies to incorporate the economic valuation of ES into the spatial optimisation of energy systems using a choice experiment to determine peoples' willingness to pay to site wind turbines in a manner which protected biodiversity and reduced visual disamenity. A more recent study by Donnison et al. [22] used the natural capital approach to determine the least-cost locations for bioenergy with carbon capture and storage power stations and their biomass feedstock, highlighting how spatially-targeted bioenergy crop deployment can maximise ES benefits. Most studies, however, have too coarse a spatial resolution to enable co-benefits between energy planning and environmental objectives to be identified [6].

The ADVENT-NEV model seeks to build upon previous applications of the natural capital approach to the siting of energy infrastructure (Table 1). It is novel in its approach of incorporating *multiple* ES into the modelling of *multiple* renewable energy technologies at a national scale using high spatial resolution data. The key contribution of this paper is its demonstration of the role that spatial energy-environment modelling that incorporates the natural capital approach, like ADVENT-NEV, could play in guiding energy infrastructure policy as countries transition to low-carbon energy systems.

2. Methodology

2.1. Model description

The ADVENT-NEV model is an energy location model that optimises the location of solar farms, wind farms, bioenergy power stations and their bioenergy crops across Great Britain (GB).[1,2] The model is applied to GB where high population density, diverse and multiple land uses, and renewable resource availability, are coupled with legally-binding targets to reduce GHG emissions.

In this paper, the model is driven by an exogenously determined energy pathway, titled 'Low Carbon without Carbon Capture and Storage' (LC no CCS) from Watson et al. [32]. The scenario details separate deployment pathways for solar, onshore wind, and bioenergy for every

[1] Only bioenergy power stations which source all their feedstock from domestically grown *Miscanthus* or short rotation coppice (SRC) poplar and willow are modelled as these crops are predicted to be the main future bioenergy feedstocks used in the UK [17,93].

[2] The ADVENT-NEV model is named after the project that created it (ADdressing Valuation of Energy and Nature Together) and the Natural Environment Valuation model [55]. The model is written in Matlab 2017a and linked to spatial data from a PostGIS database.

Table 1
Comparison of energy models used to explore decarbonisation pathways.

Model		Spatial extent	Spatial resolution	Temporal resolution	Purpose	Technologies considered			How is the environment considered?		Reference
						Solar	Wind	Biomass			
Energy systems	UK TIMES (UKTM)	National	National	4 seasons; 4 intraday	Least cost energy pathway	✓	✓	✓	Constraint	GHG emissions	[5]
Spatial energy systems	HighRES	National	Regional	Hourly	Electricity system planning and dispatch model	✓	✓		Land use restrictions	Biodiversity; visual disamenity; water availability	[9]
	ESME	National	Regional	2 seasons; 5 intraday	Least cost energy pathway	✓	✓	✓	Constraint	GHG emissions	[18]
Energy location	–	Local	1 km²	Annual	Least cost locations for renewables		✓		Weightings; land use restrictions	Biodiversity; visual disamenity	[19]
	–	Regional	1 km²	Annual	Least cost locations for renewables	✓	✓		Weightings; land use restrictions	Biodiversity; visual disamenity	[20]
	–	National	1 km²	Annual	Least cost locations for renewables	✓	✓		ES valuation	Visual disamenity	[21]
	–	National	1 km²	Annual	Least cost locations for renewables			✓	ES valuation; land use restrictions	Flooding; GHG emissions; soil carbon sequestration; visual disamenity; water stress	[22]
	IFE-TIMES-Norway	Regional	1 km²	4 seasons, 24 h	Least cost locations for renewables		✓		ES valuation; land use restrictions	Biodiversity; visual disamenity	[23]
	–	National	1 km²	Annual	Least cost locations for renewables		✓		ES valuation	Visual disamenity	[24]
	ADVENT-NEV	National	1 km²	Annual	Least cost locations for renewables	✓	✓	✓	ES valuation	Flooding; GHG emissions; pollination; soil carbon sequestration; visual disamenity; water quality	This paper

five-year time period between 2015 and 2050.[3] Although it was created before the UK set its net-zero target, it assumes similar levels of solar, wind, and bioenergy to more recent scenarios and therefore deemed relevant (see Supplementary Information (SI)). The scenario assumes wind and nuclear power play critical roles as attempts to commercialise CCS technologies fail.

The ADVENT-NEV model takes the LC no CCS pathway and identifies where that infrastructure should be located on a grid of 226,000 1 km^2 cells. We compare a 'free market' approach to the spatial allocation of this infrastructure, where the model seeks to minimise financial costs only, to the natural capital approach where both financial and ES costs are minimised. We use a social discount rate of 3.5% and present all costs as net present values (NPV £2015). The model seeks to minimise the cost of the deployment pathway sequentially for every five-year time period. An annual temporal resolution is used to determine the costs of renewable energy infrastructure to ensure optimisation can be undertaken at a high spatial resolution. Fig. 1 provides an overview of the model with further detail provided in the SI.

2.1.1. *Where can energy infrastructure be sited?*

Baseline restrictions are imposed on where energy infrastructure can be located in this analysis (see SI). These restrictions capture a range of current legal and technical constraints that prevent energy technologies being built in particular locations (e.g. land cover, slope, spacing of infrastructure). Potential siting locations for solar and wind power installations and bioenergy crop cultivations are defined as cells on a 1 km^2 grid across GB. To reduce computational burden, potential siting locations for bioenergy power stations are located at the centroids of a 50 km^2 grid.

2.1.2. *What size of solar farms, wind farms and bioenergy power stations are sited?*

To maintain computational tractability, we assume that the annual electricity output per 1 km^2 cell for each energy technology is fixed. We assume a solar farm, wind farm and bioenergy power station will generate 6,000, 21,000 and 297,840 MW h per year respectively.[4] The number of solar panels and wind turbines required to generate that amount of electricity varies spatially due to the spatial heterogeneity of solar radiation and wind speed. If there is not enough land available in the 1 km^2 cell for this amount of infrastructure, it is considered unsuitable.

2.1.3. *Total financial cost and ecosystem service cost*

The total financial cost of constructing and operating a solar farm, wind farm or bioenergy power station is the sum of the construction cost, the operational and maintenance (O&M) cost, the cost of land, the electricity grid connection cost and, for bioenergy, the bioenergy crop cost. The total social cost of the energy technology is equivalent to the total financial costs plus the ES costs. A brief description of each of these costs is provided below with more information available in the SI.

2.1.3.1. Construction cost. The construction cost of building a solar or wind farm in every 1 km^2 cell depends on the number of solar panels or wind turbines needed in that cell (Section 2.1.2) and the cost per installation. The construction cost of a bioenergy power station is independent of its location. The cost per solar panel, wind turbine and bioenergy power station are taken from UKTM [32].

2.1.3.2. O&M cost. The fixed and variable operational and maintenance costs are taken from UKTM [32].

2.1.3.3. Land cost. The value of the land that energy infrastructure occupies is represented by its opportunity cost, that is to say the value that area of land would have generated if it had remained in its previous use. The foregone agricultural production cost of land is determined by the agricultural model used within Ritchie et al. [41]. The land cost of non-agricultural land is taken from the Department for Communities and Local Government [42] and the Valuation Office Agency [43].

2.1.3.4. Electricity grid connection cost. The electricity grid connection cost is the summation of the cost of constructing power lines to connect the energy installation to the electricity network, the associated transmission losses, the value of the land needed for the new power lines and, where applicable, the cost of upgrading the electricity network. The pylon construction cost depends on the length and terrain type of the least-cost route, determined using Dijkstra's algorithm, between the electricity generator and a nearby substation [44]. The cost per km is taken from WPD [45] and terrain cost multipliers from Pletka et al. [46]. The cost of transmission losses is calculated by multiplying the fixed annual electricity output of the energy technology (Section 2.1.2) by the regional loss factor [47] and the price of electricity [48]. The land cost is calculated based on the value per hectare (Section 2.1.3.3). An upgrade cost will be paid if the least-cost pylon route is to a constrained distribution network substation [49].

2.1.3.5. Bioenergy crop cost. The bioenergy crop cost is the summation of the transportation costs, the bioenergy crop establishment and management costs, and the cost of the land used to grow the bioenergy crops. Transportation costs are based on the price of fuel and the straight-line distance between the bioenergy crop field locations and the location of the bioenergy power station they have been allocated to ([50]; Section 2.2). The establishment and management costs are taken from Wales Energy Crops Information Centre [51] and the land cost is calculated as per Section 2.1.3.3. Each of these costs is influenced by the amount of bioenergy crop that can theoretically be grown in each 1 km^2 cell as determined by the bioenergy crop yield data [52,53] and the amount of suitable land in that cell (Section 2.1.1).

2.1.4. *Ecosystem service cost*

The ES cost quantifies how the land use change associated with allocating energy infrastructure, or bioenergy crops, to a particular location affects the environment. Table 2 indicates which ES costs are considered for each technology type with further details provided in the SI. The ADVENT-NEV model draws on a range of state-of-the-art ES models (e.g. NEV, ELUM) to offer a comprehensive analysis of the ES implications of energy system development (e.g. Ref. [54,55]).

2.2. *Spatial optimisation techniques*

Hungarian and Greedy algorithms are used to identify the least-cost locations for all three energy technologies in the ADVENT-NEV model ([71–73]; [74]). First, the optimal locations for solar and wind farms are determined using the Hungarian algorithm. This algorithm identifies exact solutions to the assignment problem where n workers (i.e. solar and wind farms) must be assigned to m jobs (i.e. 1 km^2 cells) to minimise costs. Once the Hungarian algorithm is solved, a relocation cost is calculated for every wind and solar farm that has been sited to reflect the cost of relocating that wind or solar farm to the next least-cost location (see SI). After wind and solar farms are sited, a Greedy algorithm identifies the least-cost locations for bioenergy power stations and

[3] The bioenergy target does not specify how much biomass is imported, we assume that, for each time period, 20% of the target, is met by small-scale bioenergy power stations which use domestically sourced bioenergy crops.

[4] This fixed annual electricity output is calculated based on the typical output of a 5 MW solar farm, a 10 MW wind farm and a 40 MW bioenergy power station as detailed in the SI [94].

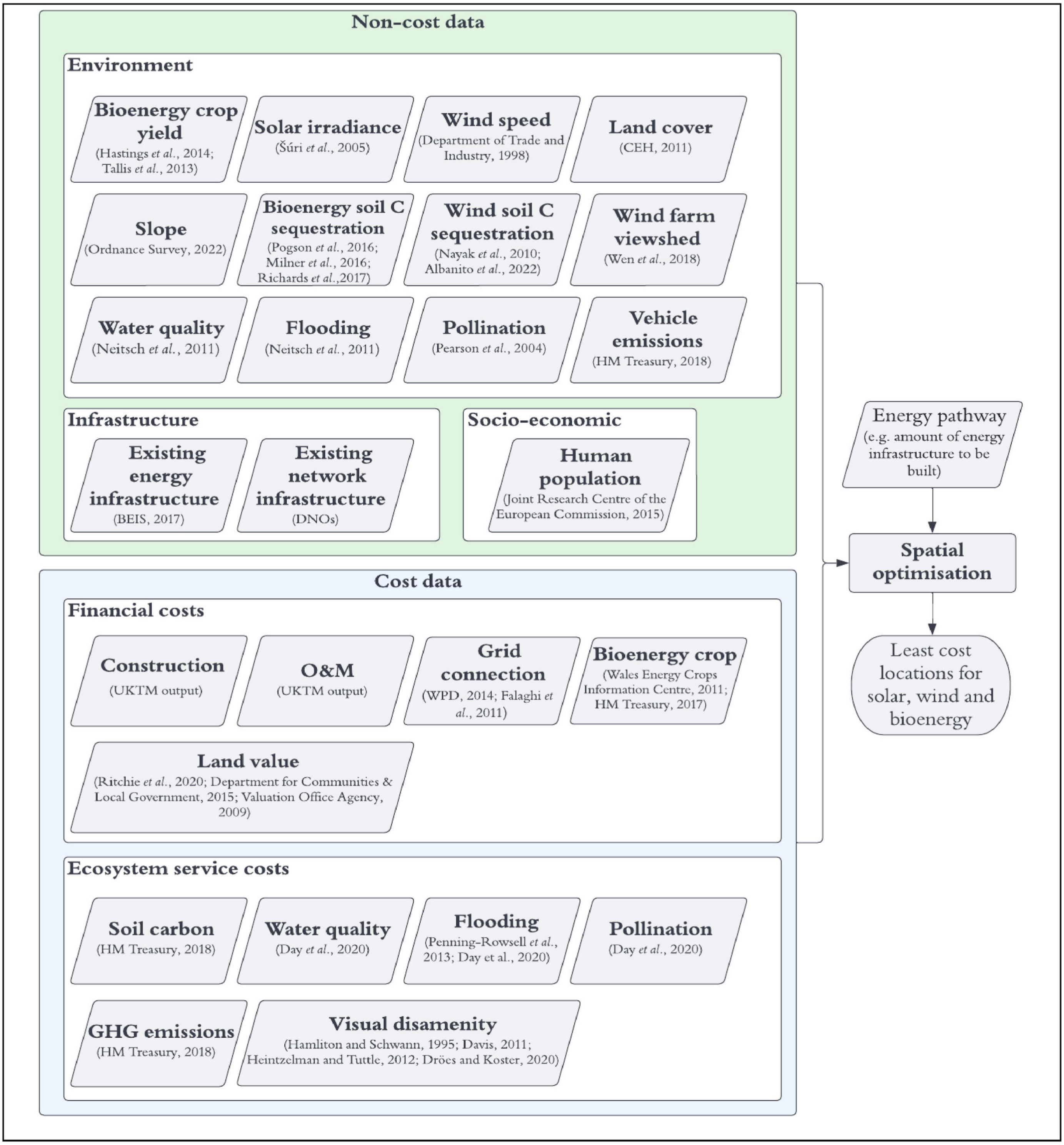

Fig. 1. Overview of ADVENT-NEV model (CEH, 2011 [33]; DTI, 1998 [34]; Joint Research Centre of the European Commission [35]; Milner et al., 2016 [36]; Nayak et al., 2010 [37]; Ordnance Survey, 2022 [38]; Suri et al., 2005 [39];Wen et al, 2018 [40]).

bioenergy crops considering the relocation costs of solar and wind.[5] This algorithm first considers each potential power station location independently, identifying which 1 km^2 cells bioenergy crops should be sourced from. Once the bioenergy crop locations have been optimised, the total cost of siting a power station in each potential location is calculated. The bioenergy power station with the lowest cost is then selected. This process is repeated until no clashes between wind, solar and bioenergy occur.

[5] The Hungarian algorithm cannot be used to find optimal locations for bioenergy as it can only allocate one 'task' (i.e. energy technology) to one 'worker' (i.e. area of land).

Table 2
Ecosystem services (ES) included within the ADVENT-NEV model for each technology. Where solar is denoted by ***s***, wind by ***w***, bioenergy power stations by ***b***, bioenergy crops by ***bc*** and pylons by ***p***.[1]

ES	Applicable tech	Environmental outcome	ES value (£)	Brief description
Avoided agricultural GHG emissions	s, w, b	GHG emissions	Carbon cost	The avoided emissions were estimated in the NEV model using the Cool Farm Tool [56].[2]
CO_2 transportation emissions	*bc*	GHG emissions	Carbon cost	Straight line distance between crop and power station multiplied by the CO_2 emissions from fuel [48].[2]
Flood risk	*bc*	Reduction in peak flow	Flood damage cost reduction	Statistical emulation is applied to outputs from the Soil Water Assessment Tool (SWAT) [57] within NEV to determine the impact of land cover change on water quantity [55]. Changes to expected damage costs is calculated using costs within the 'Multi-Coloured Manual' [58].
Pollination (Use)	s, w, bc	Pollinator species diversity	Horticultural crop yield	A pollinator diversity model predicts the diversity of 472 pollinator species as they respond to climatic and land cover change [59]. The impact on insect pollinated horticultural crops is determined by Day et al. [55].
Pollination (Non-use)	s, w, bc	N/A	Wildflower abundance	Willingness to pay for maintaining full pollination services is taken from Breeze et al. [60] and used alongside the pollinator diversity model within NEV [55].
Soil carbon change	*w*	GHG sequestration	Carbon cost	The soil carbon sequestration change associated with wind farms is from Albanito et al. [61].[2]
	bc	GHG sequestration	Carbon cost	The soil carbon sequestration change associated with bioenergy crops is taken from the ELUM model [54,62].[2]
Visual disamenity	s, w, b, p	N/A	House value reduction	Hedonic analyses are used to determine how nearby house values could decrease due to presence of new energy infrastructure. House values are taken from ONS [63] and ROS [64]. The percentage reductions in house values are taken from Dröes and Koster [65], Heintzelman and Tuttle [66], Davis [67] and Hamilton and Schwann [68] for s, w, b and p respectively.
Water quality (Use)	*bc*	Reduction in nitrogen & phosphorus at abstraction points	Water treatment cost reduction	Statistical emulation is applied to outputs from the SWAT [57] within NEV to determine how nutrients are transported into the river network. The change in water quality is monetised based upon assumed water treatment costs within the NEV model [55].
Water quality (Non-use)	*bc*	N/A	Water quality improvement	A map-based stated preference study is used to determine the non-use value individuals attach to changes in river ecological status [69].

[1] All GHG emissions were costed using the central non-traded central carbon value [90].
[2] There is no evidence to date that wind or solar farms would have substantial impacts on flooding or water quality therefore these are set to zero, as are solar farms' impacts on soil carbon sequestration. There is also no agreed quantification of the visual disamenity costs associated with bioenergy crops [70].

3. Results

3.1. Insight into the least-cost locations, and associated land use change, of renewable energy technologies

Using the ADVENT-NEV model to explore the spatial implications of the LC no CCS pathway, we demonstrate how the spatial deployment of renewable energy depends on whether that allocation is left to market forces or shaped through the natural capital approach. Fig. 2 maps the least-cost locations for solar farms, wind farms, bioenergy power stations, and bioenergy crops, as determined by the ADVENT-NEV model. It shows the spatial configuration of the energy system if the free market approach is taken (i.e. minimise financial costs only in Fig. 2a), compared to when the natural capital approach is followed (i.e. minimising both financial and ES costs in Fig. 2b). In contrast to aspatial energy models, spatial energy-environment models can consider how spatial factors influence the cost and allocation of energy infrastructure across the country. For example, when the free market approach is pursued, solar farms are allocated to the south of England due to the region's high solar radiation values and relatively low grid connection costs. In comparison, wind farms are allocated to north-west England and Scotland due to the presence of high wind speeds and low land value. Bioenergy power stations and their bioenergy crops are more uniformly distributed across GB, though notably tend to avoid high-agricultural productivity land across east and central England.

In contrast, when a natural capital approach is taken, wind farms move to locations with lower agricultural GHG emissions, soil carbon emissions and visual disamenity costs (Fig. 2b). Bioenergy crop deployment is targeted to locations that minimise GHG emissions, primarily those that displace high-emissions agricultural activities and increase net soil organic carbon sequestration.[6] The shift in the spatial distribution of solar farms is less pronounced. We see changes at a local level, with the number of solar farms located within 1 km of a settlement decreasing by 68.8% to reduce the visual impact of new energy infrastructure.

Spatial modelling also helps us to identify the magnitude of land use change. The ADVENT-NEV model estimates that the LC no CCS energy pathway would result in 1.33 million hectares (M ha) of agricultural land change by 2050 if the free market approach is taken and 1.48 M ha if the natural capital approach is pursued (Table 4).[7] Bioenergy is responsible for 99% of this land use change, culminating in 22–24% of GB's total arable land (i.e. 8-9% of total agricultural land), and nearly 160,000 ha of high-quality agricultural land, being converted to bioenergy crops (see SI). Previous studies have raised concerns of the food security implications this could have [75,76]. Future energy systems could also put pressure on land that is highly-valued for other services such as recreation or environmental protection. For example, 26% of wind farms associated with the LC no CCS pathway are sited within

[6] Although the spatial distribution of bioenergy crops is influenced by pollination, flooding and water quality benefits, the key driving force in the spatial optimisation is carbon.

[7] The total spatial footprint of the LC No CCS energy pathway is higher when the natural capital approach is pursued as energy infrastructure is not placed in locations that may be energy productive but where high-value ecosystem services are lost from development. Instead, energy infrastructure is situated in relatively less energy-productive locations, necessitating an expansion of the area of land needed for wind and solar facilities and bioenergy crop cultivation to meet energy production targets.

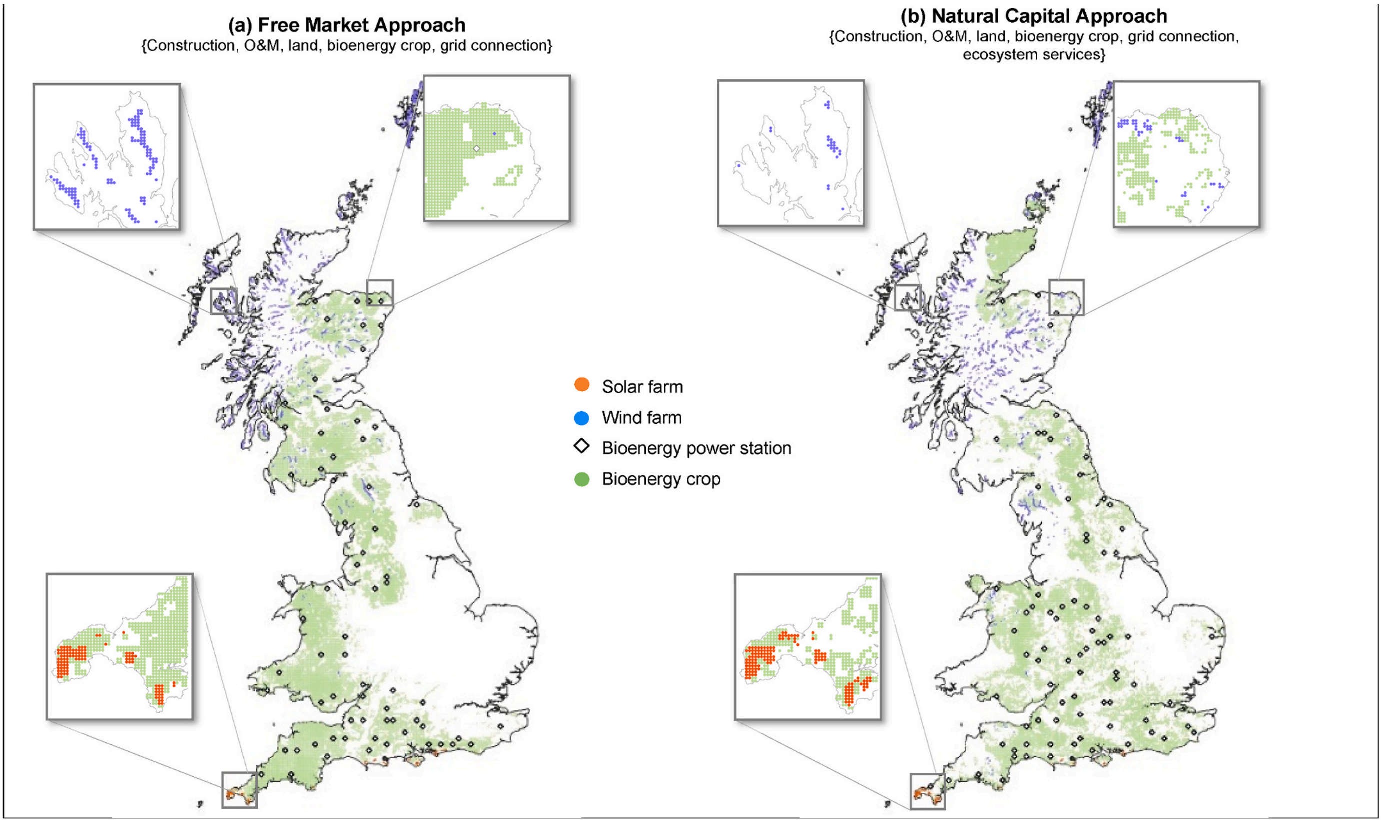

Fig. 2. Spatial distribution of the LC no CCS energy pathway's solar farms, wind farms, bioenergy crops, and bioenergy power stations depending on whether (a) a free market approach or (b) a natural capital approach (i.e. ecosystem service costs considered) is taken. Insets show energy infrastructure allocation close up in Scotland and SW England.

Table 3
Costs associated with the LC no CCS energy pathway when either the free market or natural capital approach is taken. Split into financial costs, ecosystem service costs and social costs (i.e. financial plus ecosystem service costs) where ecosystem service (ES) benefits are depicted by negative ecosystem service costs.

Technology	Capacity target (GW)	Free Market Approach Costs (£b NPV)			Natural Capital Approach Costs (£b NPV)		
		Financial	ES	Social	Financial	ES	Social
Solar	9.9	10.1	0.0	10.1	10.1	0.0	10.1
Wind	37.1	36.2	30.6	66.9	41.8	2.8	44.7
Bioenergy	4.5	18.2	−1.6	16.6	20.3	−6.2	14.1
Total	51.5	64.6	29.0	93.6	72.2	−3.4	68.8

Table 4
Spatial footprint per technology, and in total, depending on whether the free market or natural capital approach were pursued for the LC No CCS energy pathway.

Approach	Spatial footprint (ha)			
	Wind	Solar	Bioenergy	Total
Free market	5607	10,379	1,315,648	1,331,634
Natural capital	6757	10,053	1,467,566	1,484,376

National Parks in the absence of restrictions (see SI).

In Fig. 2, the model resolved spatial conflicts between the three technologies. Fig. 4 however, shows that when the model does not resolve conflicts, there is increased competition for land between renewable energy technologies with wind farms and bioenergy crops competing for land in Scotland and north-west England and solar farms and bioenergy crops competing for land in the south of England. All of the land conflicts involve bioenergy, there are no conflicts between solar and wind farms. It is likely that the presence, or absence, of cross-technology conflicts depends on the topography and climatic conditions of the country being analysed.

3.2. Insight into the environmental impacts of an energy pathway

By understanding where new energy infrastructure might be located, spatial energy-environment modelling identifies the potential ecosystem service impacts associated with an energy pathway. The ADVENT-NEV model framework can quantify the environmental impacts of an energy pathway in both monetary and non-monetary terms. For example, the model can quantify the GHG emissions associated with the land use change of an energy pathway. Fig. 3 demonstrates that when the free market approach is taken, the net carbon sequestration associated with bioenergy crops is 30% lower than when the natural capital approach is

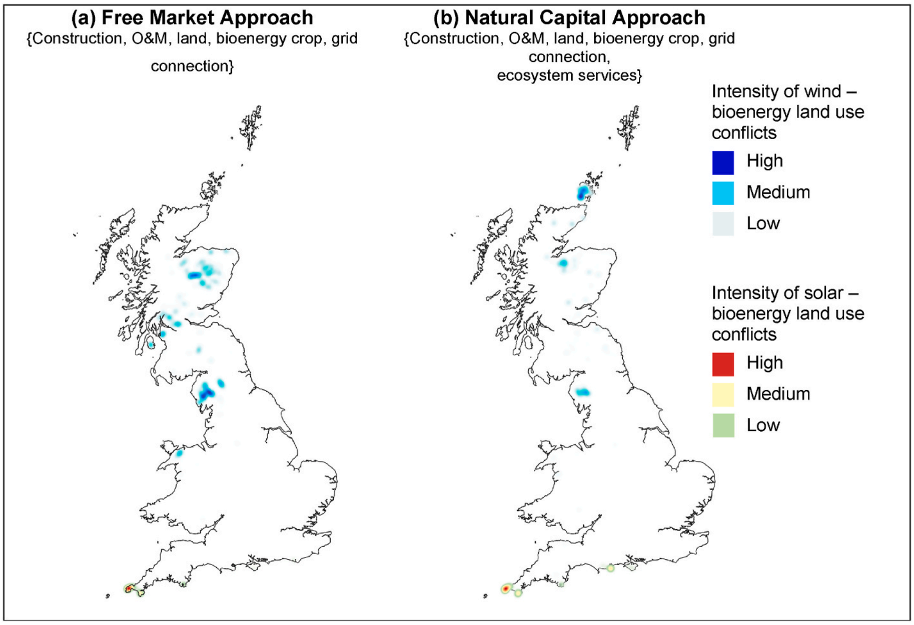

Fig. 3. Soil organic carbon sequestration associated with the LC No CCS energy pathway for the time period between the planting of the crop until the end of its lifetime (i.e. 25 years after planting) when either the (a) free market approach or (b) natural capital approach are pursued.

pursued.[8] This finding is driven by spatial differences in the sequestration of soil organic carbon by bioenergy crops [77], and indicates that a free market approach can undermine some of the assumed benefits associated with renewable energy technologies.

By adopting a natural capital approach, the ADVENT-NEV model monetises the ecosystem service impact associated with an energy pathway. For example, when the free market approach is taken, the subsequent allocation of energy infrastructure results in a net ES cost of £29.0 billion (B) (Table 3). This is primarily due to the release of GHG emissions associated with building wind turbines on high organic matter soils. Wind turbines are allocated to areas of upland peat due to the poor agricultural returns to extensive livestock farming on this land. In comparison, when the natural capital approach is pursued, the ADVENT-NEV model allocates energy infrastructure to locations which result in £3.4 B of net ecosystem benefits (Table 3). This is primarily driven by the model minimising the adverse impacts of wind and maximising the ES benefits associated with bioenergy. This results in £6.2 B of bioenergy crop ES benefits being realised rather than £1.6 B of benefits when the free market approach is pursued (Table 3). These results demonstrate the scale of the benefits that might be realised by society if policy makers were to adopt a natural capital approach in their energy system deployment strategies. In the case of the LC no CCS pathway, the social costs of that pathway would be reduced from £93.5 B to £68.8 B (Table 3). In other words, taking guidance from a spatial natural capital energy model could deliver £24.7 B in welfare gains to society compared to allowing siting decisions to be based only on market forces (Table 3).

3.3. Insight into the impacts of renewable energy expansion on the electricity network

In many areas of GB the electricity network is severely constrained, with network upgrades required before new renewable energy infrastructure can be connected. Spatial modelling is able to show where electricity network upgrades would be required if certain energy pathways are to be pursued. In the case of LC no CCS, Fig. 5 shows that no matter which approach is taken, upgrades are required. Wind farms require the highest proportion of substation upgrades, with 90% of wind farms requiring substation upgrades when the free market approach is taken, compared to 70% of bioenergy power stations and 51% of solar farms.

4. Discussion

This paper provides numerous insights into the spatial implications of a future energy pathway, demonstrating how energy location models could inform wider discussions regarding how best to use land. Only by understanding where new energy infrastructure might be located can information be provided to decision-makers regarding the potential conflicts that exist between energy decarbonisation, environment, and food security objectives. This is particularly important for the discussion surrounding bioenergy crops. It is possible that the intensification of agriculture or dietary changes could free up land thus limiting the impact of bioenergy on food production [78]. However, if these changes did not occur, there could be indirect land use change in other countries to account for GB's reduction in food production [17,79]. This could impact the magnitude of the GHG emissions, and consequently the social cost, associated with an energy pathway (see SI).

This paper also highlights how spatial energy-environment modelling can be used to determine where renewable energy infrastructure should be allocated to minimise adverse impacts and maximise co-benefits. To ensure energy pathways align with GHG emission and nature restoration targets, we advise the following policy recommendations. First, that market interventions, such as payments for ES [80], are pursued to incorporate the natural capital approach into energy system planning. For example, bioenergy crops could be included in the development of the new Environment Land Management Scheme to ensure a sustainable supply chain of biomass within the UK [81]. We advise against exclusion zones due to their inability to consider nuances in land use change impacts [82]. Second, governmental cross-departmental working across land use and decarbonisation is essential to ensure spatial trade-offs are being adequately considered in

[8] For national carbon budgets, it is important to note that studies show that any carbon sequestered in the soils by bioenergy will be released if land is converted back to agriculture at the end of the bioenergy crop's lifetime [95–97]. This release of carbon is accounted for in the ADVENT-NEV model but not shown in Fig. 3. The optimisation considers the benefit of sequestering the carbon, even if only temporarily, in the soils.

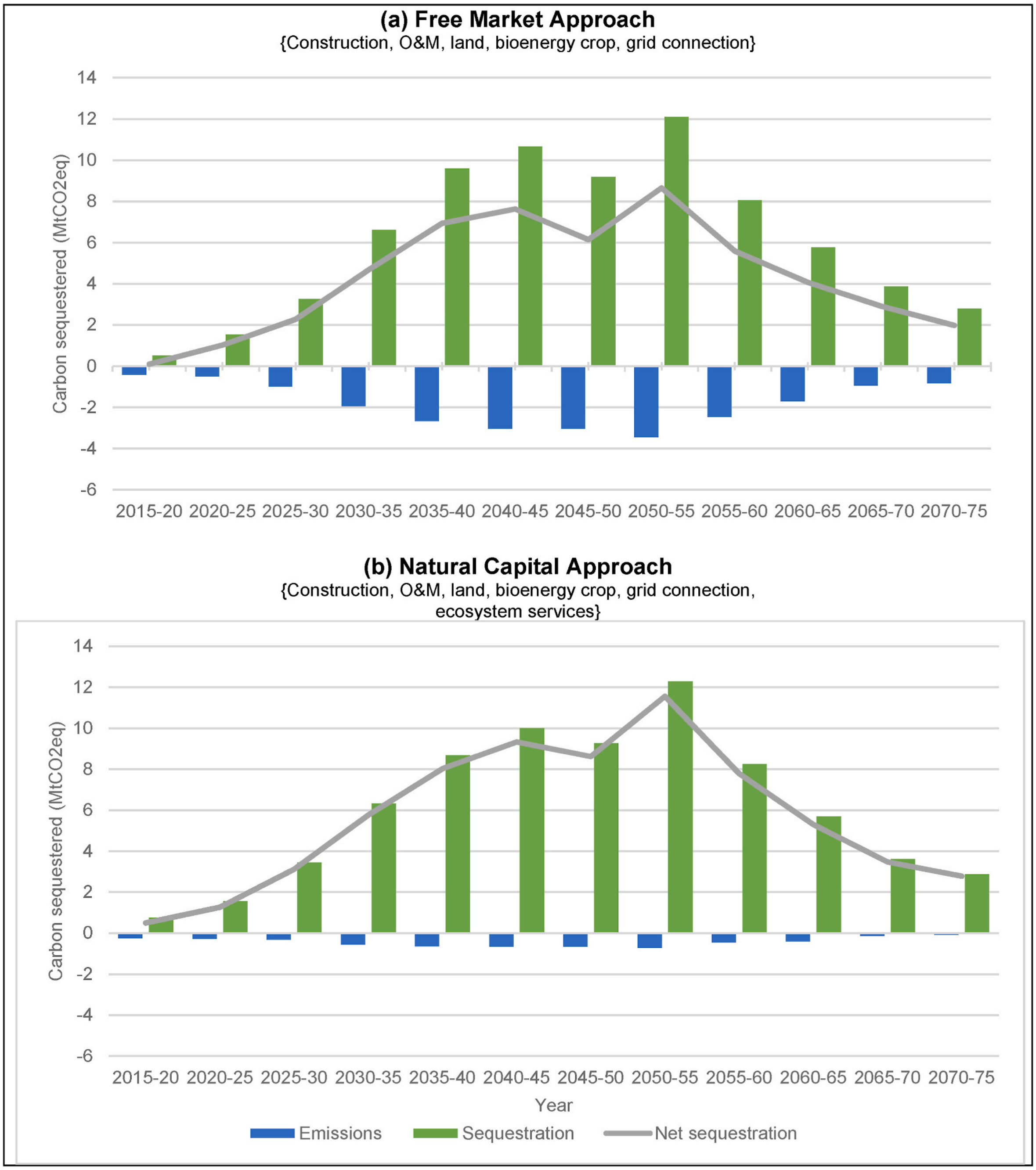

Fig. 4. Heat map of land use conflicts when the (a) free market approach or (b) natural capital approach is pursued for the LC No CCS energy pathway.

policy. Third, review the need for a land use management strategy to ensure a systems perspective is taken [83–85].

Although spatial energy location models, like ADVENT-NEV, provide insights not otherwise available to decision-makers, it is important to also recognise their limitations. The analysis in this paper often shows renewable energy infrastructure spatially clustering in certain regions (e.g. Fig. 2). In reality, current deployment is more evenly distributed across the country. There are two key model limitations that likely explain these differences. First, the simplification of grid upgrade requirements means the cost implications of grid constraints is underestimated with our analyses assuming costs of ~£1 B NPV compared to National Grid ESO [86] estimates of ~£28 B. Spatial network modelling across local, regional, and national scales is a key gap in energy modelling to date [13]. Second, the fixed energy generation per 1 km^2 cell assumption means that the benefits of spatial diversification (e.g. building wind turbines in different locations to take advantage of wind speed profiles differing spatially and temporally) cannot be explored. In addition, it overlooks the potential to allocate larger, or smaller, energy installations to specific locations or the co-location of technologies (e.g. wind and biomass) which could minimise the system's cost.

Spatial clustering would likely impact public acceptance if local communities perceive their local area has reached its 'carrying capacity' or that there is an unfair distribution of costs and benefits [87]. As approximately 60% of the UK's existing onshore wind farms occur in Scotland, with more modelled to be built there in the future, engagement with local communities will be essential ([88]; [89]). In addition, other competing land uses, like housing and woodland planting, are outside the scope of this study. That is why it is critically important to recognise that modelling outputs, like those from ADVENT-NEV, should be viewed as one piece of evidence with which to inform

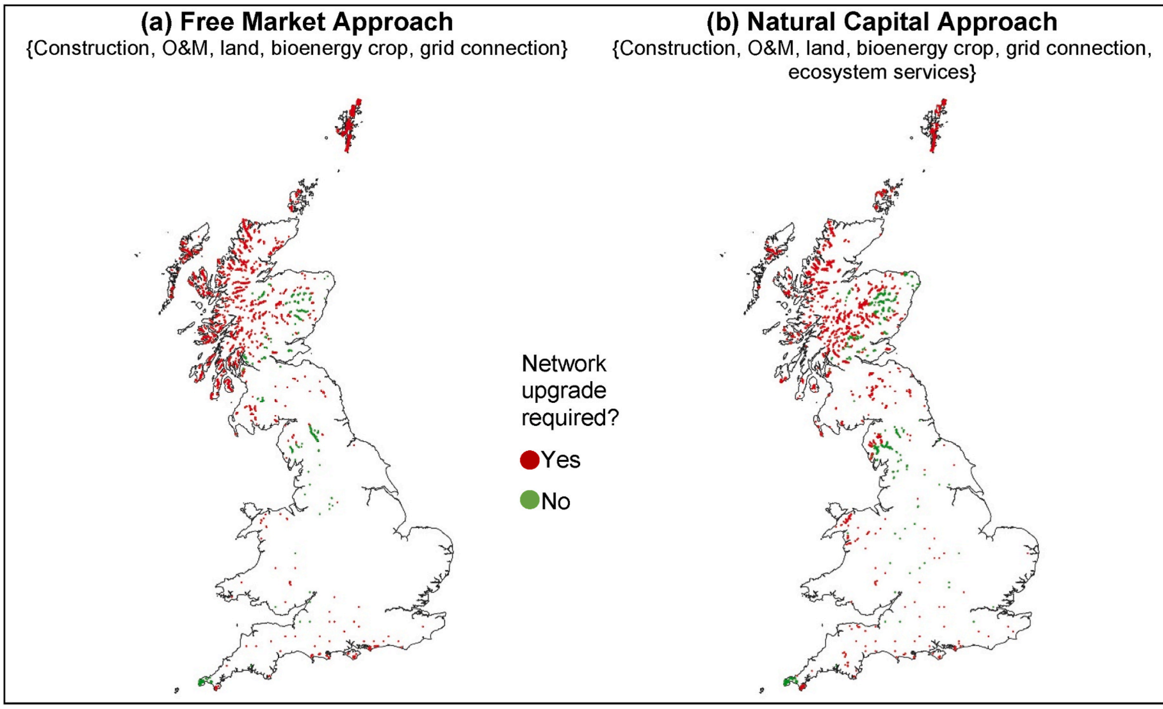

Fig. 5. Spatial distribution of energy infrastructure which required electricity network upgrades, for the LC No CCS energy pathway, depending on whether (a) the free market approach or (b) the natural capital approach is taken.

decision-making, rather than providing a definitive solution [90]. Model outputs should feed into discussions on the distributional impacts placed on local communities and the energy justice implications of different regional allocations of infrastructure [91].

A further limitation of the ADVENT-NEV model is that there is uncertainty regarding how the building of new energy infrastructure affects values. For example, the implications that bioenergy crops could have on flooding have not been studied extensively. Donnison et al. [22] estimates much higher flood reduction benefits than this study, however the spatial distribution of those benefits is similar. This indicates that there is higher uncertainty in the magnitude of the benefits but not the spatial pattern of them. Biodiversity is another ES which is particularly challenging to quantify and monetise [16]. Whilst the model provides insights into how pollinator species could be impacted by land use change, it could be further expanded to consider biodiversity more extensively (e.g. changes to wider species distribution and diversity). We would suggest that models are updated as more ES valuation data is made available. However, given the urgency of the climate change challenge, decisions regarding where to build new energy infrastructure will have to be made before we can eradicate all uncertainties.

A broader discussion is needed regarding the role of energy models in planning the future energy system. Different models which look across different spatial scales can contribute to this discussion. Models such as ADVENT-NEV model can provide insights into the spatial implications of different energy pathways to national decision-makers. Whereas, planning energy systems at a local authority level are better served by models that consider local characteristics and stakeholder knowledge, like those used for the development of Local Area Energy Plans [92]. The involvement of stakeholders, including the general public, in the ongoing development of these models will be critical. Finally, there are impacts that occur beyond national boundaries. Lifecycle assessment studies have shown how the environmental impacts associated with upstream processes (e.g. extraction of materials, manufacturing) of renewable energy technologies are not inconsequential [15]. Although these impacts will not affect the spatial siting decision within GB, they could influence the social acceptance of different energy technologies and therefore should not be overlooked in the debate.

5. Conclusion

The transition to a low carbon future means decisions must be made regarding how best to use land. Spatial modelling can provide insights into how energy pathways may impact both the natural environment and society to help inform these decisions. In this paper, we demonstrate four key insights that spatially-explicit modelling incorporating the natural capital approach can provide using the ADVENT-NEV model applied at a national scale across GB. First, we show how spatial models can determine the least-cost locations for renewable energy technologies in a way that ensures adverse impacts on the natural environment can be avoided and co-benefits realised. Incorporating the natural capital approach into energy decision making helps to ensure that energy pathways are consistent with broader environmental concerns (e.g. visual impact, biodiversity, water quality). Second, welfare gains could be realised if policy makers adopted a natural capital approach. Our results indicate that £24.7 B of societal benefits are realisable when both financial and ES costs are considered based on the modelling of the LC no CCS pathway.

Third, spatial models are critical to identifying the magnitude and spatial distribution of the land use change associated with future energy pathways. In this paper, we indicate how the bioenergy requirements of the LC no CCS pathway result in 1.48 M ha of land use change, higher than previous estimates. With this information, decision-makers can assess how much new energy infrastructure may be built in different regions of the country, and therefore proactively assess how to avoid imposing a burden of new energy installations on a particular region. Fourth, spatial models provide insights into where the electricity network may need to be upgraded to inform national strategic planning.

Overall, we demonstrate that spatial energy-environment models can provide critical insights into the consequences of different energy pathways by improving our understanding of the geospatial and contextual issues related to energy transitions. Future research should aim to integrate energy-environment models with energy systems models, to ensure energy pathways are developed that simultaneously address both climate and wider environmental challenges.

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Data access statement

All data used in the ADVENT-NEV model is detailed in the Supplementary Information and Figure 1. Not all of the data is open access as some is commercially sensitive. The modelling results are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Gemma Delafield: Conceptualization, Investigation, Methodology, Writing – original draft, preparation, Writing – review & editing, Visualization. **Greg S. Smith:** Investigation, Methodology, Writing – review & editing. **Brett Day:** Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing. **Robert A. Holland:** Conceptualization, Supervision, Writing – review & editing. **Caspar Donnison:** Investigation, Writing – review & editing. **Astley Hastings:** Investigation, Writing – review & editing. **Gail Taylor:** Writing – review & editing. **Nathan Owen:** Investigation, Writing – review & editing. **Andrew Lovett:** Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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