



# The Financial and Environmental Consequences of Renewable Energy Exclusion Zones

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## Abstract

As countries decarbonise, the competition for land between energy generation, nature conservation and food production will likely increase. To counter this, modelling, and sometimes energy policies, use exclusion zones to restrict energy deployment from land deemed as important to society. This paper applies the spatially-explicit ADVENT-NEV model to Great Britain to determine the cost imposed on the energy system when either environmental or food production exclusion zones are applied. Results show that exclusion zones impose a cost of up to £0.63 billion (B), £19.17 B and £1.33 B for the solar, wind, and bioenergy pathways. These costs give an indication of the value being placed on protecting these areas of land. When multiple exclusions are imposed on bioenergy, the high pathway is infeasible indicating a more flexible approach may be needed to meet net zero ambitions. The model also shows how the value of ecosystem services changes when exclusion zones are applied, highlighting how some exclusions increase non-market costs whereas others decrease them. In several cases exclusion zones are shown to increase social costs, the opposite of their intended use. For these exclusions to be justifiable, the unobserved values missing from the model must be as large as these increases.

**Keywords** Ecosystem services · Environmental restrictions · GIS · Low carbon energy · Spatial analysis

## Abbreviations

ADVENT	Addressing valuation of energy and nature together
ALC	Agricultural land classification
AONB	Area of outstanding natural beauty
B	Billion
CCC	Committee on climate change

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CO <sub>2eq</sub>	Carbon dioxide equivalent
GB	Great Britain
GWh	Giga-watt hour
ha	Hectare
km	Kilometre
M	Million
MW	Mega-watt
MWh	Mega-watt hour
NPV	Net present value
SSSI	Site of special scientific interest
t	Tonnes
TWh	Terra-watt hour
UK	United Kingdom

## 1 Introduction

By 2050, it is estimated that approximately 90% of global electricity generation will come from renewable energy technologies (IEA 2021). There are concerns that this scale of expansion will increase competition for land, potentially threatening food production and the natural environment, particularly in countries which are densely populated (Konadu et al. 2015; Dunnett et al. 2022). Previous studies have imposed exclusion zones to limit where new energy infrastructure can be built in an attempt to protect land categorised as important for environmental protection or food production (e.g. National Parks, high-quality agricultural land). There are some countries, including Spain, Germany, and Wales, which have imposed these exclusion zones within their spatial energy planning policies (Deshaies and Herrero-Luque, 2015; Thiele et al. 2021; Welsh Government, 2021). This paper investigates the implications of imposing these exclusion zones on the cost, spatial footprint, and environmental impact of renewable energy deployment. To do that we apply the natural capital approach to future renewable energy pathways for Great Britain using the spatially-explicit optimisation model ADVENT-NEV.

One of the most contested issues around energy systems over the last decade has been the food versus fuel debate, in particular the concern that bioenergy crop expansion will negatively impact food production (Hellegers et al. 2008; Karp and Richter, 2011; Overmars et al. 2015; Tröndle et al. 2019). It is not just bioenergy however that is subject to food production concerns, solar farm planning proposals are also frequently contested if development is proposed on high-quality agricultural land (Calvert and Mabee, 2015; Overmars et al. 2015; Wiehe et al. 2021). There are also concerns about the broader implications future energy pathways may have on the environment. Studies have shown how land use change can result in substantial changes to biodiversity, highlighting the importance of not pursuing decarbonisation ambitions to the detriment of biodiversity targets (Hansen et al. 2012; Hooper et al. 2018; Holland et al. 2019; Rehbein et al. 2020). There are direct biodiversity impacts associated with some renewable energy technologies, such as the collision risk between wind turbines and birds, but also indirect impacts including how the presence of renewable energy infrastructure may impact species' behaviour (Saidur et al. 2011; Marques et al. 2014; Wang and Wang, 2015). Another source of contention, which influences a considerable number of renewable energy planning applications, is the visual impact of new renewable energy developments (Roddis et al. 2018). Studies

have highlighted the impact that renewable energy can have on the landscape character of regions prized for their perceived visual beauty (Moran and Sherrington, 2007; Rowe et al. 2009; Hastik et al. 2015; Rand and Hoen, 2017).

Previous studies have sought to avoid, minimise or resolve the trade-offs between energy, food and nature, using various methods to identify where is 'best' to locate new energy infrastructure. The most common approach in the spatial energy modelling literature involves imposing exclusion zones to determine where new energy infrastructure can and cannot be located (Lovett et al. 2009; Parish et al. 2012; Onyango et al. 2013; Lovett et al. 2014; Konadu et al. 2015; Sunak et al. 2015; Watson and Hudson, 2015; Egli et al. 2017; Kienast et al. 2017; Wiehe et al. 2021; Price et al. 2020). These studies tend to restrict development on high-quality agricultural land, landscape designations (e.g. National Parks), and wildlife designations (e.g. Sites of Special Scientific Interest), to account for the perceived importance of these areas (Sultana and Kumar, 2012; Sunak et al. 2015; Watson and Hudson, 2015; Egli et al. 2017). These areas are protected to preserve the services they provide such as food production, landscape aesthetics or high levels of biodiversity.

In contrast to the use of exclusion zones, a small number of studies have applied the natural capital approach to energy spatial planning (Moran and Sherrington, 2007; Drechsler et al. 2011, 2017; Lester et al. 2013; Tafarte and Lehmann, 2019; Donnison et al. 2020). These studies have sought to determine socially-optimal locations for new renewable energy infrastructure by incorporating spatial non-market costs and benefits into energy decision-making (Mendelsohn and Olmstead, 2009; Bateman et al. 2013; Hinton et al. 2014; Natural Capital Committee, 2015; Welfle et al. 2020). For example, Drechsler et al. (2011) included society's willingness to pay to move wind farms away from settlements and areas important for red kites, recognising the value that society places on reducing visual impact and protecting biodiversity. Moran and Sherrington (2007) used social cost-benefit analysis to assess wind farm projects in Scotland by monetising both carbon emissions and visual disamenity. By incorporating non-market costs and benefits into decision-making, the natural capital approach ensures the trade-offs between energy generation, food production and nature conservation are made explicit (Pearce et al. 2013). These studies however have tended to focus on one or two energy technologies and only include a small number of ecosystem services.

This paper uses the spatially-explicit optimisation model ADVENT-NEV, which can determine the least-cost locations for solar farms, wind farms, bioenergy power stations and their bioenergy crops considering both market and non-market costs, to answer the following five research questions. First, how do different exclusion zones impact the market costs of the energy system? Second, how do different exclusion zones impact the non-market and social costs of the energy system? Third, if the social cost of the energy system increases when exclusion zones are applied, what is the implied 'unobserved' value that society has inherently attached to these zones, unaccounted for in our valuation of ecosystem services, to justify the use of these exclusion zones? Fourth, how do different exclusion zones impact the spatial footprint of the energy system? And finally, what other environmental issues might be overlooked by the exclusion zone approach?

Exclusion zones are used by studies as a way to protect land deemed as important for environmental protection or food production. These restrictions act as a proxy for the value of ecosystem services and food production provided by these areas of land, values which are difficult to quantify (e.g. Watson and Hudson, 2015; Egli et al. 2017; Kienast et al. 2017). It is important to understand however, that the introduction of these exclusion zones may increase the market costs of the energy system. For example, if these areas contain

the least-cost locations for a technology, excluding development from that area will force renewable energy infrastructure to be constructed in more expensive locations. By using exclusion zones, previous studies have therefore assumed that any increase in the market cost of the energy system must be smaller than the value placed on protecting the ecosystem service flows, or food production, provided within that exclusion zone. Consequently, this additional cost must represent the implied value of that area of land that would otherwise be diminished by the presence of energy infrastructure.

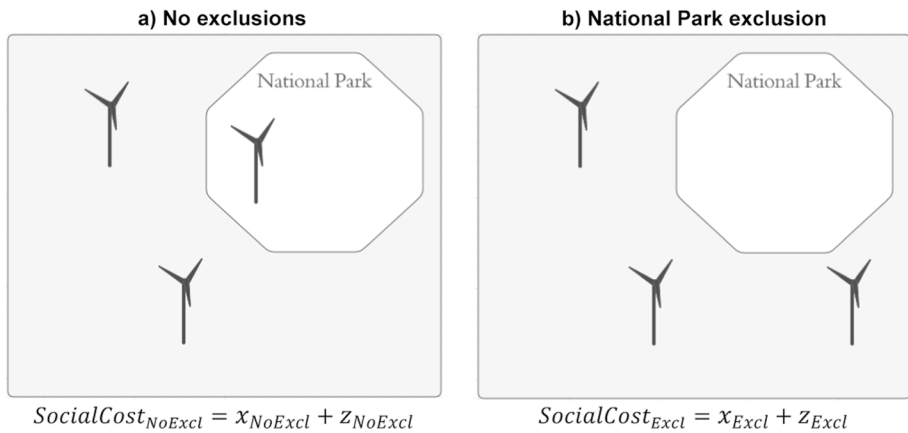
A further implicit assumption of exclusion zones is that renewable energy infrastructure, and the land change associated with it, has an adverse impact on ecosystem service flows. However, there is increasing evidence to suggest that this is not always the case and that the impact of energy infrastructure depends on what the land was previously used for and how the land is managed (Konadu et al. 2015). For example, solar farms and bioenergy crops have the potential to improve biodiversity, if their sites are managed in the right way, which suggests that excluding all land that, for example, falls within a protected area may be too restrictive (Rowe et al. 2009; Bourke et al. 2014; Hernandez et al. 2014; Hinton et al. 2014; Montag et al. 2016; Milner et al. 2016; Randle-Boggis et al. 2020). By excluding development from certain areas, we may actually limit the positive environmental impacts that could be realised from the transition to a low carbon energy system.

This paper explores both environmental exclusion zones (i.e. National Parks, Areas of Outstanding Natural Beauty (AONBs<sup>1</sup>), peatlands) and food production exclusion zones (i.e. high-quality agricultural land). We compare the spatial allocation of energy infrastructure witnessed when environmental and food production exclusions are imposed compared to what happens when no exclusions are in place. By doing this, this paper highlights the environmental, social and technical consequences of these restrictions. Our analyses show how exclusion zones impose a market-cost of up to £0.63 B, £19.17 B and £1.33 B on the energy system for solar, wind and bioenergy respectively. This relates to a 2%, 62%, and 5% increase in the total market costs for each technology's pathway. Interestingly, when multiple exclusion zones are imposed on bioenergy the highest pathway is shown to be infeasible due to lack of land, highlighting how these exclusions not only impose a cost on the energy system but may also restrict countries from meeting their bioenergy targets. Furthermore, the results highlight how the social costs of the energy system sometimes increases when exclusions are added, the opposite of what we would expect to see. This occurs typically because the amount of energy infrastructure required to meet the electricity generation target increases and consequently so does the spatial footprint and environmental impact of the pathway. This increase in social costs provides an estimate of the implied unobserved value of ecosystem services that must be missing from the ADVENT-NEV model if these exclusion zones provide the best option for society. By comparing the natural capital approach to exclusion zones, we see that that natural capital approach is able to minimise the social cost of the energy system to a greater extent by identifying locations inside and outside exclusion zones which provide the greatest benefits to society. Collectively these results can be used to feed into discussions with policymakers and the research community on energy transitions, highlighting how exclusion zones may not be the best tool to plan an energy system which minimises both market and non-market costs.

This paper is structured as follows: in Sect. 2 we provide an overview of how exclusion zones are used as proxies for ecosystem service value. Section 3 provides an overview of

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<sup>1</sup> AONBs are called National Scenic Areas in Scotland however both areas are referred to as AONB in this study. AONBs are areas of land protected for their high landscape value.



**Fig. 1** Illustrative example of the implications of imposing exclusion zones (e.g. National Parks) on where energy infrastructure can be located

the ADVENT-NEV model and analyses conducted in this study. Results are presented in Sect. 4 and discussed in Sect. 5. The key insights are summarised in Sect. 6.

### 1.1 Using Exclusion Zones as Proxies for Environmental Protection and Food Production

Without the means to quantify the value of food production or flows of ecosystem services, numerous studies, as well as some energy policies, have chosen to exclude the development of renewable energy from areas deemed important for delivery of these services instead (Lovett et al. 2009; Parish et al. 2012; Lovett et al. 2014; Konadu et al. 2015; Sunak et al. 2015; Watson and Hudson, 2015; Egli et al. 2017; Kienast et al. 2017; Wiehe et al. 2021). An illustrative example of using exclusion zones is shown in Fig. 1 where wind farm development is excluded from National Parks.

Figure 1a shows when no exclusions are in place, wind farms are allocated to their least-market cost locations both inside and outside of the National Park. The social cost of this scenario ( $SocialCost_{NoExcl}$ ) is sum of the market cost ( $x_{NoExcl}$ ) and the non-market cost ( $z_{NoExcl}$ ). In Fig. 1b, when a National Park exclusion is imposed, we see that the wind farm must be sited elsewhere. Of course, the market cost of this new location must be greater than the least-cost original location inside the park (i.e.  $x_{NoExcl} > x_{Excl}$ ). The increase in the market cost of the energy system when the exclusion zone is applied is denoted as  $y$  (Eq. 1).

$$y = x_{Excl} - x_{NoExcl} \quad (1)$$

The implicit assumption underlying such exclusions is that the value of the ecosystem services protected by the exclusion zone (i.e.  $z_{NoExcl} - z_{Excl}$ ) is greater than the market cost imposed on the energy system when the exclusion zone is imposed (i.e.  $y$ ) (Eq. 2). If this assumption is correct, then there is a net benefit for society associated with prohibiting energy infrastructure from exclusion zones.

$$y < z_{NoExcl} - z_{Excl} \quad (2)$$

Another way of thinking about the additional cost  $y$  is that it represents the lower bound value that the analyst is implicitly placing on the non-market benefits arising from restricting energy infrastructure from the exclusion zone. Therefore, to warrant the exclusion, these benefits must be at least as big as  $y$ .

A handful of studies have examined how the market costs of the energy system may change when exclusions are put in place. Wang et al (2020) show how when exclusion zones (i.e. nature reserves) are enforced in the Netherlands, the total cost of the energy system increases by up to 8%. Similarly, Price et al (2018) note a 10–20% increase in the levelised cost of the energy system when land constraints (i.e. high to moderate-quality agricultural land) are imposed in the UK. This paper provides a systematic analysis of the market cost consequences of commonly used exclusion restrictions in the context of development of renewables in the GB energy system. Moreover, as far as the authors are aware, there has been no previous research that assesses whether such exclusions can be justified on welfare grounds. Here we address that research gap. In particular, using the ADVENT-NEV model we are able to examine changes in the flows of ecosystem services associated with the deployment of the energy system (Delafield 2021). As such we can estimate the non-market costs of the energy system when siting decisions are made with and without exclusion restrictions. Those analyses allow us to evaluate whether exclusion restrictions deliver the net social benefits that they are intended to generate.

Of course, natural capital models like ADVENT-NEV are not comprehensive in their efforts to value changes in ecosystem service flows. Changes in services like landscape character and biodiversity remain hard to quantify and monetise, a task that some argue should not even be attempted (Dasgupta et al. 2021). Furthermore, the natural capital approach provides little insight into the food security implications of changes to food production related to building energy infrastructure on agricultural land. If the social cost of the energy system increases when exclusions are imposed, we could view this increase as the implied ‘unobserved value’ from the ADVENT-NEV model’s calculation of the non-market costs ( $z_{NoExcl}^{Unobserved}$ ) as shown by Eq. 3. This unobserved value would justify the imposition of the exclusion zone to ensure that value of the ecosystem services protected was greater than the increase in market-cost of the energy system.

$$z_{NoExcl}^{Unobserved} \geq SocialCost_{Excl} - SocialCost_{NoExcl} \quad (3)$$

## 2 Methodology

In this study, the ADVENT-NEV model is used to explore the impact that exclusion zones have on GB’s energy system. An overview of the model is provided in Sect. 3.1, the types of exclusions applied are shown in Sect. 3.2 and the energy pathways used are detailed in Sect. 3.3.

### 2.1 Model Description

The ADVENT-NEV model is a spatially-explicit optimisation model that determines where to locate ground mounted solar photovoltaic farms, onshore wind farms, bioenergy

power stations and bioenergy crops to minimise the total cost of the energy system (Delafield 2021). The bioenergy crops included in the model are: *Miscanthus* and short rotation coppice, the second-generation bioenergy crops predicted to be the main bioenergy feedstocks in the UK going forwards (Konadu et al. 2015). The ADVENT-NEV model identifies which locations to allocate an exogenously set amount of energy infrastructure over a set period of time. In this paper the least-cost locations (at a 1 km<sup>2</sup> cell resolution) for solar, wind and bioenergy were determined separately. While model has the capacity to do so, it is not used to resolve land use conflicts between the three technologies in this analysis.<sup>2</sup>

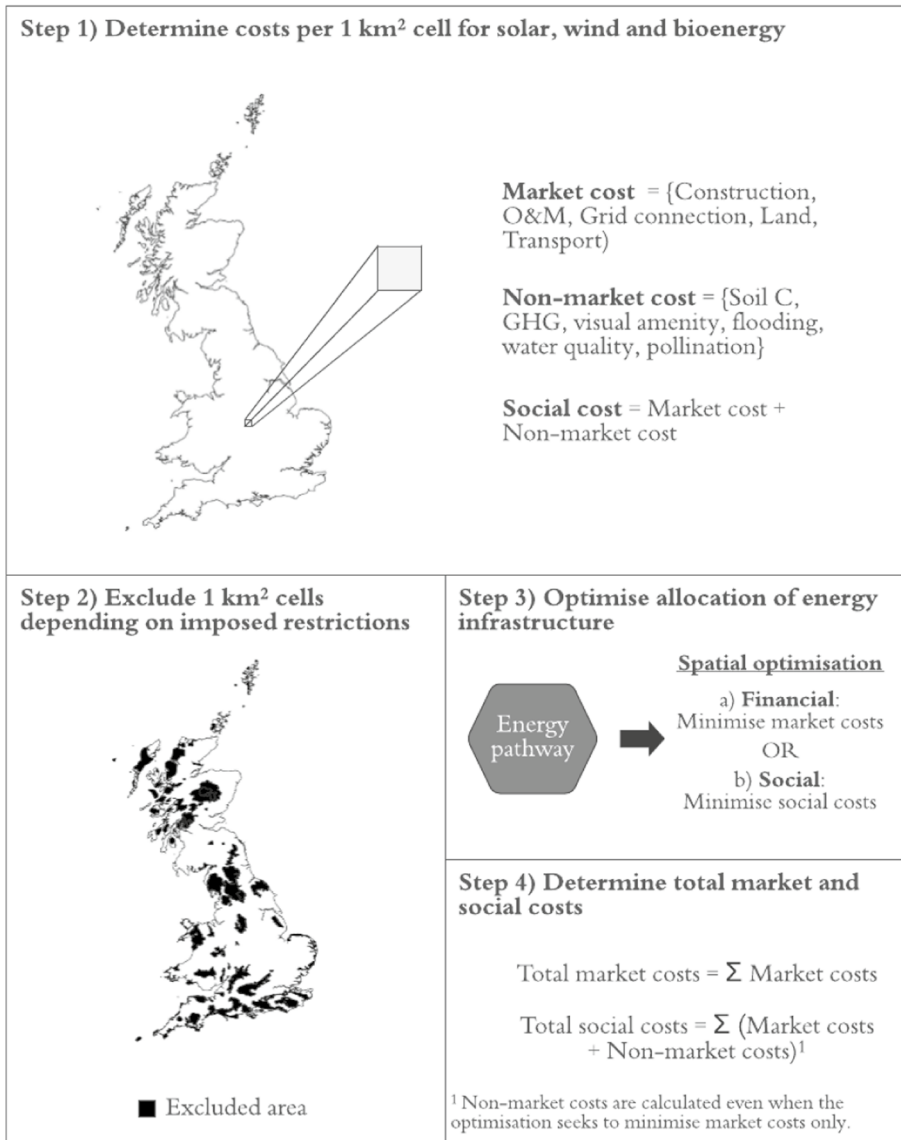
Figure 2 summarises the steps taken by the ADVENT-NEV model in identifying the best set of locations across GB in which to site new energy system infrastructure. The first step includes determining both the market and non-market costs associated with deploying energy infrastructure to all 1 km<sup>2</sup> cells of GB. The ADVENT-NEV model incorporates various market costs including: construction; operation and maintenance; grid connection<sup>3</sup>; and land; as well as bioenergy crop transport costs (Eq 4). The land cost encapsulates the value of the foregone agricultural production associated with taking land out of food production (Day et al. 2020). The temporal resolution of all of these costs is annual. The ADVENT-NEV model is aligned with Integrated Assessment Models that take an aggregate view of the energy over comparatively long temporal scales, this means that the model is unable to consider the benefits of spatial diversification (i.e. deploying wind turbines in different locations to take advantage of the fact that wind speed profiles differ spatially and temporally as per Price et al. (2020)). The coarse temporal resolution used in this study is required for spatial optimisation to be undertaken at a 1 km<sup>2</sup> resolution. Further work is needed to merge the insights provided by models which have high spatial resolution, like ADVENT-NEV, with those with high temporal resolution.

The novelty of the ADVENT-NEV model is in its inclusion of a wide range of non-market costs (Eq. 5). The model considers how wind farms and bioenergy crops impact soil carbon sequestration using data from Nayak et al. (2010) and the ELUM model (Pogson et al. 2016; Richards et al. 2017). It includes the change in greenhouse gas emissions associated with bioenergy crop transport (HM Treasury 2018) as well as agricultural land use change (Hillier et al. 2011; Day et al. 2020). The visual disamenity impacts associated with solar, wind, bioenergy and low voltage pylons are taken from the hedonic property value literature; particularly the studies by Hamilton and Schwann (1995), Davis (2011), Heintzelman and Tuttle (2012) and Dröes and Koster (2020).<sup>4</sup> Outputs from the NEV model are used to estimate the impacts to flooding and water quality, using an emulator of the Soil and Water Assessment Tool (Day et al. 2020). Pollination benefits come from the pollinator species diversity module within the NEV model (Pearson et al. 2004; Day et al. 2020). It must be noted that there are potentially substantial uncertainties in the non-market cost

<sup>2</sup> The ADVENT-NEV model is capable of solving the least-cost locations for combinations of different renewable technologies simultaneously as demonstrated in Delafield (2021) however this approach was not undertaken in this study for computational capacity reasons. Understanding land use conflict at the sub 1 km<sup>2</sup> scale is challenging as there may not be competition for the same exact piece of land within the 1 km<sup>2</sup> cell. We therefore recognise that although land use conflicts could occur they are unlikely to represent a significant bias.

<sup>3</sup> The 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, an estimate of the cost of upgrading the electricity network (Delafield, 2021).

<sup>4</sup> The visual disamenity of coal power stations are used as a proxy for bioenergy power stations.



**Fig. 2** Overview of the steps performed by the ADVENT-NEV model

calculations within the ADVENT-NEV model. Where a range of possible estimates exist, we have opted to employ ‘relatively conservative’ values based on the best available data (e.g. ELUM). There are however other impacts which are not modelled, in particular those related to indirect land use change, biodiversity loss, place attachment, and landscape character, these limitations are discussed further in Sect. 4. Further detail on all the ADVENT-NEV model is provided in Delafield (2021).

Within the ADVENT-NEV model, the costs of siting of different renewable energy technologies ( $e$ ) are calculated according to the following equations:



$$\text{MarketCost}^e = \text{ConstructionCost} + \text{O\&MCost} + \text{LandCost} + \text{GridCost} \quad (4)$$

$$\begin{aligned} \text{NonMarketCost}^e = & \text{VisualDisamenity} + \text{GHG} + \text{Pollination} \\ & + \text{SoilCarbon} + \text{BioenergyTransport} \\ & + \text{Flooding} + \text{WaterQuality} \end{aligned} \quad (5)$$

$$\text{SocialCost}^e = \text{MarketCost}^e + \text{NonMarketCost}^e \quad (6)$$

where the energy technology  $e$  can be solar ( $s$ ), onshore wind ( $w$ ) or bioenergy ( $b$ ). 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.

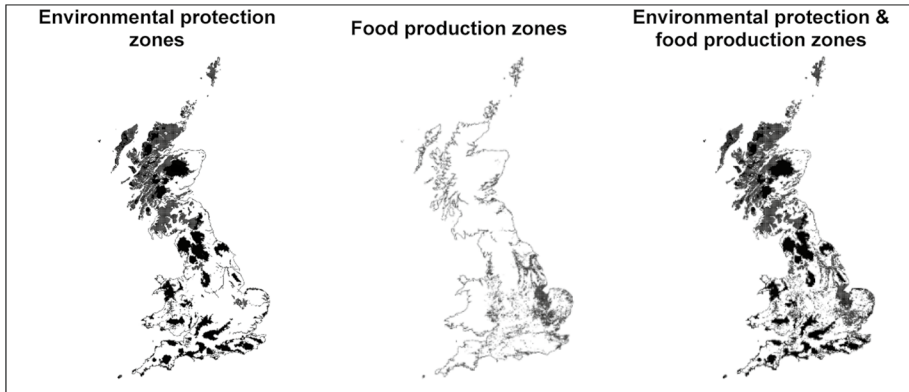
The second step identifies which 1 km<sup>2</sup> cells are considered suitable for the allocation of new energy infrastructure and is set out in Sect. 3.2 (Fig. 2). The third step is the spatial optimisation process (Fig. 2). The model can be set to either financial optimisation, where it seeks to minimise market costs only, or social optimisation, where it seeks to minimise social costs (i.e. both market and non-market costs as per Eq. 6) of the energy system (Fig. 2). The model chooses the least cost locations for solar and wind farms based on a cost per megawatt hour (MWh) until the required amount of annual electricity generation has been met. The least cost locations for bioenergy power stations and bioenergy crops are determined by a Greedy algorithm (Delafield 2021). This algorithm considers how the least-cost locations for bioenergy power stations depends not only on the location of the power station but also on where the power station sources its biomass. The size of bioenergy power stations is fixed at 40 MW and each is assumed to require 200,000 tonnes of bioenergy crops annually (Upreti 2004; BEIS 2017).<sup>5</sup> Step four in Fig. 2 highlights the key outputs of the model: the market and non-market costs of the spatially optimised energy system. All costs are reported as net present values (NPV) over a 25-year evaluation lifetime reported in £2015. The ADVENT-NEV model is written in Matlab 2017a and draws spatial data from a PostGIS database.

## 2.2 Exclusion Zones

All analyses in this paper assume that some baseline restrictions are imposed on where energy infrastructure can be located. These restrictions capture a range of current legal and technical constraints that prevent energy technologies being built in particular locations. For example, restrictions arising from current land cover or designation as a protected area, and those impacting on technical feasibility, such as slope and spacing (see SI).

Two types of exclusion zones typically applied in the literature and energy policies are examined. The first are *environmental exclusion zones* designed to protect the natural environment by restricting development in National Parks, AONBs, and on peatlands. Many studies impose these kinds of exclusions (Lovett et al. 2009; Parish et al. 2012; Onyango et al. 2013; Lovett et al. 2014; Konadu et al. 2015; Sunak et al. 2015; Watson and Hudson, 2015; Egli et al. 2017; Kienast et al. 2017; Wiehe et al. 2021). For example, Lovett et al

<sup>5</sup> The siting of larger Bioenergy with Carbon Capture and Storage (BECCS) power stations is outside the scope of this paper.



**Fig. 3** Exclusion zones

(2009) restricts bioenergy crops from being grown on designated areas and organic soils in order to protect the landscape character and biodiversity of these areas, as well as reduce the chances of carbon losses from soils. The second are *food production exclusion zones* designed to protect domestic food production like those used in Milner et al (2016) and Palmer et al. (2019). In this study we exclude solar, wind and bioenergy from being sited on high-quality agricultural land.<sup>6</sup> Figure 3 demonstrates the spatial extent of these areas, highlighting how combining exclusion zones, as done by Lovett et al (2014), leaves little land available for energy development.

### 2.2.1 Exclusion Zone Analysis

Table 1 showcases the different exclusions analysed in this study. First, we determine where renewable energy would be located if no exclusion zones are imposed (i.e. Analysis 1). Second, we explore what happens when different exclusion zones are applied, replicating what has been done by previous studies and some energy policies (i.e. Analysis 2–4). By comparing the market costs of the energy system when exclusion zones are imposed to the market costs of the energy system when no restrictions are imposed ( $y$ ), we can determine the value being placed on these exclusion areas (Eq. 1). This calculation allows us to answer research question 1.

To answer research question 2, we explore the difference in the non-market costs of the energy system when exclusion zones are imposed and not. By doing this, we can determine if the social cost of the energy system increases or decreases when exclusion zones are imposed. If the social cost increases, this will enable us to identify the magnitude of the ecosystem service benefits that would have to be provided by the exclusion zones, but missed by our natural capital assessment, in order for the exclusion zones to be a defensible environmental policy (i.e. research question 3). The spatial footprint of all analyses is calculated to answer research question 4. Finally, we determine the socially-optimal locations

<sup>6</sup> The agricultural land classification (ALC) categorises land in GB into five grades based on land's physical and chemical characteristics. The classifications range from Grade 1 (i.e. excellent quality agricultural land) to Grade 5 (i.e. very poor quality agricultural land) (Natural England, 2021). In this paper, we categorise high-quality agricultural land as ALC 1 to 2.

for energy infrastructure using the natural capital approach, considering both market and non-market costs when no exclusions are imposed (Analysis 5). This analysis will help to identify what other environmental issues might be overlooked by the exclusion zone approach but revealed by the natural capital approach. The ADVENT-NEV model determines the market and non-market costs for all analyses, however, only includes non-market costs in the optimisation of Analysis 5.

## 2.3 Energy Pathways

We examine a range of potential generation levels for 2050 from low to high as shown in Fig. 4. These levels are based upon various published energy pathways used to inform policymaking (CCC 2011; DECC, 2012; Spataru et al. 2015; Roddis et al. 2016; CCC 2018a; CCC 2018b; CCC 2020, National Grid 2020). The pathways are used as theoretical boundaries of the minimum and maximum deployment that can be expected by 2050 assuming the UK meets its net-zero emissions targets. The approach taken to determine these lower and upper bounds is detailed in the supplementary information (SI).

## 3 Results

### 3.1 Land Use Competition When No Exclusion Zones are Imposed

Analysis 1 reveals that when solar farms, wind farms and bioenergy power stations and their associated crops are located to minimise market costs, then a significant proportion of that energy infrastructure is allocated to land deemed as being important for environmental protection or food production (Fig. 5; Table 2). For example, when minimising market costs, the ADVENT-NEV model allocates up to 72% of wind farms to peatlands. This echoes a trend that has been seen historically in the UK, with wind farms being built on peatlands as they are often in exposed windy locations and therefore deliver high energy yields (Ostle et al. 2009). In addition, a noticeable proportion of energy infrastructure is allocated to areas of high landscape value, with over half of solar farms allocated to these areas (Table 2).<sup>7</sup> Both solar farms and bioenergy crops are often allocated to high-quality agricultural land. However, the magnitude of land use change associated with solar is much lower than that of bioenergy. With the high solar pathway using 15,946 ha of high-quality agricultural land whereas the high bioenergy pathway uses 543,172 ha. This is due to the sheer volume of bioenergy crops required to meet the high bioenergy pathway if the feedstock is grown domestically.

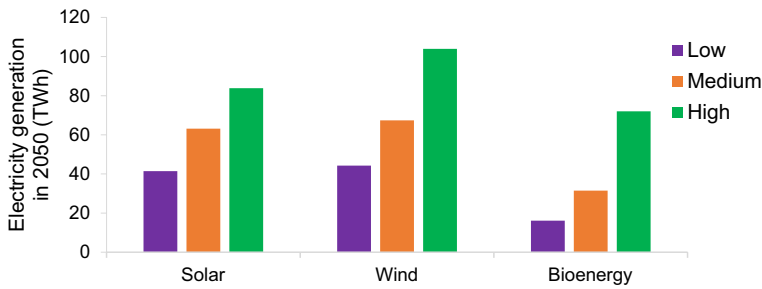
### 3.2 Changes to the Market Cost of the Energy System When Exclusion Zones are Imposed

When exclusion zones are imposed on renewable energy deployment (i.e. Analyses 2–4), the spatial distribution and cost of the energy system changes compared to when no exclusions are enforced (i.e. Analysis 1). Under Analysis 2, where environmental exclusion

<sup>7</sup> National Parks and AONBs referred to collectively as areas of high landscape value.

**Table 1** Exclusion zone analysis

Analysis	Optimisation name	Costs included in optimisation	Exclusion zones applied
1	Financial optimisation with baseline exclusions	Market costs	None
2	Financial optimisation with environmental exclusion zones	Market costs	National Parks, AONBs, peatlands
3	Financial optimisation with food production exclusion zones	Market costs	ALC 1–2
4	Financial optimisation with multiple exclusion zones	Market costs	National Parks, AONBs, peatlands, ALC 1–2
5	Social optimisation with baseline exclusions	Market costs; non-market costs	None

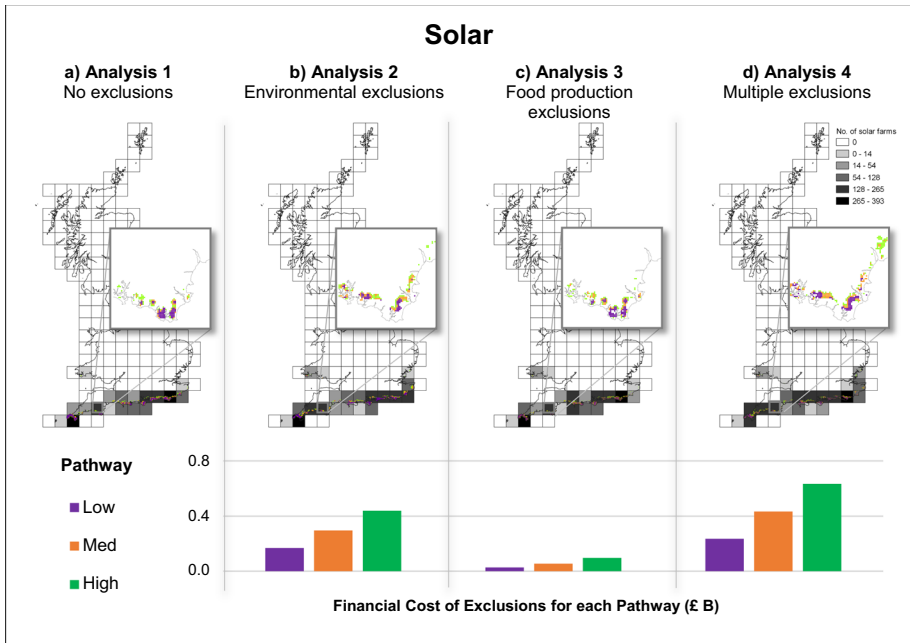


**Fig. 4** Electricity generation from solar farms, onshore wind farms and bioenergy power stations (fuelled by domestically sourced bioenergy crops) in 2050 ranging from low to high estimates derived from existing energy pathways

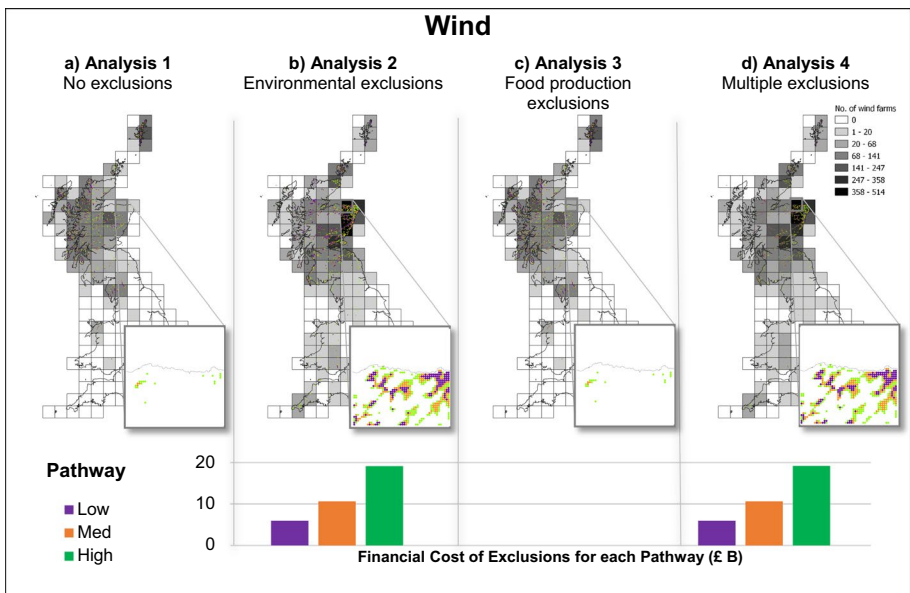
**Table 2** The percentage of solar farms, wind farms and bioenergy crops allocated to land deemed as important for environmental protection or food production when a financial optimisation is pursued with no exclusions imposed (i.e. Analysis 1)

Technology	Pathway	Overlap between renewable energy and land deemed as important for environmental protection or food production		
		Peatland	Areas of high landscape value	High quality agricultural land
Solar	Low	< 1%	52%	17%
	Med	< 1%	52%	16%
	High	< 1%	51%	15%
Wind	Low	72%	40%	0%
	Med	72%	37%	0%
	High	72%	35%	0%
Bioenergy	Low	34%	37%	2%
	Med	28%	32%	4%
	High	20%	26%	8%

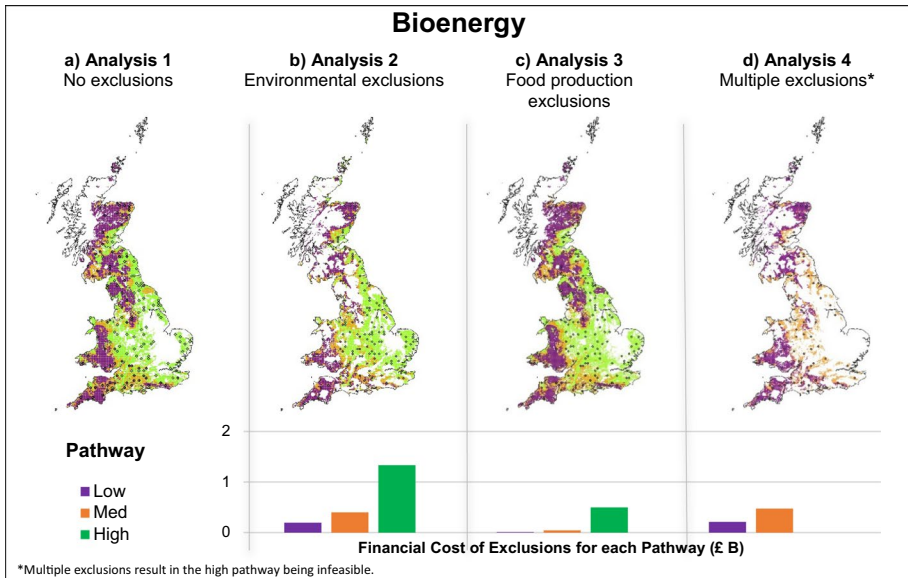
zones are imposed, displacing energy infrastructure from its cheapest siting locations increases the total market costs of the energy system by £0.44 B (+2%), £19.11 B (+62%) and £1.33 B (+5%) for the high solar, wind and bioenergy pathways respectively (Figs. 5, 6 and 7). When no exclusion zones are imposed, solar farms are allocated to coastal locations as this is where solar radiation is highest due to there being less cloud formation along the coast than further inland (Lindfors et al. 2020; Met Office, 2022). When environmental exclusion zones are imposed, solar farms are allocated slightly further inland, to less sunny locations, increasing the cost per TWh of a solar farm (Fig. 5b). Wind farms are forced to move away from upland National Parks and peatlands to locations with lower wind speeds, with the average wind speed of the locations chosen decreasing from 10.6 m/s to 8.8 m/s (Fig. 6b). Consequently, the total number of wind turbines needed to meet the energy target increases. The average cost per MWh is two thirds higher outside of these environmental protection areas, highlighting the lack of alternative locations for wind farms which have high wind speeds and low costs (see SI). Figure 7b shows how environmental exclusion zones result in bioenergy crops being grown on land of lower yields, higher agricultural



**Fig. 5** Spatial distribution of solar farms when different exclusion zones are imposed (maps) and the corresponding cost imposed on the energy system (bar charts) for low, medium and high pathways. All results assuming market costs are minimised. Insets provided of south English coastline



**Fig. 6** Spatial distribution of wind farms when different exclusion zones are imposed (maps) and the corresponding cost imposed on energy system (bar charts) for low, medium and high pathways. All results assuming market costs are minimised. Insets provided of east Scottish coastline



**Fig. 7** Spatial distribution of bioenergy power stations (diamonds) and bioenergy crops (squares) when different exclusion zones are imposed (maps) and the corresponding cost imposed on energy system (bar charts) for low, medium and high pathways. All results assuming market costs are minimised

value, and further away from the power station, increasing the cost per TWh by 5% (see SI).

Under Analysis 3, where food production exclusion zones are imposed, the incremental financial cost of the energy system is £0.10 M ( $+ < 1\%$ ) and £0.50 B ( $+ 2\%$ ) for the high solar and bioenergy pathways respectively (Figs. 5c and 7c). There is a notable change in the spatial distribution of bioenergy crops when high-quality agricultural land is excluded, with more land in central and eastern England having to be used for bioenergy crops as the availability of land in other areas of the country dwindles (Fig. 7c). If moderate-quality agricultural land (ALC 3) is also excluded, the expansion of bioenergy becomes technically and economically infeasible for all but the lowest estimates of future bioenergy crop expansion (see SI).<sup>8</sup> In comparison, there is no increase in the market cost of the energy system when wind farms are excluded from high-quality agricultural land, as wind farms are not allocated to this land even when no exclusions are in place (Fig. 6c). These costs are small as the ADVENT-NEV model includes the value of the foregone agricultural production associated with converting agricultural land to energy generation, therefore partially including the food production value that these areas of land provide in all of its analyses.

Finally, when multiple exclusion zones are imposed (i.e. Analysis 4), we see that the increases in market costs compound. For example, when multiple exclusion zones are applied to solar and wind farms, the market costs of the energy system increases by up to £0.63 B ( $+ 2\%$ ) and £19.17 B ( $+ 62\%$ ) respectively (Figs. 5d; 6d). Indeed, when all of the exclusion zones are applied to bioenergy, so much land is made unavailable for use by the

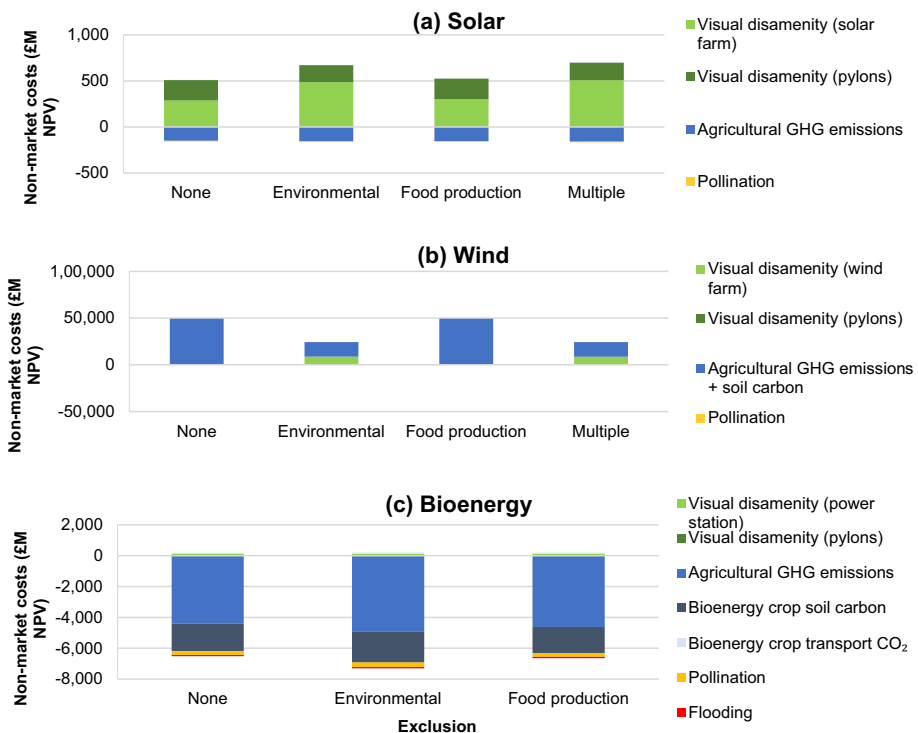
<sup>8</sup> This is not particularly surprising given that ALC 3 land accounts for nearly half of all agricultural land in GB.

energy system that the highest bioenergy pathway is not even possible (Fig. 7d). The low and medium pathways remain feasible, but the exclusion zones impose a cost of £0.21 B (+4%) and £0.48 B (+5%) respectively (Fig. 7d).

### 3.3 Changes to the Non-Market and Social Cost of the Energy System When Exclusion Zones are Imposed

The underpinning motivation for exclusion zones, both in previous studies and in energy policies, is that they ensure a better outcome for society. In this section, we test that assumption by comparing the increase in the market costs, as identified in Sect. 4.2, with the change in non-market costs resulting from the imposition of different exclusion zones. Our null hypothesis is that non-market costs should fall on account of the exclusion zone and that reduction in non-market costs should more than compensate for the increased market costs. In other words, the social cost of the energy system should decrease when the exclusions are imposed.

Table 3 provides details of that analysis for the high pathways, reporting the changes in market, non-market and social costs when different exclusion zones are imposed. The high pathway is shown to highlight the most striking results, however, results for the low and medium pathways are provided in the SI. Note how solar and wind farms result in



**Fig. 8** Non-market costs of the high energy pathways for solar, wind and bioenergy split by ecosystem service. All results assuming market costs are minimised. Note that the scale on the y axis differs per technology



**Table 3** The market, non-market and social costs of the high solar, wind and bioenergy pathway when different exclusion zones are imposed. Costs in brackets are changes from the no exclusion baseline

Exclusion	Market cost (£ B)	Non-market cost (£ B)	Social cost (£ B)
<i>Solar</i>			
None	25.53	0.35	25.88
Environmental	25.97 (+0.44)	0.51 (+0.16)	26.48 (+0.60)
Food production	25.62 (+0.01)	0.36 (+0.01)	25.99 (+0.11)
Multiple	26.16 (+0.63)	0.53 (+0.18)	26.69 (+0.81)
<i>Wind</i>			
None	30.86	49.38	80.24
Environmental	49.97– (+19.11)	24.33 (–25.04)	74.31 (– 5.93)
Food production	30.86 (+0.00)	49.38 (+0.00)	80.24 (+0.00)
Multiple	50.04 (+19.17)	24.31 (– 25.07)	74.35 (– 5.89)
<i>Bioenergy</i>			
None	25.07	– 6.32	18.74
Environmental	26.40 (+1.33)	–7.10 (–0.79)	19.30 (+0.56)
Food production	25.57 (+0.50)	– 6.45 (– 0.31)	19.12 (+0.38)
Multiple	High pathway infeasible when these exclusions are applied		

net positive non-market costs, no matter which analysis is undertaken, whereas bioenergy provides net negative non-market costs (i.e. benefits) (Table 3; Fig. 8). This is because the ADVENT-NEV model identifies solar and wind farms overall impacts on ecosystem services to be negative, largely due to visual disamenity and greenhouse gas emissions, whereas bioenergy crops provide an overall positive impact on the environment through the provision of a variety of ecosystem service benefits including carbon sequestration, pollination and water quality (Fig. 8).

From Table 3, it transpires that for the high pathways our null hypothesis only holds for analyses in which wind farms are excluded from areas of high environmental importance. The social costs of the high wind pathway decreases by £5.93 B (– 7%) when environmental exclusion zones are imposed on their own and £5.89 B (– 7%) when food production zones are applied as well (Table 3; Fig. 8). As such, our analysis supports the idea that applying environmental exclusion zones to wind power provides a reasonable proxy for ecosystem service values; the exclusion zone effectively decreases the social costs of the energy system. A more detailed analysis of these findings reveals that this result is due to the carbon sequestration benefits of excluding peatlands.<sup>9</sup> The SI shows how the null hypothesis also holds for the low and medium bioenergy pathways when environmental exclusions are applied, with the social cost of the pathways decreasing by 3%, due to the carbon sequestration benefits of protecting peatlands.

In contrast, the majority of the exclusions analysed in Table 3 result in an increase in the social cost of the energy system (i.e. an adverse impact on society). For example, when environmental exclusions are applied to solar and bioenergy's high pathways, the social cost of the energy system increases by £0.60 B (+2%) and £0.56 B (+3%) respectively

<sup>9</sup> Excluding wind farms from areas of high landscape value results in an increase in social costs (i.e. the null hypothesis does not hold).

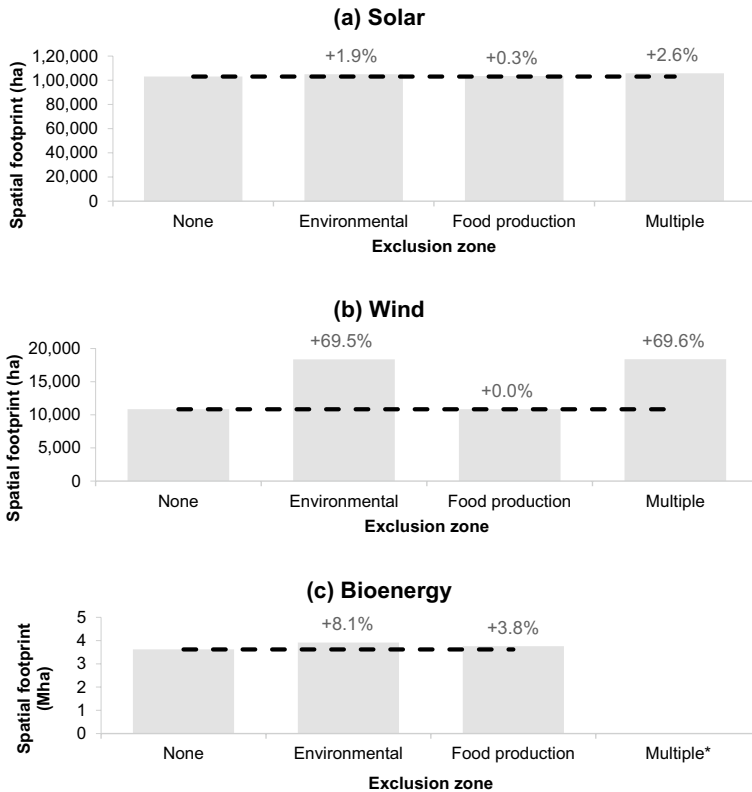
(Table 3). These results imply that excluding solar and bioenergy from areas identified as being of environmental importance precipitates a worse overall outcome for society if the high pathways are followed. Similarly, when high-quality agricultural land is excluded, the social cost of the energy system increases by up to £0.11 B (<1%) and £0.38 B (+2%) (Table 3). In comparison, this exclusion makes no difference to the social cost of wind.

### 3.4 Identification of the Magnitude of the Implied Unobserved Ecosystem Service Values Missing from Our Calculation of the Social Cost of the Energy System

The observed increases in the social cost of the energy system when exclusion zones are imposed represent the value that society would have to attach to these areas, unaccounted for in ADVENT-NEV's valuation of ecosystem services, to justify strict exclusion zones being imposed by policy (i.e.  $z_{NoExcl}^{Unobserved}$ ). For example, the implied unobserved value associated with restricting solar farms from areas of environmental protection is £0.60 B (Table 3). In other words, excluding solar farms from those areas would have to generate at least £0.60 B of value from some source other than the ecosystem services evaluated by ADVENT-NEV, to justify the policy intervention. For perspective, that is a value greater than the estimated non-market cost of the visual disamenity of all of the solar farms. Likewise, the implied unobserved value associated with restricting bioenergy crops from high-quality agricultural land would need to be at least £0.38 B (Table 3). If that policy was being justified from food security concerns, then this would be the implicit value being placed on addressing that policy objective. The novelty provided by the ADVENT-NEV model is that it allows for the explicit identification of the implied unobserved value. Such quantitative information may be of central importance to decision-makers exploring the suitability of exclusion zones.

### 3.5 Changes to the Spatial Footprint of the Energy System When Exclusion Zones are Applied

Figure 9 shows how the spatial footprint of the energy system changes when different exclusion zones are imposed for the high energy pathways (see SI for low and medium pathway results). When exclusions are in place, the model has to choose land with lower energy resources (i.e. wind speeds) so more land is needed to build the infrastructure required to generate the same level of energy output. The spatial footprint of the high solar pathway increases by 2.6% from 103,125 ha to 105,782 ha when multiple exclusion zones are imposed (Fig. 9a). The most notable percentage increase in spatial footprint however is that of wind farms, when multiple exclusions are imposed the spatial footprint of the energy system increases by 69.6% as more wind turbines have to be built to reach the electricity generation target (Fig. 9b). In comparison, when exclusions are applied to bioenergy we see the largest real increase in land use, with 293,495 ha (+8.1%) more land used when environmental exclusions are imposed. To put into perspective, this is almost twice the size of Greater London (Fig. 9c). When multiple exclusions are put in place, as previously mentioned, the high bioenergy pathway is not possible.



**Fig. 9** Spatial footprint of the high energy pathways for solar, wind and bioenergy when different exclusion zones are imposed compared to baseline exclusions. The asterix identifies exclusion zones that result in the high pathway being infeasible

### 3.6 What Else Might be Missing from the Exclusion Zone Approach?

In this section, we compare the modelling outputs from the exclusion zone (i.e. Analyses 2–4) and natural capital approaches (i.e. Analysis 5). We do this to highlight the environmental issues that might be being overlooked when applying exclusion zones but are revealed by the natural capital approach. All of the results in this section are for the high pathway, results for the low and medium pathway are provided in the SI.

There are two issues that the natural capital approach identifies that the exclusion zone approach does not. First, the exclusion zone approach does not consider the fact that in certain circumstances converting land deemed as ‘highly valuable’ to renewable energy generation can provide ecosystem service benefits. This is demonstrated by Table 4 whereby the natural capital approach allocates bioenergy crops to areas of high landscape value which results in larger ecosystem service benefits (£8.82 B) compared to when exclusions are applied (£7.10 B). When siting decisions are made using the natural capital approach (i.e. Analysis 5), more bioenergy crops are actually allocated to areas of high landscape value than when no restrictions are imposed (i.e. Analysis 1). Second, the exclusion zone approach does not allow for decisions to be made at the margin. For example, the natural capital approach concludes that it is better for society to allow some renewable energy

**Table 4** Total spatial footprint of bioenergy crops in areas of high landscape value and the total social cost of the high bioenergy pathway depending on whether financial or social optimisation is pursued, and which exclusion zones are imposed

Analysis	Spatial footprint of bioenergy crops in areas of high landscape value (ha)	Non-market costs (£ B NPV)	Social cost of pathway (£ B NPV)
1 No exclusion	626,308	- 6.32	18.74
2 Environmental exclusion	0	- 7.10	19.44
5 Natural capital approach	659,239	- 8.82	17.36

**Table 5** Total greenhouse gas emissions (from soil carbon and agricultural land use change), number of wind farms on peatlands and the total social cost of the high wind pathway depending on whether financial or social optimisation is pursued and which exclusion zones are imposed

Analysis	Greenhouse gas emissions (MtCO <sub>2eq</sub> /year)	No. of wind farms on peatlands	Social cost (£ B NPV)
1 No exclusion	43.65	2599	80.24
2 Environmental exclusion	11.79	0	74.31
5 Natural capital approach	4.10	1860	43.57

infrastructure to be sited within environmental exclusion zones, than having a blanket ban. Table 5 highlights how the natural capital approach deems it best for society to place 1,860 wind farms on peatlands, despite the known greenhouse gas emissions associated with doing this (Nayak et al. 2010). Indicating that the energy productivity of these locations sufficiently outweighs the greenhouse gas emission cost associated with siting wind farms on peat. It also highlights how the emissions associated with building wind turbines on peatlands are not uniform, nor are the emissions associated with land use change outside areas deemed important for environmental protection, demonstrated by the fact that although wind farms are allocated to peatlands in Analysis 5 the greenhouse gas emissions are still lower than Analysis 2.

The SI presents additional results reporting outcomes when exclusion zones and the natural capital approach are pursued simultaneously and show that in that analysis the social costs of the energy system increase still further. If the social costs identified by the natural capital approach and that arising under the combined approach were similar, that would imply that the exclusion zones capture the value of ecosystem services to the same extent as the natural capital approach. This additional analysis shows this not to be true.

## 4 Discussion

### 4.1 Research Question 1: How do the Exclusion Zones Impact the Market Costs of the Energy System?

The ADVENT-NEV model has provided detailed insights into the cost imposed on the energy system when environmental and food production exclusion zones are applied. By

making these costs explicit, the ADVENT-NEV model highlights that the value placed on land deemed important for environmental protection or food production is substantial (e.g. up to £19.17 B placed on multiple exclusion zones in wind's high pathway). These increases in market costs occur principally because there is an overlap between the least-cost locations for siting renewable energy technologies and areas of land deemed to be important for the environment or food production in GB, as well as a lack of alternative locations which are of a similar cost per MWh. The implications of exclusion zones in other countries is therefore likely to be strongly linked to these two conditions (i.e. overlap and availability of alternative locations).

#### **4.2 Research Question 2: How do the Exclusion Zones Impact the Non-Market and Social Costs of the Energy System?**

Our analyses reveal that for particular renewable energy siting decisions exclusion zones succeed in delivering a reduction in social costs (i.e. environmental exclusions on wind farms). More frequently, however, those exclusions only served to increase social costs. For instance, this paper shows how environmental exclusions increase the social cost of the energy system, by £0.60 B for the high solar pathway and £0.56 B for the high bioenergy pathway.

#### **4.3 Research Question 3: If the Social Cost of the Energy System Increases When Exclusion Zones are Applied, What is the Implied 'Unobserved' value that society Must Attach to these Zones, Unaccounted for in our Valuation of Ecosystem Services, to Justify the Use of These Exclusion Zones?**

The instances in which the social cost of the energy system increases when exclusion zones are applied theoretically implies that either (a) the imposition of such exclusion zones could lead to an energy system that is not 'best' for society or (b) that there is an implied 'unobserved' value inherent within the exclusion zone which is not accounted for within the natural capital approach. It is possible, for example, that our valuation of the ecosystem services provided by environmentally important areas may have been underestimated and that the application of an exclusion zone would actually increase social value. The ADVENT-NEV model sheds light on this implied 'unobserved' value would need to be for the exclusion zone to be justifiable. For example, it highlights how the ADVENT-NEV model must be under-estimating the value of areas important for environmental protection by £0.6 B to justify excluding solar farms from these areas. Although there is uncertainty within this point estimates, they provide an initial estimate to work from.

We know that the ADVENT-NEV model's calculation of non-market costs is only partial. The value of biodiversity, other than pollination, is particularly difficult to quantify and monetise and has therefore been excluded from this study (Dasgupta et al. 2021). This study is unable to determine if the biodiversity which would be lost if wind farms were built in National Parks is of greater value than the biodiversity that could be lost if the wind turbines were located elsewhere. Some studies have argued that UK National Parks do not necessarily contain large amounts of biodiversity, that they were not chosen specifically for their biodiversity value and instead they are valued more for their scenic value and their perceived 'naturalness' (Leader-Williams et al. 1990). It could therefore be argued that National Parks exclusion zones are not a particularly good proxy for biodiversity in

the UK, and that other methods of identifying how land use change will affect biodiversity are needed. Further research is required to explore these complexities, for example, studies could consider how biodiversity net gain could be incorporated into energy decision-making to compare how exclusion zones impact biodiversity alongside the identified social cost.

Other implied ‘unobserved’ values of exclusion zones not included in the ADVENT-NEV model are those of place attachment and landscape character. The visual impact estimates included in the ADVENT-NEV model do not capture the specific scenic qualities of areas of high landscape value, nor the place attachment that individuals might feel towards these areas, as these have not been quantified or monetised by previous studies (Devine-Wright 2011; Manzo and Devine-Wright 2013; Rand and Hoen 2017). It is possible, for example, that the visual disamenity impacts of siting wind farms is higher in these areas, prized for their visual beauty, than landscapes which are more urbanised (e.g. with major roads and buildings). This study provides an estimate of what these missing values would need to be to feed into the wider discussion regarding the use of exclusion zones in land use and energy policy.

#### **4.4 Research Question 4: How do the Exclusion Zones Impact the Spatial Footprint of the Energy System?**

As the ADVENT-NEV model is spatially-explicit, its outputs reveal how the total spatial footprint of the energy system changes when exclusion zones are imposed. This is a result of energy infrastructure having to be allocated to more locations with a higher cost per MWh, which increases the total number of solar panels, wind turbines or bioenergy crop fields required to meet the set energy generation targets.<sup>10</sup> Only a few studies have explicitly looked at whether more land is needed to generate the same amount of energy if exclusion zones are put in place (e.g. Kiesecker et al. 2011), others consider the impact indirectly (e.g. Neumann et al. 2021). For example, Kiesecker et al. (2011) found that only siting energy infrastructure on disturbed land in the United States increased the spatial footprint of the energy system by 11%.<sup>11</sup> Other studies overlook this impact assuming that the spatial footprint per MWh is the same no matter what exclusion zones are imposed (e.g. Kienast et al. 2017).

It is interesting to note that the spatial footprints estimated for bioenergy in this study are considerably higher than those reported by the UK government’s formal advisory body on climate change, the Committee on Climate Change (CCC) (CCC 2018a). The high bioenergy pathway (72 TWh/year), which is similar to the electricity output stated in CCC’s high biomass / natural peatland scenario (80 TWh/year), is shown to result in a spatial footprint of 3.62–3.91 M ha, this is three times higher than the CCC’s estimate of 1.2 M ha even when no exclusion zones are in place (CCC 2018a). The differences between the amount of land to meet specific energy targets is due to various factors. First, the CCC assume higher bioenergy crop yields and a much smaller amount of biomass is needed

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<sup>10</sup> If more energy infrastructure has to be built to meet targets, the cost of upgrading the electricity network is likely to increase too. The ability of the electricity network to accommodate new energy infrastructure is a key constraint of energy system planning (Calvert et al., 2013). Although this study includes substation upgrade costs, these could under-estimate the costs associated with such clustered building of new energy infrastructure.

<sup>11</sup> National Parks were excluded in the baseline analysis in Kiesecker et al. (2011).

per TWh of electricity generation (0.19 M tonnes/TWh) compared to this study (0.65 M tonnes/TWh).<sup>12</sup> Second, the CCC does not consider how the average bioenergy crop yield may decrease when different exclusions are applied.<sup>13</sup> By excluding crops from the most fertile and productive land, the ADVENT-NEV model shows how bioenergy crops begin to be planted on land with lower average yields. In previous studies average values for yield calculated at coarser spatial resolutions, or use of a national average may mask this spatial effect. A combination of these assumptions explains why the CCC estimate of land use is lower than those estimated in this paper.

In addition, previous studies typically do not make any assumptions regarding where power stations will be built, overlooking the fact that bioenergy crops need to be physically and financially available to a power station (e.g. Lovett et al. 2014). Bioenergy crops need to be grown close to the bioenergy power station to be financially viable, therefore studies which add up the total amount of biomass that could be grown in a country are overlooking the fact that not all of this biomass can be utilised.

Furthermore, it is possible that if spatial restrictions were to be imposed on the energy system, the mix of the electricity system would change thereby impacting the system's spatial footprint. For example, if the deployment of renewable energy in the terrestrial environment was restricted, then we may see an energy system which relies more heavily on technologies that are built offshore or have smaller spatial footprints (Price et al. 2018, 2020). While outside the scope of this paper, there is a need for policy analyses to explore such trade-offs, perhaps most fundamentally in choosing between between siting renewable energy in the terrestrial and marine environment.

Another complexity associated with the land use change assumed in this paper, is the implication it would have on food production. Unless land was freed up through the intensification of agriculture or through dietary changes, converting agricultural land to electricity generation would likely impact food production leading to indirect land use change either within the UK or abroad (Sanchez et al. 2012; Konadu et al. 2015; CCC 2020). This indirect land use change could potentially result in adverse ecosystem service impacts that undermine the benefits associated with the deployment of new renewable energy technology.

#### **4.5 Research Question 5: What Other Environmental Issues Might be Overlooked by the Exclusion Zone Approach?**

This paper highlights how exclusion zones do not allow for nuanced trade-offs between energy, society, and nature. First, the use of exclusion zones implicitly assumes that building renewable energy infrastructure on land of high landscape value will result in net costs to society. It does not allow for the fact that renewable energy infrastructure can be deployed on land deemed important for environmental protection but still increase the provision of ecosystem services. The natural capital approach, in comparison, highlights the potential environmental benefits that can be realised from deployment both within and outside areas perceived as being important for society. This is most notable for bioenergy, where our application of the natural capital approach identifies locations for bioenergy

<sup>12</sup> It is unclear what is driving the CCC's assumption of amount of biomass required per TWh.

<sup>13</sup> The CCC assumes bioenergy crop yields will be between 15–20 tonnes per ha per year (CCC, 2018a).

crops which provide a range of valuable ecosystem services, most notably carbon sequestration and pollination.

Second, the exclusion zone approach does not consider the knock-on effects on the environment associated with restricting renewable energy deployment from certain areas. For example, the ADVENT-NEV model indicates that a complete ban on wind farms on peatlands could actually increase the social cost of the energy system as higher costs are incurred when wind farms have to be sited in less windy locations. This paper suggests that a blanket exclusion of wind farms on peatlands may well not be worth the carbon sequestration benefits associated with protecting them.

Overall, these insights lead us to conclude that relying heavily on exclusion zones when designing a future energy system could result in adverse consequences for both the cost and the environmental impact of the energy transition. Exclusion zones are potentially inefficient policy mechanisms and the imposition of them could increase overall costs. This study underlines the importance of the natural capital approach in revealing the potentially complex implications of different siting decisions, for example those arising from an exclusion zone policy (e.g. in forcing a greater total use of land by preventing siting on high energy-yield locations). While exclusion zones are easy to impose in analyses of energy systems, that does not make them a desirable policy mechanism. In contrast, the natural capital approach demands far more by way of data and modelling capacity but opens up the possibility of systematically examining siting decisions for future energy infrastructure, identifying and quantifying the trade-offs associated with different possible policy directions.

## 5 Conclusion and policy implications

As the world decarbonises, the competition for land between energy generation, nature protection and food production is going to increase. Decision-makers will need to decide how best to use land to benefit society by carefully considering the trade-offs between various policy ambitions including: achieving net-zero, reducing fuel poverty, restoring the natural environment, and protecting national food security. In order to avoid the conflicts between energy, nature and food, previous studies and energy policies have imposed exclusion zones on where renewable energy can and cannot be built. This paper has shown how imposing these exclusion zones place substantial market costs on GB's energy system, up to £0.63 B, £19.17 B and £1.33 B for solar, wind and bioenergy respectively. In most cases, the social cost of the energy system also increases when exclusions are put in place. For example, when solar farms, wind farms and bioenergy crops are excluded from areas of high landscape value. This is in stark contrast to the motivation underpinning the application of exclusion zones in a range of previous studies (i.e. as proxies for non-market benefits). This paper therefore concludes that exclusion zones are unlikely to be effective policy measures to maximise the benefits for society. That said, the calculation of social cost in this paper is only a partial estimate of the true social value of land use change associated with energy infrastructure. There are uncertainties within the calculations made in this analysis. Our principle of using conservative values provides insights as to our 'best estimates' of the relative costs of different strategies for the placement of renewable energy infrastructure. While those estimates deliver numerous novel insights, we acknowledge that there is uncertainty over the exact magnitudes of relative costs. Future research might seek to quantify that uncertainty and, perhaps apply methods of optimisation under uncertainty



to better understand how renewable energy infrastructure might be located. That said, we provide novel insights into the magnitude of implied ‘unobserved’ place attachment, landscape aesthetic and biodiversity values that must be attached to these areas of land to justify the implementation of these exclusion zones.

Exclusion zones are also shown to increase the spatial footprint of the energy system, a consequence frequently overlooked. Most notable is the spatial footprint of bioenergy; when no exclusions are in place the high pathway results in 3.62 M ha of land use change, whereas when environmental exclusion zones are imposed it rises by 8.1% to 3.91 M ha. When multiple exclusion zones are applied to bioenergy, there is simply not enough land to grow the bioenergy crops required for the high bioenergy pathway. This study has therefore shown how exclusion zones are likely to limit the economic and physical feasibility of expanding domestic bioenergy crop production. This highlights that previous calls for limiting bioenergy crop growth from high-quality agricultural land may not be consistent with net-zero emissions targets.

The natural capital approach provides a framework to consider the unseen consequences of exclusion zones highlighting how they can have both beneficial and adverse impacts on food production and the provision of ecosystem services. This paper has identified how the natural capital approach offers a more nuanced perspective than exclusion zones, highlighting how a blanket ban on certain areas may not always be best for society. Providing policymakers with spatial tools that identify how renewable energy can provide environmental benefits will be critical to ensure a more nuanced approach is taken to decarbonising our energy systems.

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**Author's contribution** GD: Conceptualization, Investigation, Methodology, Writing – Original draft preparation, Writing – Review & Editing, Visualization. GS: Investigation, Methodology, Writing – Review & Editing. BD: Conceptualization, Investigation, Methodology, Supervision, Writing – Review & Editing. RH: Conceptualization, Supervision, Writing – Review & Editing. AL: Investigation, Writing – Review & Editing.

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