Exploring Trade-offs between Landscape Impact, Land Use and Resource Quality for Onshore Variable Renewable Energy

An Application to Great Britain

McKenna, Russell; Mulalic, Ismir ; Soutar, Iain; Weinand, Jann Michael; Price, James; Petrovic, Stefan

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Exploring trade-offs between landscape impact, land use and resource quality for onshore variable renewable energy: an application to Great Britain

R. McKenna [a, h, i, j, *], I. Mulalic [b], I. Soutar [c], J.M. Weinand [d], J. Price [e], S. Petrović [a, f], K. Mainzer [g]

[a] *Energy Systems Analysis, DTU Management, Technical University of Denmark, Denmark*
[b] *Department of Economics, Copenhagen Business School, Denmark*
[c] *Centre for Geography and Environmental Science, University of Exeter, UK*
[d] *Chair of Energy Economics, Karlsruhe Institute of Technology (KIT), Germany*
[e] *UCL Energy Institute, UCL, UK*
[f] *Danish Energy Agency, Denmark*
[g] *greenventory GmbH, Germany*
[h] *School of Engineering, University of Aberdeen, UK*
[i] *Department of Mechanical and Process Engineering, ETH Zurich, Switzerland*
[j] *Laboratory for Energy Systems Analysis, Paul Scherrer Institute, Switzerland*

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ABSTRACT

The ambitious Net Zero aspirations of Great Britain (GB) require massive and rapid developments of Variable Renewable Energy (VRE) technologies. GB possesses substantial resources for these technologies, but questions remain about which VRE should be exploited where. This study develops a transferable methodology to explore the trade-offs between landscape impact, land use competition and resource quality for onshore wind as well as ground- and roof-mounted photovoltaic (PV) systems for the first time across GB. These trade-offs constrain the technical and economic potentials for these technologies at the Local Authority level. Our approach combines techno-economic and geospatial analyses with crowd-sourced 'scenicness' data to quantify landscape aesthetics. Despite strong correlations between scenicness and planning application outcomes for onshore wind, no such relationship exists for ground-mounted PV. The innovative method for rooftop-PV assessment combines bottom-up analysis of four cities with a top-down approach at the national level. The results show large technical potentials that are strongly constrained by both landscape and land use aspects. This equates to about 1324 TWh of onshore wind, 153 TWh of rooftop PV and 1200–7093 TWh ground-mounted PV, depending on scenario. We conclude with five recommendations that focus around aligning energy and planning policies for VRE technologies across multiple scales and governance arenas.

1. Introduction and overview

The United Kingdom (UK) has passed the 2008 Climate Change Act [1], which sets a legally binding target to reduce indigenous greenhouse gas (GHG) emissions by 80% relative to 1990 levels by 2050. The Act was subsequently amended in 2019 to a 100% reduction target, i.e. net-zero GHG emissions, by 2050. The Climate Change Committee (CCC) has developed four pathways to demonstrate the ways in which the UK energy system can meet this target [2]. The four pathways have in common a further strong uptake of Variable Renewable Energy (VRE) technologies, especially solar photovoltaic (PV) as well as onshore and offshore wind – increasing from a total generation of 88 TWh in 2020 to 514 TWh in 2050.

Solar PV has seen strong growth in recent years, from just 0.04 TWh of electricity generation in 2010 to 13 TWh in 2019; of this, about 7 TWh is from systems larger than 5 MW and mainly ground-mounted and 5 TWh from smaller rooftop systems [3].

* Corresponding author. Chair of Energy Systems Analysis, Department of Mechanical and Process Engineering, ETH Zurich, Switzerland.
E-mail address: rmckenna@ethz.ch (R. McKenna).

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Whilst new small systems below 5 MW are no longer eligible for Feed in Tariffs since 2019, existing plants continue to be supported in this way. Instead, in 2020 the Smart Export Guarantee (SEG) scheme was launched, which obliges licensed electricity suppliers (with over 150,000 customers) to offer small scale low-carbon generators a price per kWh of exported electricity [3]. Current levelized costs of electricity (LCOEs) for these small-scale PV systems in a UK context are about 0.12 £/kWh [3], which is below the household electricity price of about 0.19 £/kWh [4] and therefore economically incentivizes self-consumption.

Onshore wind will also undoubtedly play a crucial role in the future UK energy system, having increased from around 7 TWh of generation in 2010 to over 32 TWh in 2019 [3]. This development was briefly slowed by a lack of political support for this technology, but the return to eligibility for the Contract for Difference (CfD) subsidies reverses this decision [5]. In addition, onshore wind has very high approval ratings amongst the public: a YouGov survey in 2018 found general support for onshore wind technology [6]. Overall support for renewable energy reached its highest ever level of 85% in 2018, increasing from 79% in 2017 [7].

Despite this general approval, onshore wind proposals can encounter local opposition from planning authorities and local communities, especially if they are not directly engaged in the planning processes [8,9]. Visual impact is one of the central arguments from local residents against onshore wind installations [10–12], although concern is reduced when people live further away from turbines [12,13] and in contexts where the affected people have previous experience with wind energy [14–17].

In order to reflect this lack of local support, studies devoted to resource assessments for onshore wind have recently tried to consider non-technical constraints and trade-offs between technologies [18–20]. But so far this has been focussed on wind, with little attention to ground-mounted PV systems.

The background analysis for the CCC study by Vivid economics [21] assessed feasible potentials for onshore wind and solar PV in the UK. Rather than consider all suitable locations and assess technical and economic feasibility of installing these technologies, this study pre-filtered the geographical potential[1] to exclude possibly unsuitable areas based on the quality of the wind resource. This means that the resulting potentials of 215–479 TWh for onshore wind and 35 TWh for rooftop PV (cf. Table 7) can be considered rather conservative (further comparisons with other studies are given in section 5).

The CCC scenarios are also strongly affected by land use competition between renewable energy technologies. This is a well-known and researched topic, especially but not only in relation to bioenergy and food. For example, Konadu et al. [23] previously delineated this with respect to land use for bioenergy in a UK context. But land use competition was apparently not a focus of the CCC [21] study and has not been widely analysed for VRE technologies in the UK. Price et al. [24] recently analysed how land and water restrictions can shape the least-cost design of Great Britain's power system in 2050, but their analysis did not engage stakeholders or draw on empirical data to develop their land use constraints.

The present study takes this background as the starting point to analyse the potential future contributions of VRE technologies to the long term decarbonization target in the UK, in the context of the CCC [2] pathways to 25–30 GW onshore wind and 75–90 GW solar by 2050.[2] We analyse and economically assess the technical potential for onshore wind, ground-mounted and rooftop PV with a detailed geospatial analysis of the whole of Great Britain (GB), which to our knowledge has not been previously done. We further explore the implications of aesthetic landscape impact and land-use competition on these potentials and costs within a quantitative framework. This paper thereby builds on and complements two related studies: firstly, in Ref. [20] we analysed the trade-off between scenicness and onshore wind costs at the national level; secondly, in Price et al. [30] we explored the system-level impacts on the power system of this new dataset, for which the detailed methodology and spatially-disaggregated results are shown for the first time in the present paper. The key contributions and objectives of this paper are as follows:

1. Test the significance of any link(s) between scenicness data and VRE planning outcomes for both onshore wind and ground-mounted PV;
2. Provide a spatially disaggregated dataset of existing installed capacity and estimated resource potentials at Local Authority level across GB;
3. Develop and apply a new combined top-down/bottom-up method for rooftop PV potentials at national scale;
4. Explore the impacts of scenicness and land use competition for the three VRE technologies and derive insights relating energy and planning policy.

The paper is structured as follows. Section 2 introduces the employed scenicness dataset and establishes the statistical relationship between this and the outcome of planning applications for wind and solar plants. Section 3 presents the methodology for the resource assessments of onshore wind, ground- and rooftop PV. Section 4 then presents the results both at national and local levels, with a focus on the implications of scenicness and land-use competition. Section 5 is devoted to a discussion of the method and the results, and section 6 concludes with policy implications.

2. Scenicness and planning applications for renewable energy plants

This section presents the “Scenic or Not” dataset in section 2.a before analyzing the link between scenicness and planning applications for wind and PV in section 2.b.

a. Scenic or Not dataset

Here we analyse the association between the scenicness and the planning outcome of energy projects using scenic ratings from *Scenic-Or-Not* (http://scenicornot.datasciencelab.co.uk/) as a measure of scenicness and detailed data about renewable energy applications in Great Britain from the Renewable Energy Planning Database [26]. Users of *Scenic-Or-Not* have rated random geotagged photographs taken at 1 km^2 resolution for the whole of Great Britain on an integer scale of 1–10, where 10 indicates “very scenic” and 1 indicates “not scenic”. The database contains 1,536,054 ratings for 212,212 images. We use the mean scenicness values for all photos rated three times or more, taken at the locations after the energy project has been implemented.

The Renewable Energy Planning Database [26] includes the date of the application, operator, information on the site, project attributes (e.g. technology and capacity), and the outcome of the application (granted or rejected) for plants larger than 150 kW. This database has previously been employed by Roddis et al. [31] and Harper et al. [32] in a similar manner, but without any scenicness data.

[1] Potential definitions can be found in McKenna et al. [22].

[2] With average annual full load hours from 2015 to 2019 of 2200 and 900, this equates to about 55–66 TWh and 68–81 TWh wind and solar respectively [3].

For onshore wind energy the mean success rate is about 0.6 (514 project applications have been rejected and 740 have been granted for the time period 2001–2017) while for the ground-mounted PV projects the mean success rate is about 0.8 (1275 project applications have been granted and 282 have been rejected). Moreover, in order to account for highly-sensitive areas, we compute for all locations in our database the distance to the closest Special Areas of Conservation (SAC), distance to the closest Special Protection Areas (SPA), distance to the closest Ramsar areas (wetlands), distance to the closest National Park, and distance to the closest airport.

The results for onshore wind are taken from Ref. [20]; here we apply the same method to explore ground-mounted PV systems. For more details on the data see Ref. [20].

b. Logistic regression of planning applications for wind and solar

We assume a standard model specification for the planning outcome for a project application i at year t:

$$\Pr\left(D_{i,t}=1 \middle| S,\mathbf{X};\ \alpha,\beta,\boldsymbol{\delta},\gamma\right)=F\left(\alpha+\beta S_{i,t}+\boldsymbol{\delta}'\boldsymbol{X_{i,t}}+\boldsymbol{\gamma_t}\right) \tag{1}$$

where $D_{i,t}$ denotes the dichotomous variable taking a value of 1 if the application decision is positive, otherwise 0; α is a constant term and γ_t is the year fixed effects; $S_{i,t}$ is the scenicness value; and $\boldsymbol{X_{i,t}}$ denotes controls for project characteristics such as technical and geographical attributes. We assume that the error term is identically and independently Extreme Value type I distributed (i.i.d. EV I) and estimate the model coefficients using maximum likelihood, viz. logit regression [33]. We are particularly interested in the value of β, as if the scenicness is not related to the application decision then $\beta = 0$, whereas $\beta < 0$ if the scenicness value is negatively related to the planning outcome.

Table 1 shows the results of the logit regression. The upper panel (a) reports the estimation results for the wind energy projects and the lower panel (b) for the ground-mounted PV projects. Model 1 includes only the scenicness value and in the following models 2–4 we sequentially introduce the year fixed effects (to account for possible year-specific structural trends such as business cycles, inflation rate and political environment), the project size, and the environmental variables, respectively. For the wind energy projects the estimated odds ratios associated with the scenicness value are below one (estimated coefficient are negative) and highly

Table 1
Logit regression results (odds-ratio) for onshore wind [20] and ground-mounted PV project planning outcomes.

	Model 1	Model 2	Model 3	Model 4
(a) Wind energy projects				
Scenicness value	0.844***	0.796***	0.768***	0.778***
	(0.033)	(0.035)	(0.036)	(0.038)
Number of turbines			1.225***	1.222***
			(0.032)	(0.032)
Capacity (MW)			0.936***	0.936***
			(0.008)	(0.008)
log distance to the closest National Park				1.171***
				(0.068)
log distance to the closest airport				0.984
				(0.114)
log distance to the closest Special Protection Areas (SPA)				0.972
				(0.044)
log distance to the closest Special Areas of Conservation (SAC)				0.874**
				(0.054)
log distance to the closest Ramsar areas				1.040
				(0.064)
Year fixed effect	no	yes	yes	yes
Constant	2.930***	162.290***	133.568***	98.401***
	(0.518)	(167.191)	(138.216)	(111.718)
Number of observations	1252	1252	1252	1252
AIC	1683	1461.83	1371.13	1370.11
Log likelihood	−839.40	−717.92	−846.94	−665.05
(b) Ground-mounted PV projects				
Scenicness value	0.973	0.972	0.972	0.970
	(0.050)	(0.051)	(0.051)	(0.052)
Capacity (MW)			0.987	0.987
			(0.008)	(0.008)
log distance to the closest National Park				1.107*
				(0.066)
log distance to the closest airport				1.232**
				(0.111)
log distance to the closest Special Protection Areas (SPA)				0.971
				(0.093)
log distance to the closest Special Areas of Conservation (SAC)				0.755***
				(0.061)
log distance to the closest Ramsar areas				1.027
				(0.085)
Year fixed effect	no	yes	yes	yes
Constant	4.985***	3.344**	3.510**	1.843
	(1.004)	(1.857)	(1.952)	(1.257)
Number of observations	1558	1558	1558	1558
AIC	1480	1434	1434	1423
Log likelihood	−738.16	−709.29	−708.02	−697.44

Note: the dependent variable is a discrete dichotomous variable taking a value of 1 if the application decision is positive, otherwise 0; ***, **, * indicate that estimates are significantly different from zero at the 0.01, 0.05 and 0.10 levels, respectively; standard errors are in parentheses. AIC is Akaike's information criterion.

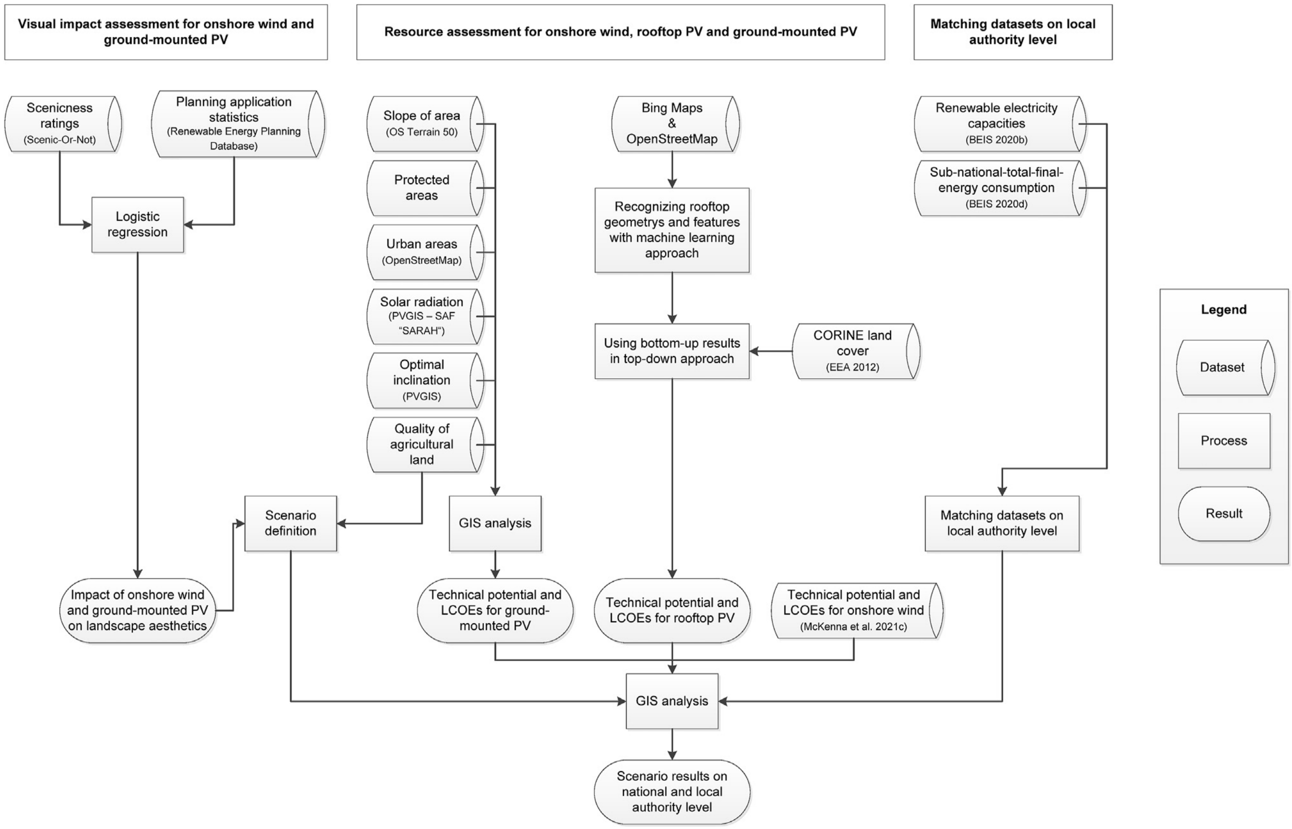

Fig. 1. Schematic of the approach of this paper, showing techno-economic and GIS analysis of 3 VRE technologies.

significant. Model 4 is our preferable specification. This model suggests that for every one unit increase in the scenicness value, we expect a 0.22 decrease in the log-odds of a positive application decision, all else being equal. Consequently, if two applications have the same attributes (as included in model 4) except for their values of the scenicness, then the application with one unit higher scenicness value has about 0.78 ($\approx \exp(-0.25)$) the estimated odds of approval as the project with the lower scenicness value.[3] The marginal effect is −0.06 (std.err is 0.011), i.e. an application with 1% higher scenicness value has 6% lower probability to be evaluated positively. For the solar PV projects the estimated odds ratios associated with the scenicness value are close to one and never significant, suggesting that the impact of the ground-mounted solar panels on landscape aesthetics is much less pronounced.

3. Resource assessment method for VRE technologies

The method employed in this paper involves first determining the geographical potential, followed by the technical one, which is then economically assessed [22]. This procedure involves the stepwise removal of unsuitable (negative) areas from total available areas in a Geographical Information System (GIS), leaving suitable (positive) areas or polygons (cf. Fig. 1). The standardized parts of the method are summarily reported with references to literature for details, and the focus in this section is on the new aspects of the methodology. This section presents the method for ground-mounted PV in section 3.a, rooftop PV in 3.b and onshore wind in 3.c. Section 3.d explains the LCOE calculation, 3.e is about matching multiple spatial datasets for VRE capacities at the Local Authority (LA) level in GB and 3.f presents the analysed scenarios.

a. Ground-mounted PV

For ground-mounted PV, the geographical potential is determined as follows. The maximum terrain slope that guarantees the technical feasibility of a ground-mounted PV plant is 15° [34–36]. Thus, all areas steeper than 15° are excluded using the OS Terrain 50 data [37]. All protected areas such as Ramsar areas, Special Areas of Conservation (SAC), Special Protection Areas and the National Parks are excluded. The National Parks data are extracted from the Office for National Statistics [38] and the other protected areas are retrieved from the Joint Nature Conservation Committee [39]. Urban areas are extracted from Open Street Map [40]. High quality agricultural land is extracted from different websites depending on the country: for England, the data come from the Ministry of Agriculture, Fisheries and Food [41]; for Scotland, Scotland's soil [42] and for Wales, it is the Welsh Government [43]. Agricultural lands of England and Wales are graded one to five with one the highest quality and five the poorest. The scale is different for Scotland; they are graded from one to seven with one being the highest quality and seven the poorest. Based on the description of each level of agricultural land for each country, the levels are matched into a single classification (from 1 to 5) across Great Britain. Thereby, the Scottish Classes 3 and 4 were equated with the Subgrades 3a and 3b in the English and Welsh classification, and Classes 6 and 7 were equated with Grade 5. In order to investigate

[3] The coefficient associated with the scenicness value in this specification is estimated at −0.25 (std.err. is 0.05). It implies that for every one-unit increase in the scenicness value, we expect a 0.25 decrease in the log-odds of the positive application decision, all else equal.

the land use competition between the agricultural land (for food or bioenergy) and ground-mounted PV, two different types of restriction are considered: a low restriction in which the lands with grade 1 and 2 are excluded, and a high restriction in which lands with grade 3 are excluded as well (cf. scenarios in section 2.f).

The technical potential for ground-mounted PV, E_{PVG}, is determined with solar radiation data SAF "SARAH" from PVGIS [44], which gives the yearly average global irradiance on a horizontal surface (W/km^2), H, for the whole of Great Britain, as long-term averages for 2005–2016. Multiplying by the hours in a year h (i.e. 8760) yields the annual irradiance in kWh/m^2. The data is converted from raster to vector in order to intersect with the geographical potential. Optimal inclinations for all parts of the world are taken from PV GIS [45], for GB this varies from 30° in the south to 40° in the north. It is assumed that all modules are oriented south facing. Hence using [46] yields the relative solar irradiation on the inclined surface relative to a horizontal surface (inclination of 0°), meaning a maximum of 17% increase from the horizontal at 30–40°. The Packing Factor (PF) considered to account for space between modules is based on the median value from Ref. [47] of 51%. The final step is a Performance Ratio (PR) of 85% and efficiency η of 15% based on [46,48], which corresponds to polycrystalline silicon, the most dominant technology on the market [49]. Equation (2) defines the technical generation potential:

$$E_{PVG} = 117\% \cdot h \cdot \eta \cdot H \cdot A \cdot PR \cdot PF \tag{2}$$

with A the total area [m2].

b. Rooftop PV

For rooftop PV, the geographical potential is determined based on a combination of the bottom-up approach based on [50], and the top down method based on [46], with different data sources to transfer the method from a German to British context (see Ref. [51] for a review of these methods). The bottom-up approach employs Bing Maps and Open-Street-Map alongside machine learning to recognize rooftop geometry and features. The method from Ref. [50] was employed for the GB context without modification as this was not required. The method has a high resolution at the individual building level, but cannot be employed for the whole of the UK for computational reasons. Instead the four cities of Leeds, Glasgow, Birmingham and London are chosen based on expert discussions about the representativeness of the building stock here for the whole of GB [52]. To connect the bottom-up method from Ref. [50] with the top-down approach, the following variables are employed: land area A is total area in m^2 in a specific land use category; building footprint area s is the plan outline of a building in m^2; and U is the total usable roof area in m^2 (if a flat roof, equal to the footprint area). Furthermore, a dimensionless ratio r is found for the four cities between the land area of each land use category i and the total footprint area of the buildings that fall into this land use type s. For this, the following land-use categories from CORINE land cover [27] at a resolution of 100 m for 2012 are employed (the update to 2018 was not yet available at the time of this study): 111: continuous urban fabric; 112: discontinuous urban fabric, 121; industrial or commercial unit. The ratio r is calculated according to Equation (3).

$$r = \frac{s}{A} \tag{3}$$

As 83% of the UK population lives in cities [53], the assumption is made that the majority of buildings and rooftop potentials are also in cities and therefore this method combining bottom-up and top-down approaches is highly transferable.

The useable roof area U is determined through the cosine of the footprint area, for each of the 72 azimuth/tilt combinations obtained from the method in Ref. [50]. A utilization factor is not required as the bottom-up methodology already delivers partial (i.e. suitable) roof areas (Fig. 8 shows some of these), excluding chimneys, obstructions etc. Equation (4) defines the useable roof area U per azimuth/tilt class i:

$$U_i = A \cdot r \cdot \frac{p_i}{\cos(v_i)} \tag{4}$$

where p_i is the proportion of class i, and v_i is the tilt of the roofs in class i.

The technical potential energy yield E_{PVR} is determined in the same manner as for ground-mounted PV above, see Equation (5), whereby the yields are looked up in Ref. [46] and irr_i is the relative irradiance for class i.

$$E_{PVR} = h \cdot \eta \cdot H \cdot PR \cdot \sum_{i=1}^{72} U_i \cdot irr_i \tag{5}$$

The LCOEs are calculated with the method in section 3.d below.

c. Onshore wind

The approach to assessing the technical potential for onshore wind is very similar to the one applied in Refs. [20,54], with the results adopted from the latter source. Details of the method can be found in the Appendix.

d. Levelized Costs of Electricity (LCOE)

The Levelized Costs of Electricity (LCOEs) are calculated in the same way for each technology, based on the following Equation (6):

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{M_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{6}$$

where n is the lifetime of the technology, I_o the investment [£], M_t the annual costs in year t [£/year], E_t energy produced in year t [MWh/year] and i the interest rate. Table 2 below gives an overview of the economic assumptions for the studied technologies. To reflect a private investor's perspective, i is assumed to be 8%.

e. Geospatial analysis at the Local Authority (LA) level

Over half of the emission cuts required to meet the UK's Net Zero aspirations rely on people and business taking up low-carbon solutions – decisions that are taken at the local level [59]. The Local Authority (LA) level is also the lowest level at which the UK Government publishes energy and related data. There is a value to the research and policy-making community in having a consolidated database including this data at LA, which we have provided in the Supplementary Material with this paper.

In order to underpin our disaggregated geospatial analysis, multiple different databases relating to the installed capacities of VRE technologies were combined. The table "Renewable electricity by local authority" [25] contains all VRE generation on a Local Authority level for the whole of the UK. The Renewable Energy Planning Database [26] mentioned above only includes larger VRE plants, i.e. those requiring planning permission and therefore over 150 kW rated capacity [26]. A further table, "Sub-national-total-final-energy consumption …" [60] includes disaggregated

Table 2
Economic assumptions for VRE technologies [55–58].

Technology	Investment (£/kW)	O&M costs	O&M cost units	Lifetime (years)
Ground-mounted PV	500	8.00	(£/kW.year)	20
Rooftop PV	1130	9.57	(£/kW.year)	20
Onshore wind	1050	0.02	£/kWh	20

electricity demand figures at the LA level. Linking these databases is not trivial, for example because the first one contains nine-digit LA codes and the second contains X–Y coordinates and in some cases postcodes. These two databases were therefore linked on the basis of LA codes and postcodes, by employing an online batch lookup tool [61]. The matched database is employed for the results analysis in section 4 and is provided as supplementary material to this article [62].

f. Accounting for scenicness and definition of scenarios

In this paper we define eight high-level scenarios that are intended to explore the solution space under consideration. The result from section 2 above demonstrates that the scenicness only has a statistically significant correlation with the planning outcomes for onshore wind (and not ground-mounted PV). It is also well researched that the landscape visual impact of rooftop PV is minimal. In the German, Swiss and French regions of the Upper Rhine Region, for example, 75% of those surveyed stated that the distance to a rooftop PV system is not relevant for their acceptance, which also reflects the wider acceptance literature [14]. Therefore we consider four scenarios for the onshore wind potential, based on gradually reducing the technical potential by quartiles of the scenicness distribution. The ground-mounted PV potential is delineated into two scenarios based on high and low restrictions to reflect agricultural land quality. Due to its limited interaction and land use competition with other technologies, the rooftop PV scenario merely reflects the technical potential. An overview of these eight scenarios is given in Table 3.

4. Results and discussion

This section presents the results, starting with high-level national results in the eight scenarios in section 4.a, followed by results at the Local Authority level in section 4.b. Section 4.c then explores the regional scenicness impacts on onshore wind before section 4.d analyses the land-use competition between areas for ground-mounted PV and onshore wind.

a. Overall results in context

Overall the results show some large technical potentials for the three technologies analysed, as detailed in Table 4 and Fig. 2 below. The latter is obtained by sorting all feasible polygons for each technology in order of increasing LCOEs and then calculating the cumulative generation by summing these polygons. The results equate to about 267-1324 TWh of onshore wind, 153 TWh of rooftop PV and 1051–7093 TWh ground-mounted PV. These results relate to total areas of 11–81 thousand km^2, 1190 km^2 and 15–93 thousand km^2 for onshore wind, rooftop and ground-mounted PV respectively. Consecutively removing the most-scenic locations based on quartiles of the distribution reduces the onshore wind potential to 962 TWh, 586 TWh and 267 TWh up to and including scenicness thresholds of 5.8, 4.67 and 3.67 respectively [22]. On the other hand, the results for rooftop and ground-mounted PV are not sensitive to these scenicness thresholds, but the two scenarios for the latter technology do reflect a strong sensitivity to the availability of agricultural land. For context, the annual UK (i.e. GB plus Northern Ireland) electricity demand in 2019 was around 300 TWh/a [63] and is expected to more than double to over 700 TWh by 2050 due to electrification of key sectors such as transport and heating [2].

The LCOEs for these technologies vary, from 0.12 £/kWh for rooftop PV, increasing rapidly to over 0.20 £/kWh, around 0.06 £/kWh to 0.10 £/kWh for ground-mounted PV and upwards of 0.04 £/kWh for onshore wind (Fig. 2).

b. Results at the Local Authority level

This section explores the results at the Local Authority level, based on the classification from 2019 with 382 distinct regions [64]. Fig. 10 in the Appendix provides an overview of the 382 regions

Table 3
Overview of eight analysed scenarios for onshore wind, ground-mounted and rooftop PV potentials.

Scenarios	Wind onshore		Ground-mounted PV		Rooftop PV	
	Rationale	Definition	Rationale	Definition	Rationale	Definition
1	Technical potential	Scenicness <=10	Technical potential with high restriction	Only agricultural land categories 4-5 are feasible	Technical potential	All partial rooftop areas across 72 inclination and azimuth categories
2	75% scenicness	Scenicness <=5.80	Technical potential with high restriction	Only agricultural land categories 4-5 are feasible	Technical potential	All partial rooftop areas across 72 inclination and azimuth categories
3	50% scenicness	Scenicness <=4.67	Technical potential with high restriction	Only agricultural land categories 4-5 are feasible	Technical potential	All partial rooftop areas across 72 inclination and azimuth categories
4	25% scenicness	Scenicness <=3.67	Technical potential with high restriction	Only agricultural land categories 4-5 are feasible	Technical potential	All partial rooftop areas across 72 inclination and azimuth categories
5	Technical potential	Scenicness <=10	Technical potential with low restriction	Only agricultural land categories 3-5 are feasible	Technical potential	All partial rooftop areas across 72 inclination and azimuth categories
6	75% scenicness	Scenicness <=5.80	Technical potential with high restriction	Only agricultural land categories 4-5 are feasible	Technical potential	All partial rooftop areas across 72 inclination and azimuth categories
7	50% scenicness	Scenicness <=4.67	Technical potential with high restriction	Only agricultural land categories 4-5 are feasible	Technical potential	All partial rooftop areas across 72 inclination and azimuth categories
8	25% scenicness	Scenicness <=3.67	Technical potential with high restriction	Only agricultural land categories 4-5 are feasible	Technical potential	All partial rooftop areas across 72 inclination and azimuth categories

Table 4
Overall results showing total available area and generation potential in the eight scenarios shown in Table 3.

Scenarios	Rooftop PV area (km^2)	Rooftop PV (TWh)	Wind area (thousand km^2)	Wind potential (TWh)	Ground-mounted PV area (thousand km^2)	Ground-mounted PV potential (TWh)
1	1190	153	81	1324	93	7093
2	1190	153	35	962	93	7093
3	1190	153	22	586	93	7093
4	1190	153	11	267	93	7093
5	1190	153	81	1324	15	1051
6	1190	153	35	962	15	1051
7	1190	153	22	586	15	1051
8	1190	153	11	267	15	1051

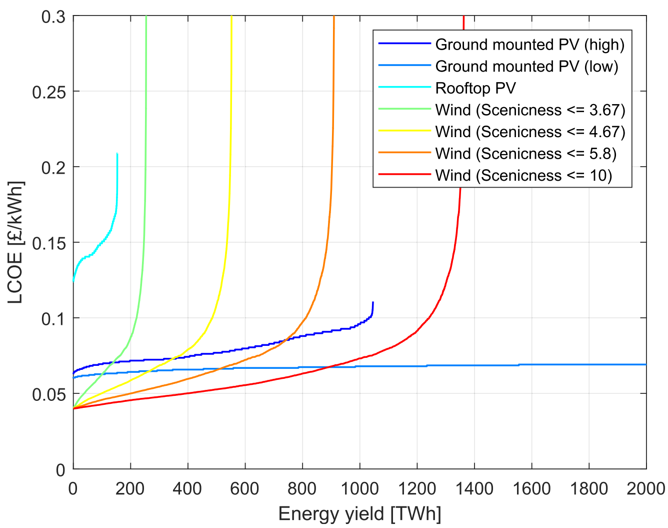

Fig. 2. Cost curves for the three VRE technologies (the curve for ground-mounted PV (high) extends to about 7000 TWh, 0.11 £/kWh). Note the current generation for onshore wind, ground and rooftop PV is about 32, 7 and 5 TWh respectively [25,26]. The wind results are reproduced from McKenna et al. [20].

along with their official names, whereas Figs. 11 and 12 show their distribution across GB and London respectively. Whilst the area of these regions varies greatly (i.e. from 2 to 26,000 km^2), their average size is about 640 km^2 – with the exception of seven very large regions, most have areas under 5000 km^2, with 321 under 1000 km^2. The reason for showing the existing solar and wind generation by LA region in these figures is to put the determined potentials into context. The figures allow on the one hand to validate the results and on the other to highlight areas where the largest gaps between current generation and determined potential exist.

Starting with onshore wind, Fig. 3 shows the generation in 2018 (left) alongside the technical potential (middle) and the potential at the 75% scenicness quartile (i.e. ≤5.8, right). The data is normalised by the total area of each LA, in GWh/km^2, and plotted on two separate logarithmic axes. The left panel of the figure clearly shows the existing distribution of onshore wind generation across GB, with the highest values coinciding with the best wind resource in the south west (e.g. Cornwall and Devon), mid-Wales (e.g. Powys, Ceredigion, Carmarthenshire), northern England (e.g. Northumberland) and most of Scotland, especially the north-western parts. Conversely, the south east and urban areas have relatively low potentials, with the exception of several regions on the east coast and to the north-east of London. The technical potential in the middle panel broadly reflects similar trends, with the contrast between rural and urban locations accentuated. This means relatively low potentials in the Midlands and the location of the most suitable sites at significant distances away from demand centres in the south end south-east of GB.

Moving to a situation with the 25% most scenic locations excluded, as in the right-hand panel of Fig. 3, reveals some interesting differences. In general, exactly the regions with the largest potentials are those most affected by the reduction in available area, confirming that the windiest locations are also the most scenic [20]. The overall potential is reduced and also spread more evenly across the remaining area, with less variation between the regions.

Fig. 4 shows the ground-mounted PV generation in 2018 (left), the high restriction scenario (middle) and low restriction scenario (right). Again the data is normalised with the total area of the region and displayed on logarithmic axes. Clear from the left hand panel is the distribution of existing ground-mounted PV systems, which are mainly in lowland areas in England and Wales (black indicates no generation in these figures). Most of Scotland, the mountainous areas of Wales and England, and predominantly urban areas all have little or no generation from this technology. The middle panel (i.e. high restriction scenario) in Fig. 4 shows potentials that are still generally higher than the current generation in the left panel, i.e. above 1 GWh/km^2. In the right hand panel (low restriction scenario) the technical potential is very high indeed, in many places exceeding 10 GWh/km^2. Note that the highest resources for ground-mounted PV at least partly coincide with those for onshore wind in Fig. 3, for example in Scotland where there are no ground-mounted PV installations (Fig. 4, left panel). This will be further explored in section 4.d.

Fig. 5 shows the results for rooftop PV, with the generation in 2018 on the left and the total technical potential on the right. Once more, these results are displayed per unit of the total region's area and scaled on a logarithmic axis. The left hand panel illustrates the concentration of existing rooftop PV capacity in primarily urban and/or lowland areas, with only a small number of regions having no installed capacity. The right hand panel demonstrates a substantial remaining potential for this technology, again concentrated in urban areas of GB – clearly visible are London, Birmingham, Manchester, Newcastle and Glasgow.

c. Scenicness impacts on regional wind potentials and costs

In a parallel study we demonstrated the general link between low-cost wind resources and locations with a high scenicness at the national level [20]. In Fig. 6 this relationship is explored for selected Local Authorities, chosen based on the following criteria. Firstly, the regions account for at least 1% each of the total GB onshore wind potential. Secondly, the generation potential in these regions is reduced to at most 98% of this total at scenicness levels up to and including 9. The figure therefore shows one point for each scenicness level from 3 to 10, whereby excluding lower values is due to the very small sample sizes. At each point, the LCOEs should be

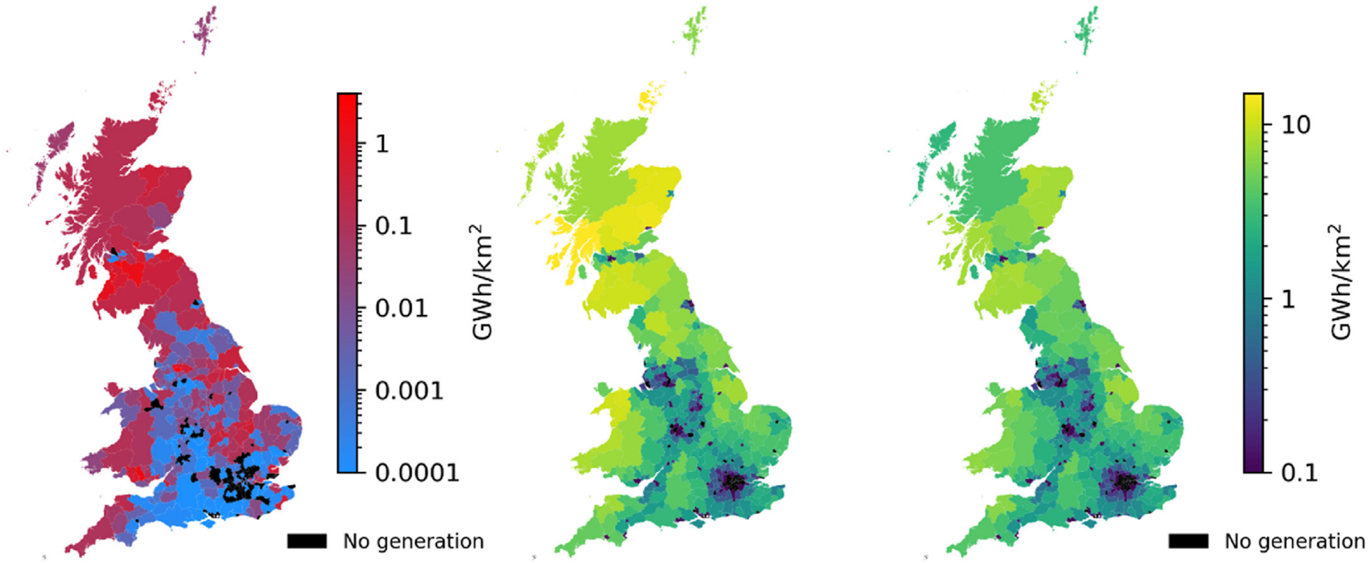

Fig. 3. Onshore wind: generation in 2018 (left, [25,26]), technical potential (middle) and potential at scenicness ≤ 5.8 (i.e. the 75% quartile, right), in units of GWh/km^2. The data is normalised by the total area of each LA and plotted on two separate logarithmic axes.

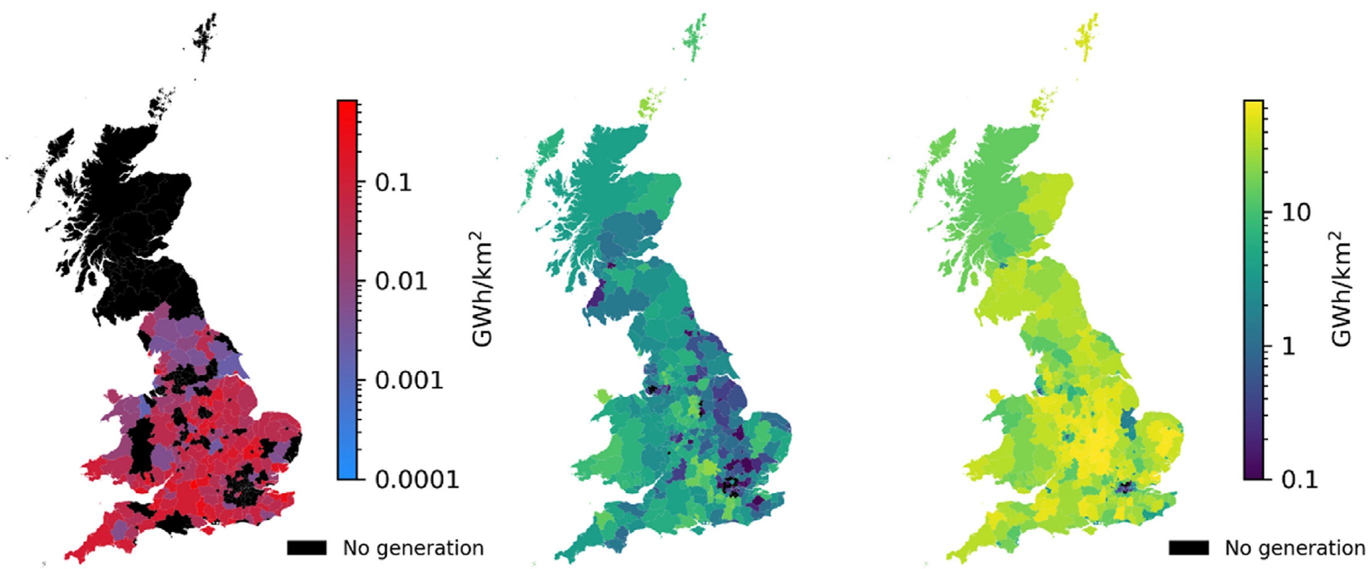

Fig. 4. Ground-mounted solar PV: generation in 2018 (left, [25,26]), technical potential in high restriction scenario (middle) and low restriction scenario (right) respectively, in units of GWh/km^2. The data is normalised by the total area of each LA and plotted on two separate logarithmic axes.

understood as the mean cumulative ones, i.e. for all scenicness levels up to and including the present one.

It is clear from Fig. 6 that there is a correlation between the size and quality (as measured by LCOEs) of onshore wind resources in a region and the scenicness values. Removing the locations with the highest scenicness values also removes the lowest cost potential. For some regions, this correlation is stronger than in others – in fact in the Shetland and Orkney Islands the curves are roughly horizontal. This is probably related to an overall very high wind speed/good wind resource throughout these whole regions, and therefore little impact, other than the obvious reduction in potential, when removing the most scenic locations. On the other hand, the locations with the strongest correlation are those such as Eden with the most varied topography and (therefore) wind speeds. In all of these regions, the removal of the most scenic locations increases the mean cumulative LCOEs. It seems that this general trend is consistant across all LAs, with regional variations related to land use cover as expected.

d. Land use competition between PV and wind

The combination of PV and wind technologies into hybrid power plants (HPPs) is a well-established concept. WindEurope [65] identifies diverse motivation for employing these, including optimized network use, high capacity factors, more stable output etc., and review nine examples worldwide. Two types of HPPs are distinguished, namely those where both plants share the same substation and grid connection, and those where the PV panels are integrated with the wind park. The latter are especially relevant in the context of land use competition because they imply a loss in

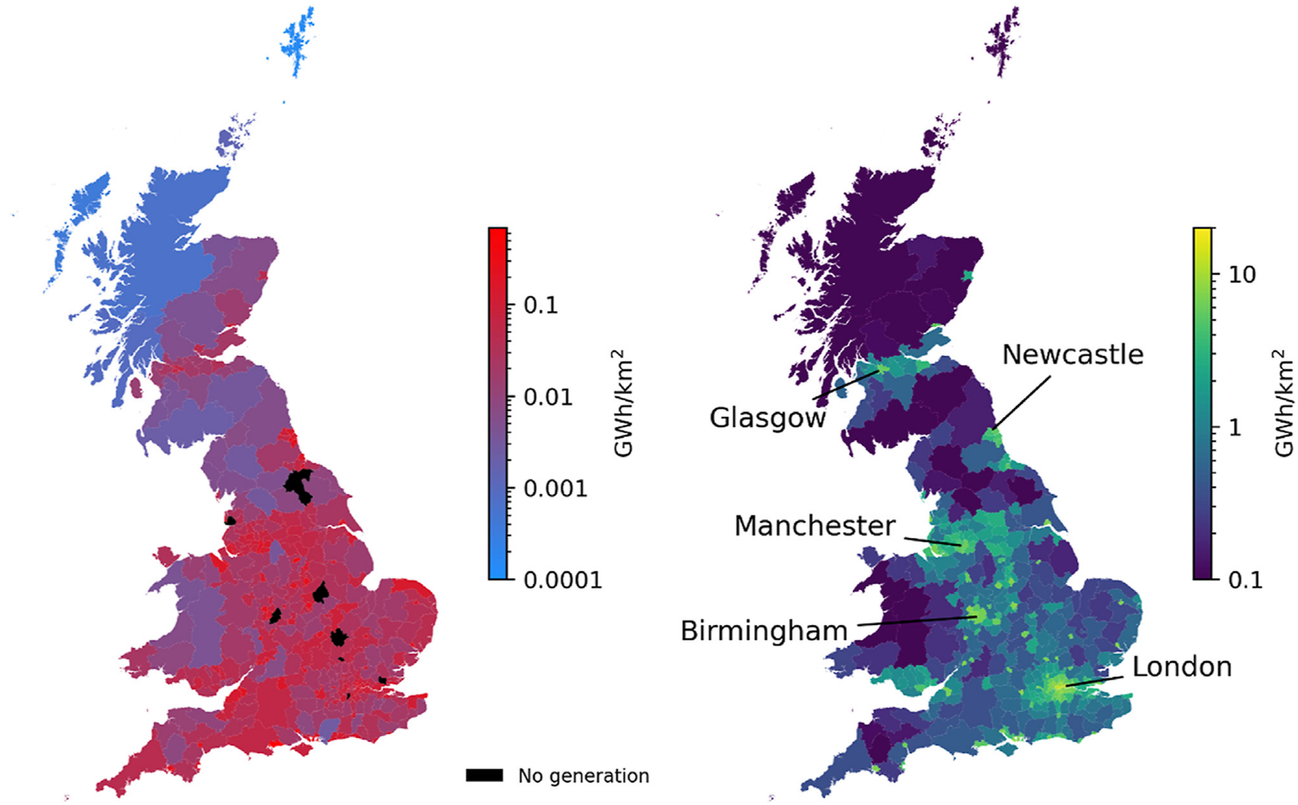

Fig. 5. Rooftop solar PV: generation in 2018 (left, [25,26]) and total technical potential (right), in units of GWh/km^2. The data is normalised by the total area of each LA and plotted on two separate logarithmic axes.

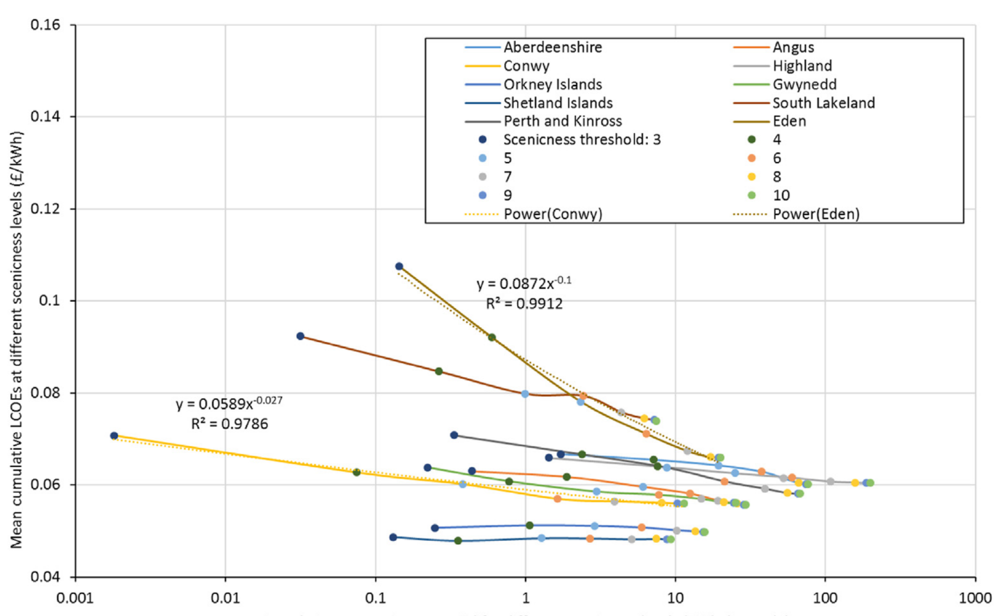

Fig. 6. Mean cumulative LCOEs and cumulative generation potential at discrete scenicness thresholds from 3 to 10 (as shown by points) for selected Local Authority regions in GB (for selection criteria, refer to the text).

output due to shared land usage. Whilst ground-mounted PV and onshore wind can be closely integrated on the same area of land, their combined capacity density (in MW/km^2) is lower than the sum of their individual capacity densities due to required offsets between the technologies. This effect is estimated to be negligible, however, for example accounting for less than 1% of the area [66]. In addition, there is a shadowing effect of wind turbines on ground-mounted PV systems, resulting in 1–8% generation losses [66,67].

For these reasons, the overlap between the potentials for onshore wind and ground-mounted PV for selected Local

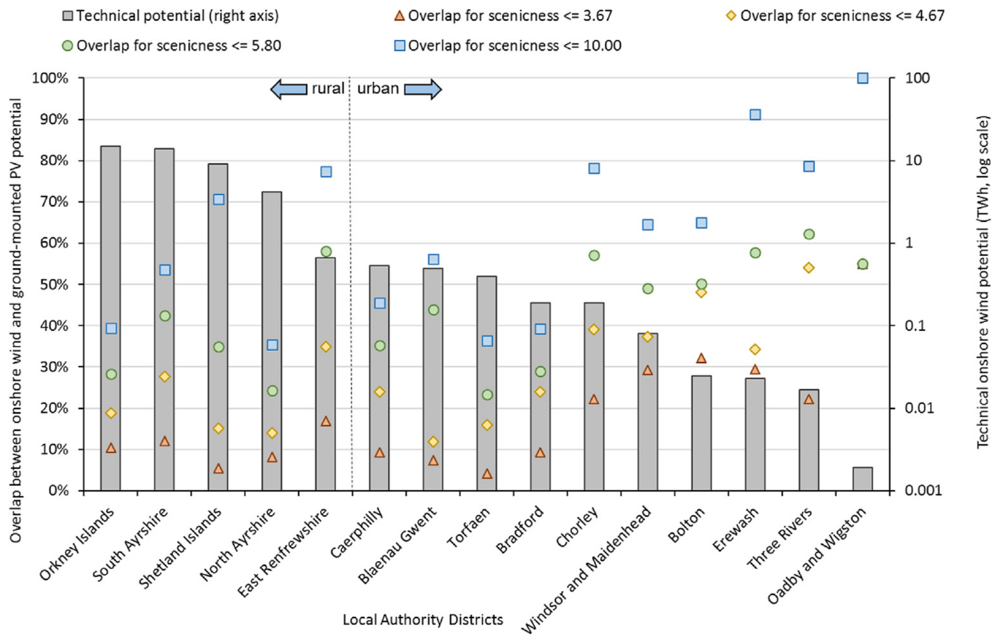

Fig. 7. Overlap between onshore wind and ground-mounted PV at different scenicness values for selected Local Authorities based on criteria detailed in the text (rural and urban denomination is based on predominant land cover category in CORINE [27]).

Authorities are shown in Fig. 7. These regions are selected based on two criteria, firstly that the overlap at the 75% scenicness threshold (5.8) is at most 80% of the overlap at the 100% threshold, and secondly the overlap in the latter case exceeds 35% of the total region's area. Furthermore, Fig. 7 only shows the low-restriction PV scenario, as the high-restriction PV scenario both exhibits low potentials and generally low overlaps below 20%.

In the low restriction PV scenario, many mostly urban areas have very high overlaps, as can be seen for the urban areas to the right of Fig. 7. The rural regions in this figure are focussed in Scotland (five left-hand bars), where the large area and good wind resource combine to around 45 TWh of generation potential. This is some of the most economic onshore wind potential in GB, located towards the bottom-left of the cost curve in Fig. 2. Stepping down the four scenicness thresholds consecutively but differently reduces the overall generation potential and overlap in these regions. In rural regions the overlap varies from about 5% to 80%, whereas the urban regions show a range of about 10–100%. Overall, the areas with the best onshore wind resource have some of the largest overlaps, which can potentially lead to trade-offs between technologies and criteria in the context of constrained land availability. It should be noted, that for a given location the total installable capacity and generation will always be higher for multiple technologies (in this case onshore wind and ground-mounted PV) than for them individually. The mentioned trade-off relates mainly to considerations on a whole energy system level, for example the optimal geospatial and temporal exploitation of renewable energy technologies for the whole nation in the context of land use constraints and existing energy system infrastructure, such as previously analysed for the USA [68,69] and GB [30].

5. Critical discussion and validation of methodology

5.1. Validation of PV rooftop results

One of the main novelties in the presented method is the integration of bottom-up (BU) with top-down approaches to rooftop PV estimations. Whilst the BU method in Mainzer et al. [50] has already been validated, the extension developed here has not. This section is devoted to the validation of the new hybrid top-down/bottom-up method for rooftop PV potential estimation, beginning with a case study for the city of Leeds and followed by a comparison of the results for the whole Yorkshire and Humber region, including 15 LA districts.

In order to give a deeper insight into the results and to validate these with existing plants and studies, we focus on Leeds as one of the cities employed to link bottom-up and top-down approaches. Fig. 8 shows the results of the bottom-up method in four panels, whereby a detailed map of the city with wards can be found in the Appendix. Panel a) shows the locations of partial rooftop areas and existing PV plants (from Ref. [28]), both displayed as point clouds, with a cutout of several collocated points in east Leeds. Panel b) shows the CLC land use categories for the same area, whereas panels c) and d) plot the technical potential (in kWh/m^2) and LCOEs (£/kWh) respectively.

Despite several studies having assessed the national potential for onshore wind and rooftop PV (Table 7), relatively few peer-reviewed studies analyse individual cities. Many studies are undertaken on a consultancy basis and are published as technical reports. In addition to those studies cited in Table 7, for example, the Mayor Of London has published a Solar Action Plan which targets 2 GW of rooftop PV by 2050, but the Plan does not include any detailed resource assessment [70]. In addition, Calderdale Metropolitan Borough Council [71] published a Renewable and Low Carbon Energy Plan including details of renewable resources. One limitation of these one-off studies for individual cities is that the methodology often differs, which makes comparisons challenging. Against this background, an extensive study by AECOM [29] covering large parts of Yorkshire and the Humber is particularly relevant. This report details resource assessments for the whole portfolio of renewable energy (heat and power) technologies across multiple Local Authorities in the region. For this reason of broad coverage, this source is employed here for the purpose of validation.

The AECOM [29] study assumes for domestic buildings that 25% of the existing stock and 50% of new build developments represent

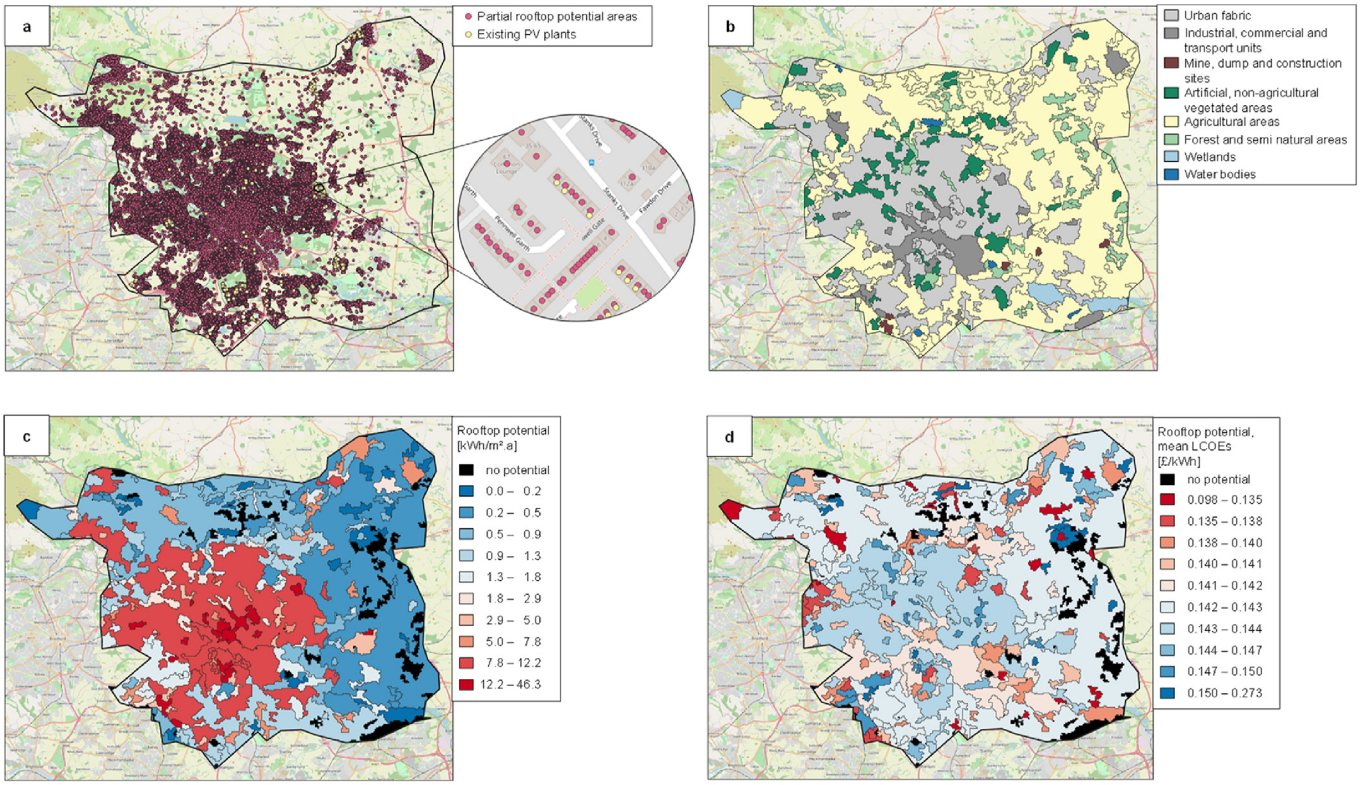

Fig. 8. Results for PV rooftop and existing plants in Leeds: a) locations of partial rooftop areas and existing PV plants (from Ref. [28]), b) CLC land use categories c) technical potential (in kWh/m^2) and d) LCOEs (£/kWh).

technically accessible resources (i.e. roofs). Due to the low rate of new build (typically 1–2%) the average here is nearer to 25% than 50% (giving a factor of 2–4 compared to the technical potential). Further, commercial and industrial buildings in the existing stock are assumed to be 40% and 80% useable respectively, with more modest assumptions of 5–30% for new builds. In a second step, module sizes are predefined for these three building types of 2 kW, 5 kW and 10 kW on domestic, commercial and industrial buildings respectively (this results in a further factor of 2–3 compared to the technical potential). In a third step, the economically viable resource is assessed based on assumed proportions of the building stock: 5–40% in 2010 and 18–45% in 2016 (this step introduces a factor of 2–10 relative to the technical potential). In order to make the results comparable to this paper, the results from AECOM [29] are therefore multiplied by a factor of eight (i.e. the product of the previously-mentioned factors).

Fig. 9 shows the results of the present paper for rooftop PV in comparison to those from AECOM [29]; whereby the left axis displays the generation potential and the right axis specifies the ratio between this study and the other study. Whilst there is clearly a wide variation in the rooftop-PV potentials in different cities/regions, the agreement between the two sources is reasonably good. In other words, the ratio of the two is close to unity in most cases, with a mean of 0.97 and a standard deviation of 0.30).

Despite this overall generally good agreement between the two studies, there are some large deviations in individual cases. In order to explore this phenomenon, we analysed the land use distributions in each of the 24 cities shown in Fig. 9. Due to having 13 land use categories [72] and only 24 observations (cities), we aggregated land use categories in order to reduce the number of model coefficients, as shown in Equation (7) below. Table 5 shows the descriptive statistics for this dataset.

$$\begin{aligned} &\textit{Vacant land} = \textit{Undeveloped land} + \textit{Vacant}\\ &\textit{Commercial land use} = \textit{CommunityService} + \textit{Industry and Commerce} + \textit{Defense Buildings}\\ &\textit{Other} = \textit{Unknown developed use} + \textit{Minerals and landfill} + \textit{Transport and utilities} + \textit{Outdoor recreation}\\ &\textit{Agricultural land and forest} = \textit{Agriculture} + \textit{Forest open land and water} + \text{Residential Gardens} \end{aligned} \tag{7}$$

It should be noted here that, by definition, the sum of land use shares for each city is 100. This means that coefficients for all land use categories (N) cannot be estimated, but only for N-1. Hence we employ the land use category “vacant” as the basis and present the regression results in Table 6.

The interpretation of these results is straightforward. Firstly, it should be noted that only the coefficient associated with residential land use is significant. The coefficient associated with commercial land use is only borderline significant. The other coefficients are not significantly different from zero. The estimation results therefore

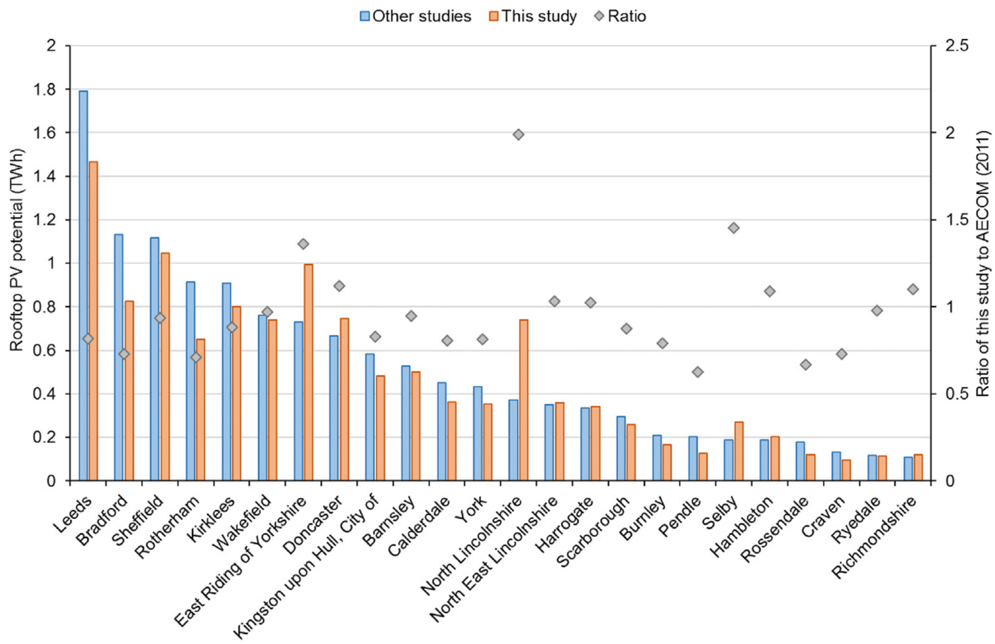

Fig. 9. Comparison of results of this study for rooftop PV with those of AECOM [29] (left hand axis) and the ratio of the two (right hand axis).

Table 5
Descriptive statistics for land use dataset and 24 cities.

	Mean	Std. Dev.	Min.	Max.
Deviation	0.97	0.30	0.62	1.99
Residential land (%)	1.85	1.79	0.15	8.43
Commercial land use (%)	1.99	2.06	0.12	10.01
Vacant land (%)	1.73	1.67	0.08	7.82
Agriculture land and forests (%)	83.26	13.21	34.99	97.16
Other land use	11.17	7.76	2.41	38.74

Notes: Deviation is defined as the ratio between the results of the present paper for rooftop PV in comparison to those from AECOM [29]; commercial land use includes community service buildings, industry and commerce buildings and defense buildings; vacant land includes underdeveloped land and vacant land; other land use includes outdoor recreation facilities, transport infrastructure, landfills and unknown use. The number of observations is 24.

Table 6
Regression results for the deviation variable defined in the text.

	(1) Deviation
Residential land (%)	−0.878***
	(0.262)
Commercial land use (%)	0.637**
	(0.258)
Agriculture land and forests (%)	0.017
	(0.160)
Other land use (%)	0.053
	(0.178)
Constant	−0.681
	(16.07)
Number of observations	24
R^2	0.595

Notes: Deviation is defined as the ratio between the results of the present paper for rooftop PV in comparison to those from AECOM [29]; commercial land use includes community service buildings, industry and commerce buildings and defense buildings; vacant land includes underdeveloped land and vacant land; other land use includes outdoor recreation facilities, transport infrastructure, landfills and unknown use. Vacant land use is the basis land use category. Standard errors are in parentheses. $^{**}p < 0.05$, $^{***}p < 0.01$.

suggest that a higher share of the residential land use is associated with a lower deviation (ratio) between the study results. In other words, the proportion of residential land use is a strongly influencing factor for the correspondence (or otherwise) between the two methods.

5.2. Comparison with previous studies

Here we also briefly put the results of this paper into the context of previous studies with a similar focus. The lack of research into the potential for ground-mounted PV in a national context means that we focus on onshore wind and rooftop PV. Table 7 shows these potentials from eleven other sources, whereby not all cover both technologies. It should also be noted that the scope differs slightly between the UK, GB and the British Isles, as does the potential assessed, between technical and feasible.

The range of results for onshore wind in terms of technical potential are 1274–4700 TWh for the UK, and the range for rooftop PV is 44–460 TWh. In both cases, the present study, with an estimated 1324 TWh and 153 TWh for wind and rooftop PV respectively, lies well within and towards the lower end of this range.

Hence the results can be interpreted as well within the range of existing studies and rather towards the conservative end for both technologies, notwithstanding minor differences in geographical coverage. Further discussion of underlying reasons for differences in results for onshore wind can be found in [73].

At this point it should also be pointed out that the developed method is based on some simplifying assumptions and is therefore not intended as a replacement for detailed local resource assessments with better quality data. Indeed, assumptions such as that all modules are facing south and relying on 83% of the population living in cities mean that the method has weaknesses in specific (e.g. rural) locations. Whilst the results for onshore wind exhibit a strong sensitivity to scenicness, both ground-mounted and rooftop PV do not. The results for the latter two technologies are therefore mainly relevant in the context of broader national energy system planning applications (e.g. Refs. [30,68,69]), for which the location and availability of land are both strong cost drivers. In addition, the

Table 7
Potentials for onshore wind and rooftop PV from selected studies.

Study	Onshore wind potential (TWh)	Rooftop PV (TWh)	Geographical scope	Potential definition
Bódis et al. [96]		44	UK	Technical
UK PMA [97]		460	UK	Technical
Defaix et al. [98]		80	UK	Technical
ETSU [99]	318	266 (BIPV[a])	UK	Total accessible
Vivid economics and ICL [21]	215–479[b]	35[b]	GB	Feasible
MacKay [100]	4700	115[c]	UK	Technical
Dalla Longa et al. [101]	1391		UK	Technical
Enevoldsen et al. [102]	2302		British Isles	'Socio-technical'
Ryberg et al. [103]	2262		UK	Technical
EEA [104]	3961–4409		UK	Technical
McKenna et al. [105]	1274		UK	Technical
This study	1324	153	GB	Technical

[a] Building-integrated PV.
[b] Based on 37 GW with 950 h FLH and 96–214 GW with 2240 h FLH for rooftop PV and wind respectively [3].
[c] South facing roofs only.

method adopts the LCOE metric for the three considered technologies, which overlooks the so-called integration costs of renewable technologies at the system level [74,75]. But the key advantage in this method is in the broad coverage, as it relies solely on open data that is widely available for other countries. In principle, the method is highly transferable to any location in the world where both OSM and Bing maps have reasonable coverage, for onshore wind scenicness or equivalent data exists, and a land use database such as CORINE or equivalent is available.

6. Conclusions and policy implications

In this concluding section, we first summarize the study's limitations and further work before reflecting on some of the current issues with RE planning across GB and highlight some of the emergent tensions between energy and planning policy, before proposing five recommendations for realigning the two in the context of net zero.

This study has developed a transferable methodology to explore the trade-offs between landscape impact, land use competition and resource quality for onshore wind as well as ground- and roof-mounted photovoltaic (PV) systems across GB. The main limitations lie in the uncertainties of the methodology, meaning it is suitable for a regional and national analysis but cannot replace detailed bottom-up studies at specific locations. The combined top-down/bottom up approach to rooftop PV assessment was only validated based on a comparison with other studies. Also, the approach to considering land-use competition with agricultural quality is relatively simple and overlooks wider but potentially relevant land uses. Hence future work should attempt to improve these methodological aspects, for example with case studies in locations with more detailed data (e.g. from 3D laser-scanning). Furthermore, whilst the developed method is in principle transferable to other locations, the scenicness data is not widely available, so methods to infer this indicator in other locations (e.g. based on land use or topography) should be developed.

British planning policy and implementation has a significant influence on individual energy projects and thus energy pathways more broadly. RE projects are subject to decision making across multiple scales and arenas of governance. At the national level, divergence of planning responsibilities has resulted in a patchwork of approaches across GB's devolved administrations. Scotland has remained supportive of onshore wind with the 2017 Onshore Wind Policy Statement [76] and net zero commitments are embedded in the 2020 4th National Planning Framework [77]. A spatial framework serves to highlight those areas most (and least) likely to gain approval based on National Park or National Scenic Area designations. Also broadly supportive of onshore wind, Wales has since 2005 considered wind proposals in the context of seven 'Strategic Search Areas', which are most appropriate for onshore wind [78]. The 2021 National Development Framework [79] supersedes this, replacing area-based targets with a national target. It includes a presumption in favour of large-scale wind energy developments, subject to some constraints. Onshore wind proposals in England, however, have since 2015 been heavily restricted by the National Planning Policy Framework, which requires projects to be aligned with wind provision set out in Local or Neighbourhood Plans, as well as demonstrate additional community backing at the point of application [80].

At the individual project level, planning decisions for VREs are shaped by local contexts and politics. The existence of multiple (often conflicting) stakeholder interests means that energy projects and pathways are shaped by conflict and negotiation [81,82]. While this may be the case across the whole of GB, contentious projects are more likely to find approval when decisions can be defaulted to an overarching national policy, as is the case for onshore wind in Scotland. Elsewhere, there is a need for pragmatism to reconcile the interests and values of actors [83].

As a relatively incoherent patchwork of policy statements, spatial approaches and governance arrangements, the GB energy planning landscape has arguably failed to evolve in step with political and cultural attitudes towards RE technologies. While public support for onshore wind at a national level has increased significantly over the last decade, onshore wind has only really found support in Scotland. However, new net zero commitments at the UK level will require planning regimes that are much more aligned with energy policy across all jurisdictions in order to provide an enabling environment for local energy developments [2,84].

The apparent trade-offs between good locations for VRE technologies, scenic landscapes and other land uses discussed in this paper suggest the need for realignment between planning policy and energy policy across local and national scales. Policymakers should reflect on the respective weighting of partly-competing factors – in this context scenic landscapes, costs of energy supply, the availability of agricultural land, and the distribution of the costs and benefits of the energy transition. The possibility to combine VRE technologies by co-locating them into hybrid power plants may represent an opportunity to increase yields but this may result in sub-optimal distributions at the system level, at which such possible consequences need to be assessed. Five key issues/recommendations for research and policy can be highlighted in this regard.

First, trade-offs between technologies, while not inevitable, are likely, given the lack of incentives for developers to propose hybrid schemes. Having an overarching national strategic vision for land use across GB embedded within planning regimes can provide clarity for developers and decision-makers alike with regard to the contribution of land to net zero. Planning has evolved from being underpinned by the notion of the 'public interest', and more recently around the similarly ambiguous objective of 'sustainable development' [85]. Given the specific trade-offs highlighted here for scenic landscapes, and interdependencies between land use and energy pathways (e.g. bioenergy cropping, forestation), there is a strong argument now for planning to be strategically aligned explicitly with net zero objectives [86]. This would not eradicate trade-offs of course, but could lend coherence in favouring decisions that provide efficient and just GHG mitigation impacts.

Second, meeting the net zero challenge requires a significant increase in VRE penetration and it is generally agreed that a diverse portfolio of technologies will be needed to maximise overall RE deployment and reduce the need for additional flexibility [87,88]. In this context, robust and transparent appraisal of the synergies and trade-offs between development options – alongside other land uses – will be needed to legitimize support for specific technologies as well as the decision-making processes adopted [89,90].

A third consideration stems from the increased emphasis among academics, policymakers, and innovation agencies on the importance of local contexts as a key part of a whole system approach to decarbonization. The Energy Systems Catapult [91] for example suggests that spatial planning of low carbon developments should be considered (alongside energy network planning and demand-side regulations) within an integrated Local Area Energy Planning framework. Understanding the potential for trade-offs across different localities will be an important consideration in such frameworks.

Fourth, it is apparent that decarbonising energy is increasingly a challenge of technological integration, rather than *only* deployment of VREs. As such, decision-making around proposed RE projects needs to account for any impacts projects may have on the electricity system, e.g. the costs of balancing supply and demand, or the need to constrain or store excess VRE generation. The decision-making around trade-offs and synergies (through co-location of different technologies, for example) therefore needs to take place in the context of such whole-system cost assessments [92]. Future spatial modelling work in this space should also seek to move away from levelised cost of technologies as a basis for understanding trade-offs. Some inroads in this direction have been made in some parallel related work to this article [20,30].

Finally, the quality of decision making at any level of governance will be determined by the degree to which relevant interests can be taken into account. Such interests include the value placed on scenic landscapes – as discussed here – although other factors are also likely to play significant roles. In order for local RE development to respond to the climate change mitigation imperative, more meaningful engagement with the public is needed, particularly in those areas where these potential trade-offs are strongest. This could most readily take the form of encouraging best practice (and clarifying the meaning thereof) around community engagement as a necessary component of RE project proposals [93]. Examples of this best practice here include promotion of shared ownership, inclusion of community-led organisations and wider communities throughout all project stages (rather than just the planning stage), and maximisation of local employment opportunities.

More generally, however, the development of national and local climate assemblies in the UK offer replicable frameworks for public deliberation around climate change responses [94,95]. Such fora provide valuable mechanisms for opening up discussions about GHG mitigation options, as well as the trade-offs these options might have with environmental and social outcomes.

Credit author statement

Conceptualisation: RM, IM, JMW; Methodology: all; Software: RM, IM, JMW, JP, SP; Data curation: RM, IM, JMW, JP, SP; Writing – Original Draft: All, Writing – Review & Editing: All; Visualisation: RM, IM, JMW, JP, SP; Supervision: RM; Project Administration: RM.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.123754.

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