

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

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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 explores 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 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 (UK Government, 2008), 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 (CCC, 2020b). 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 (BEIS, 2020b). 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 (BEIS, 2020b). Current levelized costs of electricity (LCOEs) for these small-scale PV systems in a UK context are about 0.12 £/kWh (BEIS, 2020b), which is below the household electricity price of about 0.19 £/kWh (ofgem, 2021) 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 (BEIS, 2020b). 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 (DCLG, 2017). In addition, onshore wind has very high approval ratings amongst the public: a YouGov survey in 2018 found general support for onshore wind technology (YouGov, 2018). Overall support for renewable energy reached its highest ever level of 85% in 2018, increasing from 79% in 2017 (BEIS, 2018).

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 (Boudet, 2019; Fast et al., 2016). Visual impact is one of the central arguments from local residents against onshore wind installations (Molnarova et al., 2012; Petrova, 2016; Wolsink, 2018), although concern is reduced when people live further away from turbines (Betakova et al., 2015; Wolsink, 2018) and in contexts where the affected people have previous experience with wind energy (Schumacher et al., 2019; Sonnberger and Ruddat, 2017; van der Horst, 2007; Warren et al., 2005).

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 (Höltinger et al., 2016; Jäger et al., 2016; McKenna

et al., 2021c). But so far this has been focussed on wind, with little attention to ground-mounted PV systems.

The background analysis for the CCC study (Vivid economics and ICL, 2019) 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 potential¹ 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 4.f).

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. (2015) 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 (Vivid economics and ICL, 2019) study and has not been widely analysed for VRE technologies in the UK. Price et al. (2018) 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 (CCC, 2020b) pathways of 25-30 GW onshore wind and 75-90 GW solar in 2050². 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). 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 (McKenna et al., 2021c) we analysed the trade-off between scenicness and onshore wind costs at the national level; secondly, in Price et al. (2020) 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 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;

¹ Potential definitions can be found in McKenna et al. (2021b).

² With average annual full load hours from 2015-2019 of 2200 and 900, this equates to about 55-66 TWh and 68-81 TWh wind and solar respectively (BEIS (2020b)).

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 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 (BEIS, 2014). Users of *Scenic-Or-Not* have rated random geotagged photographs taken at 1km² 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 (BEIS, 2014) 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. (2018) and Harper et al. (2019) in a similar manner, but without any scenicness data.

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 (1,275 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 (McKenna et al., 2021c); here we apply the same method to explore ground-mounted PV systems. For more details on the data see (McKenna et al., 2021c).

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 :

$$\Pr(D_{i,t} = 1 | S, \mathbf{X}; \alpha, \beta, \boldsymbol{\delta}, \boldsymbol{\gamma}) = F(\alpha + \beta S_{i,t} + \boldsymbol{\delta}'\mathbf{X}_{i,t} + \boldsymbol{\gamma}_t) \quad (1)$$

where $D_{i,t}$ denotes the discrete dichotomous variable taking a value of 1 if the application decision is positive, otherwise 0; α is a constant term and $\boldsymbol{\gamma}$ is the year fixed effect; $S_{i,t}$ is the scenicness value; and $\mathbf{X}_{i,t}$ 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 (McFadden, 1974). 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. 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 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. 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 less pronounced.

We have performed a number of sensitivity analyses. First we have assumed that the error term is i.i.d. normally distributed, viz. probit regression. The results of this probit regression model are very similar to the preferable model (4). We have also estimated logit models on a subsample when the number of votes is larger than 11 (10% percentile), 15 (25% quartile) and 25 (median), but the coefficients remain unchanged. The estimation results for these models are available upon request from the authors.

Table 1: Logit regression results (odds-ratio) for onshore wind (McKenna et al., 2021c) and ground-mounted PV project planning outcomes

	Model 1	Model 2	Model 3	Model 4
(a) Wind energy projects				
Scenicness value	0.844*** (0.033)	0.796*** (0.035)	0.768*** (0.036)	0.778*** (0.038)
Number of turbines			1.225*** (0.032)	1.222*** (0.032)
Capacity (MW)			0.936*** (0.008)	0.936*** (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*** (0.518)	162.290*** (167.191)	133.568*** (138.216)	98.401*** (111.718)
Number of observations	1,252	1,252	1,252	1,252
AIC	1,683	1,461.83	1,371.13	1,370.11
Log likelihood	-839.40	-717.92	-846.94	-665.05
(b) Ground-mounted PV projects				
Scenicness value	0.973 (0.050)	0.972 (0.051)	0.972 (0.051)	0.970 (0.052)
Capacity (MW)			0.987 (0.008)	0.987 (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*** (1.004)	3.344** (1.857)	3.510** (1.952)	1.843 (1.257)
Number of observations	1,558	1,558	1,558	1,558
AIC	1,480	1,434	1,434	1,423
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.

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 economically assessed (McKenna et al., 2021b). 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. Figure 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 in the UK 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° (Borgogno Mondino et al., 2015; Carrión et al., 2008; Perpiña Castillo et al., 2016). Thus, all areas steeper than 15° are excluded using the OS Terrain 50 data (Ordnance Survey, 2018). 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, 2020) and the other protected areas are retrieved from the Joint Nature Conservation Committee (JNCC, 2016). Urban areas are extracted from Open Street Map (OpenStreetMap Contributors, 2020). 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 (1988), for Scotland, Scotland's soil (1981) and for Wales, it is the Welsh Government (Welsh Government, 2017). 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 the land use competition between the agriculture 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 (European Commission, 2018), 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 (European Commission, 2019), 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 (Mainzer et al., 2014) 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 (Ong et al., 2013) of 51%. The final step is a Performance Ratio (PR) of 85% and efficiency η of 15% based on (Hoogwijk, 2004; Mainzer et al., 2014), which corresponds to polycrystalline silicon, the most dominant technology on the market (Gangopadhyay et al., 2013). Equation 2 defines the technical generation potential:

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

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 (Mainzer et al., 2017), and the top down method based on (Mainzer et al., 2014), with different data sources to transfer the method from a German to British context (see Gassar and Cha (2021) 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 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 diversity of the building stock here (Liddiard, 2021). To connect the bottom-up method from (Mainzer et al., 2017) with the top-down approach, the following variables are employed: land area A is total area in m² in a specific land use category; building footprint area s is the plan outline of a building in m²; and roof area U is the total roof area in m² (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 (EEA, 2012) at a resolution of 100 m for 2012 are employed (the update to 2018 was not yet available at the time this study): 111: continuous urban fabric; 112: discontinuous urban fabric, 121; industrial or commercial unit. The ratio r is calculated according to Equation 3.

$$r = \frac{s}{A} \quad (3)$$

The assumption is made that, as 83% of the UK population lives in cities (DEFRA, 2019), 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 usable 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 (Mainzer et al., 2017). A utilization factor is not required as the bottom-up methodology already delivers

partial (i.e. suitable) roof areas (Figure 8 shows some of these), excluding chimneys, obstructions etc. Equation 4 defines the useable roof area U per azimuth/tilt class i :

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

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 (Mainzer et al., 2014) and irr_i is the relative irradiance for class i .

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

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 one applied in (McKenna et al., 2014) and (McKenna et al., 2021c), with the results adopted from the latter source. The geographic potential is determined by excluding unsuitable areas for onshore wind, as follows. Based on Digital Elevation Models, regions with a slope over 20° are excluded, with slopes calculated in the same way as for ground-mounted PV (cf. section 3.a). Unsuitable areas are then excluded based on CORINE (EEA, 2012) data at 100 m from 2012. For this reason, the CORINE data is combined with OSM data to improve the coverage in and around urban areas. There is no general guidance on the buffer distances to housing and this differs between countries (McKenna et al., 2021b), but some guidance suggests 350 m for England, 2 km for Scotland and 500 m for Wales, which are the assumptions adopted (Barclay, 2012). Otherwise the assumptions relating to offset distances are based on Table 4.2 in (McKenna et al., 2014). The combination of the two datasets, OSM and CORINE, is based on the following precedence relationships. The basic approach is to prioritize OSM data where this is available, i.e. if both CORINE and OSM refer to the same polygon with (different) information, OSM takes precedence. This is based on the following steps, whereby positive and negative areas represent those suitable and unsuitable for wind energy respectively: 1. $OSM_{Positive} - CLC_{Positive}$; 2. $CLC_{Positive} - OSM_{Negative}$; 3. Unite (1) and (2); and 4. combine with OSM total area to obtain the land use categories (where available).

The technical potential for onshore wind energy is then calculated for the determined geographic potential area, again based on the method in (McKenna et al., 2014). This involves combining the land-use data with annual average wind speeds at 5 km² resolution and 10 m above ground for 2001 to 2006 inclusive from the UK Met Office (UK Met Office, 2018). These wind speeds are extrapolated to hub heights, and converted from average wind speeds to average wind speed distributions based on the roughness length of the land-use category (Silva et al., 2007). Finally, the energy generation for specific turbines is simulated based on the product of the integral of the wind speed distribution and the turbine's power curve. The most economical turbine for a specific

location is determined by minimizing the LCOEs (section 3.d), based on a database of techno-economic turbine characteristics.

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:

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

where n is the lifetime of the technology, I_0 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%.

Table 2: Economic assumptions for VRE technologies (BEIS, 2020d; Open Energy Information, 2017; Philipps and Warmuth, 2019; Vartiainen et al., 2020)

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		20
Onshore wind	1050	0.02	£/kWh	20

e. Matching multiple local datasets of VRE capacities

In order to underpin the disaggregated geospatial analysis carried out in this paper, multiple different databases relating to the installed capacities of VRE technologies were combined. The table “Renewable electricity by local authority” (BEIS, 2020c) contains all VRE generation on a Local Authority level for the whole of the UK. The Renewable Energy Planning Database (BEIS, 2014) mentioned above only includes larger VRE plants, i.e. those requiring planning permission and therefore over 150 kW rated capacity (BEIS, 2014). A further table, “Sub-national-total-final-energy consumption...” (BEIS, 2020e) includes disaggregated 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 the postcodes, by employing an online batch lookup tool (Ordnance Survey, 2021). The matched database is employed for the results analysis in section 4 and is provided as supplementary material to this article (McKenna et al., 2021a).

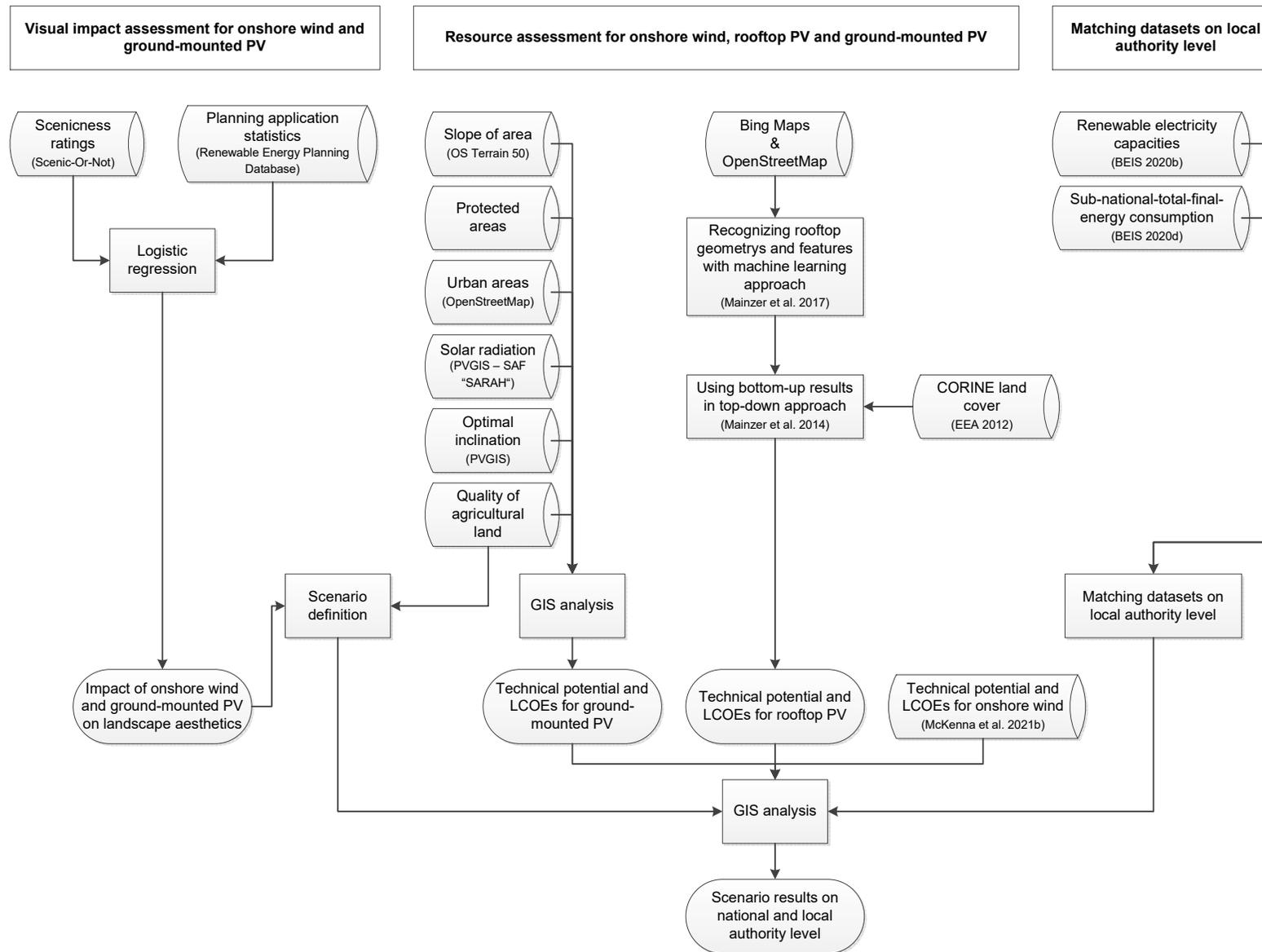


Figure 1: Schematic of the approach of this paper, showing techno-economic and GIS analysis of 3 VRE technologies

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 (Schumacher et al., 2019). 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 below.

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				
3	50% scenicness	Scenicness ≤ 4.67				
4	25% scenicness	Scenicness ≤ 3.67				
5	Technical potential	Scenicness ≤ 10	Technical potential with low restriction	Only agricultural land categories 3-5 are feasible		
6	75% scenicness	Scenicness ≤ 5.80				
7	50% scenicness	Scenicness ≤ 4.67				
8	25% scenicness	Scenicness ≤ 3.67				

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 analysis 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 shown in Table 4 and Figure 2 below. This equates to about 1324 TWh of onshore wind, 153 TWh of rooftop PV and 1200-7093 TWh ground-mounted PV. These results relate to total areas of 11-80 million km², 1,190 km² and 15-93 million km² 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 (McKenna et al., 2021b).

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

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 (Figure 2).

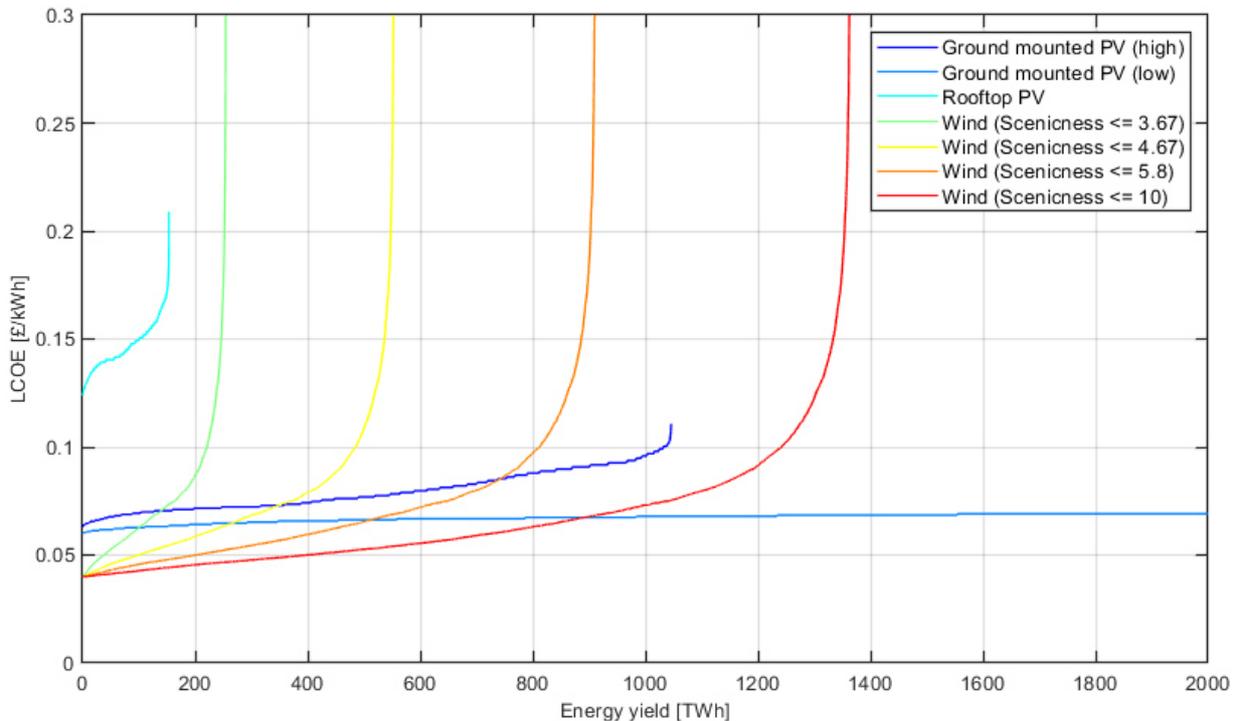


Figure 2: Cost curves for the three VRE technologies (the curve for ground-mounted PV (high) extends to about 7000 TWh, 0.11 £/kWh). Note the current generation for onshore wind, ground and rooftop PV is about 32, 7 and 5 TWh respectively (BEIS, 2020c, 2014).

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 (ONS, 2020). Figure 10 in the Appendix provides an overview of the 382 regions along with their official names, whereas Figure 11 and Figure 12 show their distribution across GB and London respectively. Whilst the area of these regions varies greatly (i.e. from 2 to 26,000 km²), their average size is about 640 km² – with the exception of seven very large regions, most have areas under 5,000 km², with 321 under 1,000 km².

Starting with onshore wind, Figure 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/km², 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-west 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.

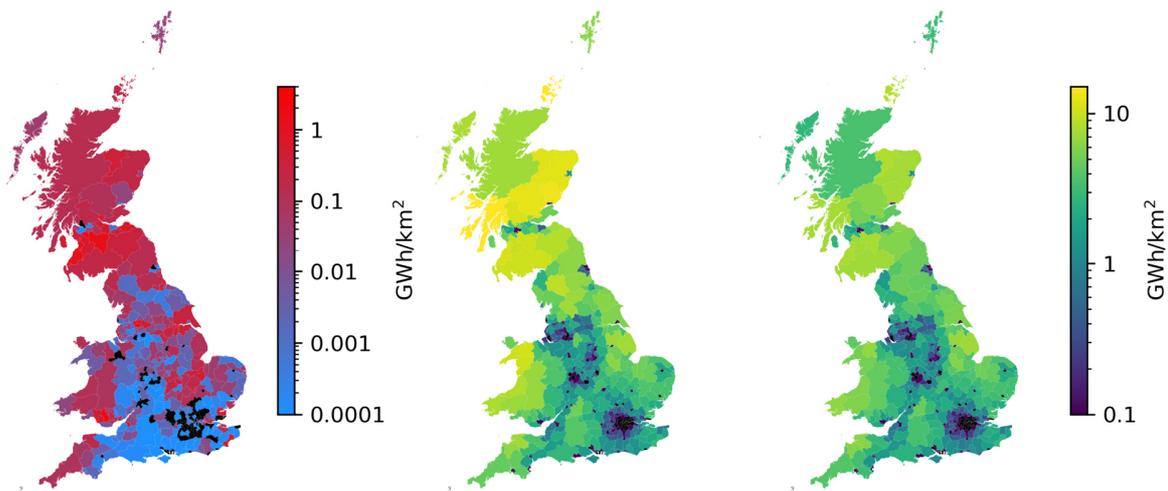


Figure 3: Onshore wind: generation in 2018 (left, (BEIS, 2020c, 2014)), technical potential (middle) and potential at scenicness ≤ 5.8 (i.e. the 75% quartile, right), in units of GWh/km². The data is normalised by the total area of each LA and plotted on two separate logarithmic axes.

Moving to a situation with the 25% most scenic locations excluded, as in the right-hand panel, reveals some interesting differences. In general, exactly the regions with the largest potentials are those affected by the reduction in available area, confirming that the windiest locations are also the most scenic (McKenna et al., 2021c). The overall potential

is reduced and also spread more evenly across the remaining area, with less variation between the regions.

Figure 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 Figure 4 shows potentials that are still generally higher than the current generation in the left panel, i.e. above 1 GWh/km². In the right hand panel (low restriction scenario) the technical potential is very high indeed, in many places exceeding 10 GWh/km². Note that the highest resources for ground-mounted PV partly coincide with those for onshore wind in Figure 3. This will be further explored in section 4.d.

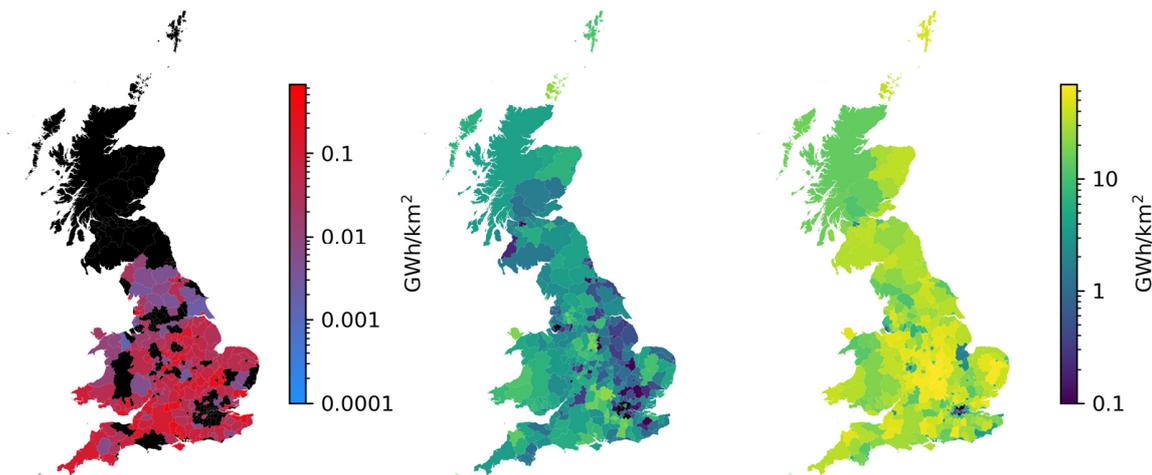


Figure 4: Ground-mounted solar PV: generation in 2018 (left, (BEIS, 2020c, 2014)), technical potential in high restriction scenario (middle) and low restriction scenario (right) respectively, in units of GWh/km². The data is normalised by the total area of each LA and plotted on two separate logarithmic axes.

Figure 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 access. 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.

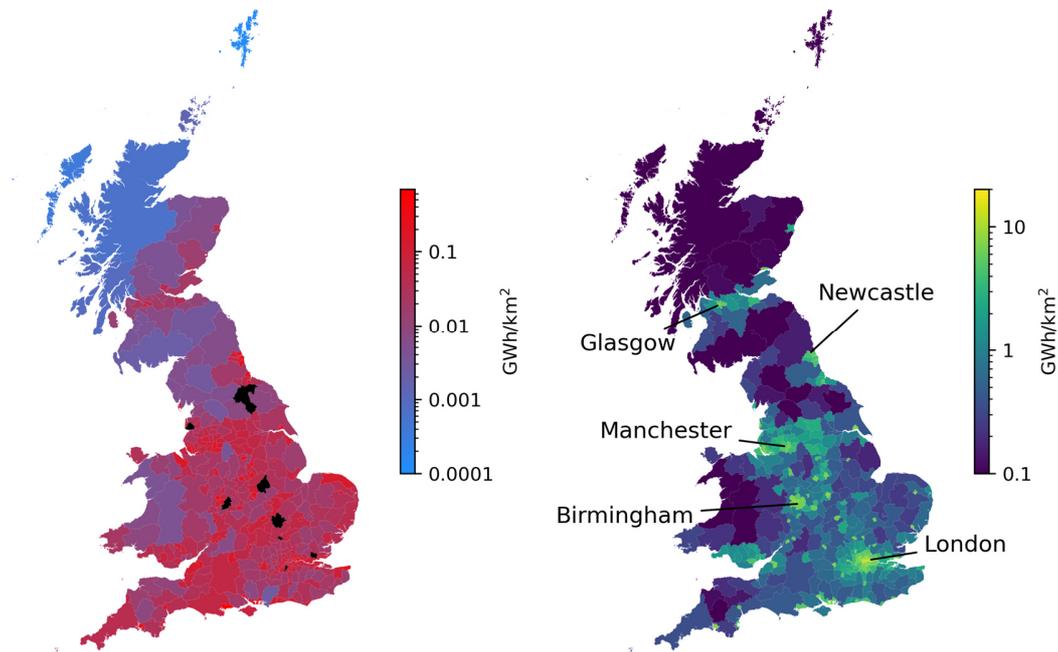


Figure 5: Rooftop solar PV: generation in 2018 (left, (BEIS, 2020c, 2014)) and total technical potential (right), in units of GWh/km². The data is normalised by the total area of each LA and plotted on two separate logarithmic axes.

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 (McKenna et al., 2021c). In Figure 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 understood as the mean cumulative ones, i.e. for all scenicness levels up to and including the present one.

It is clear from Figure 6 that there is 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 none of these regions does the removal of the most scenic locations reduce the LCOEs.

It seems that this general trend is consistent across all LAs, with regional variations related to land use cover as expected.

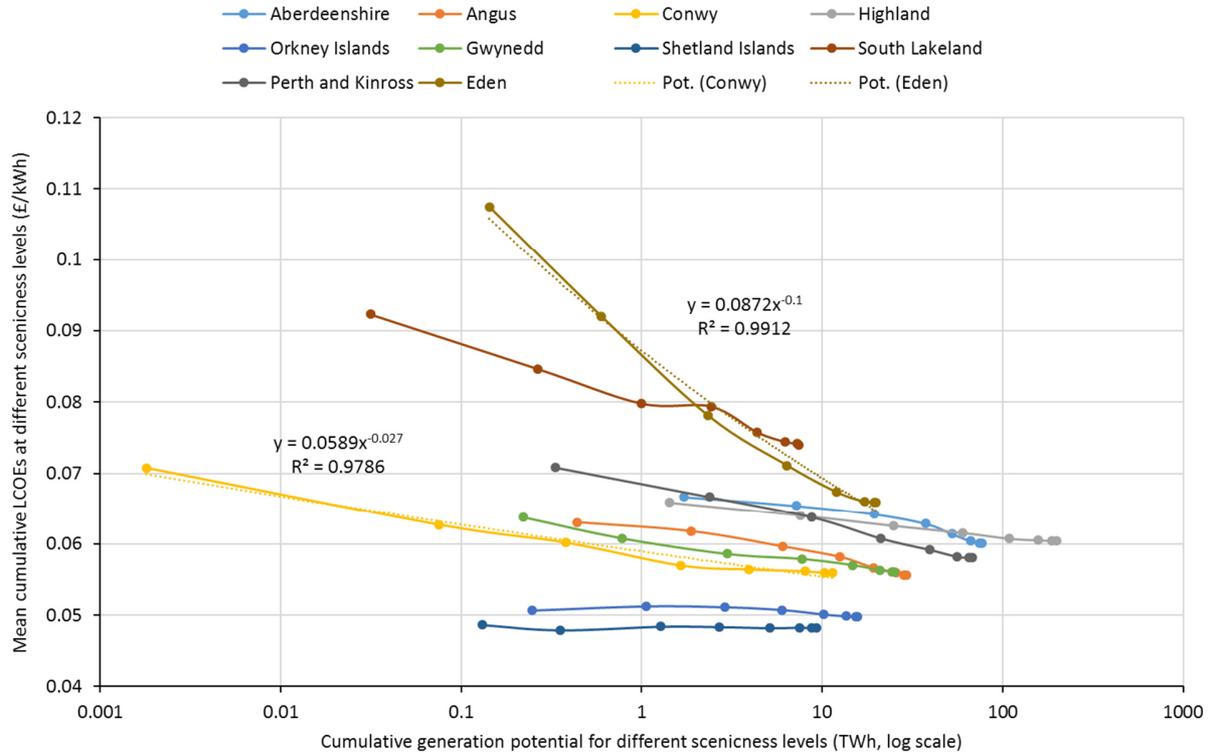


Figure 6: Mean cumulative LCOEs and cumulative generation potential at discrete scenicness thresholds from 3 to 10 (as shown by points) for selected Local Authority regions in GB (for selection criteria, refer to the text)

d. Scenicness and land competition between PV and wind

The combination of PV and wind technologies into hybrid power plants (HPPs) is a well-established concept. WindEurope (2019) 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 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/km²) is lower than the sum of their individual capacity densities due to required offsets between the technologies. Love (2003) demonstrated this for a highly-renewable US energy system, showing the trade-off between these two technologies when installed to meet a pre-specified demand. In addition, there is a shadowing effect of wind turbines on ground-mounted PV systems, resulting in 1-8% generation losses (Deltenre et al., 2020; Mamia and Appelbaum, 2016).

For these reasons, the overlap between the potentials for onshore wind and ground-mounted PV for selected Local Authorities are shown in Figure 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, Figure 7 only shows the low restriction PV scenario, as the low PV scenario both exhibits low potentials and generally low overlaps below 20%.

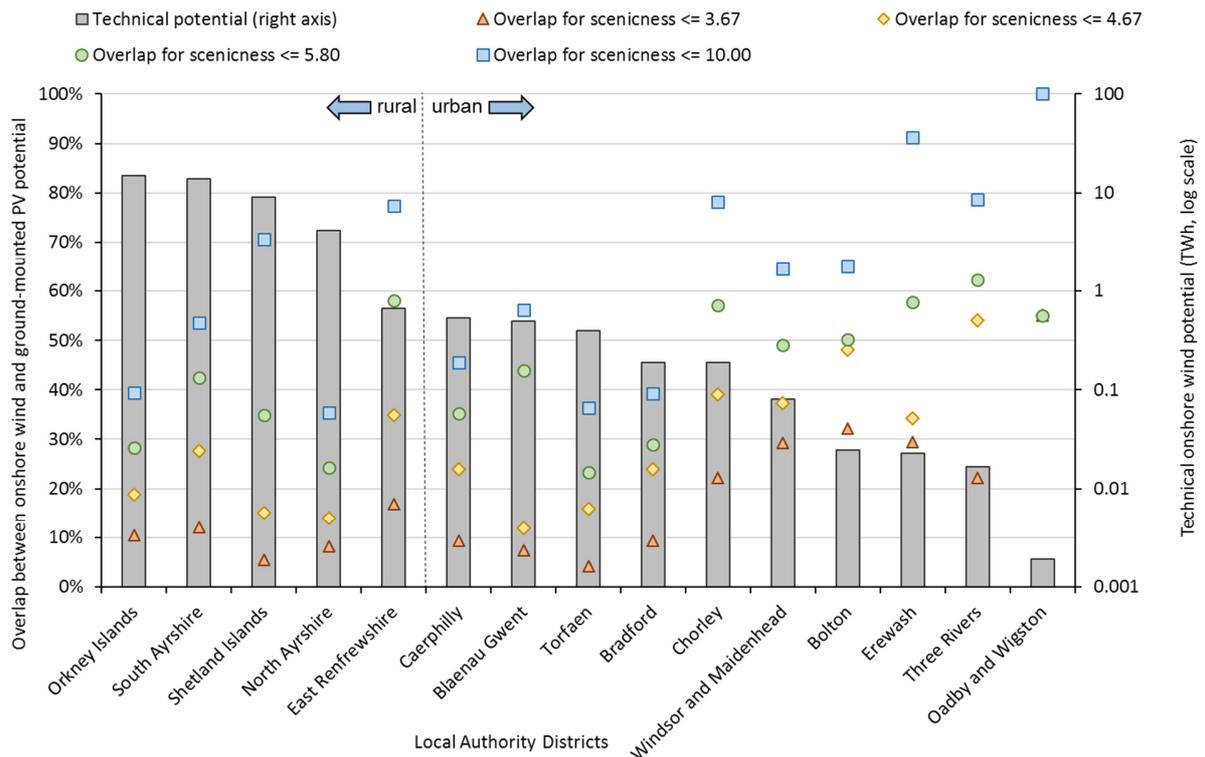


Figure 7: Overlap between onshore wind and ground-mounted PV at different scenicness values for selected Local Authorities based on criteria detailed in the text (rural and urban denomination is based on predominant land cover category in CORINE (EEA, 2012))

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 Figure 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 Figure 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 5-80%, 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, meaning inevitable trade-offs between technologies and criteria in the context of constrained land availability.

5. Critical discussion and validation of methodology

One of the main novelties in the presented method is the integration of bottom-up with top-down approaches to rooftop PV estimations. Whilst the BU method in Mainzer et al. (2017) has already been validated, the extension developed here has not been. 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. Figure 7 shows the results of the bottom-up method in four panels, whereby a detailed map of city with wards can be found in the Appendix. Panel a) shows the locations of partial rooftop areas and existing PV plants (from Stowell et al. (2020)), 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/m²) and LCOEs (£/kWh) respectively.

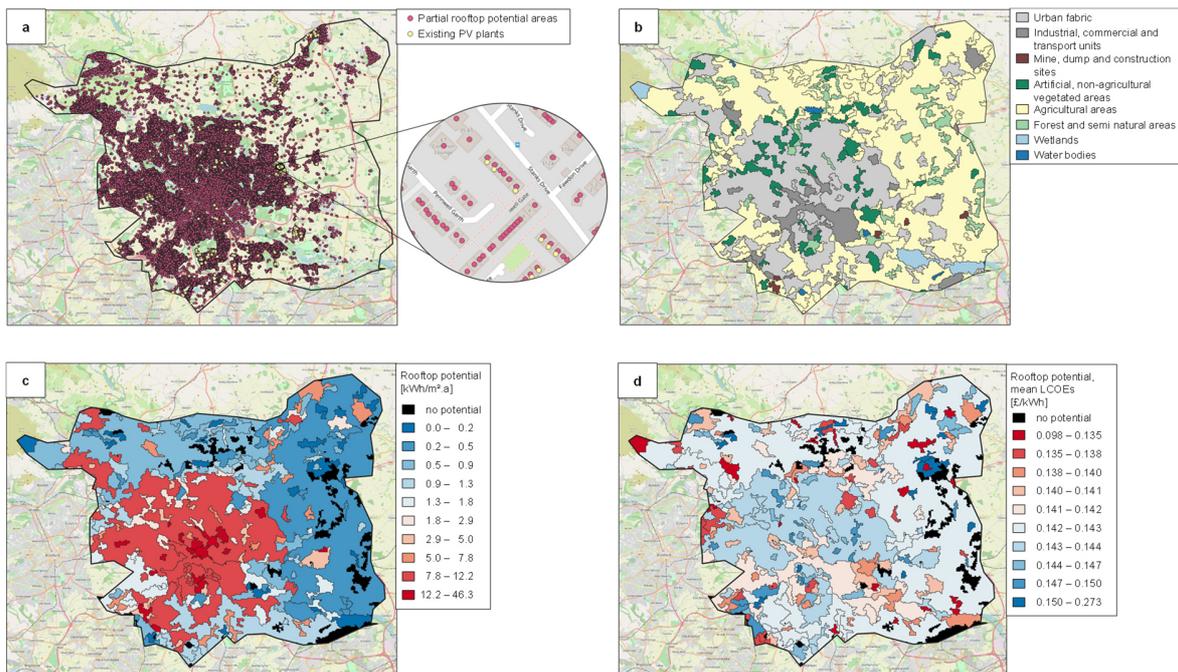


Figure 8: Results for PV rooftop and existing plants in Leeds: a) locations of partial rooftop areas and existing PV plants (from Stowell et al. (2020)), b) CLC land use categories c) technical potential (in kWh/m²) and d) LCOEs (£/kWh)

Despite several studies having assessed the national potential for onshore wind and rooftop PV (Table 7), relatively few peer-reviewed studies analyze 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 **Fehler! Verweisquelle konnte nicht gefunden werden.**, 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 (Greater London Authority, 2018). In addition, Calderdale Metropolitan Borough Council (2018) 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 (2011) 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 (2011) study assumes for domestic buildings that 25% of the existing stock and 50% of new build developments represent technically accessible resources. 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% usable 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 (2011) are therefore multiplied by a factor of eight (i.e. the product of the previously-mentioned factors).

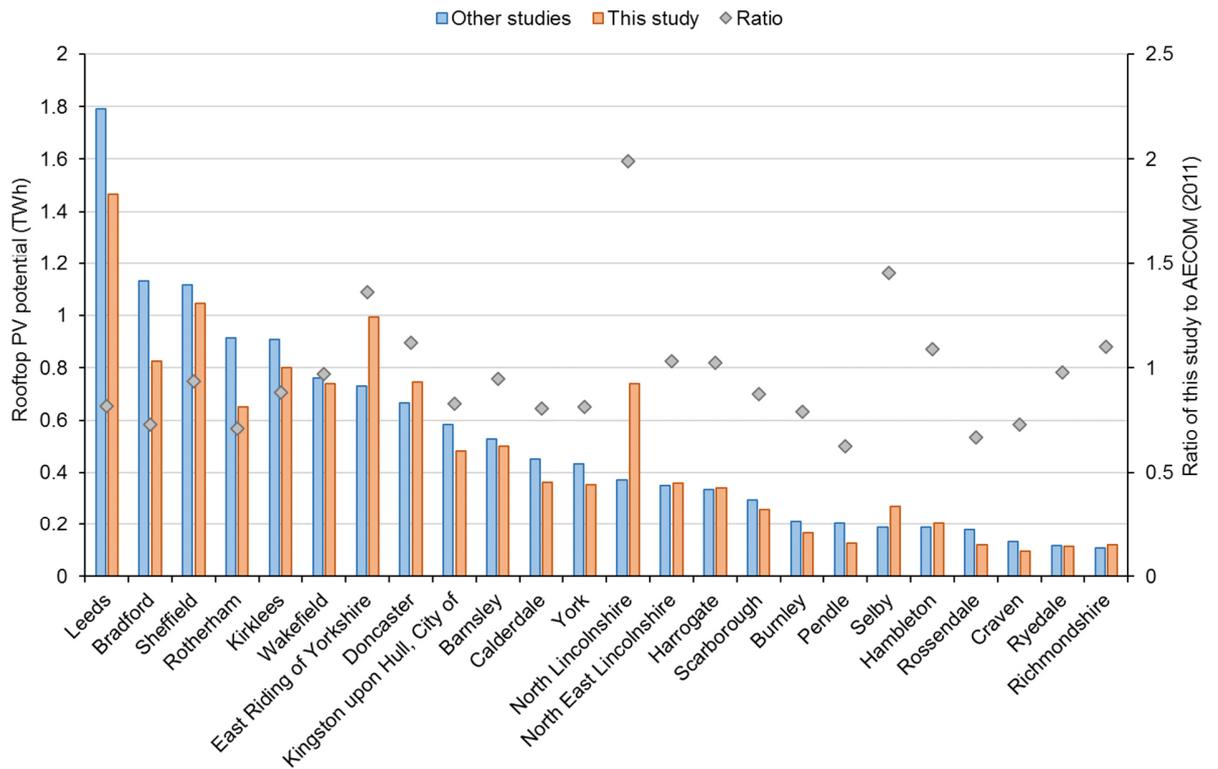


Figure 9 shows the results of the present paper for rooftop PV in comparison to those from AECOM (2011), whereby the left axis displays the generation potential and the right axes specifies the ratio between this study and the other study. Whilst there is clearly a wide variation in the rooftop-PV potentials 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 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

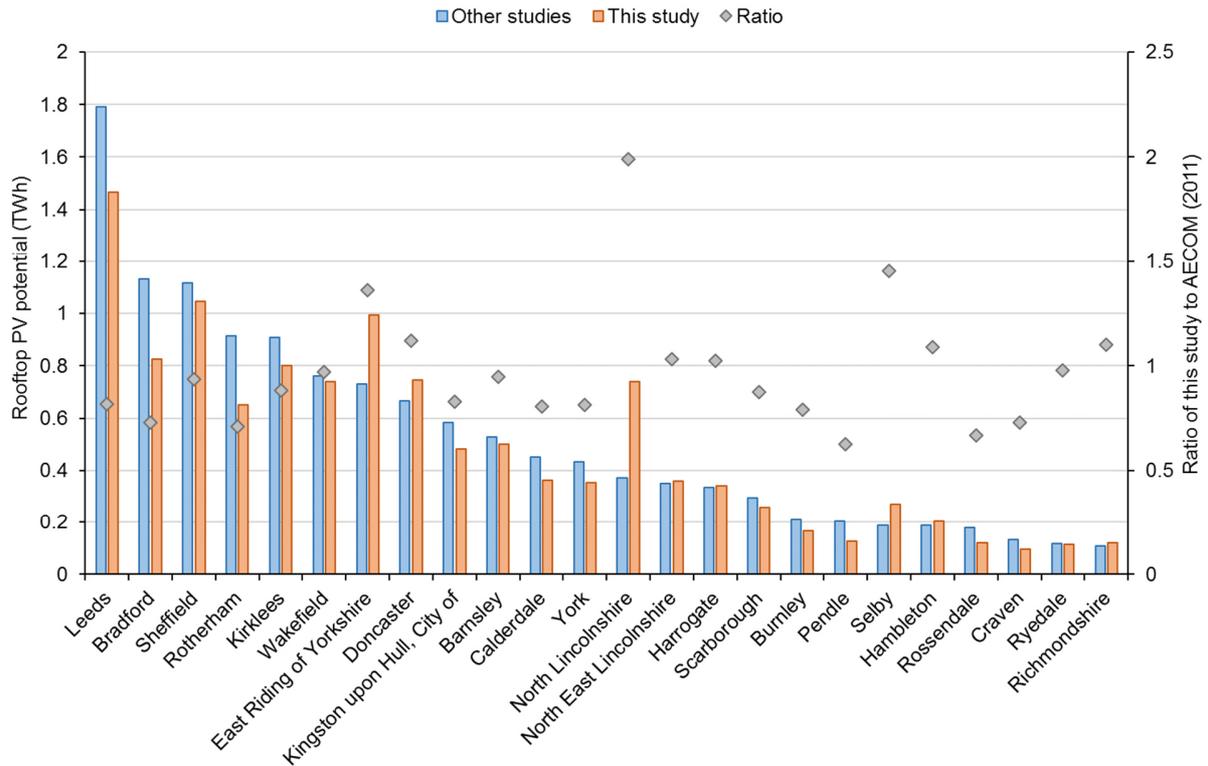


Figure 9. Due to having 13 land use categories (MHCLG, 2020) and only 24 observations (cities), we aggregated land use categories in order to reduce the number of model coefficients, as shown in Equation 7 below. Table 5 shows the descriptive statistics for this dataset.

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

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 (2011); 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. Number of observations is 24.

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.

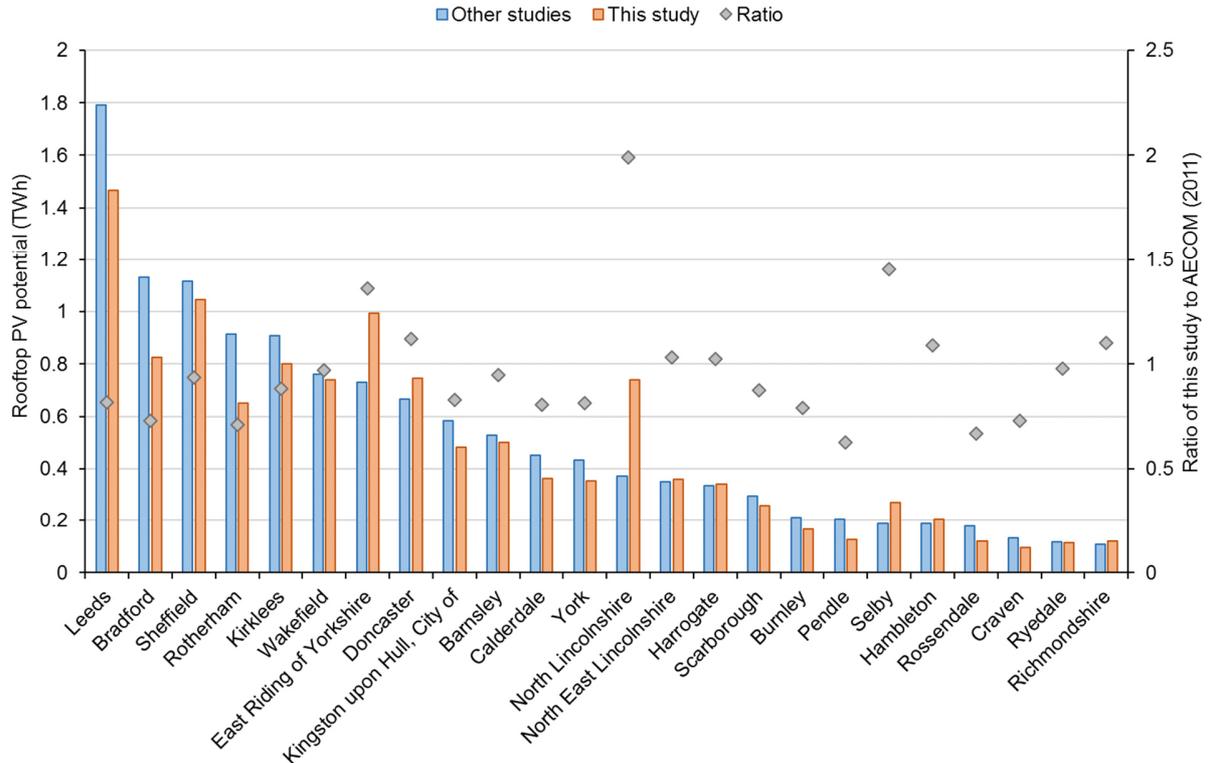


Figure 9: Comparison of results of this study for rooftop PV with those of AECOM (2011) (left hand axis) and the ratio of the two (right hand axis)

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 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.

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 below 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 44-540 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. Certainly for the rooftop PV, the results are closer to the studies for feasible potential¹, especially the recent one from Vivid economics and ICL (2019).

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 (2011); 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.

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 can be found in McKenna et al. (2020).

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. (2019)		44	UK	Technical
UK PMA (2009)		460	UK	Technical
Defaix et al. (2012)		80	UK	Technical
ETSU (1999)	318	266 (BIPV#)	UK	Total accessible
Vivid economics and ICL (2019)	215-479 [§]	35 [§]	GB	Feasible
MacKay (2008)	4700	115*	UK	Technical
Dalla Longa et al. (2018)	1391		UK	Technical

Enevoldsen et al. (2019)	2302		British Isles	'Socio-technical'
Ryberg et al. (2019)	2262		UK	Technical
EEA (2009)	3961-4409		UK	Technical
(McKenna et al., 2015)	1274		UK	Technical
This study	1324	153	GB	Technical

* South facing roofs only; # Building-integrated PV; § Based on 37 GW with 950 h FLH and 96-214 GW with 2240 h FLH for rooftop PV and wind respectively (BEIS, 2020b).

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. 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, and a land use database such as CORINE or equivalent is available.

6. Conclusions and policy implications

In this concluding section, we reflect 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.

British planning policy and the 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 (Scottish Government, 2017) and net zero commitments are embedded in the 2020 4th National Planning Framework (Scottish Government, 2020). 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 (Welsh Government, 2005). The 2021 National Development Framework (Welsh Government, 2021) 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 (Smith, 2016).

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 (Bridge et al., 2013; Roelich and Gieseckam, 2019). 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 (Bhardwaj et al., 2019).

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 coherent with energy policy across all jurisdictions in order to provide an enabling environment for local energy developments (CCC, 2020b; HoC, 2019).

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. Five key issues/recommendations for research and policy can be highlighted in this regard.

First, while some trade-offs are inevitable, having an overarching national strategic vision for land use across GB embedded within planning regimes can provide clarity for developers and decision-makers alike. Planning has evolved from being underpinned by the notion of the 'public interest', and more recently around the similarly ambiguous objective of 'sustainable development' (Maidment, 2016). 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 (CCC, 2020a). 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 (CCC, 2019; PÖYRY, 2011). 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 (Rohe and Chlebna, 2021; Smith, 2007).

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 decarbonisation. The Energy Systems Catapult (2018) 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 need to take place in the context of such whole-system cost assessments (BEIS, 2020a). 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 (McKenna et al., 2021c; Price et al., 2020).

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 (regen and Electricity Storage Network, 2020). 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 (Climate Assembly UK, 2021; Mellier-Wilson and Toy, 2020). 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.

7. Acknowledgements

The authors gratefully acknowledge the contributions of David Schlund, who carried out some of the wind analysis whilst a Student Assistant at KIT, as well as Camille Moutard, upon whose Master Thesis at DTU this article builds (*Assessing the 'acceptable' onshore wind potential in the UK*, 2019, <https://findit.dtu.dk/en/catalog/2451029061>). The usual disclaimer applies.

8. Appendices

A list and maps of the Local Authority regions employed in this analysis is shown in Figures 10, 11 and 12 below.

1	Hartlepool	65	South Cambridgeshire	129	Canterbury	193	Rushcliffe	257	Trafford	320	Belfast
2	Middlesbrough	66	Allerdale	130	Dartford	194	Cherwell	258	Wigan	321	Causeway Coast and Glens
3	Redcar and Cleveland	67	Barrow-in-Furness	131	Dover	195	Oxford	259	Knowsley	322	Derry City and Strabane
4	Stockton-on-Tees	68	Carlisle	132	Gravesham	196	South Oxfordshire	260	Liverpool	323	Fermanagh and Omagh
5	Darlington	69	Copeland	133	Maidstone	197	Vale of White Horse	261	St. Helens	324	Lisburn and Castlereagh
6	Halton	70	Eden	134	Sevenoaks	198	West Oxfordshire	262	Sefton	325	Mid and East Antrim
7	Warrington	71	South Lakeland	135	Folkestone and Hythe	199	Mendip	263	Wirral	326	Mid Ulster
8	Blackburn with Darwen	72	Amber Valley	136	Swale	200	Sedgemoor	264	Barnsley	327	Newry, Mourne and Down
9	Blackpool	73	Bolsover	137	Thanet	201	South Somerset	265	Doncaster	328	Ards and North Down
10	Kingston upon Hull, City of	74	Chesterfield	138	Tonbridge and Malling	202	Cannock Chase	266	Rotherham	329	Clackmannanshire
11	East Riding of Yorkshire	75	Derbyshire Dales	139	Tunbridge Wells	203	East Staffordshire	267	Sheffield	330	Dumfries and Galloway
12	North East Lincolnshire	76	Erewash	140	Burnley	204	Lichfield	268	Newcastle upon Tyne	331	East Ayrshire
13	North Lincolnshire	77	High Peak	141	Chorley	205	Newcastle-under-Lyme	269	North Tyneside	332	East Lothian
14	York	78	North East Derbyshire	142	Fylde	206	South Staffordshire	270	South Tyneside	333	East Renfrewshire
15	Derby	79	South Derbyshire	143	Hyndburn	207	Stafford	271	Sunderland	334	Na h-Eileanan Siar
16	Leicester	80	East Devon	144	Lancaster	208	Staffordshire Moorlands	272	Birmingham	335	Falkirk
17	Rutland	81	Exeter	145	Pendle	209	Tamworth	273	Coventry	336	Highland
18	Nottingham	82	Mid Devon	146	Preston	210	Babergh	274	Dudley	337	Inverclyde
19	Herefordshire, County of	83	North Devon	147	Ribble Valley	211	Ipswich	275	Sandwell	338	Midlothian
20	Telford and Wrekin	84	South Hams	148	Rossendale	212	Mid Suffolk	276	Solihull	339	Moray
21	Stoke-on-Trent	85	Teignbridge	149	South Ribble	213	Elmbridge	277	Walsall	340	North Ayrshire
22	Bath and North East Somerset	86	Torridge	150	West Lancashire	214	Epsom and Ewell	278	Wolverhampton	341	Orkney Islands
23	Bristol, City of	87	West Devon	151	Wyre	215	Guildford	279	Bradford	342	Scottish Borders
24	North Somerset	88	Eastbourne	152	Blaby	216	Mole Valley	280	Calderdale	343	Shetland Islands
25	South Gloucestershire	89	Hastings	153	Charnwood	217	Reigate and Banstead	281	Kirklees	344	South Ayrshire
26	Plymouth	90	Lewes	154	Harborough	218	Runnymede	282	Leeds	345	South Lanarkshire
27	Torbay	91	Rother	155	Hinckley and Bosworth	219	Spelthorne	283	Wakefield	346	Stirling
28	Swindon	92	Wealden	156	Melton	220	Surrey Heath	284	Gateshead	347	Aberdeen City
29	Peterborough	93	Basildon	157	North West Leicestershire	221	Tandridge	285	City of London	348	Aberdeenshire
30	Luton	94	Braintree	158	Oadby and Wigston	222	Waverley	286	Barking and Dagenham	349	Argyll and Bute
31	Southend-on-Sea	95	Brentwood	159	Boston	223	Woking	287	Barnet	350	City of Edinburgh
32	Thurrock	96	Castle Point	160	East Lindsey	224	North Warwickshire	288	Bexley	351	Renfrewshire
33	Medway	97	Chelmsford	161	Lincoln	225	Nuneaton and Bedworth	289	Brent	352	West Dunbartonshire
34	Bracknell Forest	98	Colchester	162	North Kesteven	226	Rugby	290	Bromley	353	West Lothian
35	West Berkshire	99	Epping Forest	163	South Holland	227	Stratford-on-Avon	291	Camden	354	Angus
36	Reading	100	Harlow	164	South Kesteven	228	Warwick	292	Croydon	355	Dundee City
37	Slough	101	Maldon	165	West Lindsey	229	Adur	293	Ealing	356	East Dunbartonshire
38	Windsor and Maidenhead	102	Rochford	166	Breckland	230	Arun	294	Enfield	357	Fife
39	Wokingham	103	Tendring	167	Broadland	231	Chichester	295	Greenwich	358	Perth and Kinross
40	Milton Keynes	104	Uttlesford	168	Great Yarmouth	232	Crawley	296	Hackney	359	Glasgow City
41	Brighton and Hove	105	Cheltenham	169	King's Lynn and West Norfolk	233	Horsham	297	Hammersmith and Fulham	360	North Lanarkshire
42	Portsmouth	106	Cotswold	170	North Norfolk	234	Mid Sussex	298	Haringey	361	Isle of Anglesey
43	Southampton	107	Forest of Dean	171	Norwich	235	Worthing	299	Harrow	362	Gwynedd
44	Isle of Wight	108	Gloucester	172	South Norfolk	236	Bromsgrove	300	Havering	363	Conwy
45	County Durham	109	Stroud	173	Corby	237	Malvern Hills	301	Hillingdon	364	Denbighshire
46	Cheshire East	110	Tewkesbury	174	Daventry	238	Redditch	302	Hounslow	365	Flintshire
47	Cheshire West and Chester	111	Basingstoke and Deane	175	East Northamptonshire	239	Worcester	303	Islington	366	Wrexham
48	Shropshire	112	East Hampshire	176	Kettering	240	Wycharon	304	Kensington and Chelsea	367	Ceredigion
49	Cornwall	113	Eastleigh	177	Northampton	241	Wyre Forest	305	Kingston upon Thames	368	Pembrokeshire
50	Isles of Scilly	114	Fareham	178	South Northamptonshire	242	St Albans	306	Lambeth	369	Carmarthenshire
51	Wiltshire	115	Gosport	179	Wellingborough	243	Welwyn Hatfield	307	Lewisham	370	Swansea
52	Bedford	116	Hart	180	Craven	244	East Hertfordshire	308	Merton	371	Neath Port Talbot
53	Central Bedfordshire	117	Havant	181	Hambleton	245	Stevenage	309	Newham	372	Bridgend
54	Northumberland	118	New Forest	182	Harrogate	246	East Suffolk	310	Redbridge	373	Vale of Glamorgan
55	Bournemouth, Christchurch and Poole	119	Rushmoor	183	Richmondshire	247	West Suffolk	311	Richmond upon Thames	374	Cardiff
56	Dorset	120	Test Valley	184	Ryedale	248	Somerset West and Taunton	312	Southwark	375	Rhondda Cynon Taf
57	Aylesbury Vale	121	Winchester	185	Scarborough	249	Bolton	313	Sutton	376	Caerphilly
58	Chiltern	122	Broxbourne	186	Selby	250	Bury	314	Tower Hamlets	377	Blaenau Gwent
59	South Bucks	123	Dacorum	187	Ashfield	251	Manchester	315	Waltham Forest	378	Torfaen
60	Wycombe	124	Hertsmere	188	Bassetlaw	252	Oldham	316	Wandsworth	379	Monmouthshire
61	Cambridge	125	North Hertfordshire	189	Broxtowe	253	Rochdale	317	Westminster	380	Newport
62	East Cambridgeshire	126	Three Rivers	190	Gedling	254	Salford	318	Antrim and Newtownabbey	381	Powys
63	Fenland	127	Watford	191	Mansfield	255	Stockport	319	Armagh City, Banbridge and Craigavon	382	Merthyr Tydfil
64	Huntingdonshire	128	Ashford	192	Newark and Sherwood	256	Tameside				

Figure 10: List of LA regions and codes employed in Figure 11 (ONS, 2020)

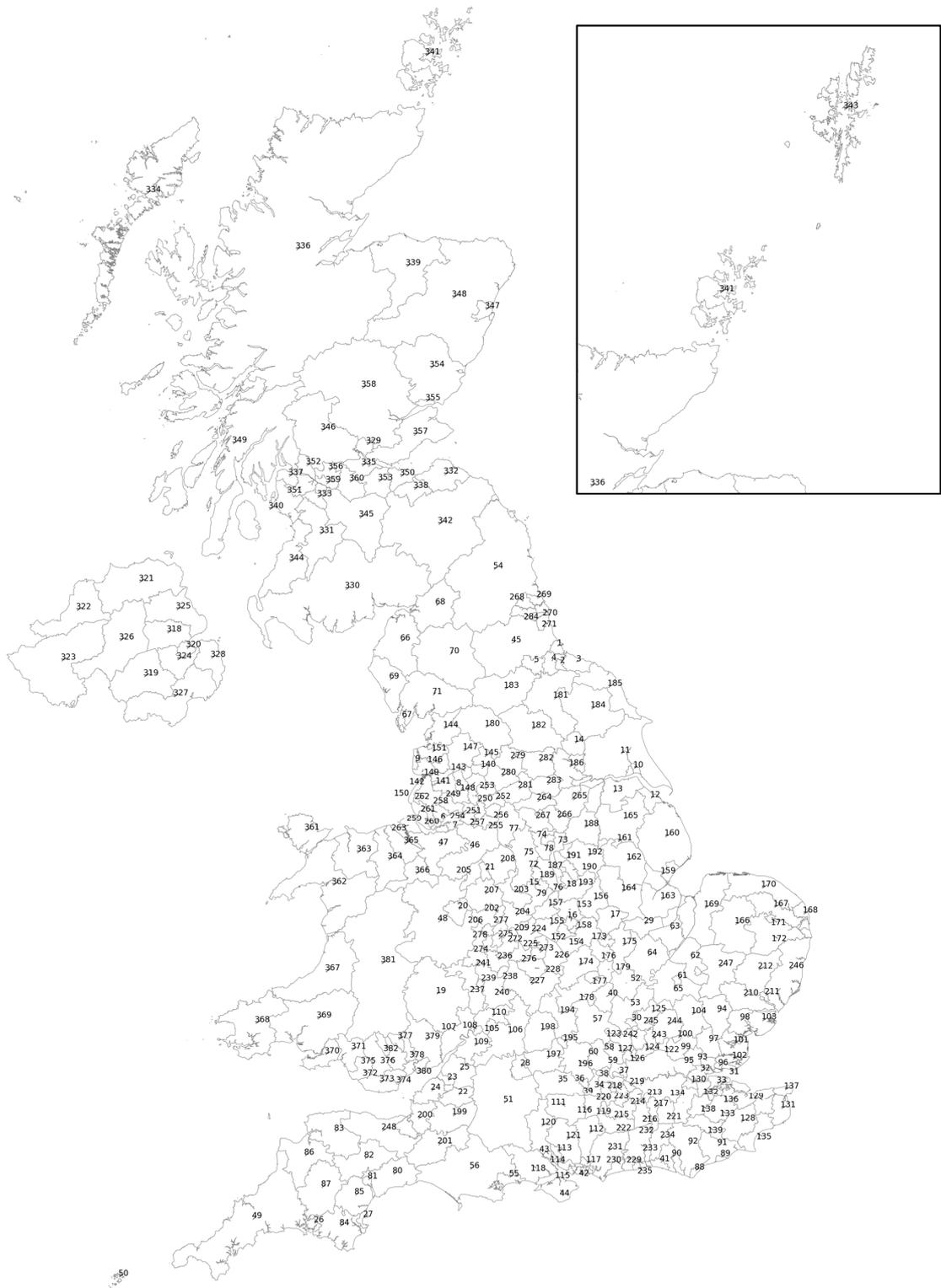


Figure 11: Map of UK showing numbered LA regions corresponding to the list in Figure 10 (the Shetland Islands are cut off in the north-east corner of the map due to space constraints) (ONS, 2020)



Figure 12: Detail of LA regions in Greater London, corresponding to those in the list in Figure 10 (ONS, 2020)

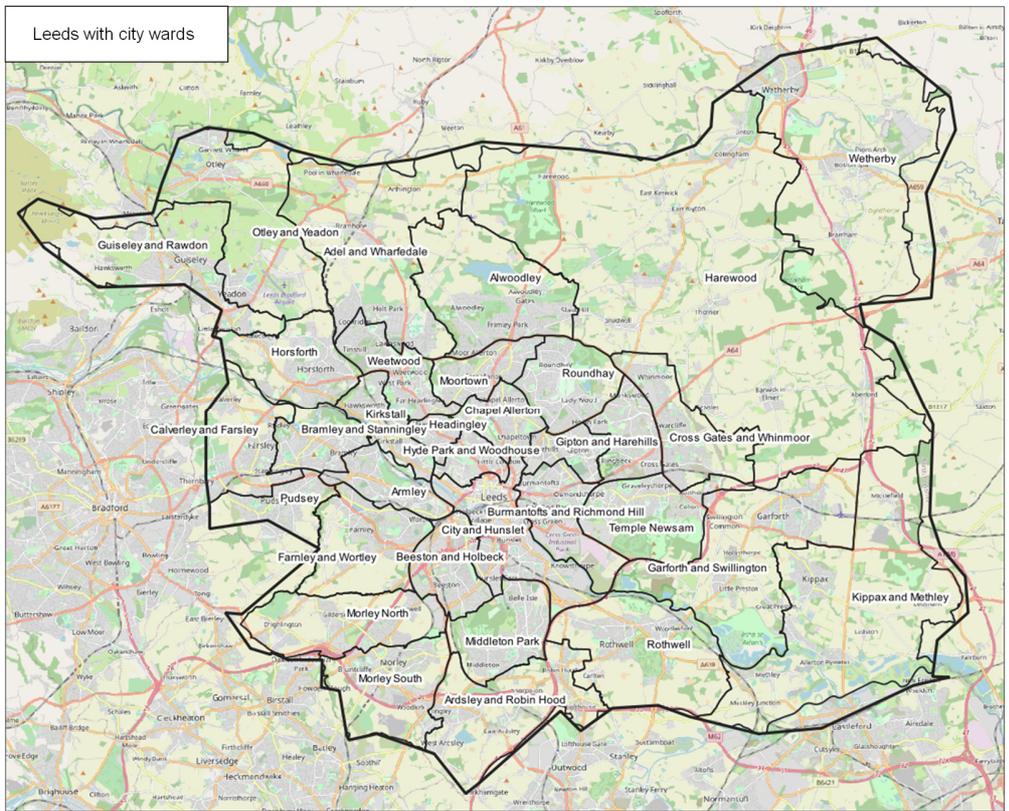


Figure 13: Map of Leeds city showing city wards for comparison with Figure 7 in the main text

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