Assessing socially acceptable locations for onshore wind energy using a GIS-MCDA approach

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Abstract

In the context of Great Britain, onshore wind provides the most cost-effective method of renewable electricity generation. However, projects often face opposition to development based on social issues, and there are concerns that existing geospatial modelling approaches fail to fully integrate these effects into their assessment. Building upon previous statistical analysis, this paper presents a geospatial multi-criteria decision analysis that integrates the technological, legislative and social constraints to determine suitable sites for onshore wind turbine development in Great Britain. The findings suggest that the capacity estimates for wind are less than 5% of what was previously estimated, yet opportunities remain for further exploitation of this resource.

Keywords: onshore wind; GIS; MCDA; social acceptance; Great Britain

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1 INTRODUCTION

Increased environmental concern and issues surrounding security of supply have led to a global drive to develop renewable energy systems. This has led to a large increase in the development of these technologies, which has resulted in significant interest in identifying suitable locations for these to be installed.

Whilst onshore wind power generation is now both a mature technology and competitive with traditional energy supplies in many countries, there are difficulties in identifying suitable sites to install wind turbine. To assist this development, many geospatial models have been proposed. However, there are concerns that current models provide limited actionable guidance, and, in particular, fail to account for the challenges faced in projects obtaining planning permission. This can be highlighted in the UK, where more than 50% of wind turbine projects in the UK are rejected at planning [1], suggesting that wind turbines are being proposed in areas which are socially unsuitable for the development. Such influences are currently poorly fitted into national models, and this can be reflected by previous national estimates for Great Britain that indicated the installed capacity could exceed 200 GW [2, 3], a figure which is generally considered well beyond that what is feasible, and well below the current installed onshore wind energy of 12 GW [1].

The overall objective of the programme of work, to which this paper contributes, is to build a predictive model for locating onshore wind turbine projects, integrating resource availability and the likelihood of a project receiving planning acceptance [4]. In the first stage, statistical analysis was conducted to identify the key influences for planning acceptance of onshore wind turbines [5]. This paper presents the second stage of the analysis, outlining the geospatial model developed for assessing site suitability and decision making for identifying suitable sites for wind turbine development.

Compared with previous methodologies, this study proposes a multi-level weighted sum method approach, which aims to address the concerns of combining non-commensurate dataset commonly used when assessing the site suitability of wind turbines. This approach helps to reduce the subjectivity which can often influence the outcome of such models and aims to provide a more accurate tool for capturing the social, technical and

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legislative restrictions which can impact the development of onshore wind technologies.

The work presented here has four parts: an overview of the literature relevant to onshore wind GIS modelling; a description of the research methodology; presentation of the model results; and, finally, discussion of the theoretical and practical implications of the research and further research opportunities.

2 BACKGROUND

Identifying suitable locations for onshore wind turbines requires the assessment of a range of largely geospatial parameters. As a result, there has been extensive use of Geographic Information Systems (GIS) which are designed to capture, store, manipulate, analyse, manage and present spatial or geographic data [6]. Such GIS approaches are often paired with Multi-Criteria Decision Analysis (MCDA) to provide a method to interpret the geospatial data and rank potential options from model data.

Early developments in onshore wind GIS-MCDA modelling started in the late 1990s [7, 8]. In recent years, there has been significant international interest to model wind turbine site suitability, and a range of methods have been developed [9–25]. These models typically are formed of the stages as shown in Figure 1. First, input parameters are selected covering environmental, technical and social. For example, ideal sites are typically identified as having high average wind speeds; not being close to urban areas; not in protected landscapes (e.g. National Parks); not close to airports (to minimize radar interference); close to roads for access; and finally, close to powerlines for grid connection. Each location is then scored against these input parameters, and incompatible areas are excluded from further analysis, such as areas that have already been developed (roads and buildings).

For remaining sites which could be developed, a score is calculated to assess the overall suitability of the site. While several techniques are used (including outranking technqiues such as ELECTRE [9]), the Weighted Sum Method (WSM) is

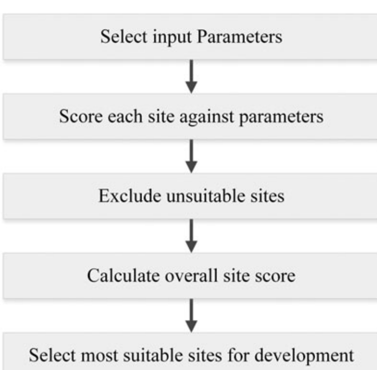

Figure 1. *An overview of the typical structure of GIS-MCDA methodologies.*

predominantly used as a method to combine the different layers into a single score as follows:

$$A_i^{\mathrm{WSM}} = \sum_{j=1}^{n} w_j a_{ij} \quad \text{for } i = 1, 2, 3, \ldots, N$$

where w is the parameter weighting, a is the parameter value and i is the attribute layer in the model. This rating can then be used to determine the most suitable sites for development.

A concern surrounding the WSM is that the method is often applied without any insight into the meanings of two critical elements: the weights assigned to attribute layers and the procedures for combining the layers [6]. While methods such as the Analytic Hierarchy Procedure (AHP) have been used to reduce the subjectivity of parameter weighting [19], models remain highly sensitive to the weightings used. In several studies, the selection of the weighting parameters was not fully explained [7, 14, 25, 26], and, as such, there are concerns that the model results provide the sub-optimal location of potential wind turbine development.

To address concerns of parameter weighting, there has been increased interest in quantitatively assessing which parameters influence the likelihood of wind turbines receiving planning permission [27, 28]. This approach has recently been integrated within GIS modelling to assess the influence of geospatial parameters in the UK [5]. This can be considered as a form of retrospective GIS analysis, where the existing spatial distribution of sites is assessed to enable prediction of where future turbines may be acceptable. The results suggest that the (1) *the turbine rated capacity*, (2) *percentage of the local population with high levels of qualifications*, (3) *the average age* and (4) *local political composition* emerge as key influences affecting planning approval, while other typically used parameters such as proximity to urban areas appear less influential. However, these findings have yet to be integrated into a GIS-MCDA.

Finally, the issue of the standardization of non-commensurate criteria within the WSM and GIS-MCDA has yet to be satisfactorily addressed. To create a single site, suitability score requires the combination of a range of economic, environmental and social parameters which cannot be directly summed together into a single scale. Many of the existing methodologies have avoided this issue by focussing on economic criteria only (*wind speed*, *distance to powerlines, etc.*) [15, 17, 22–24], but this method overlooks the social issues which often limit the suitability of sites for wind turbine development. In situations where economic and social parameters are combined, linear transformations are often used to standardize each variable to allow for them to be directly summed [9, 12, 19, 20, 29]. However, there is limited empirical justification for such approaches [30] and the results of such analyses are highly influenced by the inherent subjectivity of the weighting parameters are used.

The method proposed in this study aims to address the above concerns with existing methodologies. First, whilst traditional methodologies have combined different types of parameters (e.g. *economic*, *environmental*) into a single scoring parameter, this study proposes a multi-level approach whereby parameters are grouped into commensurate groups. In doing so, this reduces the subjectivity that is often introduced into parameter weighting used within WSM and AHP methods. Second, this study integrates the outcomes from previous statistical analysis that assesses the likelihood of a wind turbine receiving planning permission in Great Britain [5]. In doing so, the model aims to better more accurately locate suitable sites for the development of onshore wind turbines.

3 METHODOLOGY

The overall structure of the GIS model is shown in Figure 2, and the stages are described in the following subsections.

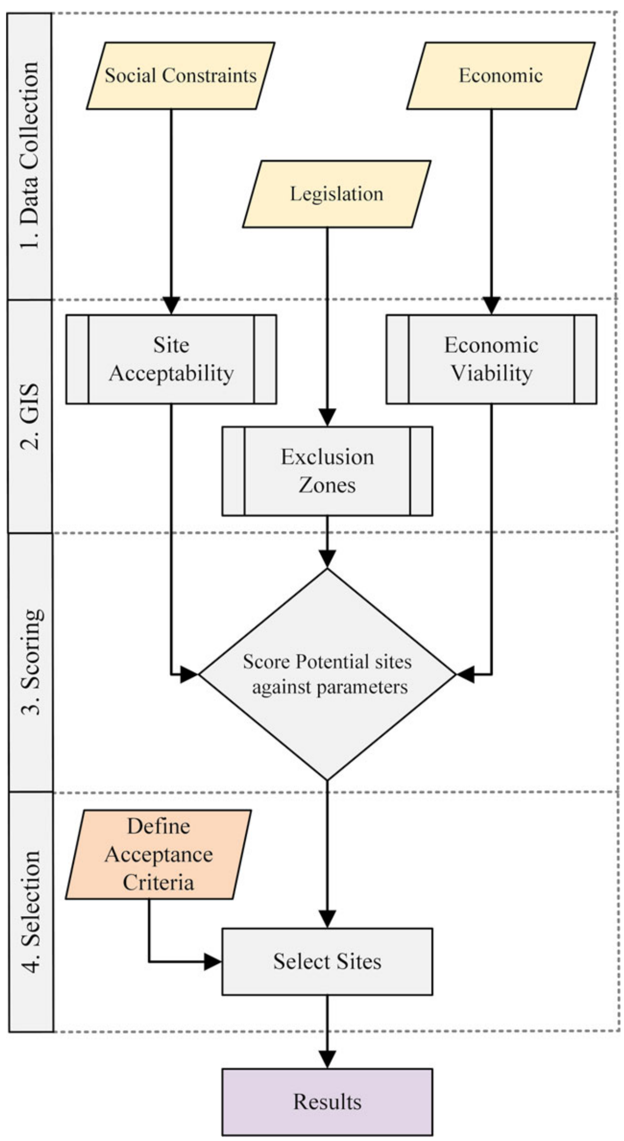

Figure 2. *Overview of the onshore wind GIS-MCDA structure.*

3.1 Model formation

A preliminary scoping study was conducted to formulate the model and identify parameters which influence wind turbine developments. The identification of criteria involves a systematic analysis of factors that may impact installation of the wind farms. This considered the academic work listed within the literature review, consultancy reports [16, 31] and wind turbine planning guidance [32].

The study was conducted across Great Britain (England, Scotland and Wales). This was chosen because of the broadly similar categorization of land types, nature designation, data availability and legislation across these regions. To allow for a more detailed understanding of the local effects, this paper also highlights the results from two case study areas, with the Solent and the Midlands regions selected as shown in Figure 3. These two areas were selected for several reasons:

- The regions are similar in size (4173 km^2 and 4214 km^2, respectively) with a mix of rural and urban areas and similar estimated population (1.1 and 1.3 million).
- Both regions have large areas which have been previously indicated for onshore wind turbine development. However, there are large differences in the number of wind turbines developed, with no wind turbines built in the Solent while more than 30 projects built in the Midlands [1].
- The author has local knowledge of the Solent region and previous wind turbine projects which have been proposed in the area.

Once key parameters were identified, relevant data were collected from a range of sources for geospatial [33, 34], environmental [35] and demographic variables [36]. A full explanation of the datasets is available within the previous statistical modelling [5].

3.2 GIS model

To overcome the limitation of existing MCDA studies, a layered model approach was used to separate non-commensurate datasets. Instead of combining variables into a single score, the suitability of sites was scored against three aggregated variables: (1) *Exclusion zones*, (2) *Economic viability* and (3) *Social acceptability*. These are explained in the following paragraphs.

Exclusion zones consider whether the site would technically be suitable for development. This was based on several sources of information: first, existing legislation and ecological guidance as discussed within the literature review. However, it was observed that there are few strict rules of where developments are allowed: for example, there is no legal specification for the minimum distance between a house and a turbine [37]. The existing development patterns of wind energy projects were, therefore, assessed to identify whether specific regions were avoided by developers. Based on this research, the following hierarchical taxonomy was developed to categorize the types of exclusion criteria:

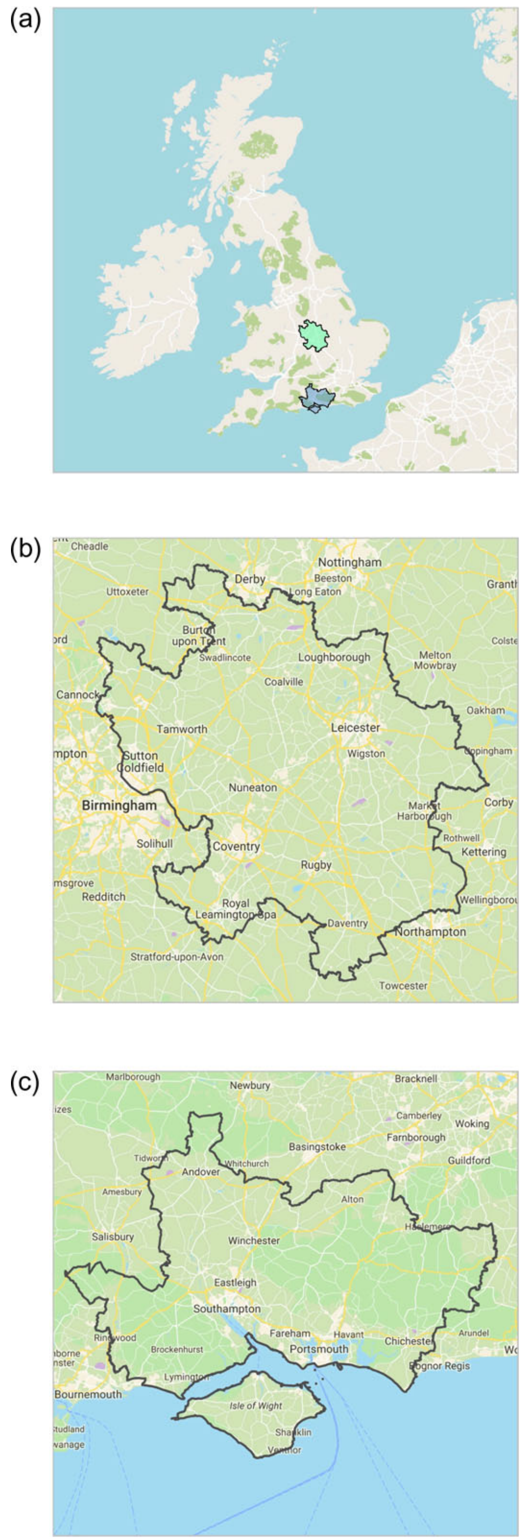

Figure 3. *Analysis extent and regions selected for case studies. (**a**) Overview map, (**b**) Midlands region and (**c**) Solent region.*

- *Hard planning criteria*: Legislative restrictions that prevent the development in specific areas. For example, wind turbines must not be built within a toppling distance of main roads. It is interesting to note that there are no minimum distances between dwellings and wind turbines.
- *Soft planning criteria*: Areas where there are no legislative restrictions but are generally avoided by onshore wind developers. These were derived from statistical analysis of existing wind energy planning applications. As an example, it is technically possible to build in National Parks; however, only two projects have been built within them and, therefore, these regions in the UK are largely considered as non-developable areas.
- *Buffer criteria*: Areas nearby sensitive features which are generally protected from development. While the site itself may not be designated, this explores whether there is any geospatial trend for sites to be located away from certain features. For example, wind turbines sites are not banned near airports or nearby national parks; however, these areas are frequently avoided by developers.

Table 1 highlights the parameters used within the layers and the exclusion distance used within each of the three scenarios.

Economic viability of the site assesses the potential cost effectiveness of a wind energy project. For wind projects, this is influenced by the (1) *Wind Speed*, (2) *Distance from national grid*, (3) *Site access* and (4) *Ground clearance* (site preparation) [17]. For this study, it was considered suitable to only use the first two parameters, as site access and ground clearance are primarily only issues in more sparsely countries. Annualized wind speed data were used [38], and logarithmic height transformations were used to account for the height of the wind turbine. The power curve for a typical 2 MW wind turbine [39] was used to calculate the energy yield based on a given wind speed.

Table 1. *Parameters and exclusion distances used within the model.*

Parameter	Exclusion distance		
	Hard planning criteria	Soft planning criteria	Buffer criteria
Airports	0	2.00	10.00
Roads	0.15	0.15	0.15
Railways	0.15	0.15	0.15
Military sites	–	0.00	10.00
Urban areas	–	0.00	2.00
Powerlines	0.15	0.15	0.15
Landscape designations[a]	–	0.00	2.00
Nature designations[b]	–	0.00	2.00

[a]National Parks, Areas of Outstanding Natural Beauty, Heritage Coast.
[b]National Nature Reserves (NNR), Natura 2000, Special Protection Areas (SPA), Sites of Special Scientific Interest (SSSI).

Table 2. *Parameters determined to influence the planning acceptance of wind turbines.*

Variable	Unit	Odds ratio	Estimate	Note
Turbine capacity MW	MW	1.418	0.349	Set as 2 MW (a single turbine)
Year	year	0.889	−0.117	Set as 2017
Distance to railways	km	1.018	0.018	
Distance to urban region	km	1.139	0.130	
Distance to AONB	km	1.015	0.015	
Distance to National Park	km	1.026	0.025	
Distance to Ramsar	km	1.015	0.014	
Distance to Natura 2000	km	0.984	−0.017	
Qualifications, L4	% of population	0.968	−0.032	
Mean age	years	0.959	−0.042	
Political, labour share	% of local council	1.004	0.004	
Nearest turbine (operational)	km	0.985	−0.015	
Nearest turbine (rejected)	km	1.019	0.019	

Finally, *Social acceptability* predicts the likelihood of a project receiving planning permission. This layer is based on previous analysis which used logistic regression methods to identify the key influential parameters that determine whether a wind turbine successfully obtained planning consent [4, 5]. An overall predictive accuracy of 63% was achieved with the model, with the most influential parameters shown in Table 2. The odds ratio (OR) shown indicates how much the predicted planning acceptance rate changes for each unit of the parameter. The OR and estimates are presented; an OR = 1 indicates that the parameter does not affect odds of the planning outcome, an OR > 1 indicate that the parameters positively influence planning acceptance, and an OR < 1 represents a negative parameter influence. For example, for each km, a site is further away from an urban region, its likelihood of receiving planning approval increases by 0.13%.

Each of the layers was calculated as a raster layer, with a spatial resolution of 250 m, with input data being resampled to this spatial resolution. This resolution was selected as it is high enough to model a suitable site for a single turbine whilst being computationally efficient to calculate values across the study area, and such a figure is comparable to previous national studies [24, 25]. Several studies have used resolutions of 100 m [14, 19], but these have focussed on a smaller study regions than considered within this report.

The analysis was conducted using the programming language *R* [40] with supporting geospatial packages *raster* [41] and *sp* [42]. Data visualizations were produced using the package *ggplot2* [43] and *treemapify* [44].

3.3 Multi-criteria decision analysis

The model considered the suitability of a site for the installation of single wind turbines and was based on a 2 MW wind turbine which represents the average size of onshore turbines constructed in 2016 [39]. Based on planning guidance, a spacing between turbines of 500 m was used [32], resulting in a development density of 8 MW/km^2.

As shown in Figure 4, each site is categorized based on its economic viability (*X*-axis) and site suitability (*Y*-axis), with four types of suitability defined (low/potential/good/excellent). More flexibility is given to the site suitability parameter to reflect that there is less certainty to this value. To estimate the potential capacity of sites that could be developed, all sites that score '*Excellent*' or '*Good*' were selected as suitable for development. Finally, sensitivity analysis was used to explore the variability of these scoring criteria on the predicted capacity estimates.

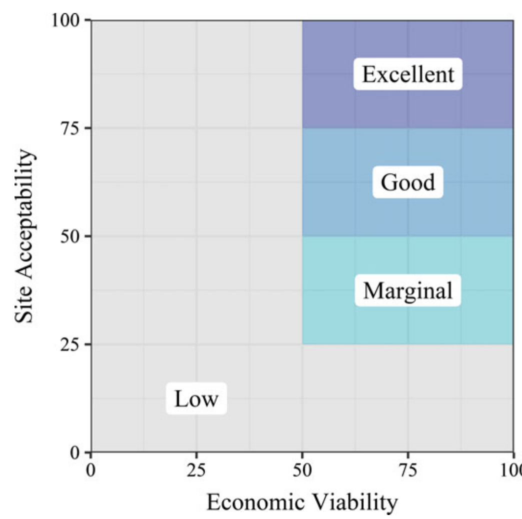

Figure 4. *Two-dimensional classification rules used to assess site potential within the GIS-MCDA.*

4 RESULTS

The results from the geospatial model layers are presented in Figure 5, which shows the three separate layers of the analysis (economic viability, site acceptability and legislative exclusion). These layers are combined to determine the site suitability score displayed under the medium development restriction scenario, as shown in Figure 6. Nationally, it can be seen from the results

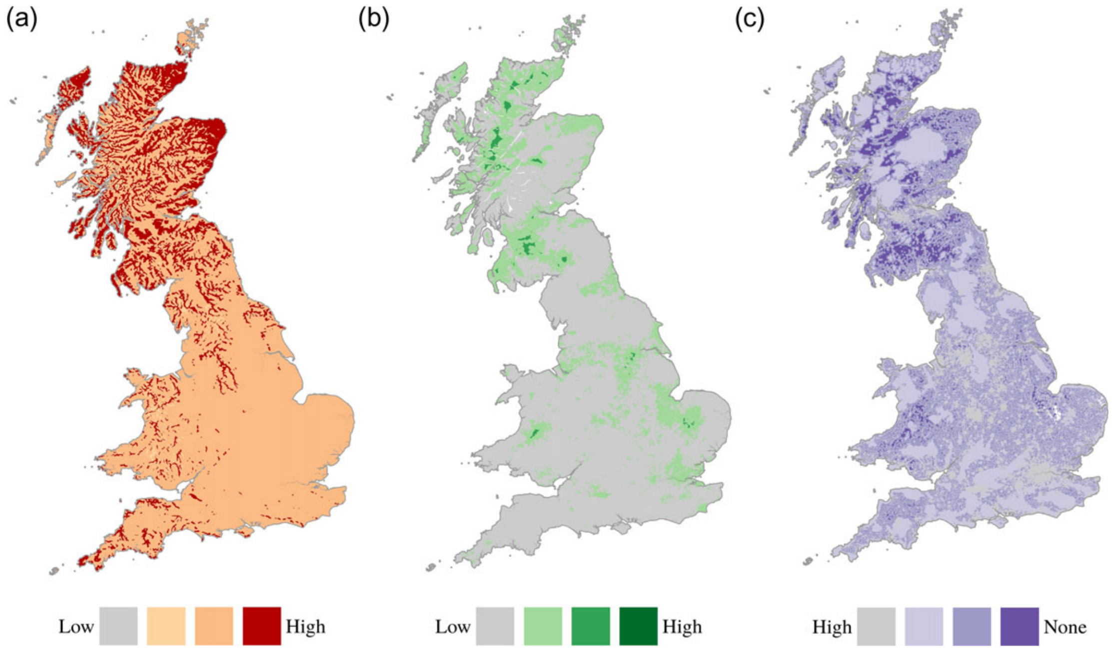

Figure 5. *Results for the three onshore wind GIS layers within the model. Darker colours indicate desirable characteristics for wind turbine sites. (**a**) Economic viability, (**b**) site acceptability and (**c**) exclusion.*

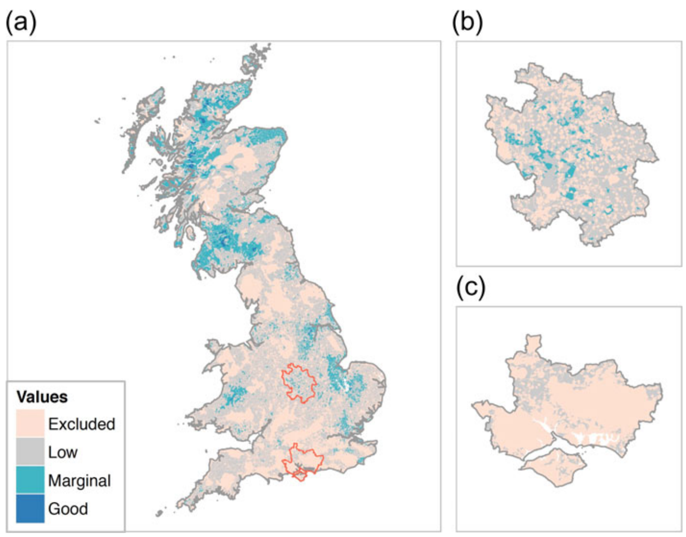

Figure 6. *Comparison of wind turbine potential under the medium development scenario. (**a**) National, (**b**) Midlands region and (**c**) Solent region.*

that sites appear to be more suitable within Scotland, East of England and mid Wales. For the Solent region, 77% of the land was excluded with no sites being deemed 'Good' or 'Excellent' for wind development. In comparison, 45% of the Midlands region was excluded for development with 1.2 GW of potential site capacity identified from suitable sites.

Table 3 provides a cross-tabulation of suitability scores against the exclusion criteria, to assess the impact of each of the three exclusion regions on national development patterns. Sites assessed higher than 'Good' and outside of 'Soft Criteria' were considered as potentially suitable for development. Such sites cover 0.74% of the country and represent 13 GW of potential capacity if fully utilized.

Table 3. *Site score suitability matrix comparing exclusion criteria against site suitability, coverage of land covered by each classification.*

Suitability score	Hard criteria	Soft criteria	Buffer criteria	No exclusion	Total
Low	11.43	25.58	37.7	2.82	77.5
Marginal	2.78	5.9	8.98	3.07	20.72
Good	0.07	0.93	0.51	0.23	1.74
Excellent	0	0.005	0.003	0	0.008
Total	14.275	32.418	47.186	6.12	100

The comparative suitability of the regions can also be explored through density plots as shown in Figure 7. As explained in Figure 4, each non-excluded site is represented as a point, and the regional variation in acceptability and economic viability can be viewed on separate scales. The site acceptability within the Solent region is generally less than the national average and the Midlands, although the economic viability is generally similar.

Figure 8 displays the results of the sensitivity analysis of the model. The figures highlight how the predicted overall capacity varies depending on the combination of the three model layers. For example, if we only require the '*Hard*' planning criteria, have an economic viability of 25 and acceptance rate of 5, our

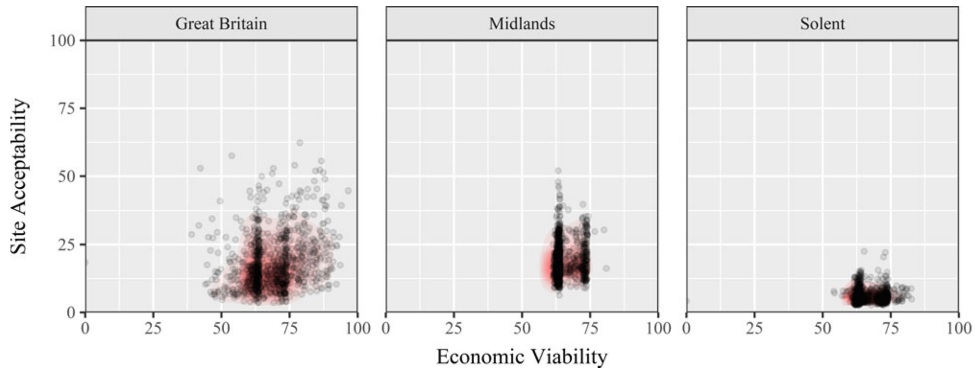

Figure 7. *Two-dimensional density plots for wind turbine sites within the Midlands and Solent regions.*

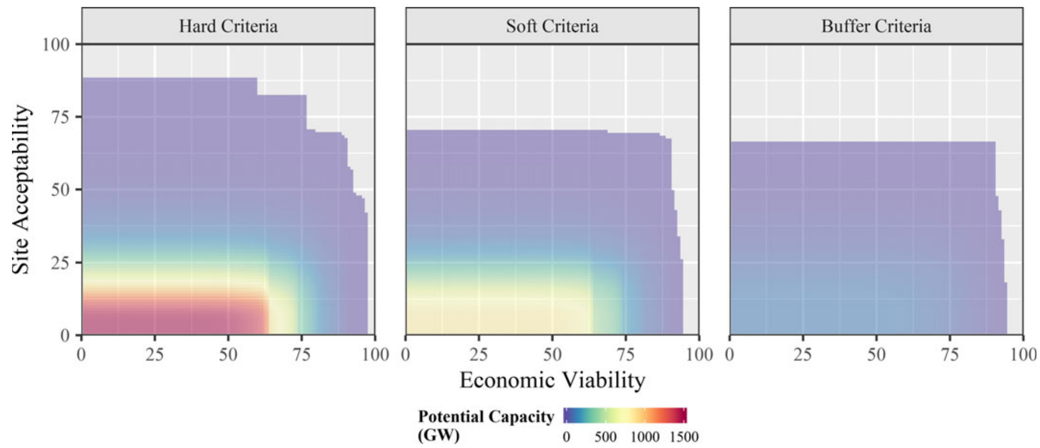

Figure 8. *Sensitivity analysis of model results within the onshore wind GIS-MCDA.*

overall capacity for wind installation would exceed 1500 GW if all potential land was developed. This figure helps explain the sensitivity of the model caused by varying input assumptions.

It can be seen that there are large amounts of variation within site acceptability across the study region, with Scotland being highly suitable compared to many parts of England and Wales. This is further highlighted by Figure 9, with the treemap comparing the area of administrative regions against the estimated resource potential from the model. The graph highlights how there is a disproportionate availability of suitable onshore wind sites within Scotland, and how a select number of administrative areas have access to a large proportion of the wind resource. In particular, the Highlands, Dumfries and Golloway and Aberdeenshire over 30% of the national wind resource, despite covering only 19% of the land area.

5 DISCUSSION

The analysis suggests that for Great Britain, 13 GW of onshore wind would be highly suitable within a medium development restriction scenario, which considered the '*hard*' and '*soft*' planning criteria. If the stricter '*buffer*' criteria are met, the estimated capacity is reduced to 4 GW. Both these estimates are significantly lower than previously estimated capacity limit figure of 200 GW [2, 3]. This highlights the impact of considering likelihood of planning acceptance within the GIS-MCDA and the constraint this places on development, and suggests that the UK is nearing its capacity for socially acceptable wind turbine sites in the UK.

The case studies of the Solent and Midlands highlight the regional variations in onshore wind potential resource as shown in Figures 6 and 7. From a resource perspective, the Solent area is highly suitable with many hilly regions and its coastal location offering high wind speeds. However, the opportunity for development is limited by National Parks and Areas of Outstanding Natural Beauty (AONB), and the sites that are located outside of these regions are largely unsuitable for development due to the demographic composition. In comparison, the Midlands region faces much less restriction in where developments could be made and presents much greater opportunity for future development despite the nominally lower wind resource.

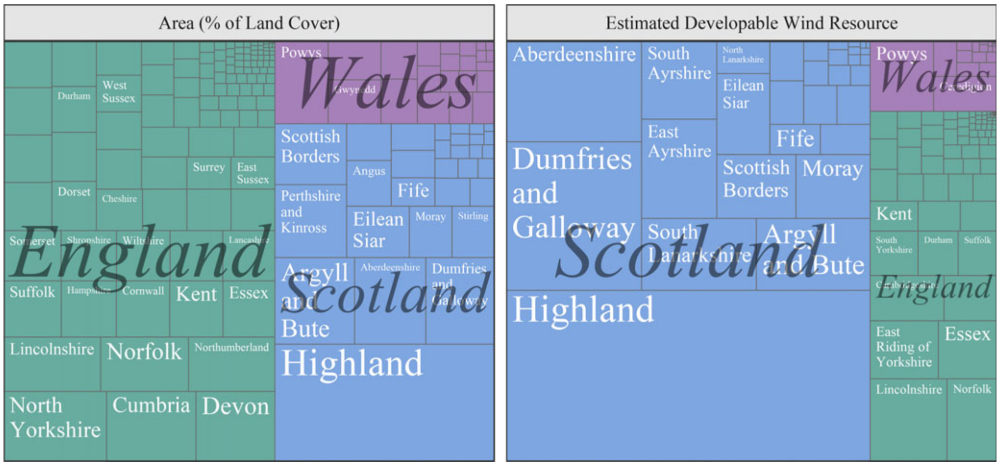

Figure 9. *A treemap comparing the area against the estimated resource for counties within Great Britain.*

The results further highlight that cost is not the dominant issue in determining the suitability of a wind energy site, as wind speeds are largely satisfactory and, in Great Britain, most sites are an acceptable distance to powerlines for a wind turbine to be economic. A number of previous studies have placed a high weighting on wind resource [22, 24, 45], reflecting the interest of the developer to maximize returns. In reality, it may be the developers' interest to select a less windy site that is more likely to receive planning permission.

On a national level, it is important to consider the distribution of potential sites and the consequent impact this may have on the electricity transmission network. As demonstrated in Figure 7, the GIS-MCDA results indicate that regions in Scotland are most suitable for development; however, such areas are distant to large load centres such as cities, requiring transmission networks or energy storage to be upgraded [46].

The layered approach used within this methodology allows the results to be more easily interpreted and reduces the concerns surrounding standardization of parameters. Rather than assessing sites using a single parameter, we can understand whether a site is likely to be acceptable to the three different stakeholders i.e. government (legislative), developers (economic) and local population (planning acceptance).

6 LIMITATIONS AND FUTURE WORK

Geospatial models are highly influenced by the availability and quality of the data provided for the analysis. In this case, wind speed is only available at 1 km resolution and does not account for roughness of surface caused by urban developments of varying land cover such as forests [38]. The errors from any dataset would have propagated through the analysis and, combined with errors from other layers, may cause inaccuracies in the output map. Future work will, therefore, expand upon the sensitivity analysis of these results to better capture such error.

Whilst the analysis has tried to understand the chance of a project being accepted, it has only considered parameters which can be geospatially modelled. As previous studies have highlighted, such parameters in themselves only provide part of the explanation as to why wind farms are accepted [5, 37, 47]. Greater emphasis must also be placed on non-geospatial issues such as the planning process and local engagement of a wind project if it is to be successful at planning.

The analysis has also not considered the impact of electricity transmission networks, and the potential requirement of grid reinforcement. It is already being seen in the UK that grid reinforcement is being made to transfer electricity and this is becoming a limiting factor in the development of renewable energy projects [48]. The majority of sites identified as suitable for development are distant from large load centres, and, therefore, would place additional strain on the transmission network to transfer this electricity across the country. Such issues are more likely to determine the development patterns of future onshore wind projects in Great Britain.

The model only considers the suitability of individual wind turbines and does not assess whether an area is suitable for development of a larger wind farm. There would be economies of scale in proposing a single larger development, and as such, these locations would be preferential to developers. Calculating larger areas of turbines would require more detailed knowledge in land ownership and transmission networks; however, this methodology would form an essential part of such detailed analysis.

The analysis did not consider the influence of the cumulative number of wind turbines within a certain area. It is not fully understood within literature whether there is a limit to the development potential of wind turbines, although some evidence suggests that regions can reach a saturation level [49]. Many of the areas which have been proposed within the model have already got large levels of installed onshore wind [1] which may influence the acceptance of future projects.

7 CONCLUSION

The authors have presented a GIS-MCDA which can be used to assist in locating onshore wind turbines. Although previous studies have attempted to assess the social impacts of wind turbines, this is the first study to the authors' knowledge that has directly included the likelihood of the wind turbine receiving planning acceptance within a geospatial model. Consequently, the results of this model have highlighted that the potential resource is significantly lower than previous estimates, but there appear to be opportunities for further development of onshore wind turbines within Great Britain.

A second novel aspect of this approach developed was through the use of a layered GIS-MCDA approach. Instead of combining non-commensurate data into the decision-making process, input parameters were aggregated into three layers: (1) *Social acceptability*, (2) *Economic viability* and (3) *Legisilative restrictions*. By avoiding the use of standardization often used within the WSM, there is less distortion to the input data and a reduction of the potential errors within the model results. This also provides greater insight into the model results as it is easier to understand the factors influencing site suitability.

Using two case studies, the results have shown how the onshore wind capacity can vary significantly for similar types of regions within the same country. This can be influenced by physical restrictions such as landscape and nature designations, or '*hidden*' factors such as local demographics and political composition. It is, therefore, important that these factors are understood when wind turbines are being considered within a region to be able to derive more realistic capacity estimates.

The findings of this study can be used by a range of stakeholders to improve the planning and development of wind turbines. As examples, regional planners could more accurately estimate the potential capacity within their region, and project developers could gain a greater understanding of where sites should be proposed to increase the likelihood of receiving planning permission. However, these results should support, not replace, local level planning.

Whilst the analysis was completed within Great Britain, the concepts developed can be applied internationally. It should be noted, however, that the specific planning acceptability data will have to be that of the region to be studied [5], as planning acceptance and legislative restrictions are likely to be highly region specific.

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