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Research paper

Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation

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HIGHLIGHTS

- We have assessed central Southern England for wind and solar energy suitability.
- We apply a method with expert validation to two related types of renewable energy.
- A high number of environmental constraints limit suitability for renewables.
- The region is less suitable for wind energy generation than for solar developments.

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ABSTRACT

As global growth in renewable energy projects accelerates, site identification will come to the forefront, where a key consideration is to minimise the environmental impact of the development. A large area of southern England (17,094 km^2) was assessed for suitability for wind and solar farm developments in three stages using geographic information systems. A multi-criteria decision making framework incorporating an analytical hierarchy process involving expert stakeholders was applied, which is a novel approach for this type of study. A binary constraint layer was created identifying entirely unsuitable locations. A factor layer was developed to indicate suitability in relation to a range of variables. Suitability layers for wind farm and solar farm development were then created covering the region. The environmental constraints used in the model accounted for over 60% of the study area for both wind and solar developments. Suitability for wind energy was generally low, with only 0.5 km^2 accounting for the 'most suitable' category. Solar suitability was higher overall; and a greater area (294 km^2) within the 'most suitable' category, suggesting the region is better suited for solar farm developments. Stakeholder input resulted in higher weightings for economic considerations for the solar model, prompting the most suitable areas to coincide with locations of the national grid connections. A sensitivity analysis indicated that model was generally reliable. This method can be used to assist appropriate site selection for onshore renewable energy projects across large geographical areas, helping to minimise their environmental impacts.

1. Introduction

In response to a range of international and national policy drivers, the installed global renewable energy capacity doubled between 2000 and 2012. Worldwide, wind and solar photovoltaics (PV) were two of the fastest growing electricity generation technologies. For example, in 2012 in the United States, cumulative installed wind capacity increased by nearly 28% and cumulative installed solar PV capacity grew more than 83% from the previous year (US Department of Energy, 2013). China meanwhile has the largest global wind energy capacity, and is seeking to expand from an installed solar PV capacity of 3 GW in 2011 to at least 35 GW by 2015 (Wayne, 2013).

The United Kingdom is following the global trend with commercial onshore wind and solar PV subsidised through government incentives, which helps to promote a diversified energy sector. The Department for Energy and Climate Change (DECC) has updated its 'Renewable Energy Roadmap' and confirmed its stance on increasing renewable energy nationwide (DECC, 2012). This commitment to expanding the renewable energy sector is, in part, a response to international policy drivers—the European Union Renewables

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Directive, 2009/28/EC requires member states to produce a proportion of their electricity from renewable technologies (European Union, 2009), and the UK has set an individual target of 15% from renewable sources by 2020 (DECC, 2012). Wind and solar energy are at the forefront of this expansion, but negative impacts can be associated with these two renewable energy technologies.

The most contentious issue associated with wind farms is the visual impact, which whilst assessed objectively in the literature (e.g. Rodrigues, Montanes, & Fueyo, 2010), is often viewed subjectively by the public (Leung & Yang, 2012) and is a main issue motivating organised political and community opposition to proposals. It has been shown there is a link between the presence of wind turbines and bird mortality, but the death rate per turbine is often low, leading Sovacool (2009) to conclude the number of avian deaths caused by wind turbines is minor compared with fossil fuel sources. Impacts on human health have also been studied, with shadow flicker and operational noise quoted as potential issues (Harding, Harding, & Wilkins, 2008; Torrance & Goff, 2009).

Solar PV farms have only recently begun to match wind power commercially, resulting in fewer assessments and little quantified data on their environmental impacts. Tsoutos, Frantzeskaki, and Gekas (2005) carried out one of the earliest studies to identify negative impacts caused by solar farms, concluding visual and ecological impacts would be minimal, views supported by other studies e.g. Kaygusuz (2009), Turney and Fthenakis (2011). The principal environmental concern with solar farms is the area of land required. Chiabrando, Fabrizio, and Garnero (2009) concluded the large area of land required for solar PV reduces the viability of the technology. However, it was acknowledged by Chiabrando et al. (2009) and Kaldellis, Kapsali, Kaldelli, and Katsanou (2013) that careful design and site selection allow the impacts to be readily mitigated. The UK Government has specifically endorsed an expansion in this form of renewable energy, and a 25-fold increase in capacity has been seen from 2010 to 2013 (DECC, 2013a) reflecting the global trends outlined above; but it has since expressed concerns related to loss of food production, and removed farm subsidy payments available through the EU Common Agricultural Policy for agricultural land used for solar farms (Defra, 2014).

The environmental impacts caused by wind and solar developments are partially dependant on the location of the development, where careful design and appropriate site selection can mitigate the associated negative impacts (Kaldellis et al., 2013). As more renewable energy projects are promoted, viable land will become the key constraint (Grassi, Chokani, & Anhari, 2012), confirming that appropriate site selection will become paramount for the future development of onshore wind farms and solar farms. This stands to become a global challenge as rising populations and modernising economies place pressure on available space for food production (McMichael, Powles, Butler, & Uauy, 2007), housing and environmental protection; while renewable energy technologies will be viewed as favourable, as fossil fuel use may be impacted by climate change policies and the cost of carbon (Arent, Wise, & Gelman, 2011).

When considering geospatial problems such as wind farm or solar farm site selection, there are two key tools available to the decision maker: multi-criteria decision making (MCDM) and geographic information system (GIS). Due to their complimentary nature, they can readily be used in unison (Sanchez-Lozano, Teruel-Solano, Soto-Elvira, & Garcia-Casclaes, 2013). One of the most popular MCDM techniques is the analytical hierarchy process (AHP) which, due to the use of a pairwise comparison of variables, provides a robust method to calculate the relative importance of each variable with regards to the final outcome (Saaty, 1980). As a result, previous studies have used a GIS-MCDM approach when conducting suitability studies for wind farms (e.g. Tegou, Polatidis, & Haralambopoulos, 2010) and solar farms (e.g. Charabi & Gastil, 2011) where few comparative studies have examined both forms of energy generation in a single area.

Whilst there are no UK-specific GIS-MCDM solar farm studies, Baban and Parry (2001) is the only UK specific GIS-MCDM wind farm study, though its focus was predominantly on developing a methodology. Given the low volume of UK-specific literature and the particular challenges of finding locations in a crowded island nation with a developed economy, we use the case study of South Central England to address on-shore wind and solar farm site selection. Using a GIS-MCDM approach, we carry out a regional assessment of the suitability for wind farm and solar farm developments and look to compare the findings with existing developments within the study area. In addition, we use the AHP process to weight our variables and validate the weightings by consulting with expert stakeholders who work in renewable energy site orientation. The experts thus informed our development of constraint layers and factor layers in our analysis of regional suitability—a novel aspect of this research. The study also includes an assessment of the suitability model by conducting a sensitivity analysis.

2. Methods

2.1. Study area

The study area, referred to as South Central England, is situated on the south coast of the UK and occupies an area of 17,094 km^2 (Fig. 1). The region has a population of approximately 5916,600 and the main cities are Bristol, Oxford, Reading and Southampton. Outside of the urban areas the majority of land is agricultural with two areas designated as National Parks. The annual solar irradiation for the region is approximately 1000 $kW\,h\,m^{-2}\,yr^{-1}$ (Laleman, Albrecht, & Dewulf, 2011) with the average wind speed at a height of 45 m being 6.2 $m\,s^{-1}$ (DECC, 2013b). The region has an installed wind capacity of 23.56 MW with a further 9.32 MW under construction, whilst the installed non-domestic solar capacity is 94.21 MW with a further 142.54 MW under construction (DECC, 2013c).

2.2. Multi-criteria decision making and analytical hierarchy process

Decision makers can use MCDM to consider various subjective and conflicting criteria (Ishizaka & Labib, 2011) whilst assessing the suitability of an area with regards to a specific development. The method is often used in conjunction with GIS (Sanchez-Lozano et al., 2013) whereby the suitability of an area is displayed with visual aids. A review of GIS-MCDM methods was conducted by Pohekar and Ramachandran (2004) which concluded the AHP method was the most widely used technique used in sustainable energy studies. The AHP method was first presented by Saaty (1980) as a way of comparing a number of variables, whereby a pairwise comparison allows a specific weighting of relative importance to be assigned to each variable being considered. Xiang and Whitley (1994) summarised the claims against AHP as a decision making tool into five areas; axiomatic foundation (Dyer, 1990), elicitation questions (Dyer, 1990), the 1 to 9 measurement scale (Holder, 1990), the eigenvalue method (Holder, 1990) and rank reversal (Belton & Gear, 1983; Dyer, 1990). Whilst acknowledging these potential issues with the method, AHP has been shown to be flexible and can allow for its inconsistencies to be checked (Ramanathan, 2001). It allows the importance of each criterion to become clear (Macharis, Springage, De Brucker, & Verbeke, 2004) and it supports decision makers through generation of the geometric mean of the pairwise comparisons (Zahir, 1999). Due to the aforementioned benefits to decision makers, and the method being determined

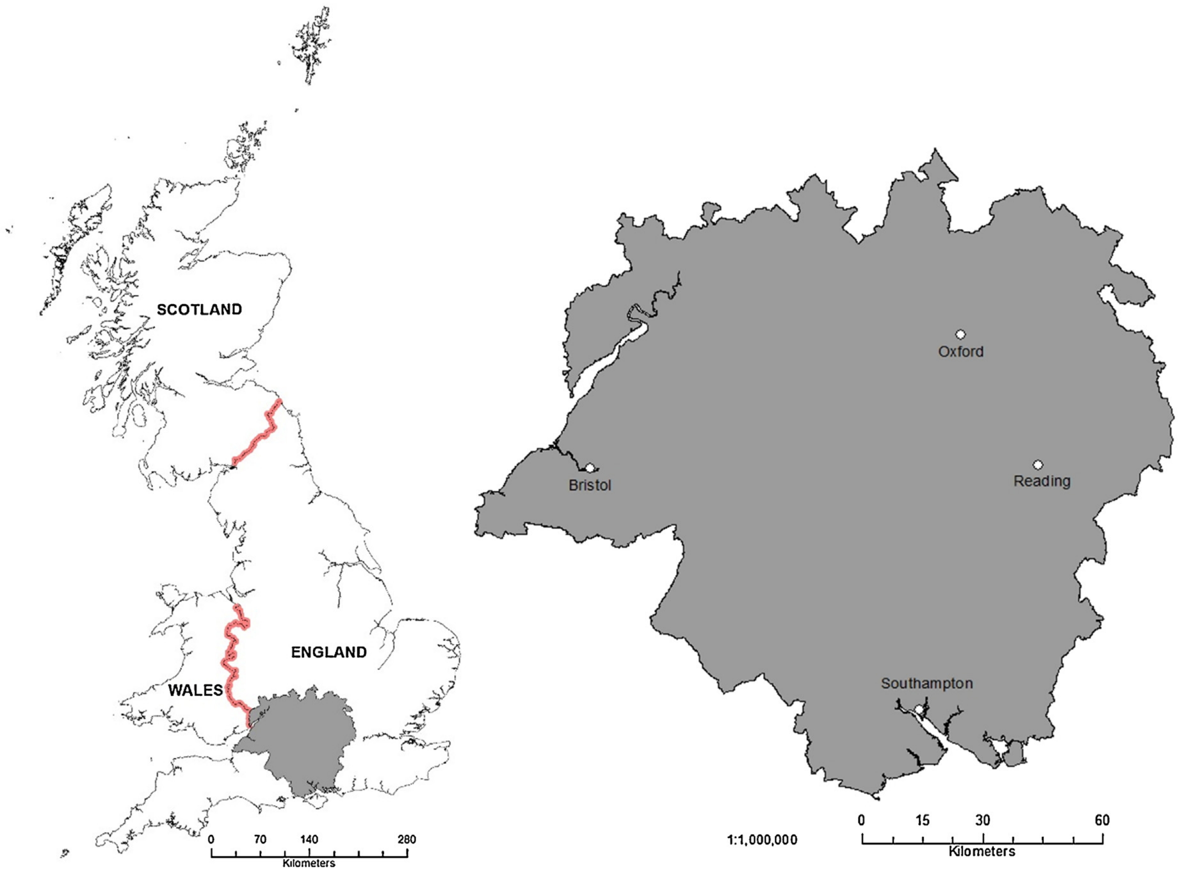

Fig. 1. The study area of South Central England.

as the leading method for GIS-MCDM sustainable energy studies (Pohekar & Ramachandran, 2004), it was deemed appropriate to use this method for the study. The pairwise comparisons can be completed by experts from the field, offering additional insight into understanding the problem. Ishizaka and Labib (2011) identified four key stages to an AHP study:

- The first is 'problem modelling' which provides the focus on the relevant criteria and sub-criteria.
- The second is 'pairwise comparison' which provides a relative importance to each variable without having to simultaneously assess all variables.
- The third is 'weight aggregation' which uses the relative weights of each variable and combines them so as to determine the global priority.
- The last is 'sensitivity analysis' which modifies the original weightings so as to observe changes to the original results.

2.3. Description of method

ArcMap 10.1 was used for processing and analysis of the data as the software can perform a large array of functions associated with MCDM. In addition, it is similar in nature to software used by decision makers involved with origination activity.

The suitability for wind and solar farm developments were assessed separately resulting in two suitability assessments, one for wind and one for solar.

The data used for this study were separated into constraint and factor variables. The constraint variables were used to identify areas where a renewable energy development could not usually occur. The factor variables were used to assess the suitability of the non-constraint areas by identifying high and low suitability values with regards to a wind farm or solar farm development. These variables were selected based on a review of peer reviewed literature which scrutinized 41 studies concerning impacts of wind and solar developments on the environment and ten concerning renewable energy-based GIS-MCDM.

2.3.1. Identification of constraint variables and constraint layers

Each constraint variable (see Table 1 and Appendix A for sources) for wind or solar was classified using a binary scale, where 0 represented the presence of a constraint and therefore was not viable for a development, and 1 represented the absence of a constraint and therefore was potentially viable for a development. Once the constraint variables were converted to binary, they were multiplied together which produced the wind constraint layer (CL) and the solar CL. The buffer distances used in this study have been adopted from Baban and Parry (2001) as their study was UK specific so appropriate to our region. Whilst Baban and Parry's study addressed wind developments, their buffer distances have been applied to both technologies in this study so as to represent a similar environmental context in the suitability model. Larger buffer distances, which have been recommended in the literature, were rejected due to their studies not being UK-specific; e.g. Hansen's (2005) wind farm study based in the Baltic Sea region, suggested up to 1500 m buffer from properties, and Aydin, Kentel, and Duzgun's (2010) wind farm study based in west Turkey, suggested up to 5000 m buffer for bird habitats and wetlands.

Table 1 summarises the constraint variables, short hand codes, the online source where the original data was collected from and the buffer distance or threshold. The reference column refers to the reference which states a development could occur beyond the

Table 1
Constraint variables, short hand code, buffer distance and academic reference providing the buffer distance or threshold, and the online source of the original data. All files used in the analysis were converted to raster with a resolution of 90 m. A description of each dataset, including the website used to access the data, can be found in Appendix A.

Constraint		Buffer distance (m) or threshold	Reference	Source of data
Agricultural land classification	C1	Grades 3a, 3b, 4, 5	S. Stokes, personal communication, June 2013.	Natural England
Historically important areas	C2	1000	Baban and Parry (2001)	English Heritage
Landscape designations	C3	1000	Baban and Parry (2001)	Natural England
Residential areas	C4	500	Baban and Parry (2001)	Meridian 2 OS Maps
Wildlife designations	C5	1000	Baban and Parry (2001)	Natural England
Aspect (solar only)	C6	SE–SW facing	S. Edwards, personal communication	Derived from DEM (CGIAR-CSI)
Slope	C7	10°	Baban and Parry (2001)	Derived from DEM (CGIAR-CSI)

given buffer distance or the threshold. (For example, the reference for the Agricultural land classification is S. Stokes—a sustainable energy professional and land agent who advised to avoid Grades 1 and 2 land classes; not Natural England, which is the source of data). The rationale for each constraint variable is as follows:

- The *agricultural land classification* (C1) dataset consisted of six nationally recognised grades of land; grades 1 and 2 were classified as 0 due to their high arable value. Grades 3a, 3b, 4 and 5 were classified as 1 due to the lower fertility of the land.
- The *historically important* (C2) dataset comprised of battlefields, national scheduled monuments and UNESCO World Heritage Sites, as a development on these sites could damage the cultural heritage of the area. The presence of these elements and their respective 1000 m buffer were classified as 0 with all other areas classified as 1.
- The *landscape designation* (C3) dataset comprised of National Parks and Areas of Outstanding National Beauty (AONB) as a development on these sites has the potential to adversely affect the scenic quality of the designated areas. The presence of these elements and their respective 1000 m buffer were classified as 0 with all other areas classified as 1.
- The *residential area* (C4) dataset consisted of all dwellings and single properties identified by the Meridian 2 OS Maps dataset (date accessed 02/07/2013). A buffer of 500 m was applied to each dwelling and these areas were classified as 0 with all areas outside of the buffer classified as 1.
- The *wildlife designations* (C5) dataset consisted of UK Sites of Special Scientific Interest (SSSI), National and Local Nature Reserves (NNR and LNR); European Special Protection Areas (SPA) and Special Areas of Conservation (SAC); and international Ramsar sites as a development on these sites have the potential to adversely affect the ecological quality of the area and is likely to be obstructed by national and/or international conservation policies. All of these elements and their 1000 m buffer were classified as 0 and all areas outside of the buffer were classified as 1.
- The *Aspect* (C6) dataset (the direction of the slope) and the *Slope* (C7) dataset (the gradient of the land) were derived from the digital elevation model (DEM) and only applied to the solar suitability models. The aspect dataset was classified so that the south east to south west facing slopes were 1 as this is an ideal slope direction. All other slope directions were classified as 0. The slope dataset was classified so that all gradients greater than 10% were 0 as this would be too steep for a development. Subsequently all gradients lower than 10% were classified as 1.

2.3.2. *Identification of factor variables, pairwise comparison and factor layers*

Seven experts who work in site origination for solar and wind farms were invited to independently consider the environmental factors when siting a renewable energy project by completing the pairwise comparisons for a wind and solar farm development. The experts included EIA project managers, technical leads for solar and wind technologies and an associate consultant planner working on EIA projects. This fits the general requirement set out in Xiang and Whitley (1994, p. 283) that '*individuals chosen are usually analysts or consultants who explore land suitability problems for the decision-makers or clients, rather than being the decision-makers or clients themselves*'. Their knowledge of working in the relevant sector as practitioners validated the choices made for the analysis, and therefore was a step included in this study.

The initial twelve factor variables produced from the review of literature were reduced to the seven shown in Table 2. *Altitude*, *distance from woodland* and *distance from water bodies* were discounted due to the experts and existing GIS-MCDM literature confirming their low importance in site consideration. *Distance from high priority ecological areas* (SSSI, NNR, SPA, SAC, Ramsar) and *Distance from low priority ecological areas* (LNR) were combined so as to simplify the ecological factor when conducting site consideration. When collating the pairwise comparisons, a geometric average method was applied to the responses as this provided a generalised output (Lee, Chen, & Kang, 2009) and produced the final weightings shown in Table 2.

The pairwise comparisons were tested for their Consistency Ratio (CR), which is the measure of inconsistency from the experts' judgement. The CR was calculated from knowing the Consistency Index (CI), which is the deviation of consistency, and the Random Consistency Index (RI), which is an average CI from a randomly generated matrix (Saaty, 1980).

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

The threshold for an acceptable level of inconsistency is 10%, where a value greater than 10% requires the weightings to be revised so as to reduce the inconsistencies of the pairwise comparisons completed by the experts (Saaty, 1980; Zahedi, 1986).

The factor variables were aggregated using a weighted sum function which produced two factor layers (FLs), one for wind and one for solar. The FLs were a suitability map for the entire study area of South Central England and had the potential to have a maximum value of 1, high suitability, and a minimum value of 0, low suitability.

2.3.3. *Factor variables*

The 'distance' factor variables were created using the general linear weight distance tool within ArcGIS. Subsequently, all factor variables (Table 2) were standardised to a linear scale using the following equation (Malczewski, 1999) where x equals the value of a variable in the original data set:

$$\frac{(x - \min(x))}{(\max(x) - \min(x))} \tag{3}$$

The scale ran from 0 to 1, where a value of 1 represented the best possible location and 0 represented the worst possible location.

Table 2
Factor variables, short hand code, the weighting gained from the pairwise comparisons and the source from where the originally data was collected. All files used in the analysis were set to raster with a resolution of 90 m. A description of each dataset, including the website used to access the data, can be found in Appendix A.

Category	Factor		Weighting		Source
			Wind	Solar	
Technical	Wind Speed	F1	0.555		DECC
	Solar Radiation	F2		0.489	Derived from DEM (CGIAR-CSI)
Visual	Distance from historically important areas	F3	0.078	0.065	Derived from English Heritage
	Distance from residential areas	F4	0.130	0.049	Derived from Meridian 2 OS Maps
Ecological	Distance from wildlife designations	F5	0.130	0.069	Derived from Natural England
Economic	Distance from transport links	F6	0.046	0.069	Derived from Meridian 2 OS Maps
	Distance from network connection	F7	0.062	0.259	Derived from National Grid

The technical category consisted of *wind speed* (F1) and *solar radiation* (F2). Wind speed provided the annual average wind speed for the UK at a height of 45 m and at a resolution of 1 km, as this was the highest height made available by DECC (Date accessed 28/06/2013). The wind speed data was resampled to a 90 m resolution so as to be consistent with the other raster datasets. The data was standardised so that the minimum value, 0 ms^{-1}, represented 0, and the maximum value, 8.6 ms^{-1}, represented 1. The solar radiation was derived from the DEM, which had a resolution of 90 m, by using the in-built tools of ArcGIS and represented the total amount of incoming solar insolation (direct and diffuse) per year. The data was standardised so that the minimum output, 536 $kW\,m^2\,yr^{-1}$, represented 0 and the maximum output, 1076 $kW\,m^2\,yr^{-1}$, represented 1. Both outputs are shown in Appendix B.

The visual category consisted of *distance from historically important areas* (F4) and *distance from residential areas* (F5) and were derived using the same elements as used for historically important areas (C2) and residential areas (C4). The ecological category consisted of *Distance from wildlife designations* (F5) and was derived using the same elements as used for wildlife designations (C5).

The economic category consisted of *distance from transport links* (F6) and *distance from network connection* (F7). The distance from transport links dataset included main roads and train lines, where close transport links were preferential due to lower infrastructure costs. The distance from network connection dataset consisted of the main electricity cables which can support 275 kV and 400 kV, where a close connection represented lower connection costs.

2.3.4. Suitability layer

The CL and FL were multiplied together which produced the suitability layers (SLs) for the wind farm suitability and solar farm suitability. Each pixel in the non-constraint area, i.e. areas not accounted for by the presence of the constraint layer, was assessed separately for its suitability of siting either a wind farm or a solar farm, with the potential maximum value being 1 and minimum value being 0.

2.3.5. Sensitivity analysis

The final step was the sensitivity analysis where the factor and constraint variables were manipulated, producing new outputs which could be compared with the original suitability assessment. This process is a common step when conducting a MCDM and AHP study (Ishizaka & Labib, 2011) and provides a way of assessing the results that were derived from the weightings provided by the experts (Meszaros & Rapcsak, 1996) which may be subject to some error or bias. Four sensitivity analysis layers (SALs) were produced; two for siting wind farms and two for siting solar farms:

SAL 1	All wind factor variables have the same weightings
SAL 2	All solar factor variables have the same weightings
SAL 3	All economic factor variables for wind have a weighting of zero
SAL 4	All economic factor variables for solar have a weighting of zero

SAL 1 and SAL 2 used an equal weighting for all factor weightings as this assessed the suitability of the original model (Nekhay, Arriaza, & Guzman-Alvarez, 2009). SAL 3 and SAL 4 assessed the suitability potential when the economic variables were omitted, this is to say it allowed the suitability of wind and solar to be assessed based on natural conditions. In doing so, the remaining environmental variables were kept in the same proportion to one another as produced by the weightings provided by the experts.

3. Results

3.1. Constraint layers

The wind CL produced a viable area of 6470 km^2 (37.8% of South Central England) whilst the solar farm CL produced a viable area of 3714 km^2 (18.6% of South Central England). The solar CL had a lower non-constraint area due to the inclusion of constraint variable C6 – aspect as this variable was not a requirement when considering the environmental constraints for siting a wind farm.

3.2. Pairwise comparisons

Seven experts from the renewable energy sector completed the pairwise comparisons for either a wind farm development, solar farm development or both. As a result, there were five completed matrices for each technology. The completed matrices showed that wind speed (F1) and solar radiation (F2) were, respectively, the two most important factors when considering an appropriate site location for a wind farm or solar farm (Table 2). Distance from network connection (F7) was deemed to be more important when considering the site location of a solar farm (25.9%) compared with a wind farm (6.2%). Distance from residential areas (F4) and distance from wildlife designations (F5) where considered to be more important when considering the site location of a wind farm.

The weightings for a wind farm development produced a consistency ratio (CR) value of 4%, and for a solar farm development they produced a CR value of 6%. Both of these results were within the 10% threshold meaning the pairwise comparisons completed by the experts did not need to be amended.

3.3. Suitability layers

The SLs were used to assess the suitability of the study area for a wind farm or solar farm development once the constraint variables have been considered. When displaying the SLs, a maximum value of 0.803 and minimum value of 0.5 were selected. The value of 0.803 was chosen as this was the highest suitability value expressed in any of the SLs or SALs. The minimum value was capped at 0.5 for two reasons. First, values lower than 0.5 indicated that the location in question would not be favourable—the suitability score is too low for a wind farm or solar farm to be usually considered. Second, it was to assist the decision makers

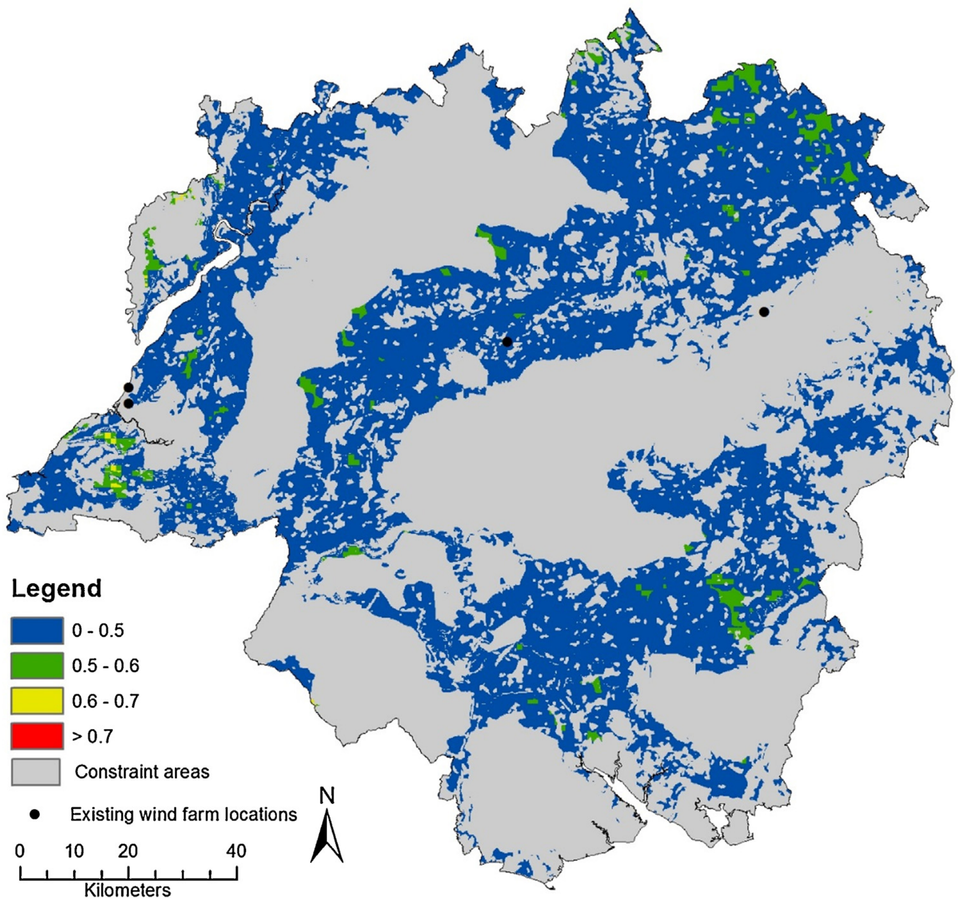

Fig. 2. Suitability layer (SL) for wind farm developments in South Central England. The grey areas show the location of the wind constraint layer and therefore cannot be considered for a development. The coloured areas represent the categorization of suitability: 0–0.5 represents the 'not suitable' category; 0.5–0.6 represents the 'least suitable' category; 0.6–0.7 represents the 'moderately suitable' category and >0.7 represents the 'most suitable' category.

when conducting analysis of the results. To aid interpretation of the suitability layers, the pixels were split into four categories; pixel values from 0 to 0.5 were grouped as 'not suitable', values from 0.5 to 0.6 were grouped as 'least suitable', values from 0.6 to 0.7 were grouped as 'moderately suitable' and values greater than 0.7 were grouped as 'most suitable'.

3.3.1. *Wind suitability*

The majority of South Central England was not suitable for a wind farm development, with large sections of the study site having a suitability value of 0.5 or less (Fig. 2). The average value for the wind SL was 0.548, with a maximum suitability value of 0.711, meaning the best possible location to site a wind farm fell within the 'most suitable' category. However, this grouping accounted for <0.1% on the non-constraint area. There were a few areas where the wind SL had a 'moderately suitable' value, though these were localised. The 'not suitable' category had a minimum value of 0.413 and accounted for 6% on the non-constraint area. The largest category was the 'least suitable', which accounted for 87.9% of the non-constraint area which resulted in the 'moderately suitable' grouping accounting for 6% on the non-constraint area.

3.3.2. *Solar suitability*

The solar SL had a higher overall suitability than the wind SL with a mean value of 0.644 and a maximum value of 0.803. Whilst the study area had a high overall suitability, there were still areas which had low suitability scores (Fig. 3). The 'most suitable' accounted for 9.3% of the non-constraint area whilst the 'moderately suitable' category accounted for 72.3% of the non-constraint area. The 'least suitable' category accounted for 17.4% of the non-constraint area whilst the 'not suitable' category was the smallest; with a minimum value of 0.413, it accounted for only 1% of the non-constraint area.

3.3.3. *Comparison of wind and solar suitability layer*

The low overall suitability for the wind analysis reflects the large area accounted for by lower suitability categories. The 'not suitable' and 'least suitable' for the wind SL accounted for 6076.7 km^2, compared with 538.9 km^2 for the solar SL. The 'moderately suitable' and 'most suitable' categories for the wind SL occupied a smaller area than the solar SL, 393.5 km^2 and 2590.2 km^2, respectively, even though the non-constraint area for the wind analysis was nearly twice as large as the non-constraint area for the solar analysis.

There are very few (four) existing onshore wind farms greater than 1 MW in the study area (Fig. 2) and they are located in either the 'not suitable' category, or areas discounted as suitable in this study by the presence of the constraint variables. The existing solar farms (Fig. 3) are greater in abundance and whilst there are isolated cases where they exist in the presence of the constraint layer, they predominantly exist in areas of the 'moderately suitable' and 'most suitable' categories.

3.4. *Sensitivity analysis*

The four sensitivity analysis layers (SALs) were expressed on the same scale as the two original suitability maps with a maximum value of 0.803 and a capped minimum value of 0.5. See Fig. 4 for the maps generated.

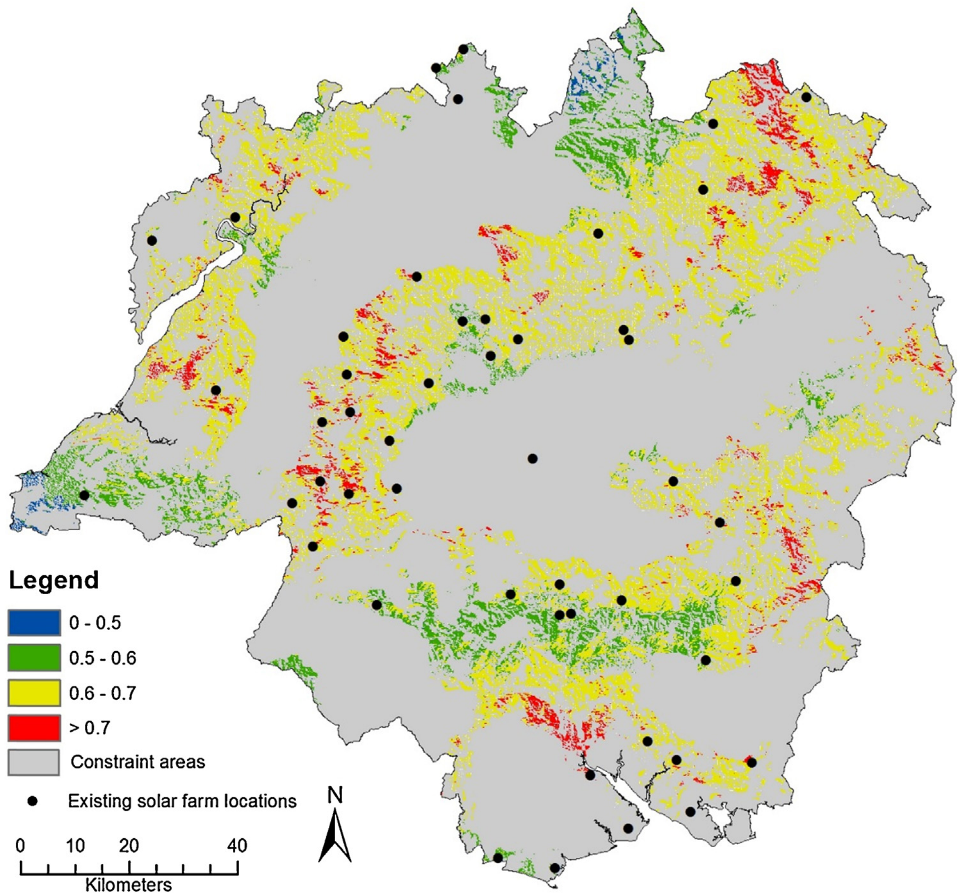

Fig. 3. Suitability layer (SL) for solar farm developments in South Central England. The grey areas show the location of the solar constraint layer and therefore cannot be considered for a development. The coloured areas represent the categorization of suitability: 0–0.5 represents the 'not suitable' category; 0.5–0.6 represents the 'least suitable' category; 0.6–0.7 represents the 'moderately suitable' category and >0.7 represents the 'most suitable' category.

3.4.1. Wind sensitivity analysis

SAL 1 (equal weightings for all wind variables) had a lower overall suitability compared with the wind SL with a mean of 0.489, a peak value of 0.704 and <0.1% of the non-constraint area being 'most suitable' category. The 'not suitable' category accounted for 57.7% of the non-constraint area, an increase 51.7% from the wind SL. As a result, the 'least suitable' and 'moderately suitable' categories were lower in SAL 1, 41.4% and 0.9%, respectively, compared with the wind SL. Despite SAL 3 (economic factors rated as zero) having a higher maximum suitability score than the wind SL, 0.744 compared with 0.711, the mean value was lower, 0.515, and there was a greater proportion of the values being 'not suitable', 35.8%. The 'least suitable' and 'moderately suitable' categories were smaller than the wind SL, 62.1% and 2.1%, respectively, whilst the 'most suitable' category accounted for the same area as the wind SL, <0.1%.

3.4.2. Solar sensitivity analysis

SAL 2 (equal weightings for all solar variables) and SAL 4 (economic factors rated as zero) showed declines in overall suitability compared to the solar SL as the mean values were 0.485 and 0.568, respectively, whilst the area of 'most suitable' decreased to <0.1% for both. The 'moderately suitable' category experienced the sharpest decline with SAL 2 (1.6%) and SAL 4 (14.5%) accounting for a much lower percentage than the original solar SL (72%). Consequently, the lower suitability categories occupied a greater area, hence the shift in the scale from predominantly red and orange in the solar SL to blue in SAL 2 and SAL 4.

4. Discussions

This study developed and applied a GIS-MCDM method to assess the suitability of developing the land in South Central England for two prominent onshore renewable energy sources: wind farms and solar farms. In doing so, it contributes towards the literature surrounding GIS-based renewable energy suitability studies with the novelty and added credibility of the use of expert validation. It is the first UK-specific study to assess regional solar farm suitability alongside regional wind farm suitability using GIS-assisted multi-criteria evaluation. This approach can aid decision makers in moving towards the 15% of electricity to be derived from renewable resources by 2020. The method could also be applied more widely with appropriate adaptation to account for locally appropriate constraints, so could contribute to the sustainable expansion of renewable energy around the world.

The GIS-MCDM model showed that site identification in South Central England favours solar PV farms, as the study site was better suited to being developed for solar farms compared with wind farms. Furthermore, the sensitivity analysis showed the original wind and solar SLs (Figs. 2 and 3) were sensitive to changes in the weightings obtained from the pairwise comparisons (Fig. 4), suggesting that the model was appropriate for the study.

In South Central England the environmental constraints are in abundance, with the wind constraint variables accounting for 62.2% and the solar constraint variables accounting for 81.4%. Whilst these numbers are high, they are similar to other studies. Tegou et al. (2010) study in Levos Island, north east Greece, had a constraint layer which accounted for 56.8% whilst Sanchez-Lozano

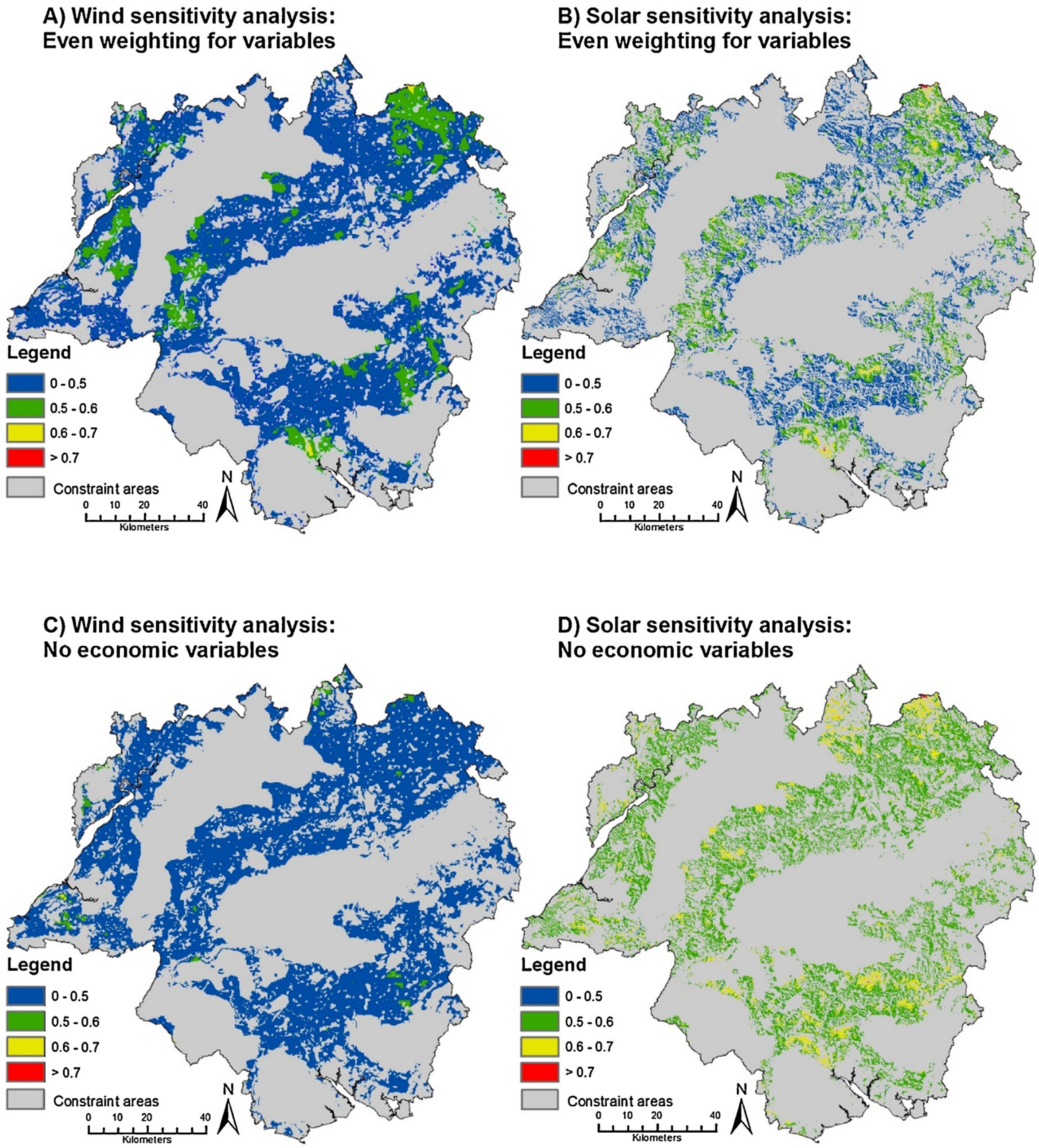

Fig. 4. Sensitivity analysis layers (SALs) for wind farm and solar farm developments. (A) SAL 1—wind even weight. (B) SAL 2—solar even weight. (C) SAL 3—wind no economic variables. (D) SAL 4—solar no economic variables. The coloured areas represent the categorization of suitability: 0–0.5 represents the 'not suitable' category; 0.5–0.6 represents the 'least suitable' category; 0.6–0.7 represents the 'moderately suitable' category and >0.7 represents the 'most suitable' category.

et al. (2013) study in Cartegena, south east Spain, had a constraint layer which accounted for 86.2%.

The sensitivity analysis showed the original SLs to be visually sensitive to changes made to the weightings of the factor variables (Fig. 4), a preferential outcome when conducting GIS sensitivity analysis (Feick & Hall, 2004). The exclusion of the two economic variables resulted in both wind and solar suitability declining, predominantly due to the higher values within the economic variables overlapping with the higher values for wind speed and solar radiation.

4.1. Analysis of the experts' opinions

The overriding consensus in the literature is that the impact caused by a solar development is mostly environmentally benign (Kaygusuz, 2009; Turney & Fthenakis, 2011) and whilst wind farms do have an environmental impact, it is minimal compared with other technologies (Saidur, Rahim, Islam, & Solangi, 2011). This view was supported by the opinions from the experts, who considered the environmental variables to be of low importance when siting a wind farm or a solar farm (Table 2). Additionally, as solar developments have less of an impact than wind developments (Saidur et al., 2011; Turney & Fthenakis, 2011), the buffer distances applied here as suggested by Baban and Parry (2001) for a wind development may appear overly cautious when applied to the solar model. However, it has been noted that low lying areas, <200 m, are underrepresented in England with regards to the volume of protected areas (Oldfield, Smith, Harrop, & Leader-Williams, 2004) and protected areas are of the utmost importance when considering conservation approaches (Chape, Harrison, Spalding, & Lysenko, 2005). Given the low-lying nature of South Central England, a precautionary approach was taken by applying the suggested wind farm buffer distances to the solar model and in doing so, it increased the environmental consideration of the study.

The weightings produced from the pairwise comparisons completed by the experts heavily favoured two variables for the solar model; solar radiation and distance to a network connection. These two variables accounted for 74.8% of the importance weightings (Table 2) with the 'most suitable' areas occurring in areas where these two variables overlapped. In the wind model, wind speed accounted for 55.5% of the importance weightings whilst the importance of the remaining variables was fairly evenly spread (Table 2). As a result, the wind SL did not have a clear link between two variables, unlike the solar SL. Whilst detailed inputs were received from seven experts, there could be much to gain from increasing the number of expert responses from a wider background, e.g. EIA listed statutory stakeholders and local planning officials. This would allow for a more holistic insight into the preferences for site selection.

The weightings produced by the experts also indicated that the distance from a network connection was more important when siting a solar farm (25.9%) compared with siting a wind farm (6.2%). One suggestion for this is as solar farms require more land per GW h of energy produced (Fthenakis & Kim, 2009), construction costs become more of an issue, whereby a distant connection to the national grid could have an economic cost which outweighs the electricity generated from the solar farm thereby making a close grid connection for solar developments more pertinent.

4.2. Comparison with similar studies

This study highlights the most and least suitable areas for wind farm and solar farm developments within South Central England with the suitability scores relative to the scale and spatial extent of the study area. Consequently, the findings are not directly comparable to other location-specific wind and solar GIS-MCDM studies. For example, Charabi and Gastil (2011) conducted a study on the solar PV suitability of Oman and calculated the minimum annual solar radiation to be 1522 $kW\,h\,m^{-2}\,yr^{-1}$ and the maximum to be 3024 $kW\,h\,m^{-2}\,yr^{-1}$. In their study, the minimum value of 1522 $kW\,h\,m^{-2}\,yr^{-1}$ was deemed too low to be suitable for a solar PV development, yet their value is greater than the maximum value used in this study, 1027 $kW\,h\,m^{-2}\,yr^{-1}$. This confirms the input variables and the results of 'most' and 'least' suitable areas are not directly comparable to similar non-UK renewable energy suitability studies.

4.3. Comparison with existing developments

The comparison of the wind and solar suitability outputs (Figs. 2 and 3) with the location of operational wind farms and solar farms greater than 1 MW highlights the delicate balance of site selection. Operational wind farms in South Central England were predominantly located in areas suggested to be of lower suitability, whereas operational solar farms were generally more in line with the suitable areas, albeit there are operational solar farms located in lower areas of suitability. The low number of operational wind farms greater than 1 MW indicates that finding an appropriate site in South Central England is less likely than for a solar farm but local and national interests may be important. The low overall suitability of the study for wind farms reiterates this as the study showed that South Central England is more suitable for solar developments with a higher maximum and mean value, 0.803 and 0.644, respectively, compared to wind suitability, 0.711 and 0.548.

4.4. Wider considerations

In the UK wind power receives fewer subsidies and as stated by Fthenakis and Kim (2009), wind power requires less land per output of energy than solar. These two factors indicate that per km^2, wind farms have the potential to generate more electricity than solar farms and could be considered, on a national scale, a more suitable option. However, when factoring in UK planning policies, only considering the technical elements of site selection could be misguided. The local planning authority is required to consider the impact of a proposed wind farm and solar farm development and not just the power producing potential of the site. Therefore, consideration of the environmental constraints is essential when the developer is considering a viable site. The politicised nature of wind power has led to organisations such as Hampshire County Council (within our study area) to make the controversial decision to introduce a ban on all turbines on county council land (Jarvis, 2012) and other English councils have promoted similar restrictive policies. These arguments highlight the delicate balance a developer must consider when selecting a site location; they must find a site with the necessary natural and technical requirements which will have a minimal environmental impact, and a favourable planning environment.

These sentiments reiterate the findings of Grassi et al. (2012); as more renewable energy developments are completed, finding appropriate sites will become the key issue. This indicates a proactive approach towards early identification of suitable areas for renewable energy sources is needed, especially given the fragile relationship between the development of renewable energy facilities and sustainable development (Dincer, 2000).

It is acknowledged by the authors that due to the large scale of the study area, the assessment required a high level approach to be taken. As such, the list of constraint and factor variables is not exhaustive. Should a decision maker be fine-tuning a site location then there would need to be representation of more locally important variables, for example the inclusion of listed buildings. In England there are over 370,000 listed buildings meaning an assessment to this scale would have resulted in all locations being faced with some level of constraint. However, if the study were to be replicated to a greater scale, where localised issues play more of a prominent role, then listed buildings would need to be represented. Other variables, including stakeholder views, which could be considered on a local scale or case-by-case basis include the prevalence of existing similar developments, financial incentives during time of application, and external political pressure.

5. Conclusions

The value of this work can be seen by its ability to be utilised by two key stakeholders in the Renewable Energy Technology (RET) market; policy makers and developers. It can be used by policy makers to identify more suitable areas for RET onshore development, thereby steering the development of the technologies in a controllable manner. In doing so, it is a more proactive assessment of the viability of an area than has been expressed by some councils in the UK, e.g. Hampshire's blanket ban on wind farms on council own land (see above). In can also be used by developers to identify locations where their development will have a lower potential environmental impact, thereby increasing the likelihood of the proposal receiving planning permission.

The results of this work can be used to increase the ability of the UK in meeting its 15% target for electricity derived from renewable sources. Early identification of suitable sites can save the developer and local authority a lot of time and money, and in doing so increase the likelihood of succeeding with a development. This in turn will obviously result in more electricity being derived from renewable sources. Beyond the UK, the implications are generally the same, as all of the EU nations are committed to the Renewables Directive 2011/94/11 EC, whilst both developed and developing economies world-wide (e.g. USA, Australia, China, Brazil and India) have also made commitments to increase their energy derived from renewable sources. The method we present here can be applied in any location with suitable data availability so could support this global trend, albeit with adaptations to fit the local situation.

A further area which could be explored is the potential to identify UK hybrid renewable energy generation locations. The energy generated from wind and solar PV systems can be considered intermittent (Nakata, Kuboand, & Lamont, 2005), but used in conjunction on the same site, the two can somewhat compensate for each other's weaknesses (Hongxing, Wie, & Chengzhi, 2009). The balance between the two renewable energy technologies has prompted GIS-MCDM studies into assessing the viability of hybrid sites e.g. Aydin, Kentel, & Duzgun (2013) looked at the suitability of introducing hybrid sites into western Turkey. The work in this study could therefore be replicated to a higher resolution which could allow for the identification of potential UK hybrid generation sites.

Renewable energy is a fast growing global sector, promoted by numerous national and international policy drivers. As this sector develops, the environmental conditions will present more of a constraint, ensuring that identification of appropriate sites for energy generation will become paramount—particularly where land is limited and local planning contexts may not be fully supportive. Therefore, the overall aim of this study was to identify suitable locations for wind farm and solar farm developments within a case-study area (South Central England) with an emphasis on environmental considerations. We employed MCDM methods which incorporated the established AHP, for which the weightings of the variables were established by experts in solar and wind origination. Our study indicated that much of the region was unsuitable for wind or solar energy generation due to the constraint variables, while indicating potentially favourable locations. The region was found to be more suited for solar development, a conclusion supported by the greater volume of installed solar capacity and the number of solar farms compared with onshore wind. Whilst the results are broad in their nature and should be treated with some caution; our method can aid investigations into the impact of renewable energy facilities by identifying suitable areas for future developments based on the environmental considerations.

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Appendix A.

Data sources.

Layer	Source	Website	Date produced	File type	Resolution	Date accessed
Agricultural grade of land	Natural England Website	http://www.gis.naturalengland.org.uk/pubs/gis/GIS_Register.asp	2002	Vector	N/A	25/06/13
Historically important areas	English Heritage Website	http://services.english-heritage.org.uk/NMRDataDownload/	2007	Vector	N/A	26/06/13
Landscape designations	Natural England Website	http://www.gis.naturalengland.org.uk/pubs/gis/GIS_Register.asp	2012 & 2013	Vector	N/A	25/06/13
Residential areas	Meridian 2, Ordnance Survey	http://www.ordnancesurvey.co.uk/oswebsite/products/meridian2/	2012	Vector	N/A	02/07/13
Wildlife designations	Natural England Website	http://www.gis.naturalengland.org.uk/pubs/gis/GIS_Register.asp	2012	Vector	N/A	25/06/13
Aspect (solar only)	Created in ArcMap 10.1. Derived from DEM (CI-GAR)	http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp	2008	Raster	90 m	12/07/13
Slope	Created in ArcMap 10.1. Derived from DEM (CI-GAR)	http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp	2008	Raster	90 m	12/07/13
Wind speed	DECC	https://restats.decc.gov.uk/cms/annual-mean-wind-speed-map	1998	Raster	1 km	09/07/13
Solar radiation	Created in ArcMap 10.1. Derived from DEM (CI-GAR)	http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp	2008	Raster	90 m	12/07/13
Distance from historically important areas	Created in ArcMap 10.1. Derived from English Heritage	http://www.gis.naturalengland.org.uk/pubs/gis/GIS_Register.asp	2007	Vector	N/A	26/06/13
Distance from residential areas	Created in ArcMap 10.1. Derived from Meridian 2	http://www.ordnancesurvey.co.uk/oswebsite/products/meridian2/	2012	Vector	N/A	02/07/13
Distance from wildlife designations	Created in ArcMap 10.1. Derived from Natural England	http://www.gis.naturalengland.org.uk/pubs/gis/GIS_Register.asp	2012	Vector	N/A	25/06/13
Distance from transport links	Created in ArcMap 10.1. Derived from Meridian 2	http://www.ordnancesurvey.co.uk/oswebsite/products/meridian2/	2012	Vector	N/A	02/07/13
Distance from network grid	Created in ArcMap 10.1. Derived from National Grid	http://www.nationalgrid.com/uk/LandandDevelopment/DDC/GasElectricNW/undergroundcables/shape/	2013	Vector	N/A	14/07/13

The table provides the variables, short hand code, type of data, vale range, source—be it downloaded or created in ArcGIS, and the website from where the data was originally downloaded.

Appendix B.

Fig. B1.

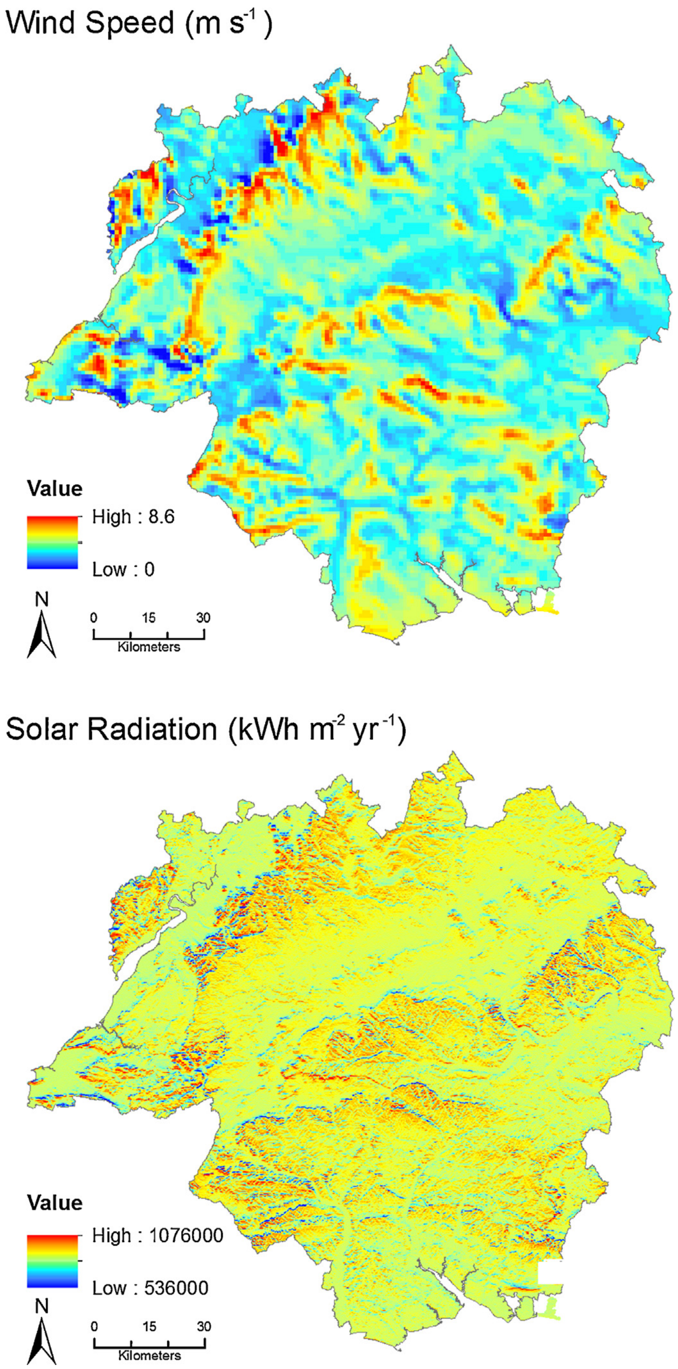

Fig. B1. Wind speed map and solar radiation map (DECC, 2013b).

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