Renewable energy deployment in the UK: spatial analysis of opportunities and threats

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Abstract

The decarbonisation of the power sector is key for reaching the UNFCCC Paris agreement goal of limiting global mean surface temperature rise to well below 2°C. This implies a large scale deployment of low carbon energy sources. The location of variable renewable energy technologies (VRE) determines the total output and the timing of production. Further, environmental, technical and social effects of VRE deployment are location dependent. This poses the question how social, environmental and technical constraints influence high renewable energy scenarios in terms of costs, share of renewable electricity production as well as emissions. To answer this question, the following approach was used: (1) GIS analysis to develop 27 scenarios with low, medium and high social, environmental and technical constraints for VRE development; (2) the scenarios were used as input to the high spatial and temporal resolution electricity system model highRES for 2050; and, (3) costs, emissions and storage investments were compared across scenarios using high and low constraints. The results show that costs (£88/MWh vs £81/MWh), grid CO2 intensity and storage investments in the high constrained scenario are higher than the low constrained scenario; whereas VRE generation, flexible generation and transmission line investments are lower. This suggests that in order to develop sites with low costs and achieve higher public support for VRE to include those affected by VRE deployment into the planning, development and operation of VREs.

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Introduction

The decarbonisation of the power sector is key for reaching the UNFCCC Paris agreement goal of limiting global mean surface temperature rise to well below 2°C. The UK is committed to reducing its emissions by at least 80% in 2050 from 1990 levels (Parliament of the United Kingdom, 2008). The portfolio of energy technologies to tackle the climate problem in the next 50 years is already industrially available (Pacala, 2004). Variable renewable energy (VRE) technologies, such as wind and solar are an essential component of this portfolio. However, unlike traditional thermal generation, the location of VRE determines the total output and the timing of production. Thus, it is advantageous to spread the deployment of VRE to system optimal locations (i.e. best interaction with demand, other generation and integration options). Additionally, by considering these spatial dependencies at early stages of power system planning, the extension of the transmission grid could proceed in ways that take advantage of the spatial diversity of VRE potential. Further, the spatial location affects the technical feasibility and the impact that VREs could have on the environment and the communities they are sited. As an example, onshore wind energy raises environmental issues primarily due to its visual impact and is thus often not allowed in areas such as nature reserves or areas of outstanding natural beauty (Bassi, Bowen, & Fankhauser, 2012). Opposition towards wind farms has been growing in the UK with local opposition being particularly strong (Damian Carrington, 2012; Haggett, 2011). While benefits of wind energy development accrue for the entire country, the perceived negative impacts affect the local population who is often not compensated (Bassi et al., 2012). If the local population feels unjustly treated strong emotional oppositional activism occurs (Cass & Walker, 2009). In the UK the majority of projects is developed and owned by commercial companies and not the communities compared to other European countries (e.g. Germany and Denmark) (Bassi et al., 2012). Landscape is very important in British cultural identity and there are strong groups that have landscape protection as a key priority (Toke, Breukers, & Wolsink, 2008). Also, the decisions on wind power projects are disproportionally influenced by minority groups (Bell, Gray, & Haggett, 2005). These issues lead to long delays in the planning process and high failure rates of new wind energy installations (McLaren Loring, 2007). As a result of these factors certain areas will not be suitable as potential sites for VRE deployment due to technical, environmental and social reasons. This will effectively limit the area where projects can be deployed and influence the levelised costs of electricity, integration costs and social acceptance of VRE deployment. Overall, this means that the system optimal locations are limited and as a result total system costs are likely to be higher.

A substantial body of literature has analysed the spatial potential of RES in the UK: Gooding et al., (2013) analysed the physical and socioeconomic PV potential. Tenerelli and Carver, (2012) and Lovett, Dockerty, Papathanasopoulou, Beaumont, & Smith, (2015) assessed the energy crop potential for two regions. Aylott et al., (2010) estimated the supply from short-rotation coppice under different constraints. Drew et al., (2013) estimated the generation potential of wind turbines in London. Samsatli, Staffell, & Samsatli, (2016) identified the potential for wind turbines under technical and environmental constraints. However, all of these studies focused on single technologies and do not quantify the electricity system costs due to restrictions of deployment. Thus there is a lack of studies that carry out a holistic assessment of the potential for concurrent deployment of several VREs including limiting factors affecting this deployment and resulting costs. To compare a large scale deployment of RES with other options, the cost and potential implications of excluding areas from RES development should be discussed in the research, public and policy domains. This would aid the decision of which decarbonisation strategy is politically and publicly feasible. Furthermore, quantifying the costs associated with excluding certain areas is an essential step to discussing compensation for communities affected by RES development. We close this research gap by developing a framework of scenarios that combine different levels of technical, social and environmental criteria of exclusion areas in order to scope out the feasible potential and location of VRE deployment. We then use a spatially and temporally explicit electricity system model to quantify the system costs resulting from the difference in land and sea availability for VRE deployment. This approach allows us to answer the following research questions: How do social, environmental and technical constraints influence high renewable energy scenarios in GB? How do energy scenario costs with high social, technical and environmental restrictions compare to scenarios with low restrictions? If costs are substantially different could this be used to potentially subsidize communities that approve new renewable sources? Would this be a new class of policy intervention to incentivize renewables not yet used in the UK?

The paper is structured as follows: In the next section we will present the methodology to generate the scenarios and the models used in this study. Section three will give the results for two extreme scenarios. The last section presents preliminary conclusions, policy recommendations and an outlook on further research.

Methodology

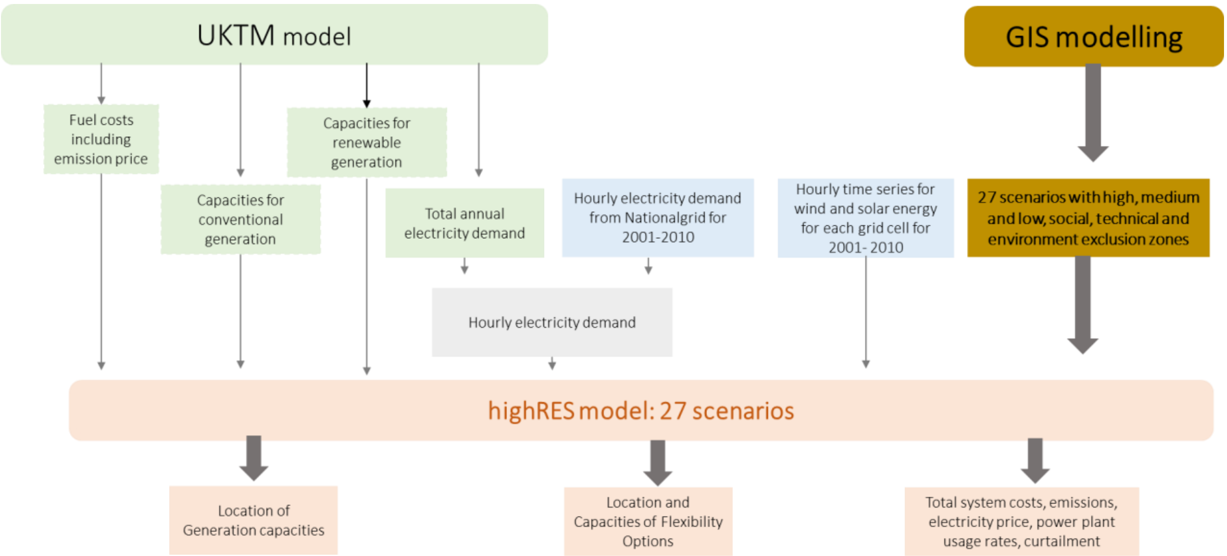

Figure 1 Overview of the methodology

Figure 1 gives an overview of the methodology showing the three modelling sections (GIS modelling, the UKTM model and highRES model) and data exchange between them: We use the long time horizon model UKTM (Daly, Scott, Strachan, & Barrett, 2015) to develop internally consistent whole energy system scenarios that both meet the UK's Climate Change Act 2008, i.e. a reduction of greenhouse gas emissions of 80% relative to 1990 levels by 2050, and have high penetration of VRE (no CCS scenario). The high spatial and temporal resolution electricity system model highRES minimises power system costs to meet hourly demand subject to a number of technical constraints. The core focus of highRES is a good representation of VRE: We use hourly gridded capacity factors for wind and solar energy with a spatial resolution of 35km x 50km (0.5° x 0.5°) from 2001- 2010. To derive hourly capacity factors for onshore and offshore we use data from NCEP Climate Forecast System Reanalysis (CSFR) (Saha et al.,

2010) and for rooftop and ground mounted PV from the Satellite Application Facility on Climate Monitoring (CMSAF) (Schulz et al., 2009). Renewable generation is modelled at the grid cell level (see Figure 2). Demand is modelled on a zonal level (Pfenninger & Keirstead, 2015) (see Figure 2) and demand supply matching occurs between the 20 zones which are connected by the transmission grid. UKTM sets the electricity system boundaries for 2050: We use total electricity demand, fuel prices and generation capacities from UKTM as input into highRES (as illustrated in Figure 1). Capacities from UKTM are the following: 43GW of solar, 38GW of offshore wind, 31GW of onshore wind, 33GW of nuclear energy, 7 GW of biomass energy and 8GW of other sources in 2050. UKTM gives us an electricity demand of 503TWh in 2050 (258TWh in 2015) including the electrification of heating and transport. HighRES finds the optimal location for generation capacities as well as the optimal capacities and locations of VRE integration options for 2050. These are transmission grid extension, flexible generation and electricity storage. Other outputs from highRES are total electricity system costs, electricity prices, power plants usage rates, emissions and renewable curtailment.

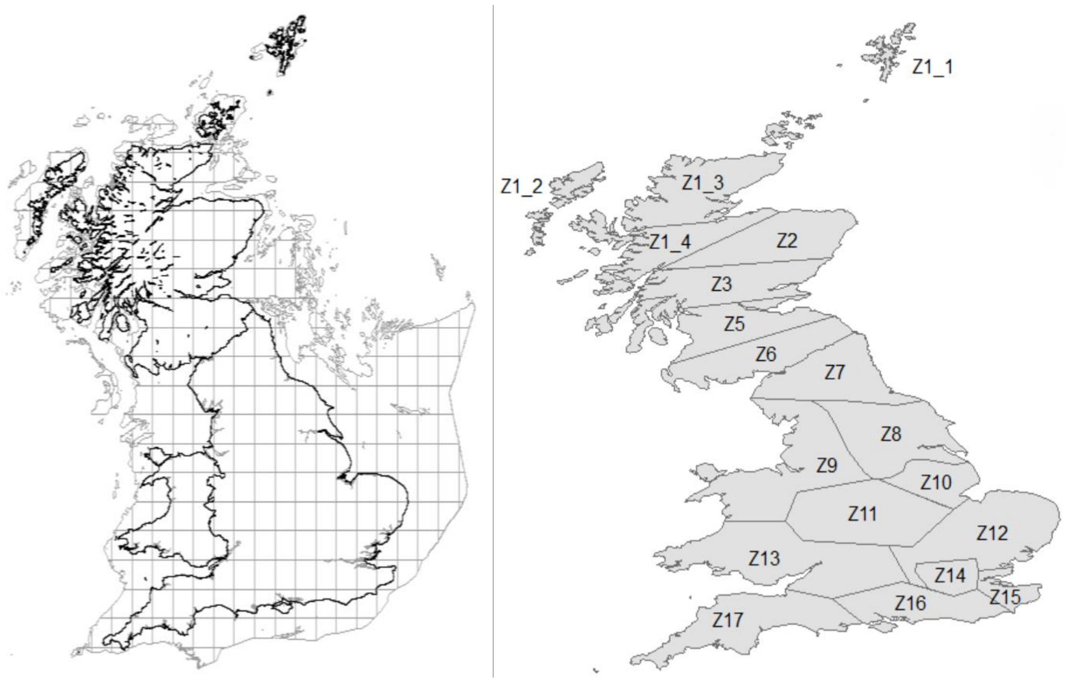

Figure 2 Grid cell level (left), zonal level (right)

A literature review was performed to define low, medium and high social, environmental and technical constraints for VRE development. Table 1 presents the 27 scenarios that resulted from the review process. In order to limit the area available for VRE deployment taking into account different combinations of the constraints presented in table 1, GIS tools were used to exclude the areas in each grid cell for the 27 scenarios. The total buildable area for VRE development in each grid cell was then used as input into the highRES model, as a means of informing the model of the maximum VRE capacity that can be placed in each grid cell.

27 model runs were performed, with each run differing in the area available for PV, onshore and offshore wind development potential in each grid cell. The total system costs, share of renewable generation to cover demand and emission resulting from the difference in exclusion zones were then compared.

Table 1 Social, environmental and technical constraints for solar, offshore wind and onshore wind energy

	Solar Energy			Offshore wind			Onshore wind		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Social	▪ Areas of Outstanding Natural Beauty (AONB)	▪ Areas of Outstanding Natural Beauty (AONB)	▪ Areas of Outstanding Natural Beauty (AONB)	▪ 12 nautical mile coastal buffer ▪ Special Protected Areas with 1km buffer	▪ 12 nautical mile coastal buffer ▪ Special Protected Areas with 1km buffer ▪ 25% maximum penetration of OSPAR MPA and MCZ	▪ 12 nautical mile coastal buffer ▪ Special Protected Areas with 1km buffer ▪ 50% maximum penetration of OSPAR MPA and MCZ	▪ Buffer around houses of 350 metres	▪ Buffer around houses, commercial and industrial buildings of 800 metres	▪ Buffer around houses, commercial and industrial buildings of 2000 metres, ▪ No building in zones of outstanding national beauty
Environmental	▪ ALC grade 1 & 2 ▪ Urban, Non-agricultural ▪ RAMSAR sites ▪ Sites of Special Scientific Interest (SSSI) ▪ Special Areas of Conservation (SAC) ▪ Special Protected Areas (SPA) ▪ RSPB sites	▪ ALC grade 1 & 2 ▪ Urban, Non-agricultural ▪ RAMSAR sites ▪ Sites of Special Scientific Interest (SSSI) ▪ Special Areas of Conservation (SAC)	▪ ALC grade 1 & 2 ▪ Urban, Non-agricultural ▪ RAMSAR sites ▪ Sites of Special Scientific Interest (SSSI) ▪ Special Areas of Conservation (SAC)	▪ Tourism and Natural Beauty: 12nm buffer ▪ More than 21 vessels per week in 2x2km grid square ▪ 6 nautical mile coastal buffer	▪ Tourism and Natural Beauty: 12nm buffer ▪ More than 21 vessels per week in 2x2km grid square ▪ 6 nautical mile coastal buffer ▪ More than 10 vessels per week in 2x2km grid square	▪ Tourism and Natural Beauty: 12nm buffer ▪ More than 21 vessels per week in 2x2km grid square ▪ 6 nautical mile coastal buffer ▪ More than 5 vessels per week in	▪ No restrictions	▪ Special protection sites, sites of specific scientific interest, Ramsar sites, special protection areas (bird directive)	▪ All potected areas ▪ Forests

	▪ Coastal Woodland trust & Forest parks	▪ Special Protected Areas (SPA) ▪ RSPB sites ▪ Coastal ▪ Woodland trust & Forest parks ▪ National & regional parks ▪ BIOMES & BIOSPH (Scotland)	▪ Special Protected Areas (SPA) ▪ RSPB sites ▪ Coastal ▪ Woodland trust & Forest parks ▪ National & regional parks ▪ BIOMES & BIOSPH (Scotland) ▪ Peat		▪ 2km buffer operational oil and gas wells and wells in construction	2x2km grid square ▪ 2km buffer operational oil and gas wells and wells in			
Technical	▪ No restriction	▪ exclude > 15 degrees and North facing slopes	▪ exclude slopes > 10 degrees and North +Northwest slope	▪ Depth: 80m	▪ Depth: 70m	▪ Depth: 60m	▪ Slope higher lower 35 degrees ▪ buffer of 150 meters around highway ▪ buffer of 150 meters around the railway network ▪ buffer of 5 km around airports	▪ Slope higher lower 25 degrees ▪ buffer of 150 meters around highway ▪ buffer of 150 meters around the railway network ▪ buffer of 5 km around airports	▪ Slope higher lower 15 degrees ▪ buffer of 150 meters around highway ▪ buffer of 150 meters around the railway network ▪ buffer of 5 km around airports

Results

This paper presents the results for the year 2050 of two extreme scenarios using the weather year 2010: scenario number one (low environmental, technical and social restrictions) and scenario number 27 (high environmental, technical and social restrictions). For scenario one, the levelised cost of electricity is £81/MWh. HighRES invests into 21GW of flexible generation, 24 GW of storage and 245GW of transmission extension, with 62% of demand covered by VRE production and a grid CO2 intensity of 1.2gCO2/kWh. In scenario 27 levelised costs of electricity amount to £88/MWh. The model installs 16GW of flexible generation, 29GW of storage and 166GW of transmission. Renewable generation covers 56%, storage 5% and flexible generation 0.4% of demand and the grid CO2 intensity amounts to 2.1g CO2/kWh.

Since scenario 27 is the result of the highest levels of constraints on all of the domains – environmental, technical and social - the highRES model is restricted in terms of the locations where new VRE will be deployed, thus the system wide optimal spatial configuration is no longer available. As a consequence of this, the model invests in deployment in locations which are closer to demand and as a result less into transmission line extension and more into storage. Additionally, as the generation from VRE is lower in scenario 27, the model dispatches gas more often leading to a higher grid CO2 intensity, although both scenario 1 and scenario 27 lead to very low CO2 grid intensity for electricity delivery by 2050.

Conclusions and Outlook

There is a lack of models and studies that account for the necessary spatial and temporal detail to find-cost effective solutions for high variable renewable energy futures. Here, we perform a detailed GIS analysis in combination with a long running energy systems model (UKTM) and a high resolution electricity model (highRES) to explore the difference in costs, emissions and VRE generation due to environmental, technical and social constraints. Costs and emissions are lower in the scenario with low restrictions. The difference in costs, system configuration as well as emissions shows the importance of involving all affected partners in the planning process in order to make the energy transition successful. This methodology was able to attribute a value of VRE development to a specific location. As a consequence, sites with high value need to be developed in cooperation with the communities as co-owners of the project or by some form of compensation them. We need to design novel policies which allow us to better include those affected by VRE deployment into the planning, development and operation of VREs. Studying best practices of past projects in the UK and other countries would give us valuable insights.

The results for all 27 scenarios and 10 years of weather data will be presented in a future paper. Future work will also include interconnection to Europe and demand side response as additional VRE integration options. Building on this research we recommend several future work streams which would support the large scale implementation of VRE: As it can take a long time from planning to approval and building of the transmission system including these into the GIS assessment and defining technical, environmental and social scenarios of exclusion gives valuable insights. Our methodology can be used in a participatory research design. Including a wide range of stakeholders which are part of the planning process or affected by the deployment of wind and solar energy projects and let them define the exclusion criteria would give novel insights which can translate directly into policies. This could be done in an iterative modelling process, where the model is being run to explore the difference in costs between a constrained and an unconstrained scenario. The stakeholders can then negotiate under what conditions they would accept less restrictive constraints. These could be compensation, being an owner of the project, or investment into additional conservation measures.

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