Spatially and Temporally Explicit Energy System Modelling to Support the Transition to a Low Carbon Energy Infrastructure – Case Study for Wind Energy in the UK

Marianne Zeyringer[1], Hannah Daly, Birgit Fais, Ed Sharp and Neil Strachan
[1]UCL Energy Institute, University College London, United Kingdom

ABSTRACT

Renewable energy sources and electricity demand vary with time and space and the energy system is constrained by the location of the current infrastructure in place. The transitioning to a low carbon energy society can be facilitated by combining long term planning of infrastructure with taking spatial and temporal characteristics of the energy system into account. There is a lack of studies addressing this systemic view. We soft-link two models in order to analyse long term investment decisions in generation, transmission and storage capacities and the effects of short-term fluctuation of renewable supply: The national energy system model UKTM (UK TIMES model) and a dispatch model. The modelling approach combines the benefits of two models: an energy system model to analyse decarbonisation pathways and a power dispatch model that can evaluate the technical feasibility of those pathways and the impact of intermittent renewable energy sources on the power market. Results give us the technical feasibility of the UKTM solution from 2010 until 2050. This allows us to determine lower bounds of flexible elements and feeding them back in an iterative process (e.g. storage, demand side control, balancing). We apply the methodology to study the long-term investments of wind infrastructure in the United Kingdom.

Keywords: Energy System Model, Dispatch Model, Optimisation, Wind Energy, Spatially Explicit, Temporally Explicit

INTRODUCTION

Under the Renewable Energy Directive[1], the European Commission (EC) implemented the target to increase the share of renewable energy in gross final energy consumption from 8.5% in 2005 to 20% in 2020. Further, in its Framework for Climate and Energy Policies the EC proposed a reduction in greenhouse gas emissions of 40% below the 1990 level and an increase in the share of renewable energy to at least 27% by 2030[2]. These targets imply an increase of distributed, variable power generation. Transitioning to this low carbon energy future needs long-term planning and technically feasible solutions. The economic modelling of electricity markets is not possible without accounting for technical constraints. Investment decisions regarding renewable energy generation, transmission and storage are interconnected. Renewable energy sources (RES) and electricity demand vary with time and space and the energy system is constrained by the location of the current infrastructure in place. A large-scale deployment of renewable energy generation can be facilitated by combining long-term planning for these infrastructure investments with seasonal, daily and short-term dynamics of supply and demand[3].

1 European Commission. Directive 2009/28/EC of the European parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC". (2009).

2 European Commission. A policy framework for climate and energy in the period from 2020 to 2030. (2014). at <http://ec.europa.eu/energy/doc/2030/com_2014_15_en.pdf>

3 Haller, M., Ludig, S. & Bauer, N. Decarbonization scenarios for the EU and MENA power system: Considering spatial distribution and short term dynamics of renewable generation. Energy Policy (2012). doi:10.1016/j.enpol.2012.04.069

Energy system models integrate several components of the system. However, they have a simplified time and geographical resolution[4,5]. This is a trade off between technical detail and level of integration which sacrifices detailed modelling of grid and dispatch in order to gain long-term insights for the whole energy system[6]. Therefore, the representation of RES in energy systems models is usually highly stylized[7]. When introducing geographically differentiated availabilities in the energy system model we would generally consider a supply cost curve. Consequently, only regions with high enough availabilities would be considered as possible in the solution[5]. For example, figure 1 illustrates the difference in hourly wind power output between a randomly selected day in one region and a mean day for 2010 using NCEP Climate Forecast System Reanalysis data[8] and own analysis as described under the Methodology section.

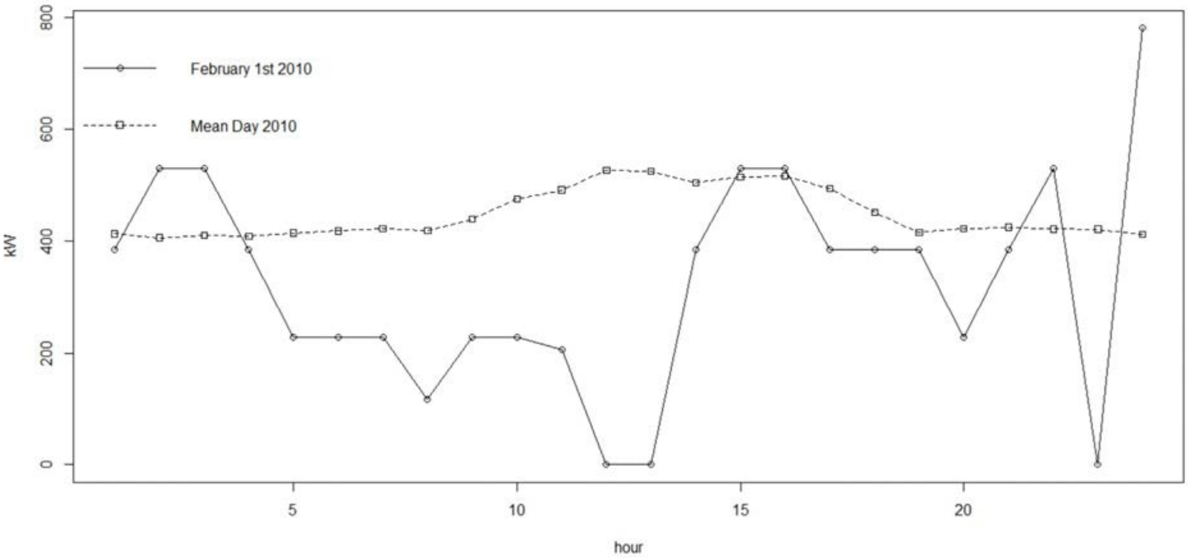

Figure 1 Wind energy output per 2.5MW turbine for one randomly selected day and region in England and Wales vs. the mean over all days and regions in England and Wales

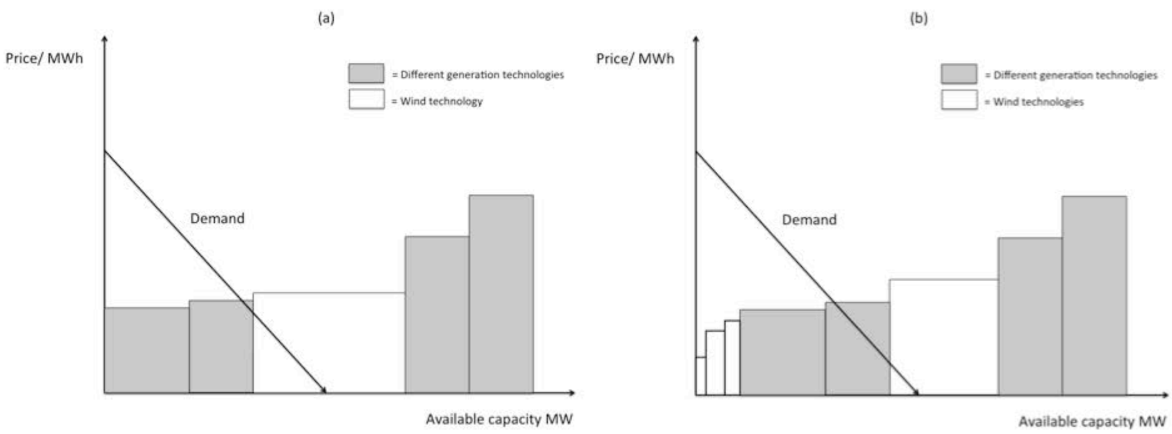

Figure 2 Effects of the spatial resolution on the ordering of a supply curve in an energy system model: (a) model with one wind region, (b) model with fours wind regions[9]

4 Pfenninger, S., Hawkes, A. & Keirstead, J. Energy systems modeling for twenty-first century energy challenges. Renewable and Sustainable Energy Reviews 33, 74–86 (2014).

5 Simoes, S., Huld, T., Mayr, D., Schmidt, J. & Zeyringer, M. The impact of location on competitiveness of wind and PV power plants – case study for Austria. in (2013).

6 Sullivan, P., Krey, V. & Riahi, K. Impacts of considering electric sector variability and reliability in the MESSAGE model. Energy Strategy Reviews 1, 157–163 (2013).

7 Ludig, S., Haller, M., Schmid, E. & Bauer, N. Fluctuating renewables in a long-term climate change mitigation strategy. Energy 36, 6674–6685 (2011).

8 Saha, S. et al. The NCEP Climate Forecast System Reanalysis. Bull. Amer. Meteor. Soc. 91, 1015–1057 (2010).

Figure 2 shows the effects of using different spatial resolutions represented by a single technology for one region (a) and several wind technologies for several regions on the supply curve of an energy system model. In Figure 2 (a) using one average wind region makes it too expensive to be included in the supply curve which meets demand. Differently, in Figure 2 (b) three wind locations are part of the solution[9]. A similar graph can be drawn showing the effects of the temporal resolution on the ordering of a supply curve in an energy systems model.

If using geographically aggregated renewable resource data in a dispatch model, the choice of flexible instruments will be under- or overestimated. Averaging wind availability and demand does not capture events of e.g. low wind availability and high demand when the usage of backup plants or stored electricity is necessary.

Most studies do not include the systemic view necessary[3] combining long-term planning with an adequate representation of the spatial and temporal characteristics of RES to provide sufficient insights into the transition to a low carbon infrastructure. Recently, there have been first approaches for more detailed temporal modelling in order to account for fluctuating RES: Kannan and Turton[10] introduce dispatch elements into the Swiss TIMES model. They implement 4 seasonal, 3 daily and 24 hourly time slices. They conclude that this approach gives more detail but cannot replace a dispatch model. Ludig et al. [7] introduce a higher temporal resolution into the LIMES model for Germany.

Others such as Pina et al.[11], Deane et al.[12] and Welsch et al.[13] developed hybrid modelling approaches soft-linking energy system models with temporally detailed power system models. Their approach results from accepting that greater insights can be gained by drawing on the strengths of different models [12].

All studies we reviewed focus on a better description of the power sector section by improving the temporal resolution but disregard the modelling of spatial characteristics of RES. Both elements are important as intermittent RES and demand vary with time and in space due to the small spatial resolution over which these vary. Further, without considering the location of transmission and generation capacities, effects on the transmission grid and the need for its extension cannot be evaluated. We conclude from our review that there is a lack of research methodologies able to answer the following questions: What are the cost effective, technically feasible long term decarbonisation strategies leading to a low carbon power system? What is the role of flexible elements in the energy system to support a large-scale integration of RES?

We therefore propose a hybrid-modelling approach that addresses both temporal and spatial characteristics of RES by combining an energy system model with a power dispatch model. Energy system models give a more comprehensive overview of the entire sector including its long term planning. Power systems models are better suited to high resolution modeling of the electricity sector studying technical feasibilities and market implications but they usually do not take planning decisions. They thus rely on scenarios or inputs from other models. A combination of these two approaches can give valuable insights into the power sector and examining the technical feasibility and market implications of the results from a long term planning model.

UK CASE STUDY

We apply the model to the UK, which is in the process of integrating high shares of intermittent RES into its system. Thus, it is a good case study. The target share of energy from RES in gross final energy consumption amounts to 15% in 2020 from 1.3% in 2005[1]. The UK government estimates offshore wind to represent 37%, onshore wind 29%, ocean energy 3% and solar PV 2% of gross renewable electricity consumption in 2020[14]. According to the Department of Energy & Climate Change [14] the UK has the best wind, wave and tidal resources in Europe. Wind and tidal energy sources are geographically diverse over varying terrain, meaning that analysis of spatial variability is

9 Simoes, S., Zeyringer, M., Mayr, D., Huld, T. & Nijs, W. Impact of modelling geographical disaggregation of wind and PV electricity generation in large energy system models: a case study for Austria. *submitted to Energy* (2014).

10 Kannan, R. & Turton, H. A Long-Term Electricity Dispatch Model with the TIMES Framework. *Environ Model Assess* **18,** 325–343 (2013).

11 Pina, A., Silva, C. A. & Ferrão, P. High-resolution modeling framework for planning electricity systems with high penetration of renewables. *Applied Energy* **112,** 215–223 (2013).

12 Deane, J. P., Chiodi, A., Gargiulo, M. & Ó Gallachóir, B. P. Soft-linking of a {Citation}power systems model to an energy systems model. *Energy* **42,** 303–312 (2012).

13 Welsch, M. *et al.* Modelling elements of Smart Grids – Enhancing the OSeMOSYS (Open Source Energy Modelling System) code. *Energy* **46,** 337–350 (2012).

14 Department of Energy & Climate Change. National Renewable Energy Action Plan for the United Kingdom Article 4 of the Renewable Energy Directive 2009/28/EC 1. (2010).

interesting. UK electricity demand is centered in the South, whereas the resource potential is concentrated be found in the North: High wind speed regions and the main tidal energy opportunities are both found in Scotland[15],[16]. As wind energy will represent the largest share of variable RES we concentrate in this modelling exercise solely on this resource. There is a limited number of studies for the UK considering spatial and temporal characteristics of variable renewables and demand and their interaction: Sinden[15], Green and Vasilakos[17], Coker et al.[18] and Iyer et al.[19]

METHODOLOGY

We soft-link two models in order to analyse long term investment decisions in generation, transmission and storage capacities, and the effects of short-term fluctuation of renewable supply: The national energy system model UKTM (UK TIMES model) and a dispatch model, both developed at the UCL Energy Institute. This approach allows us to determine the technical feasibility of the UKTM solution until 2050. Further, the dispatch model gives additional insights into the electricity market. The modelling process is illustrated in Figure 3 and will be explained in more detail in the following paragraphs. The dashed arrow refers to future work.

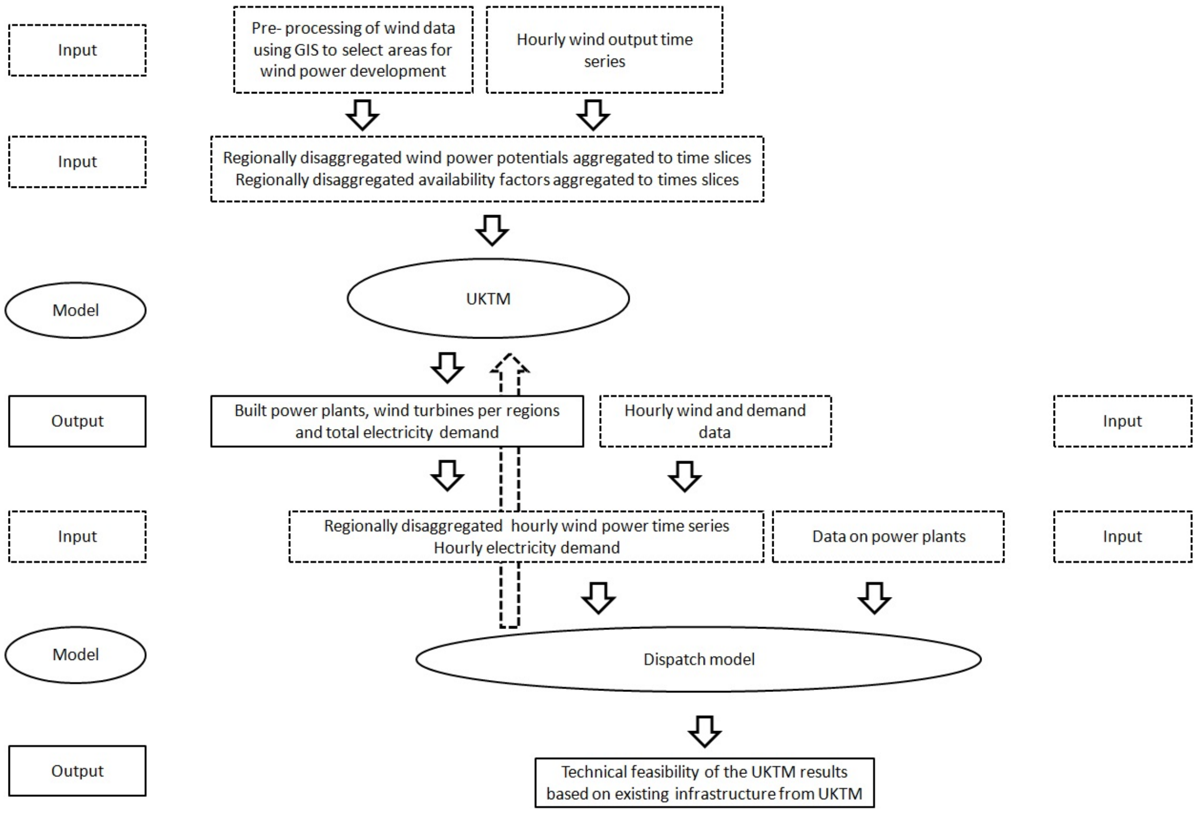

Figure 3 Graphical representation of the modeling approach

UKTM is a linear optimization bottom-up technology-rich model based on the TIMES model generator. It minimizes total energy system costs required to satisfy the exogenously set energy service demands subject to a number of additional constraints[20]. UKTM contains 16 time slices: 4 seasons and 4 intraday (day, evening, late evening, night)

15 Sinden, G. Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand. *Energy Policy* **35,** 112–127 (2007).

16 IPCC. *Renewable Energy Sources and Climate Change Mitigation Special Report of the Intergovernmental Panel on Climate Change.* (Cambridge Univ Pr, 2011). at <http://srren.ipcc-wg3.de/report/IPCC_SRREN_Full_Report.pdf>

17 Green, R. & Vasilakos, N. Market behaviour with large amounts of intermittent generation. *Energy Policy* **38,** 3211–3220 (2010).

18 Coker, P., Barlow, J., Cockerill, T. & Shipworth, D. Measuring significant variability characteristics: An assessment of three UK renewables. *Renewable Energy* **53,** 111–120 (2013).

19 Iyer, A. S., Couch, S. J., Harrison, G. P. & Wallace, A. R. Variability and phasing of tidal current energy around the United Kingdom. *Renewable Energy* **51,** 343–357 (2013).

20 Loulou, R. & Labriet, M. ETSAP-TIAM: The TIMES integrated assessment model Part I: Model structure. *Computational Management Science* **5,** 7–40 (2008).

and one region (UK). The model comprises a time period from 2010 (the base year) to 2050 with one model period covering 5 years (represented by one representative year). More information on UKTM can be found in Daly et al.[21] and on the TIMES model generator in Loulou and Labriet[20] and in Loulou[22].

Similar to other dispatch models[23,24], our power system model maximizes welfare or, in other words, minimizes annual variable electricity production costs. Costs are defined for each electricity generation source as the sum of the variable operation and maintenance costs and fuel costs. In addition, we also include CO_2 emissions. Input data are the power plants resulting from UKTM and variable electricity production costs per plant. For the dispatch model we combine them with technical information such as start costs and ramping rates. Other data are hourly demand time series and hourly resource time series. In order to be able to at a later stage assess grid infrastructure investments we divide the UK into transformer segments. Therefore, we distribute each grid cell (0.5° x 0.5°)to the closest transmission transformer[25]. This gives us 90 regions as illustrated in Figure 4.

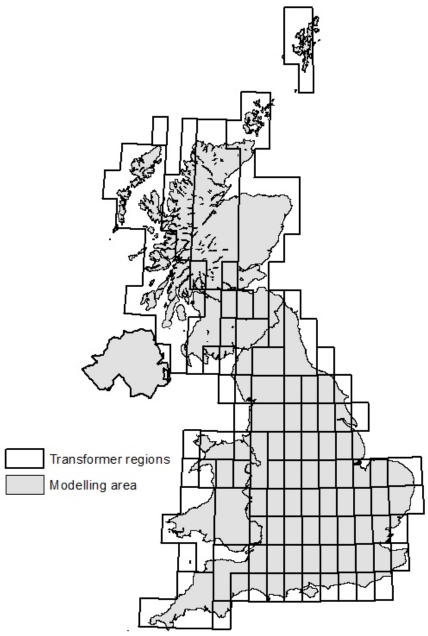

Figure 4 The 90 transformer regions

In the scope of this analysis, we use highly spatially and temporally resolved time series for potential sites of onshore wind power installations. We obtained wind speed data from the NCEP - CFSR climate reanalysis (National Centre for Climate Prediction Climate Forecast System Reanalysis) [8]. We interpolate the meteorological data to a 0.5° x 0.5° decimal grid. Wind speed is provided at 10 m above the Earth's surface by NCEP – CFSR. This was adapted to turbine hub height using the power law, and a Hellman exponent of 1/7 onshore and 1/9 offshore. This dataset gives us hourly wind power output for a 2.5 MW turbine from 2000 until 2010 in kW For this preliminary study we use the wind data for the year 2010. We calculate the availability factor of wind energy for each of the 16 UK time slices. The availability factor in TIMES describes the percentage of the year in which the technology is functional. The total wind potential per grid cell is calculated by subtracting cities, roads, protected areas and water bodies from the total available area in each grid cell. We model a wind turbine of the size of 2.5 MW. We assume that the distance between two wind turbines has to be at least five times the rotor diameter. The rotor diameter of a 2.5 MW turbine amounts to 90 meters[26]. This translates to an area of approximately 1km^2 needed per wind turbine. These assumptions results in

21 Daly, H. E., Dodds, P. E. & Fais, B. The UK TIMES Model Documentation V1.00. (2014).

22 Loulou, R. ETSAP-TIAM: The TIMES integrated assessment model. Part II: Mathematical formulation. *Computational Management Science* **5,** 41–66 (2008).

23 Brancucci Martínez-Anido, C. *et al.* Medium-term demand for European cross-border electricity transmission capacity. *Energy Policy* **61,** 207–222 (2013).

24 Weigt, H., Jeske, T., Leuthold, F. & von Hirschhausen, C. 'Take the long way down': Integration of large-scale North Sea wind using HVDC transmission. *Energy Policy* **38,** 3164–3173 (2010).

25 Nationalgrid. Transmission Network: Shape files. at <http://www2.nationalgrid.com/uk/services/land-and-development/planning-authority/shape-files/>

26 Fraunhofer Institute. Windmonitor. (2014). at <http://windmonitor.iwes.fraunhofer.de/windwebdad/www_reisi_page_new.show_

a total wind power potential of 114 GW. Availability factors vary between 3% and 71% per time slice and region. On average the time slice showing the highest AF is autumn night with 29%. We locate the existing plants in each grid cell using the DECC planning database on renewable generation[27] and allocate them to the wind power time series. This gives us the yearly wind power output for each turbine. We run the UKTM in a low GHG emission scenario meaning a reduction in GHG emissions of 80% compared to 1990 levels. For comparison, we perform two runs: an aggregated run with one single region and a regional run with 90 wind regions based on the transformer segments. In a next step we use the results on all built power plants including built wind turbines per region and total electricity demand as an input into the dispatch model. We use the 2010 energy demand as provided by Nationalgrid[28]. Assuming that its shape will not change we scale the hourly values to the total electricity demand for 2050 resulting from UKTM. As we know where UKTM builds the wind turbines we can again allocate the wind time series to get the hourly electricity production per wind turbine. We then run the power dispatch model for the year 2050. The hourly dispatch enables us to study the technical appropriateness of the solution given by UKTM assuming no infrastructure change and define upper bounds and lower limits, which can be fed back in an iterative process.

RESULTS, CONCLUSIONS AND OUTLOOK

Figure 5 shows that the spatial disaggregation of wind energy resources leads to a higher share of wind energy in the UKTM runs: In the aggregated scenario, the total wind capacity installed in 2050 is 23GW and 40GWh are generated. In the regional scenario 27GW of wind are installed and 72GWh are produced in 2050.

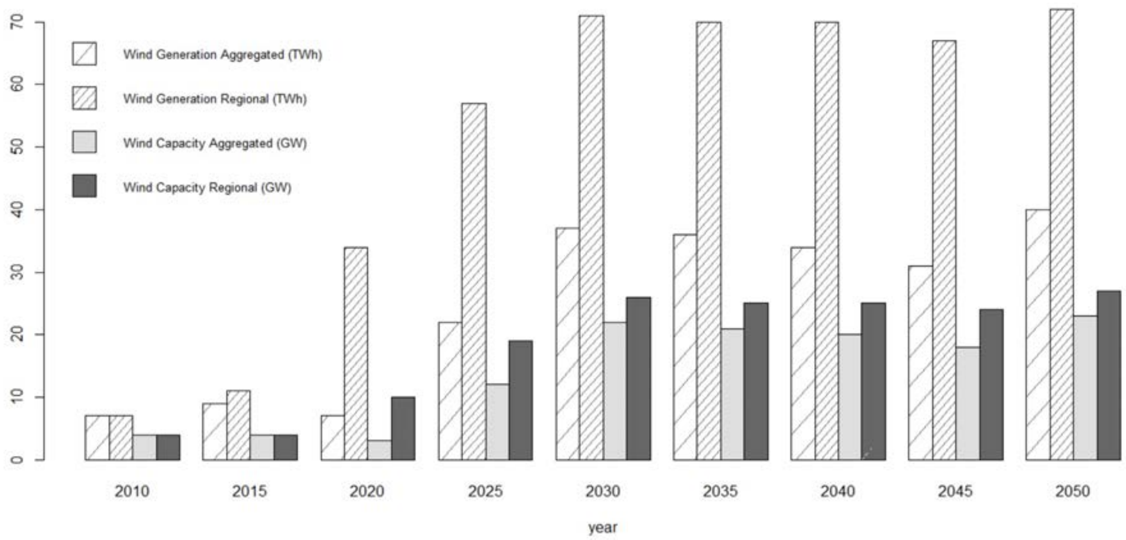

Figure 5 Wind generation and capacity per year for the aggregated and regional run

In the disaggregated run 27 regions out of 90 are selected. As figure 6 illustrates the selected regions are found around the coastal areas of England and Wales, in Scotland and Northern Ireland with higher wind availabilities.

page?page_nr=73&lang=en&owa=&owa_own_header=0>

27 Department of Energy & Climate Change. DECC Planning Database- Montly Extract. (2014). at <http://restats.decc.gov.uk/app/reporting/decc/monthlyextract>

28 Nationalgrid. Demand_Jan 2010 to December 2012. *http://www2.nationalgrid.com/UK/Industry-information/Electricity-transmission-operational-data/Data-Explorer/*

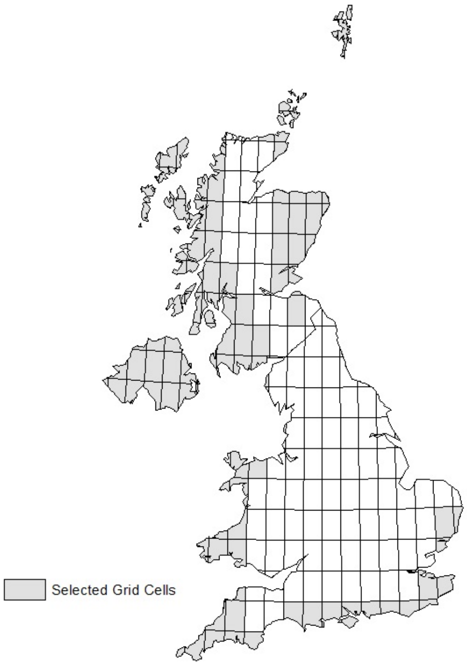

Figure 6 Regions selected by the UKTM

Preliminary runs using the dispatch model show compared to UKTM higher wind curtailment (45% vs. 37%). In 5% of the hours supply does not fulfil demand. These results indicate that the energy system model installs a too high amount of baseload capacity and not enough flexible generation for the system to operate without disconnecting demand. In our case study the energy system model installs 21 GW of nuclear until 2050 (total installed capacity amounts to 73GW in both runs). In both runs the total electricity generation from nuclear in 2050 amounts to 177 TWh of nuclear in both runs (total electricity production is 332 TWh in the regional and 311 in the aggregated run). In the aggregated run in 2050 3% of the total generation comes from gas (0% in the regional run) compared to 47% in 2010.

Our methodology allows to better represent the power sector in energy system models. This will become increasingly important when evaluating high shares of fluctuating RES. The modelling approach combines the benefits of two models: an energy system model to analyse decarbonisation pathways and a power dispatch model which can evaluate the technical feasibility of those pathways and the impact of intermittent RES on the power market.

In a next step we will run the dispatch model from 2010 until 2050. Further, we will conduct a sensitivity analysis changing the wind resource years and the shape of the demand profile allowing to account for a large scale deployment of e.g. electric vehicle or heat pumps. Further research will focus on feeding the results from the dispatch model back to the energy system model by introducing upper bounds (e.g. maximum wind capacity without backup capacity) and lower limits (e.g. storage) and running the two models in an iterative process. We will include an algorithm to extend the existing electricity grid[29] based on the price difference in two nodes into the dispatch model. As a result we will be able to not only include costs for flexible elements but also for line extensions into UKTM.

29 Leuthold, F. Economic Engineering Modeling of Liberalized Electricity Markets: Approaches, Algorithms, and Applications in a European Context. (Dresden University, 2010).