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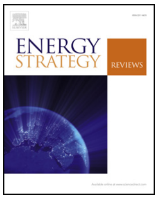

# The role of floating offshore wind in a renewable focused electricity system for Great Britain in 2050

Andy Moore[*], James Price, Marianne Zeyringer[**]

*University College London, UCL Energy Institute, Central House, 14 Upper Woburn Place, London, UK*

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ABSTRACT

Floating offshore wind energy is an emerging technology that provides access to new wind generation sites allowing for a diversified wind supply in future low carbon electricity systems. We use a high spatial and temporal resolution power system optimisation model to explore the conditions that lead to the deployment of floating offshore wind and the effect this has on the rest of the electricity system for Great Britain in 2050. We perform a sensitivity analysis on three dimensions: total share of renewables, floating offshore costs and the impact of waves on operation. We find that all three impact the deployment of floating offshore wind energy. A clear competition between floating offshore wind and conventional offshore wind is demonstrated, with less impact on other renewable sources. It is shown that floating wind is used to provide access to greater spatial diversification. Further, access to more distant regions also affects the optimal placement of conventional offshore wind, as spatial diversification is spread between floating and bottom-mounted sites.

## 1. Introduction

Greenhouse gas emissions, in particular carbon dioxide, are leading to global climate change [1], with the majority of global emissions coming from the energy sector [2]. In the UK, the Climate Change Act 2008 [3] was introduced with the target of reducing emissions by 80% by 2050 relative to 1990 levels. As with many developed countries, the UK's electricity production is a major contributor to national emissions, accounting to approximately 30% in 2014 [4]. The sector is also seen as “low hanging fruit” for decarbonisation as electricity is a homogenous good [5] and low carbon electricity options are commercially viable [5,6]. The UK Department for Business, Energy & Industrial Strategy (BEIS) expects PV and onshore wind to be the cheapest form of electricity generation in the UK from 2020 with offshore wind reaching similarly low costs soon after [7].

Renewable energy currently contributes to 25% of total electricity generation in the UK [8], with wind and solar energy amounting to 14% [9]. Due to reductions in costs [9] and the current prohibitive planning regime for onshore wind [10], offshore wind is likely to feature prominently in the UK's future low carbon electricity system. However, critics often point to the high integration costs of large scale wind energy deployment, such as the need for backup generation, enhanced transmission infrastructure and storage [11]. One option to manage the variability of wind energy is spatial diversification [12], taking advantage of the decreasing correlation of wind speed at greater spatial separation to reduce total variability of supply [12–14]. Floating offshore wind represents the next generation of offshore wind, accessing depths up to 700–1300 m, where wind speeds are typically higher [15]. Alongside higher wind speeds, access to sites spread over a larger area may provide increased potential for spatial diversification. Floating turbines could lead to lower wind integration costs due to the benefits of spatial diversification but are currently more expensive than fixed structures, with the first commercial plants only now coming into operation. Given their potentially important role it is key to understand which factors make this technology feature in the UK's future low carbon electricity system.

Several studies [12–14,16–21] have investigated the benefits of spatial diversification of wind energy but not including floating offshore wind energy. Two studies have investigated the total resource of offshore wind including floating wind turbines and sought out the most appropriate build sites: [22], used geospatial constraints with a component based cost model to produce maps of LCOE for both fixed and floating wind turbines in the UK Renewable Energy Zone (REZ). [23], performed a similar analysis of offshore regions, specifically for floating wind, around the coast of North West Spain. However, these studies do not take an energy or electricity systems view and so are not suitable to

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[*] Corresponding author.
[**] Corresponding author.
*E-mail addresses:* abmoore92@googlemail.com (A. Moore), m.zeyringer@ucl.ac.uk (M. Zeyringer).

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give insights into the conditions that would lead to the deployment of floating wind and the role it could play in a renewable focused electricity system.

We aim to close this gap in the literature by using a high spatial and temporal resolution electricity system model to investigate the impact of system and technology conditions on deployment of floating wind in the GB electricity system: The total renewable penetration in the system affects the need for system integration measures such as spatial diversification [14]. Cost is a key factor in deployment, as the technology is less mature than conventional offshore wind. Finally, the production of floating turbines may be affected by waves, depending on the foundation design [24]. We categorise these factors as: a) system conditions defined by a renewable energy portfolio standard and b) technology conditions defined by firstly the cost ratio between conventional and floating offshore turbines and secondly the sensitivity to waves. This allows us to analyse the conditions leading to the deployment of floating turbines and their effect on the rest of a cost-optimal and low-carbon GB power system in 2050.

Key results of our analysis are i) the cost crossover point at which floating turbines become part of the optimal system, ii) the generating technologies and their locations that are replaced by floating turbines, and iii) any further changes to the system design and operation such as a need for storage and dispatchable generation.

The article is structure as follows: In the following section we present the methodology describing the modelling approach for offshore wind, the electricity model and its linkage to an energy systems model, and define the scenarios used in the comparative analysis. In section three we analyse the results on LCOE supply curves, the impact of the scenario on installed capacity, the competition between different renewables and flexibility measures, and the system benefit of floating wind installation. Finally, in section four we present our conclusions.

## 2. Methodology

We use a power system optimisation model with high spatial and temporal resolution, highRES, to design the least-cost power system under different system and technology-specific conditions. For system conditions we vary the renewable portfolio standard (RPS), defined as the share of annual generation from solar and wind. For technology-specific conditions we vary the cost ratio of floating to mid depth fixed foundation wind, as well as the sensitivity to waves. We run 40 scenarios to determine which conditions lead to the deployment of floating offshore wind as illustrated in Fig. 1. This allows us to assess the competition between floating offshore wind turbines and other sources of renewable energy.

In the following section we describe the modelling of offshore wind energy for this study, the highRES model and its linkage to the long-term energy system model, UK TIMES (UKTM), and elaborate on the model setup.

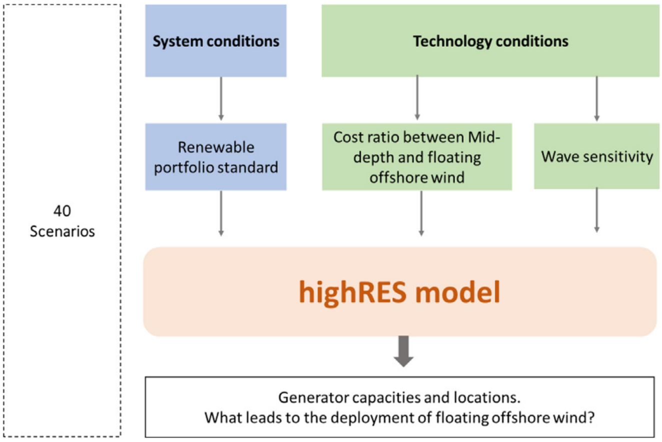

**Fig. 1.** Overview of the methodology.

### 2.1. Modelling of offshore wind

#### 2.1.1. Geospatial restrictions

We categorise geospatial restrictions on renewable energy by social, technical and environmental restrictions (see Table 1 for offshore wind). Offshore wind restrictions include Marine Conservation Zones, Marine Protection Areas, shipping lanes, oil and gas infrastructure, as well as a coastal buffer. Where there is an overlap, we remove existing wind farms from the restrictions. Further, floating wind is restricted by distance to shore and water depth. A 200 km distance limit is used, in line with Dogger bank, a far-offshore wind farm currently in development, and a 1000 m depth limit is assigned as used in Refs. [15,25–27].

#### 2.1.2. Cost regimes

We take all technology costs from the energy systems model UKTM [32–34] (UK TIMES model) which is used by the UK government [35,36]. We introduce further cost detail by splitting the available area into specific depth regimes while maintaining the UKTM cost source by calculating scale factors for each region. We analyse cost and depth data for UK offshore wind farms from the 4C Offshore database [37], which shows two distinct cost regimes, with the cut-off at 20 m visible in Fig. 2.

We use the cost database to calculate scale factors as opposed to taking the costs directly. The costs are scaled against a generic turbine at 15 m depth, the current average, calculated by taking a linear regression of the shallow region. Floating wind projects in the database are found to cost 40% more per MW than those in the mid depth region. Table 2 shows the depth ranges and costs used in the model for the three types of offshore wind. Cost values are taken from the 4C Offshore database [37]. Total available capacity is calculated from the geospatial analysis. Cost scale factors are assigned relative to UKTM values.

#### 2.1.3. Electrical losses

Electrical losses are calculated based on distance to shore, assuming that the least-loss connection is used, either HVAC and HVDC based on the results of a simulation of a 500 MW farm [38]. This results in losses between 0.7 and 2.3%, with HVAC for connections shorter than (and HVDC longer than) 73 km.

#### 2.1.4. Floating turbines and waves

There are three key types of floating turbine support structure, the tensioned leg platform (TLP), spar buoy, and semi-submersible. There is no consensus on the best design, for example the Energy Technologies Institute (ETI) suggests that the most appropriate design for the UK is the TLP [39], which is used in the GICON-SDF Pilot project under construction in Germany. However, two projects under construction off the Scottish coast use other designs: Hywind uses a spar-buoy support while Kincardine uses a semi-submersible design [37]. As a result of this future technology uncertainty we the different types of floating foundation are not separated out in the model setup. Instead, we apply cost and environmental factors to a generic turbine.

Among the other advantages and disadvantages of the three main floating foundation designs, each has a different response to wave conditions, with the TLP and spar buoy more stable than the semi-submersible [39,40]. Significant wave height, defined as the mean height of the largest 1/3 of waves, is input to highRES as an environmental parameter to account for the impact of waves on energy production. Following [41] we take a 4 m significant wave height tolerance, and as in Ref. [24] we assume full shutdown when the operational tolerance is breached. The NOAA WaveWatch III dataset is used with a 3-h 0.5° longitude/latitude resolution [42], so production is stopped for any given 3-h period with a significant wave height greater than 4 m. This dataset shows that waves are typically more extreme in the

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