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

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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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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.

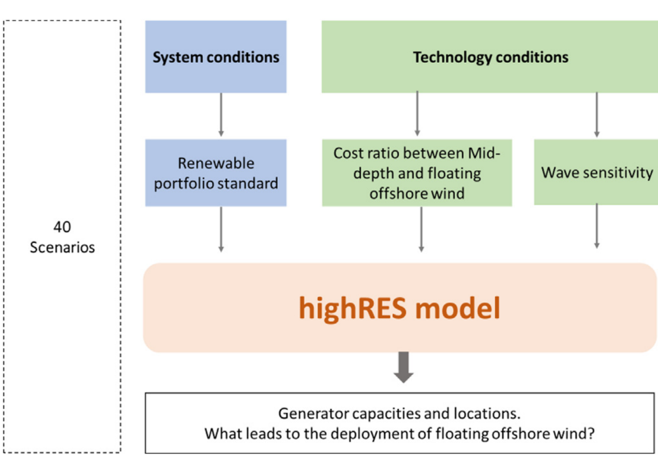


Fig. 1. Overview of the methodology.

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

Table 1
Geospatial restrictions applied to offshore wind.

Exclusion Domain	Impact	Exclusion	Description
Environmental	Environmental Conservation	12 nautical mile coastal buffer; Special Protected Areas with 1 km buffer; OSPAR MPA and MCZ	Increased bird activity near coast. Special Protected Areas are specifically for birds. Impact of offshore wind farms on the environment still unclear [28]
Social	Tourism and Natural Beauty	12 nautical mile coastal buffer	Visual impact
	Shipping (all)	More than 7 vessels per week in 2 × 2km grid square	Automatic Identification System (AIS) used. Threshold maintains key requirements of Chamber of Shipping [29,30]
	Fishing	6 nautical mile coastal buffer More than 5 vessels per week in 2 × 2km grid square	Inshore fishing industry is most affected by changes to access [29,30]
	Military	More than 1 vessel per week in 2 × 2km grid square	Captures military use around naval bases [30]
	Offshore Infrastructure	2 km buffer operational oil and gas wells and wells in construction	Similar distance between large infrastructure within an offshore wind farm [31]
Technical	Floating Wind Farms	200 km distance to shore; 1000 m depth	Similar distance to the furthest offshore wind farm in development in the UK floating wind restricted to 1000 m depth limit as in Refs. [15,25–27]

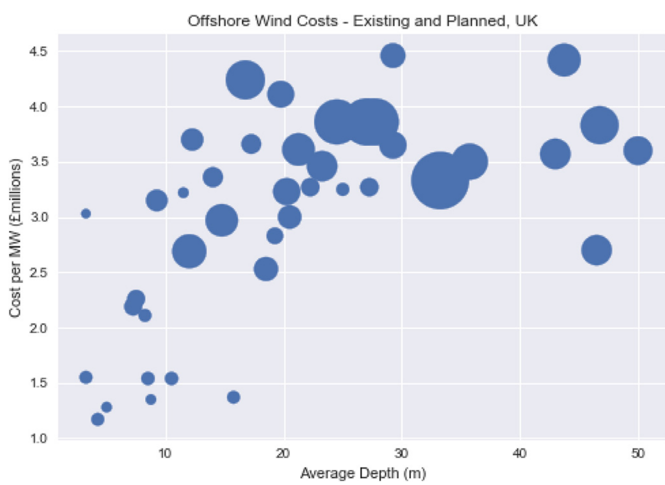


Fig. 2. Total project costs per MW for existing and planned offshore wind farms in the UK, with bubble size showing total capacity.

Table 2
Depth ranges, costs and available capacity for the three types of offshore wind.

	Depth	Project Cost (£m/MW)	Scale Factor	Total Available Capacity (GW)
'generic'	15 m	*2.95*	*1*	
Shallow	0–20 m	2.53	0.86	8.86
Mid	20–70 m	3.58	1.21	364
Floating	70–1000 m	*Scenario specific*	*Scenario specific*	1114

Atlantic than the North Sea, and larger in winter than summer.

2.2. highRES model and UK TIMES linkage

2.2.1. Overview

The high spatial and temporal resolution electricity system model (highRES) [43] minimises power system costs to meet hourly demand subject to a number of technical constraints. It uses a full year of hourly time steps with weather inputs at a 0.5° resolution (see Fig. 3 left) and makes capacity and dispatch decisions to satisfy hourly electricity demand in 20 zones connected by a simplified representation of the transmission grid (see Fig. 3 right). Location, capacity, and dispatch of renewable and conventional generators, transmission, and storage are included as decision variables in a cost-optimising deterministic linear program. The high spatial and temporal resolution make it possible to account for the variability of wind and solar resources in space and time and as a result we can model the benefits of spatial diversification.

We use the long time horizon model, UKTM [32–34,44], to set the electricity system boundaries for 2050. UKTM is a linear, bottom-up, technology-rich cost optimising model instantiated within the TIMES[1] framework. It minimises total energy system costs required to satisfy the exogenously set energy service demands subject to a number of additional constraints [45]. A key strength of UKTM is that it represents the whole UK energy system under a given decarbonisation objective, which means that trade-offs between mitigation efforts in one sector versus another can be explored. Here, we study the power system design for the year 2050 as this is when the UK committed itself through the Climate Change Act 2008 [3] to reduce its greenhouse gas emissions by 80% relative to 1990 levels.

Fig. 4 shows how UKTM, meteorological data and GIS modelling feed into highRES. The key inputs to highRES are the generator, storage and transmission costs, hourly weather data, demand, and geospatial constraints such as minimum distance from the shoreline. We use UKTM to define the boundary of the electricity system (i.e. annual electricity demand). Where there is overlap, the same technology costs are used for highRES as in UKTM. The hourly demand profile is calculated by taking the historical demand profile from National Grid and rescaling it to the annual electricity demand output from UKTM for 2050. The demand profile for 2010 is used and disaggregated to the 20 demand zones defined in National Grid's 2005 GB Seven Year Statement, shown in Figs. 2 and 3. Solar and wind generation is input to the optimisation stage as hourly capacity factors, calculated from weather data. Solar irradiance data is taken from the Satellite Application Facility on Climate Monitoring's (CMSAF) Surface Solar Radiation Data Set - Heliosat (SARAH) [46]. Wind data is taken from the National Centre for Climate Prediction Climate Forecast System Reanalysis (NCEP CFSR) dataset [47]. A full explanation of the renewable energy production methodology is provided in the supplementary information of [43]. GIS modelling is used to apply spatial constraints on the deployment of renewable capacity under the categories of social, environmental, and technical restrictions, which reduce the available area for each renewable energy type in each region.

2.2.2. Key equations in highRES

The most important equations are outlined here, while a full appendix of the highRES model is available in the supplementary information of [43].

Demand is met hourly within the 20 zones using variable renewables and conventional generators, storage, and transmission such that

[1] http://iea-etsap.org/index.php/etsap-tools/model-generators/times.

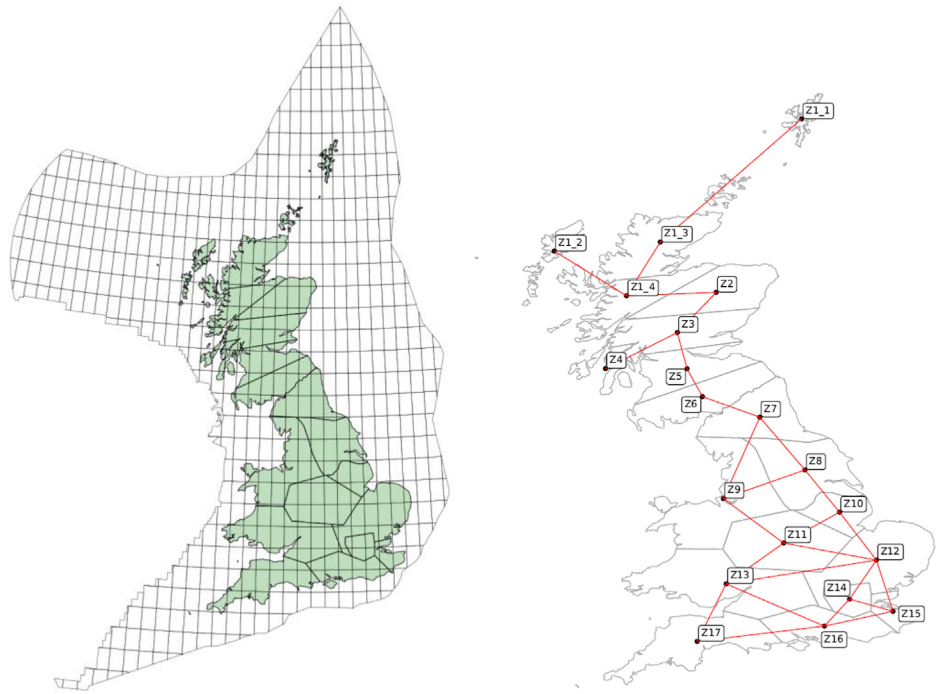


Fig. 3. Geographic representation in highRES. Left side: 0.5° longitude and latitude grid squares (regions) for reanalysis weather data input - renewable capacity and generation is managed at this resolution within the Renewable Energy Zone. Right side: 20 zones and transmission infrastructure according to National Grid zones.

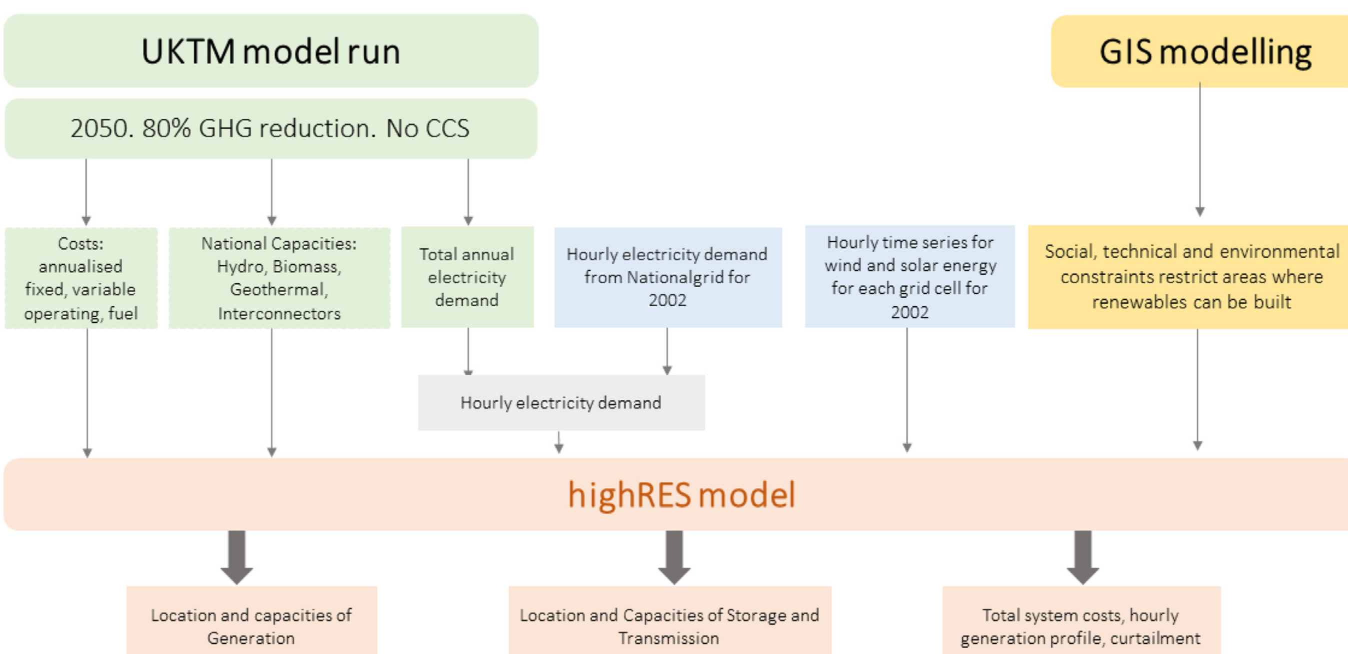


Fig. 4. Description of the highRES modelling methodology.

$$demand_{z,h} = \sum_{vre,r} generation_{vre,r,z,h} + \sum_{non-vre} generation_{non-vre,z,h} - \sum_{s} store_{in_{s,z,h}} + \sum_{s} store_{out_{s,z,h}} + \sum_{z'} transmission_{z,z',h} \quad (1)$$

where r are the regions within the zone, z are the demand zones, h is the time period, *vre* are the variable renewable generators, *non-vre* are the conventional generators, s is the storage technology, *store_in* is the energy committed to storage, *store_out* is the energy taken out of storage, and *transmission* is the net energy flow from zone z' to z.

The full system is optimised by minimising the objective function,

$$cost = generators_{varom+capex} + transmission_{capex} + storage_{varom+capex} \quad (2)$$

where *transmission*, *storage*, and *generators* have fixed annualised project costs per MW capacity including capex and fixed operating costs, and variable operating costs per MWh generated including fuel costs where necessary.

A renewable portfolio standard (RPS), defined as the minimum percentage of demand met by renewable energy, is used to investigate different shares of renewables. The energy produced by non-renewable sources is constrained by

$$\sum_{non-vre,z,h} generation_{non-vre,z,h} \leq (1 - RPS) * \sum_{z,h} demand_{z,h} \quad (3)$$

where RPS is the renewable portfolio standard in percent.

Further equations provide limits on ramp rates for generators, determine storage losses from cycle efficiency as well as losses over time, and apply transmission losses.

2.3. Study setup

As outlined earlier, we use UKTM to ground highRES in a 2050 energy system by providing costs and annual electricity demand. A single UKTM scenario is used throughout, with an 80% greenhouse gas (GHG) emission reduction target to 1990 levels by 2050, with no carbon capture and storage (CCS). This is to ensure that the electricity demand is representative of a significantly decarbonised energy system, and because of the sizable uncertainty around the large scale deployment of CCS given the cancellation of the UK government's CCS commercialisation competition in2015.[2]

We use highRES to decide on the cost optimal installed capacities and locations of open cycle natural gas, nuclear, solar, onshore wind, and offshore wind, which is split into three parts: shallow (0–20 m), mid depth (20–70 m), and floating (70–1000 m) to meet the electricity demand. We fix capacities for Hydro, Biomass, Geothermal power and Interconnectors to France and Ireland to UKTM capacities (see Table 3).

Storage was modelled in the form of Pumped Hydro and Sodium Sulfur (NaS) batteries, with pumped hydro capacities restricted to existing sites in Wales and Scotland, totalling 2.8 GW. Transmission was implemented as HVAC overhead lines over ground, and HVDC subsea cables to connect the Shetlands and Western Isles in Scotland to the mainland.

For this analysis, we run highRES using the year 2002 for wind and solar generation as it has previously been shown to require above average flexible generation, so as to test the system in its least renewable-friendly weather year [43].

We construct scenarios by varying three parameters, separated into a system condition and two technology conditions as shown in Table 4. The system condition is set using a Renewable Portfolio Standard (RPS), defined in equation (3). Wind and solar are counted towards the RPS, and not geothermal, hydro, or biomass, so that the RPS represents the introduction of system integration issues related to weather dependency. RPS is increased from 20 to 90%, which serves to explore a significant increase in variable renewables from the 2016 wind and solar contribution of 14% [9].

To compare floating wind with conventional offshore wind, the cost scenarios are built using a scaling factor. Using the results of an expert elicitation which anticipates LCOE converging by 2050 [48], and the 4COffshore database which currently shows a 40% higher cost for floating projects, a range of 40% cost penalty to 20% cost advantage is used. The most expensive floating wind scenario represents the present-day ratio, and the cheapest setting represents a scenario where significant cost savings are found in floating projects that do not transfer to conventional offshore wind. The nomenclature used states floating costs in terms of mid depth wind, for example in the C_{120} scenarios floating wind costs 20% more than mid depth offshore wind. Finally, the impact of waves is set either on, with 4 m tolerance, or off.

3. Results and discussion

In the first section we analyse the input data with a focus on calculating levelised costs of electricity (LCOE). In the subsequent sections we discuss the model results: First, we analyse the impact of the scenario on the installed offshore wind capacity, followed by the impact of floating turbines on the other renewables and lastly we show the spatial distribution of floating offshore wind capacities.

[2] http://www.londonstockexchange.com/exchange/news/market-news/market-news-detail/other/12597443.html.

Table 3
Capacity parameters provided by UKTM.

Generator	Capacity (GW)
Hydro	1.59
Biomass	6.58
Geothermal	0.48
Interconnector EU	5
Interconnector Ireland	0.8
Electricity Demand	503 TWh/yr

Table 4
Scenario setup and naming convention.

Type of Condition		Settings	*Example Names*
System condition	Renewable Portfolio Standard (RPS)	20,40,60,80,90%	$RPS_{20}C_{80}W_{on}$ $RPS_{90}C_{140}W_{off}$
Technology conditions	Floating Wind Cost (C)	80,100,120,140%	$RPS_{60}C_{120}W_{off}$
	Wave Sensitivity (W)	ON,OFF	

3.1. LCOE supply curves

In this section before interpreting the results from the model, we analyse the input data. The cost-optimiser designs least cost systems that meet an hourly demand constraint, so the total system cost of each source is considered. To further understand how this is separated into direct costs and integration costs (methods to balance the timing and location of renewables with demand), we first look only at the direct cost of energy supply ignoring the integration costs, by using LCOE. LCOE does not consider system effects, so to understand the integration cost associated with different renewable sources we first compare the LCOE of each source then show that the optimiser produces a different generator mix.

To analyse the available generators we use supply curves of the LCOE for the chosen weather year, shown in Fig. 5. From the geospatial analysis we find that the total available resource for offshore wind is 8450 TWh/yr, slightly lower than that found in Ref. [22], who found a total resource of 11,963 TWh/yr. The difference is due to the water depth and distance to shore constraints applied to floating wind in our input. The 2050 annual demand from UKTM of 503 TWh can be easily met; however, the important factors missing from supply curve analysis are timing and location of production, which are instrumental in highRES.

Fig. 5 shows that onshore wind and shallow offshore wind are the cheapest sources initially, with steep supply curves due to the relatively small resource and the number of regions with low wind capacity factors on and near to the land. Solar energy is relatively expensive ranging from £78 to £129/MWh. Mid depth and floating offshore wind represent a huge potential supply. In the most expensive cost setting, mid depth offshore wind can provide 1700 TWh of annual generation at lower LCOE than floating turbines.

The abundance of wind resource of each type demonstrates that any deployment of floating wind rather than mid depth offshore wind in the sensitivity analysis is due to cost and/or system benefits as opposed to limited resource.

3.2. Scenario impact on installed offshore wind capacity

In this section we discuss the results of the sensitivity analysis, with a focus on the capacity of offshore wind of different types. We perform a sensitivity analysis on two key technical parameters for floating offshore wind, the cost and environmental sensitivity (waves). Further, the

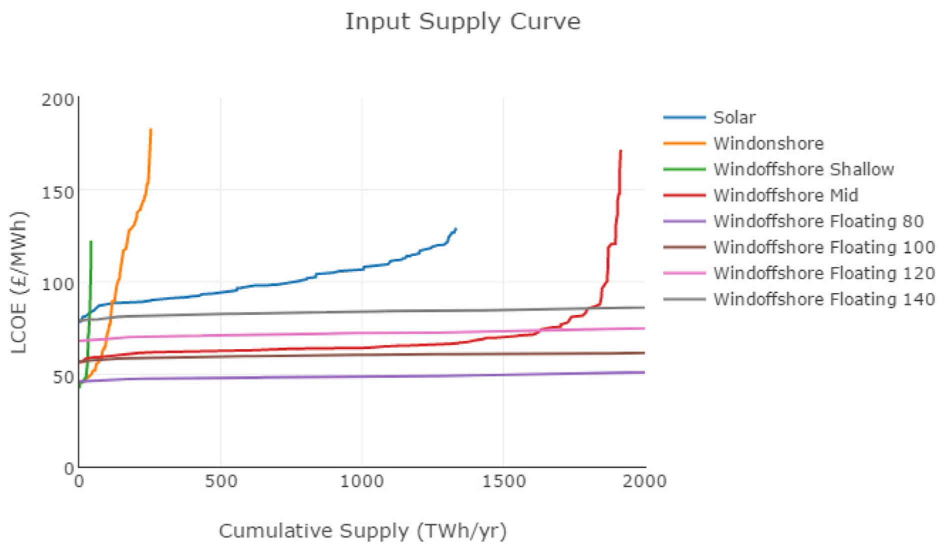
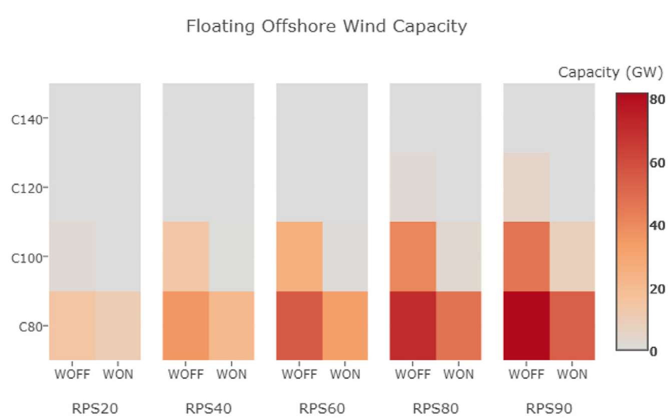


Fig. 5. Supply curves for renewable energy produced by taking cumulative annual energy supply ordered by LCOE (not accounting for integration costs). Each cost bracket for floating wind is shown, not considering wave losses.

electricity system is constrained by renewable portfolio standards increasing from 20 to 90%, while the RPS as defined here by solar and wind penetration was 14% in 2016 [9].

The general trends can be seen in Fig. 6, where the national capacities, in GW, of floating and mid depth offshore turbines are shown for each combination of floating cost, wave sensitivity, and renewable portfolio standard. Here we do not show shallow offshore turbines as



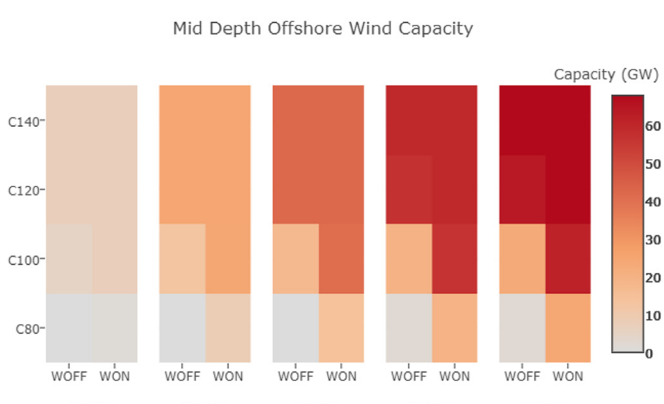


Fig. 6. Installed capacity in GW of floating and mid depth offshore wind in a cost optimal power system with varying floating technology parameters (cost, C, and wave tolerance, W) and system design (renewable portfolio standard, RPS). The floating cost is given in percentage terms relative to the mid depth offshore turbine.

the capacity for shallow depths is 5.5 GW for all scenarios, except those with $C_{80}W_{off}$, across all RPS. This is because there is a sharp change in annual generation between the best and worst sites, shown by the steep shallow offshore supply curve in Fig. 5.

Firstly, the introduction of a 4 m significant wave height operating threshold has a direct impact on deployment. The capacity installed for a given W_{on} scenario is in line with the equivalent W_{off} scenario with 20% higher cost. This shows that from a system perspective, it is worth paying 20% more to remove sensitivity to waves.

Cost has a pronounced, consistent impact on deployed capacity. As previously mentioned, the current cost ratio between mid depth and floating turbines is approximately 140% [37], which in our study represents the most expensive scenario. Even at very high renewable portfolio standards floating deployment is restricted by this cost, with zero deployment for the two $RPS_{90}C_{140}$ scenarios. Deployment increases with decreasing cost, and does so later for systems with lower shares of renewables.

Importantly, 5 GW of floating wind is deployed in the $RPS_{90}C_{120}W_{off}$ scenario despite there being more than three times the total annual energy demand available solely from mid depth sites at a cheaper project LCOE. This would appear to contradict the supply curves shown in Fig. 5, demonstrating the system benefit afforded by spatial diversification, and the use of what at first appears to be more expensive generation to achieve it.

Increasing the RPS leads to increased capacity of all renewables, including floating wind. For the lowest cost scenario, floating wind provides the lowest LCOE available from renewable sources alongside shallow depths and onshore wind. As the RPS is increased, however, solar is introduced to the system despite the higher LCOE. Solar generation has a negative correlation to all forms of wind, whereas wind sources are positively correlated, with the strongest correlation between offshore wind regions, shown in Fig. 10. For high renewable share scenarios, the model deploys solar capacity in regions that give a more negative correlation of solar and wind generation, demonstrating the use of technological diversification to smooth output.

3.3. Competition between renewable sources

To investigate the impact of floating turbines on a future electricity system with high shares of renewables we run a further nine cost settings for floating offshore wind at 5% relative cost increments to conventional offshore wind for the $RPS_{90}W_{off}$ scenarios.

The impact of floating turbine cost on the renewable, storage, and

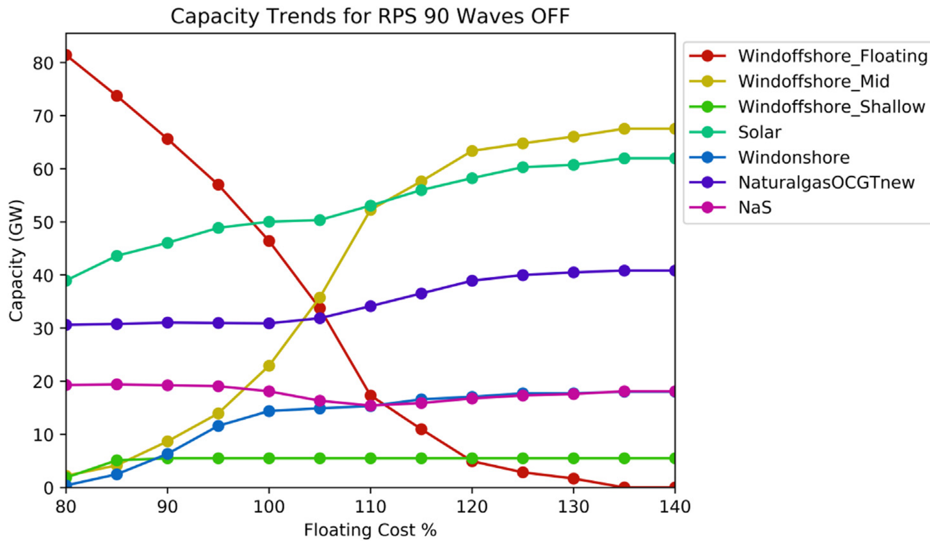


Fig. 7. Installed capacities for 90% renewable portfolio standard and waves turned off at 5% relative cost increments.

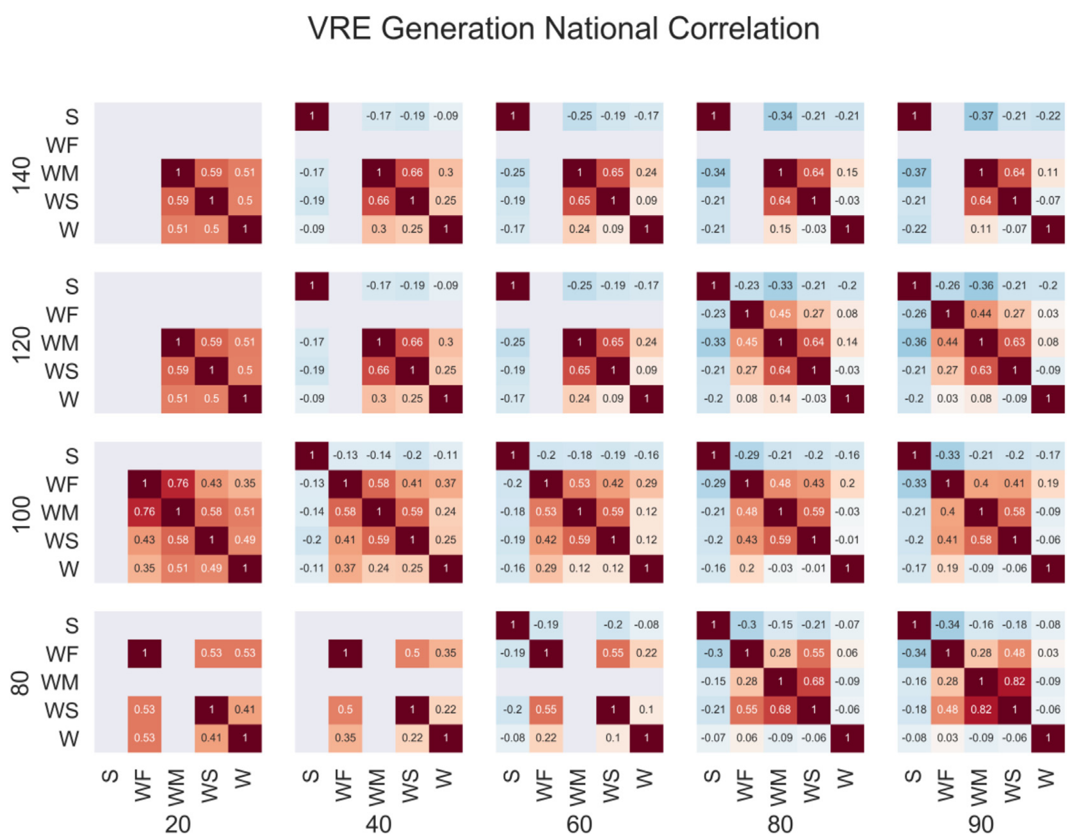


Fig. 8. Correlation of Solar (S), Floating wind (WF), Mid depth offshore wind (WM), Shallow offshore wind (WS), and onshore wind (W) in the scenarios with wave sensitivity turned off. Correlations are calculated from hourly national generation profiles.

backup gas capacities is shown in Fig. 7. Here we see that as floating offshore wind becomes cheaper, the capacity of other generators reduces. However, there is clearly a stronger relationship between the mid depth offshore wind capacity and floating wind than the other sources. This is because they have similar timing of production. The nationally-aggregated hourly generation dispatched for each technology in each scenario, as decided by highRES, is taken and the correlation between technologies shown in Fig. 8, which shows that the utilised resource from the three offshore regions is more correlated than with onshore wind and solar. As previously mentioned, capacity in the shallow region remains consistent due to the significantly lower LCOE available in some sites, except for the lowest floating cost scenario. For example, in the $RPS_{90}W_{off}C_{105}$ scenario, where the mid and floating capacities are almost equivalent, mid depth and floating wind generation have a positive correlation of 0.55, whereas solar and floating wind have a negative correlation of -0.33.

Despite the similar production profiles, floating wind clearly has a positive system impact alongside other offshore wind. This is highlighted by the fact that the capacities for mid depth and floating wind cross over at the 104% cost point. Almost as much floating wind as mid

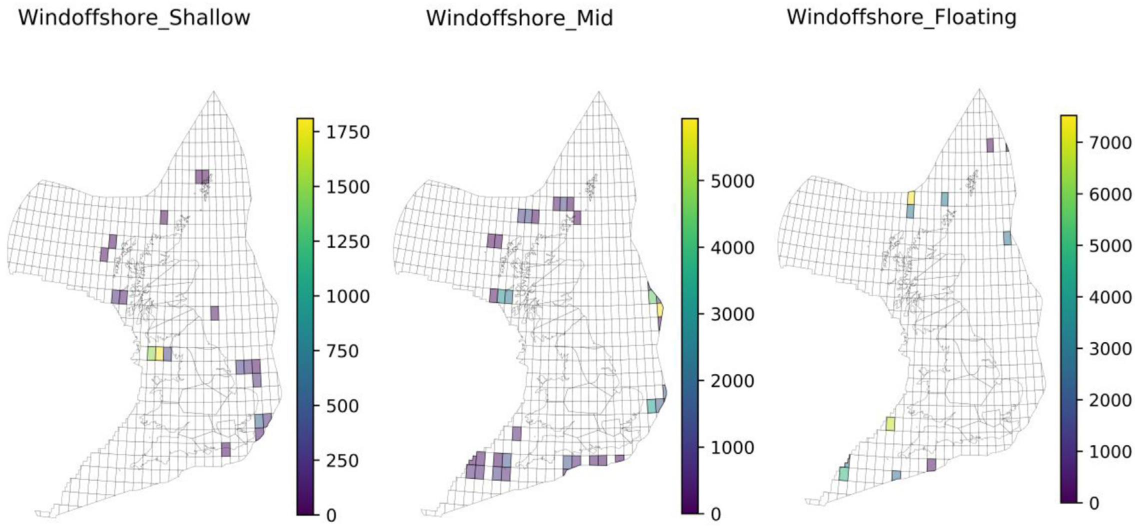


Fig. 9. Location of offshore wind capacity in MW for the $RPS_{90}C_{105}W_{off}$ scenario, in which total capacities of floating and mid depth wind are close to equal.

depth was installed in $RPS_{90}C_{105}W_{off}$, with similar national capacity factors. This demonstrates that the optimal sites to install in are not just those with the highest capacity factors, but those which provide a balance in terms of timing of supply with the other sources of offshore wind generation.

Shortfalls in supply are met by natural gas and storage. In the RPS90 scenarios, natural gas has a very low capacity factor, ranging between 2.4 and 2.6%. It is used as a backup in situations where storage and renewables are unable to meet demand. NaS battery storage, however, has a capacity factor between 8.5 and 11.5%, and is used for daily peak shifting. Natural gas capacity decreases as floating turbine installations increase, showing that spatial diversification can be used to reduce extreme low-generation events.

3.4. Spatial distribution of floating offshore wind

The optimiser makes use of floating wind for further spatial diversification. As demonstrated in Fig. 9 and Fig. 10 floating wind provides access to sites that are further apart than the mid depth regions. The introduction of floating wind reduces the capacity of mid depth wind and further causes the mid depth installations to be more concentrated, with fewer regions utilised.

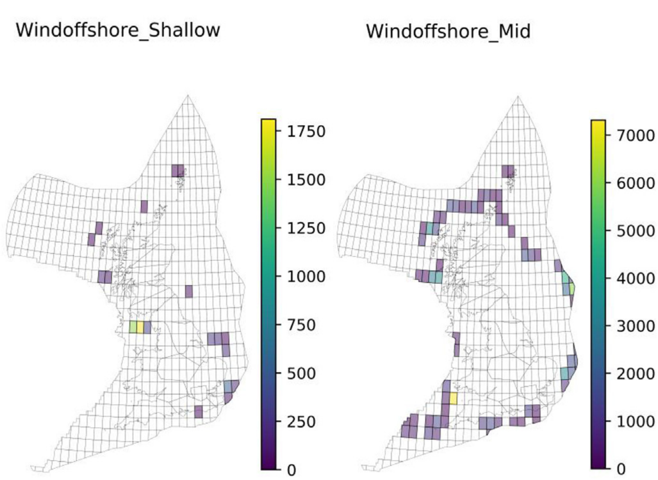


Fig. 10. Location of offshore wind capacity in MW for the $RPS_{90}C_{140}W_{off}$ scenario, in which no floating offshore wind is installed.

4. Conclusions

Here we use a cost optimisation model of the British electricity system to explore the technology and system conditions that lead to the deployment of floating offshore wind energy. To investigate the different roles of shallow, mid depth, and floating offshore wind we split the offshore region into three depth categories. Conducting a geospatial analysis we find that 8450 TWh/yr is available from offshore wind.

As the share of generation provided by renewables (i.e. the RPS) increases, the capacity of floating offshore wind increases, along with other renewable sources. Further, as the cost of floating wind decreases, its capacity increases. If floating turbines are made more sensitive to wave conditions, the capacity decreases. The impact of a 4 m significant wave height tolerance is found to be approximately equivalent to a 20% increase in cost.

We show a clear competition between floating and mid depth (bottom mounted) offshore wind: As floating wind cost is reduced, and as a result its capacity increases, the capacity of other renewable sources decreases, with the most pronounced impact on mid depth offshore wind. For a system with a 90% share of solar and wind, floating wind capacity starts to feature in the electricity system when the cost is up to 35% higher than mid depth wind. The deployed capacity of floating wind reaches parity with mid depth wind when costs are just under 5% higher. This cost premium represents the 'system benefit' of floating wind to a 90% renewable share scenario in the form of enhanced spatial diversification. Access to more geographically dispersed sites with a different timing of production allows for a reduction in installed backup generation capacity. Further, the use of floating turbines causes a spatial concentration of mid depth offshore wind. This is because the capacity deployed in these sites is reduced and spatial diversification is provided by the combination of all offshore wind as opposed to solely within the mid depth and shallower waters.

Current policy support for offshore wind energy in the UK (i.e. the contracts for difference system) does not incentivise developers to build in sites that are beneficial to the system, instead concentrating on total energy output. Floating wind can complement bottom-mounted offshore wind by providing an aggregate increase in spatial diversification. We suggest that as the share of variable renewable electricity increases, and as floating wind is deployed in the UK, the policy regime is altered to incentivise developers to build in system-optimal locations.

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