Chapter 19
An Overview of Offshore Wind Farm Design

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Abstract For offshore wind energy to be viable, the design of wind turbines is not the only important factor—rather, the design of wind *farms* is also crucial. The current chapter discusses the challenges of designing an optimum wind farm and identifies the various factors that need to be considered. Lastly, the chapter presents the novel EERA-DTOC tool for designing offshore wind farm clusters.

19.1 An Overview of Offshore Wind Farm Design

There are two stages in the design of offshore wind farms, run by two different stakeholders. The first stage is often the choice of sites for tendering through a national authority, such as the Danish Energy Agency or the Crown Estate in the UK. During this stage, a number of different exclusion zones have to be managed, such as nature reserves, shipping lanes, oil exploration areas, light house cones, risks of unexploded ordnance or the chances for finding archaeological remains. Typically, the locations thus determined will be opened in a call for tenders, where the second stage of the wind farm design is done at the wind power developers. They now look into wind, wave and sea bed conditions, availability of foundation and turbine types and installation ships, layout of the wind farm, both taking wakes and cabling into account, projected operation and maintenance cost, and try to roll all of this information into typically a bid for a price per produced kWh. In some jurisdictions, the cost of transporting the power onshore is priced in with the wind farm, in other places the transmission system operator will have the duty of providing a suitable grid connection point in the vicinity of the wind farm. Usually, the cheapest bidder will be awarded the contract. Once that has happened, the detailed design of the wind farm will go on, including in-depth investigations of the sea bed, contracting of suppliers of hardware and services, detailed layouting of the farm, and finally the construction. As the last step before power delivery, the transmission system operator will check for grid code compliance, together with the checkout of the

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suppliers. Then, the wind farm will go into an operational state and will produce power for the next 25 years.

19.2 Strategic Planning

The first real offshore wind farm was built in Denmark, in 1991 in Vindeby. It consists of 9 Bonus 450 kW turbines on gravity foundations. It was followed by the similar sized wind farm at Tunø Knob in 1995. Both sites are in relatively protected Danish waters, and are now owned and operated by DONG Energy. Also for the permitting of the wind farm, the process was new and had to be a collaborative work of the Danish Energy Agency (DEA) as the permitting government authority and Elkraft, then the executing developer. A similar process still exists in Denmark under the name of Open-Door Policy, where new projects can be proposed and then will make their way through the permitting process. However, the more relevant process in recent years is the tendering process, where first parliament agrees on the size and overall location of the next Danish offshore farm, and then the DEA investigates the area and designs a call for tender. This was the procedure for the first large-scale offshore wind farm at Horns Rev in 2002, with 80 turbines and 160 MW total, and it has been refined ever since. The developer bids in with a price per kWh produced by the offshore wind farm. In this way it is hoped that the overall prices for offshore wind power come down over time.

Uncertainty about the input parameters for the wind farm design leads to higher prices from the developers. Therefore, already for the tender for the Anholt wind farm the Danish Climate and Energy Ministry changed the process so that the relevant sea bed investigations and the Environmental Impact Assessment (EIA) was handled and the outcome be known before the bids were given (Energinet.dk 2010). In this EIA, coordinated by the Danish Transmission System Operator Energinet.dk, a larger area was investigated in detail before the final call for tenders was published with regard to sea bed conditions, hydrography, geomorphology, coastal morphology, water quality, marine life and vegetation, benthic habitats, fish, birds, marine mammals, landscape issues, raw materials, marine archaeology, recreational areas, protected areas, ship and aerial traffic, fishery and others, during construction, operation and dismantling.

The influence of uncertainty on the price was exposed during the process leading to the Anholt wind farm. In this case, the Danish parliament required a new offshore wind farm to be built in too short a time to get a good process underway. This resulted in only one bidder (DONG Energy), who then claimed that the preparation time was too short to bring the uncertainties down, and added a significant mark-up to the best guess price. The next tender leading to the Horns Rev 3 wind farm had longer time for bidding, and subsequently for construction, and therefore attracted several bids. The outcome was 32 % cheaper than the price at Anholt. This price means, according to the Danish Ministry for Climate, Energy and Buildings, an economic benefit for rate payers in the order of 2.2 billion kroner over the lifetime of the wind farm, in comparison to previous cost estimates (EFKM Denmark 2015). While this in part is due to moving technology (larger turbines were available since) and a better wind climate, reduced uncertainties also were a factor.

In the UK, the Crown Estate administers all the sea bed outside the 12-mile zone, and thus is the regulating authority for offshore wind farms in the UK. In three tendering rounds, the Crown Estate has increased the size of the area one could bid for, to the current Round 3 sites with over 1 GW potential each. Wind farms in the UK, despite an at least comparable wind resource to Denmark, are netting a higher strike price (in a "Contracts for Difference" scheme, the fixed price paid per kWh for the first e.g. 15 years; the premium is then the difference between the market price and the strike price) than their Danish counterparts. One important difference is that the transmission is in Denmark, but also in e.g. Germany, taken care of by the TSO. Thereby, the cost of transmission is spread over the total customer base of the TSO. In the UK, the transmission is a part of the strike price and therefore has to be financed as part of the wind farm investment.

19.3 Offshore Wind Farm Design

The main driver for wind farm design is the cost of energy. A simple model for the Levelised Cost of Energy, LCOE, is shown in Eq. (19.1):

$$LCOE = \frac{CaPEX \bullet CRF + OpEX}{AEP} \tag{19.1}$$

where CaPEX is the Capital Expenditure (i.e. the cost of wind turbines, foundations, cables, transmission system etc., their installation and financing), CRF is the Capital Recovery Factor (essentially a simplified representation of the discounted cash flow), OpEX are the Operating Expenses (i.e. operation and maintenance expenses), and AEP is the Annual Energy Production. Within this model, several sub-models are amenable to optimization. For example, in a radial cabling layout in the wind farm, where one radial connects a string of turbines to the substation, the cables further from the substation carry less electricity and could therefore be of smaller diameter. However, the installation cost can be double the cost per metre than the cable itself, and changing the cable on the installer ship incurs lost time too, so the optimization is less straightforward than just determining the electrical needs.

Construction of the offshore farm is a major cost factor. The industry has moved to dedicated ships installing the foundations and turbines, working as jack-up barges (Fig. 19.1) for a stable working platform in up to 30+ m water depth. Those ships can cost up to 200,000 €/day, and can install up to 2 turbines a day in optimal weather conditions. In larger wind farms, many processes work in parallel, installation of foundations, cable laying, removal of Unexploded Ordnance (UXO), diving for cable connection or inspection of the works done, and other things. For example, at the peak of construction of the currently largest offshore wind farm,

Fig. 19.1 A2SEAs SEA JACK during the construction of the Gwynt y Mor wind farm. Image Source: A2SEA (2016)

there were 1000 people working simultaneously on 60 vessels in the London Array (2016) site.

The OpEX is, to a large degree, determined by maintenance cost—both scheduled preventive and corrective maintenance, and the related lack of availability. The optimization of those depends heavily on the weather windows for accessibility of the farm. Already in 2001, Risø National Laboratory (now part of DTU) presented a tool to estimate weather windows and calculate the corresponding availability and outages of the turbines (Christensen and Giebel 2001). A main factor was the wave pattern at the site, as the significant wave height was more often a determining factor than too high winds. In 2012, researchers from University of Strathclyde (Dinwoodie et al. 2012) presented a similar picture using actual data: the availability in winter for three actual wind farms was significantly lower than in summer, which was attributed to the lack of accessibility to the sites (Fig. 19.2). In a notional 300 MW wind farm, this difference would mean over 2 million euros per month in lost production.

Finally, the last factor going into the determination of the LCOE is the AEP. Since usually, the wind distribution is mostly given by the choice of site by the national authority, and since the wind speed is not varying strongly across the area offshore (at least for current wind farm sizes sufficiently away from the shore), the most determining factor are the wake effects. By their very nature, wind turbines extract energy out of the wind, which means that the wind behind a turbine is less strong. If that diminished wind speed then comes to the next turbine, that turbine will produce less than if it was in free flow conditions. Researchers developed models to calculate this effect already in the 1980s, and by now a wealth of models with

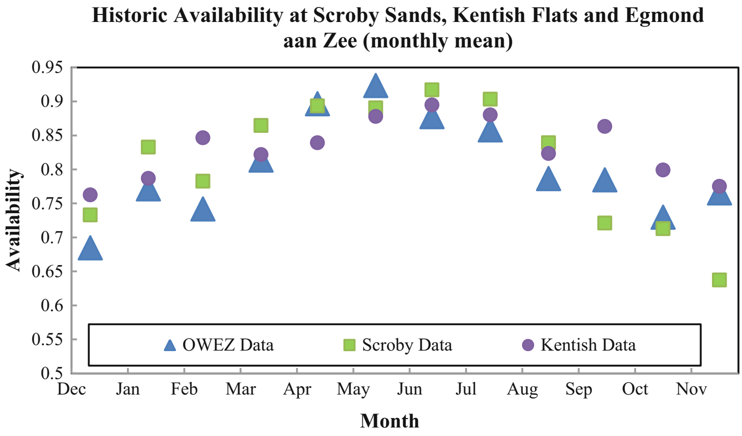

Fig. 19.2 Availability of three wind farms in the Netherlands and the UK. Source: Dinwoodie et al. (2012)

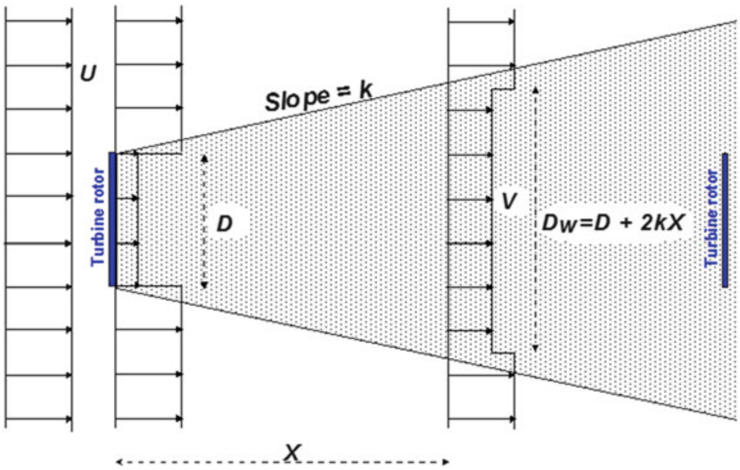

Fig. 19.3 Wake deficit and expansion as modelled by the PARK model of N.O. Jensen

varying degrees of sophistication have been developed. One of the simplest models is the PARK model developed by N.O. Jensen (Fig. 19.3), embodied in the siting software WAsP (2016). In reality, the wake expansion covers the fact that the wake expands relatively little, but meanders right and left in the atmospheric turbulence, which in the 10-min averages usually used for the AEP calculations gives the average wake loss given by the picture. Offshore, due to the reduced turbulence, the expansion parameter k is different from its onshore value. On the other end of the scale, Computational Fluid Mechanics (CFD) and Large Eddy Simulation (LES) models can calculate the wind flow in a wind farm with much higher resolution, but require significantly more running time, up to weeks on a supercomputer.

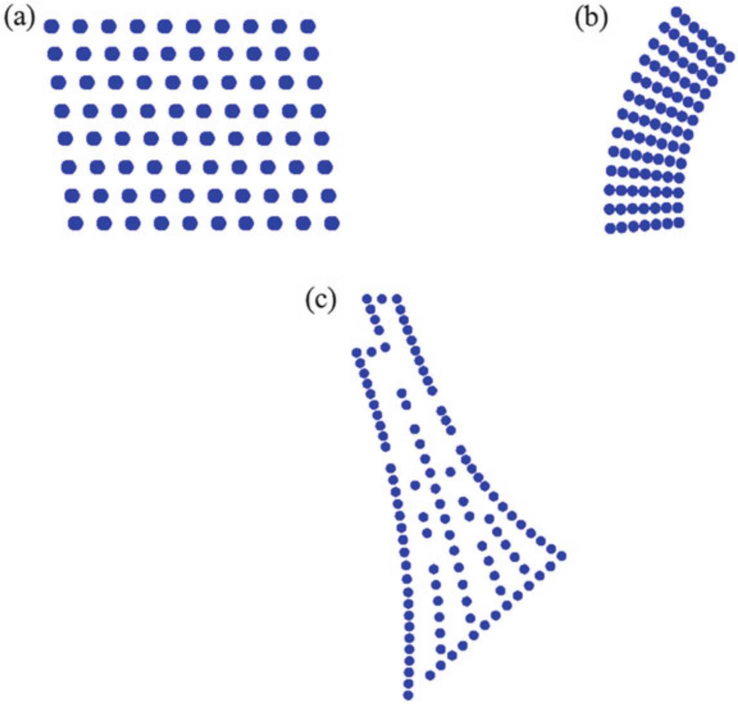

Fig. 19.4 The layouts of the (**a**) Horns Rev 1, (**b**) Horns Rev 2 & (**c**) Anholt OWFs. Source: Nygaard (2015)

Some major parameters with which to influence the total wake loss in a wind farm are the turbine spacing and layout. One can distinguish different generations of designs when looking at the development of the Danish offshore wind farms.

The first attempts were regular layouts like the one at Horns Rev 1 (and Nysted, built a year later), as shown in Fig. 19.4a. However, since the wake effects are very sensitive to the wind direction, already small changes in wind direction (as they happen frequently) will change the power output of the farm significantly, making the power less predictable and more difficult to integrate into the grid. This insight led to a second generation layout like the Horns Rev 2 (Fig. 19.4b), and Rødsand wind farms. Since the straight lines in the wind farm are not pointing into the same direction, the sensitivity towards wind direction changes is much reduced.

For the Anholt wind farm (Fig. 19.4c), built in 2012, developer DONG Energy chose a different layout. A more thorough assessment of the wake effects led to a perimeter centred layout, based on the notion that the second row shows the strongest wake effects, so an elimination of the second row will reduce the overall wake effects. However, this is not precedence for future wind farms. Also after Anholt there were farms planned in the UK with more regular layouts.

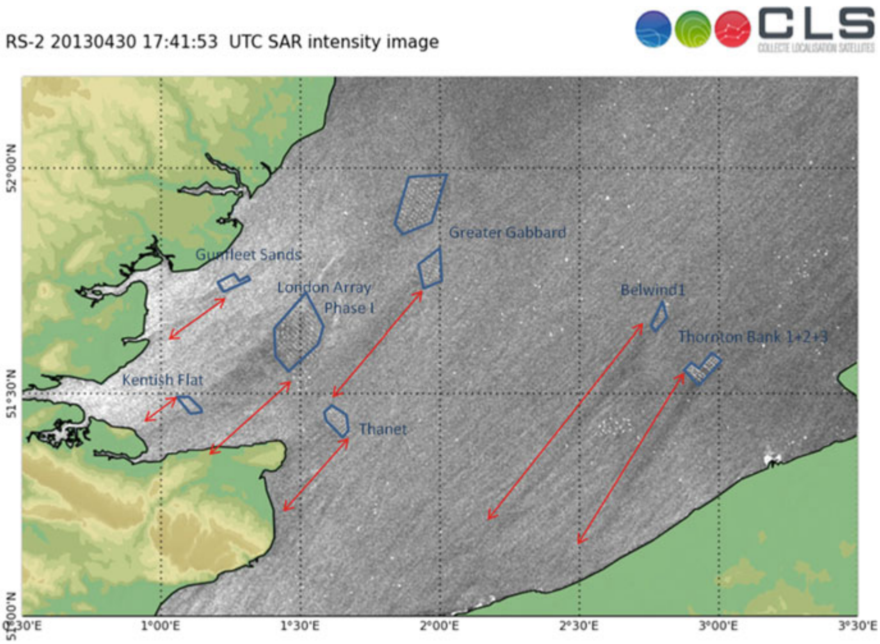

Fig. 19.5 RADARSAT-2 intensity map of the southern North Sea observed 30 April 2013 at 17:41 UTC. The *blue lines* outline wind farms and the *red arrows* the wind farm wake. The SAR-wind processing chain was set up by Collecte Localisation Satellites (CLS). Source: Hasager et al. (2015)

Wakes are not only an issue within a wind farm, they also extend for many km downstream of the wind farm. The wind speed near the sea surface can be measured using Synthetic Aperture Radar (SAR), e.g. mounted on satellites (Hasager et al. (2015)). In certain weather situations, the area of reduced production can extend several tens of kilometres. At Belwind wind farm the wake is around 55 km long, at Thornton Bank 45 km, at London Array 15 km, at Thanet 14 km and at Kentish Flat 10 km (but probably continues inland). It is the intensity image where the darker area is due to lower wind speed (Fig. 19.5).

19.4 EERA-DTOC and Wind & Economy

Over the last 3.5 years, the European Energy Research Alliance (EERA) integrated many of the institutes' softwares into a common Design Tool for Offshore Clusters (eera-dtoc.eu) in a project sponsored by the EU in years 2012–2015 (project budget 4 million euro). While strategic planners were envisaged as a potential target group, owing to the consortium membership in the EERA-DTOC project, the main emphasis went into making a good tool for offshore wind farm developers

(DTU Vindenergi 2016). Therefore, it integrated the workflow and the models from different planning aspects, i.e., wind climate, wakes and electrical models from grid to turbine plus a LCOE model, which currently embodies the cost function of an offshore developer. A number of EERA members' state-of-the-art models and software products, most notably DTU Wind Energy's own but also tools for the design of the grid inside the farm and the connection to the shore were integrated in the Design Tool for Offshore Clusters (DTOC) (Hasager and Giebel 2015). The tool, also commercially available under the name *Wind & Economy* (Wind and Economy 2016), was designed, integrated and developed by Overspeed, a SME from Oldenburg with specialty in wind consultancy and wind related software development.

The EERA-DTOC tool was designed based on input from end users. Its aim is to support the optimisation of LCOE by comparing different variants for the farm layout. A central concept of the DTOC tool is the organization of wind farm variants as scenarios and scenario trees. The single scenario is a fine-grained project variant, distinguished by all project parameters and the employed model chain including the model parameters. Scenarios can be cloned or duplicated, and inherit the settings from the higher level scenario.

This philosophy supports one of the central user stories (i.e., use cases): '*As a developer I can determine the optimum spacing, position, turbine model and hub height of turbines within an offshore wind farm*'.

The DTOC software supports the generation and comparison of the calculation results of many design scenarios. Comparative reporting of those results enables then the selection of optimized configurations. The work flow to optimize through comparing LCOE is shown in Fig. 19.6.

In order to calculate the LCOE, the submodels for e.g. cabling, AEP and grid compliance have to be called for each scenario. GIS data is also integrated in the tool, taking thus e.g. bathymetry into account. The runs start with the calculation of the wind climate calling a remote WRF installation at one of the three offering centres (DTU Wind Energy, CENER or CIEMAT). Typically, two or three runs are made, one run calculating a wind climate without any wind farms, one run with all currently running farms, and one run also including future wind farms planned in the

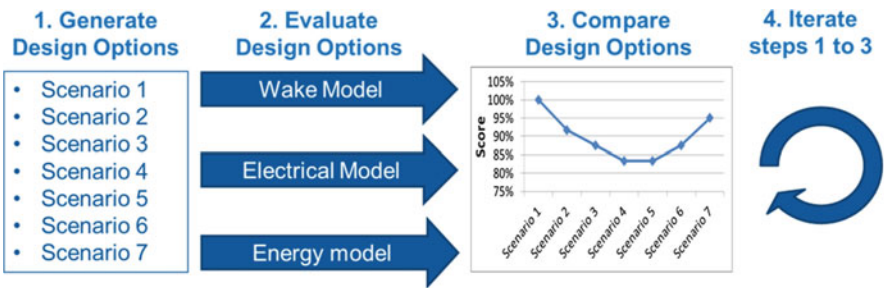

Fig. 19.6 Work flow for the DTOC-tool based optimization process

area. In this way, a timeline can be established when the production is going to drop due to wake effects from new wind farms. Since this wind climate is notionally the same for all wind farm configurations, it is run only once. This wind climate is then put into different farm layout options, which are compared according to Fig. 19.6. Therefore, instead of having to convert data from one program to the next, the user can handle many more scenarios before the bidding process begins.

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