

## 1

## Introduction

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Development of offshore wind energy is a great scientific and engineering challenge. It involves multiple disciplines, thus this textbook aims to contribute by giving concise information on design of offshore wind farms, addressing technology and power system integration. One chapter is devoted to operation and maintenance modelling. Other aspects, such as met-ocean conditions, soil, spatial planning, impact on the environment and so on, are not part of this textbook. This chapter open by describing the historic development of offshore wind energy (Section 1.1) and continues by introducing the topics being addressed in this textbook (Section 1.2). Thereafter, follows a brief section on cost of energy calculations (Section 1.3) before the chapter is concluded with considerations on the future development of offshore wind energy (Section 1.4).

### 1.1 Development of Offshore Wind Energy

The argument for the development of offshore wind energy is generally for providing clean energy without any emissions of carbon dioxide (CO<sub>2</sub>) or other greenhouse gasses and, in this way, battling climate change. Offshore wind development contributes to long-term security of supply as a domestic renewable resource, rather than import or exhausting limited fossil fuel reserves, and can be a means of boosting industry activity with supplies for construction and operation. Many large cities are located close to the sea, hence offshore wind farms can be built in proximity to them. This can be attractive as an alternative to long transmission lines or deploying power plants on land close to large cities with high property values. The wind resource is generally much greater

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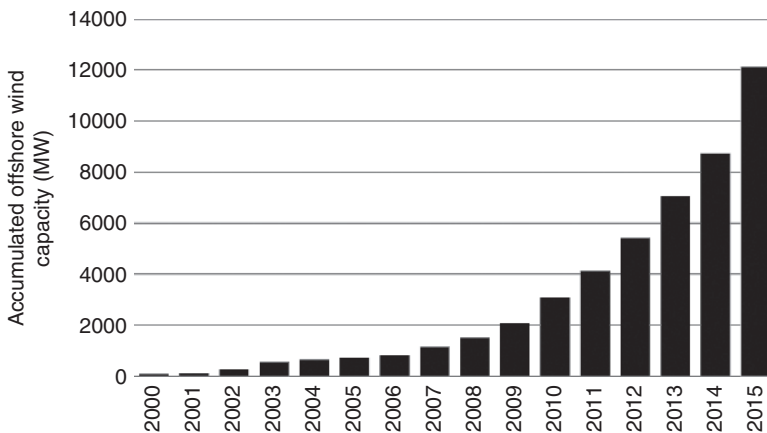
Companion website: [www.wiley.com/go/tande/offshore-wind-energy](http://www.wiley.com/go/tande/offshore-wind-energy)

offshore than over land, and offshore wind farms can be built with very low negative environmental impact (WWF, 2014).

As can be concluded from the above, there are clearly many good reasons to develop offshore wind energy. But, as for any new source of energy, the market and technology needs to be matured before it can compete without any support. The technology must be proven with a professional supply chain, and developers must be able to carry out offshore wind farm projects with low risk and deliver energy at competitive cost.

The first offshore wind turbine was a 220 kW turbine installed about 250 m from shore at 6 m water depth outside Nordersund in southern Sweden in 1990. The year after, in 1991, the first offshore wind farm was installed. This was Vindeby, comprising eleven 450 kW turbines about 1 km from shore at 2–4 m water depth outside Lolland in Denmark. These early developments may seem small compared to the state of the industry today but were utterly bold and pushed the limits at their time. They demonstrated offshore wind energy to be viable and that challenges related to installation and operation of wind turbines offshore could be overcome. The development of offshore wind energy continued to be slow, however, and it was not before the turn of the century that development started to gain real momentum (Figure 1.1). In this period (2000–2015) the typical size of offshore wind farms increased from tens of MW to hundreds of MW, and wind farms were built further from shore and in deeper waters. By the end of 2015, the accumulated installed offshore wind capacity was 12.1 GW, distributed in 14 countries, with the United Kingdom top of the list with 5.1 GW, followed by Germany (3.3 GW), Denmark (1.3 GW) and China (1.0 GW) (Table 1.1).

Almost all wind capacity built in the period (Table 1.1) was bottom fixed, with the exception of projects in Norway (Hywind, 2.3 MW, 2009), Portugal (WindFloat, 2 MW, 2011) and Japan (Fukushima 2 MW, 2013), which apply floating wind turbines to harness the rich wind resources in deep sea regions. These installations represent a new bold development in offshore wind energy and tens of projects are in preparation to bring the technology forward. For example, in Japan the Fukushima project was expanded, in 2016, with installation of two more floating turbines, rated 5 and 7 MW, and Statoil is continuing development of the Hywind concept, installing six 5-MW units comprising a 30-MW floating wind farm in Scottish water to be completed in 2017 (Figure 1.2).



**Figure 1.1** Global accumulated offshore wind capacity since 2000. Source: Data from Nikolaos 2004, McCarthy 2013 and GWEC 2016.

**Table 1.1** Installed offshore wind capacity by the end of 2015. Data from GWEC (2016).

Country	Capacity (MW)
UK	5067
Germany	3295
Denmark	1271
PR China	1015
Belgium	712
The Netherlands	427
Sweden	202
Japan	53
Finland	26
Ireland	25
South Korea	5
Spain	5
Norway	2
Portugal	2

The largest offshore wind farm built up to 2015 was the London Array that was completed in 2013. It has an installed capacity of 630 MW, consisting of 175 turbines each rated 3.6 MW. The wind farm is located about 20 km offshore with an area of about 100 km<sup>2</sup> at water depths up to 25 m in the outer Thames estuary, UK. In 2015 the wind farm produced about 2.5 TWh (London Array, 2016), that is corresponding to a capacity factor<sup>1</sup> of 45% or almost 4000 full load hours.<sup>2</sup> In comparison, wind farms on land are generally exposed to less favourable wind resources and, therefore, achieve lower generation. For example, the International Renewable Energy Agency (IRENA, 2016) reports that the global average capacity factor for onshore wind was 27 % in 2015, that is corresponding to 2365 full load hours.

The energy from offshore wind farms can replace generation based on fossil fuel, hence reduce emissions of CO<sub>2</sub> by some 300–700 g CO<sub>2</sub> per kWh wind generation, that is about 300 g/kWh for replacing natural gas and about 700 g/kWh for replacing coal fired power plants. Indeed, the actual savings will depend on how the power system is operated together with the wind farm. For the London Array (Figure 1.3), on average, yearly savings are assumed to be 925 000 tonnes of CO<sub>2</sub> based on 420 g/kWh and a wind farm capacity factor of 39%, or, to put this in perspective, savings equal to the emissions of 289 000 passenger cars (London Array Limited, 2016).

1 The capacity factor is a normalized measure of the generation defined as the ratio between the annual average generation and the installed capacity:  $C_F = 100 \frac{E}{8760 \cdot P_r}$

Here,  $C_F$  is the capacity factor (%),  $E$  is the annual generation and  $P_r$  is the installed capacity.

2 Full load hours (FLH) is another normalized measure of the generation. It is defined as the ratio between the annual generation and the installed capacity:  $FLH = \frac{E}{P_r}$

Here,  $FLH$  is the full load hours (h),  $E$  is the annual generation and  $P_r$  is the installed capacity.



**Figure 1.2** Illustration of the Hywind Scotland 30-MW floating wind farm scheduled to be in operation by late 2017 about 25 km offshore from Peterhead. The turbines are each rated 6 MW and the water depth is 95–120 m (Statoil, 2015). *Source:* Reproduced with permission of Statoil.



**Figure 1.3** The London Array 630-MW offshore wind farm in operation in the outer Thames estuary. The wind farm spans about 100 km<sup>2</sup> and includes 175 turbines each rated 3.6 MW installed in waters up to 25 m deep (London Array Limited, 2016). *Source:* London Array Limited.

## 1.2 Offshore Wind Technology

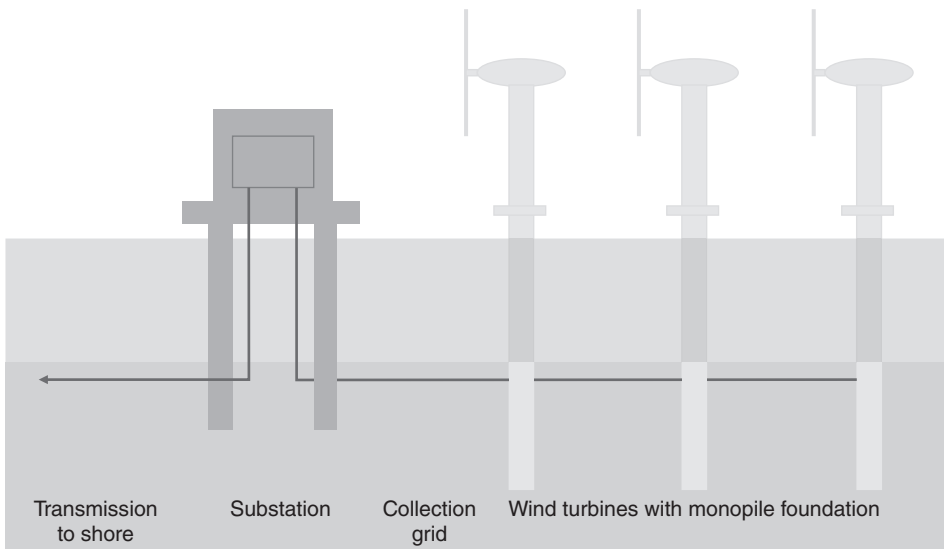
The significant elements of an offshore wind farm are (i) the wind turbines themselves, (ii) their substructure and foundation, (iii) the internal collection grid, (iv) the substation and (v) the transmission to shore (Figure 1.4).

Offshore wind turbines are typically quite similar to land-based turbines but with greater rating and adapted to the marine environment. The largest turbines (2016) are 8 MW with 180 m rotor diameter (Campbell, 2016). Chapter 2 gives more details on turbine technology with emphasis on the electrical design, while Chapter 3 addresses the mechanical drivetrain.

In shallow water (up to 40–60 m), monopiles or other bottom-fixed structures are commonly used, whereas in deeper water floating support structures are generally thought to be a better option. Chapter 4 gives more details on support structures, both bottom-fixed and floating.

Modern wind turbines include advanced control systems that provides for autonomous and safe operation generally aiming to maximize the energy output at all times, though respecting constraints that may be set by the wind farm Supervisory Control and Data Acquisition (SCADA) system. Turbine control systems are elaborated in Chapter 5, while wind farm control is described in Chapter 8.

The internal grid, substation and transmission to shore can have alternative configurations depending on the size of the wind farm and distance to shore. The internal grid is commonly operated with alternating current (AC) at about 33 kV, though 66 kV solutions are emerging for connecting larger turbines. The design should be carefully assessed, including application of broadband models of the electrical system to accurately calculate switching transients and high frequency resonance phenomena (Gustavsen *et al.*, 2011). Alternative internal grid design with direct current (DC)



**Figure 1.4** The main elements of an offshore wind farm. (Not to scale, for illustration only.) The turbines are normally installed 5–10 rotor diameters apart. Graphic by Tande, SINTEF.

collection systems have been proposed, though so far such systems have not been implemented in any commercial offshore wind farm (Chapter 6). The internal grid is coupled to one or more offshore substations that are connected to the transmission network. The substation normally includes a transformer that brings the voltage up to transmission level, for example 150 kV. If the distance to shore is short and the wind farm has limited capacity, transmission by high voltage alternating current (HVAC) is the normal option. Often it is suggested that if the wind farm is more than 100 km from shore and rated above 200 MW, high voltage direct current (HVDC) may be the preferred option. This requires, however, application of a HVDC converter station offshore and on land. These represent quite significant investments, thus industry has recently shown interest in also applying HVAC for longer distances and higher capacities. Studies conducted as part of NOWITECH give evidence that losses in HVAC may be reduced by operating the HVAC cable at a variable voltage below rated, thus stretching the limits in terms of distance and capacity of HVAC transmission (Gustavsen and Mo, 2016). Chapter 9 gives more detail on alternative transmission technologies and substation configuration.

Operation and maintenance (O&M) of wind farms are significantly more challenging offshore than onshore. Getting service personnel on-board offshore wind turbines is not trivial, and the same goes for equipment and spare parts. While various options can be applied to secure efficient O&M, it is not straightforward to select the best one. Chapter 7 elaborates on this, presenting an O&M simulation model and a model for O&M vessel fleet optimization.

Chapters 10 and 11 consider how offshore wind farms interact with the power system. Chapter 10 starts with an introduction to power system operation and control, and the connection requirements for generators in an interconnected power grid. Thereafter, the possibilities for offshore wind power plants to provide power system operation support are elaborated. Chapter 11 discusses the economics of offshore wind power in view of the relevant electricity markets and regulatory and policy issues related to incentive schemes for offshore wind development.

### 1.3 Levelized Cost of Energy

Offshore wind farms need to be designed to be safe, reliable, comply with grid and environmental requirements and give high energy output. An optimized design can be said to achieve this at minimum cost per kWh produced over the lifetime of the wind farm. It is, therefore, useful for anyone engaged in design of offshore wind farms to understand the basic concept for calculating cost of energy. As an example, say that it is found that by expanding the space between the turbines in an offshore wind farm some additional energy output can be gained. But this also means additional cost to pay for longer cables between the turbines. So, is it a good idea or not? This can be answered in economic terms by comparing the cost of energy for both cases.

The levelized cost of energy (LCOE) is the most commonly used metric to describe the cost of electric energy from power plants. It gives the average cost of production of one unit (kWh) levelized over the lifetime of the power plant. The total energy output and the total costs over the lifetime of the plant are both discounted to the start of operation by means of the chosen discount rate, and the LCOE is derived as the ratio of

the discounted total cost and energy output. For offshore wind energy, the LCOE can be calculated according to Equation 1.1, based on (IRENA, 2016):

$$\text{LCOE} = \frac{\sum_{t=1}^n \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (1.1)$$

Here, LCOE is the average lifetime levelized cost of electricity generation,  $I_t$  is the investment expenditures in the year  $t$ ,  $M_t$  is the operations and maintenance expenditures in the year  $t$ ,  $E_t$  is the electricity generation in the year  $t$ ,  $r$  is the discount rate and  $n$  is the lifetime of the offshore wind farm.

By definition, if the LCOE of a project is equal to the average lifetime selling price of electricity from the project, the investment gives a return equal to the discount rate. A higher electricity price means higher profit, whereas an electricity price lower than the LCOE would mean less return on the investment or possibly a loss.

The level of detail for describing the expenditures,  $I_t$  and  $M_t$ , and the electricity generation,  $E_t$ , depends on the scope of the analysis. The elements shown in Figure 1.5 are included in the LCOE calculation (IRENA, 2016). The lifetime  $n$  of an offshore wind farm is typically assumed being 25 years, although, for financial decisions, often a shorter time is required for return on investment. The discount rate,  $r$ , should generally reflect the cost of capital and vary from market to market and over time, also depending on the perceived risk of the project. Typically, discount rates are assumed in the range of 5–10% in LCOE studies.

The LCOE of offshore wind farms put in operation in the period 2010–2015 are shown in Figure 1.6. It can be seen that there is a significant spread in cost between the projects, which is typical for market and technologies in their infancy. Projections for future cost indicate significant potential for cost reduction and that, by sometime after 2025, the LCOE of offshore wind energy can be brought down to grid parity. In 2016, three offshore wind projects awarded through auctions got much attention because of their low kWh selling price. These are marked with the star symbol in Figure 1.6. The

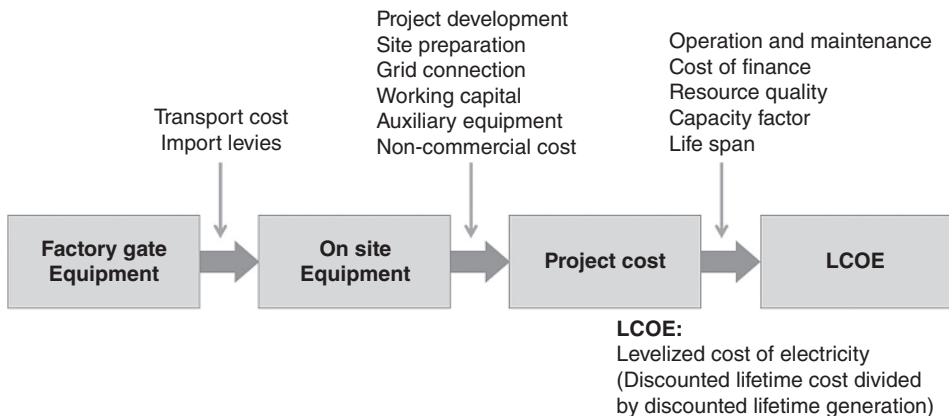
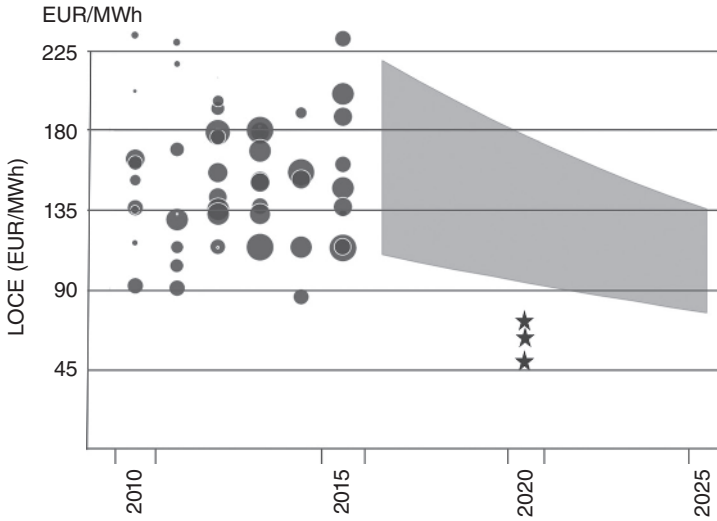


Figure 1.5 Metrics in calculation of LCOE. Source: IRENA (2016).



**Figure 1.6** Historical LCOE of offshore wind farms and projection as reported by IRENA (2016) compared with reported auction prices for three new offshore wind farms to be in operation by 2020 (star symbols). Costs for these three wind farms are, from the top, 72.7 EUR/MWh for Borssele (NL) 700 MW (Dong, 2016), 63.8 EUR/MWh for Vesterhav (DK) 350 MW (Vattenfall, 2016a) and 49.9 EUR/MWh for Kriegers Flak (DK) 600 MW (Vattenfall, 2016b). The graph is prepared converting data from IRENA (2016) to EUR/MWh assuming an exchange rate of 9 EUR = 10 USD for 2015.

three projects are all at very favourable locations with no or negligible cost for grid connection to shore, excellent access to site and other conditions that can explain the low price, and are not ‘typical’ for future offshore wind farms. Still, they give a clear signal that possibly, the cost of offshore wind energy can be brought down more quickly than earlier anticipated.

To better understand the LCOE numbers in Figure 1.6 or others, it is useful to do some simplified calculations. Lumping all investment expenditures to  $t=1$ , assuming the annual energy output to be the same for all years  $t=1$  to  $n$  and assuming the annual operations and maintenance expenditures to be the same for all years  $t=1$  to  $n$ , Equation 1.1 can be rewritten as:

$$\text{LCOE} \cong \frac{I}{E \cdot a} + \frac{M}{E} = \frac{i}{\text{FLH} \cdot a} + \frac{m}{\text{FLH}} \quad (1.2)$$

Here,  $i$  is the lump sum investment expenditures  $I$  expressed per installed kW,  $m$  is the assumed annual average operations and maintenance expenditures  $M$  expressed per kW,  $\text{FLH}$  is the assumed annual average electricity generation  $E$  divided by the rated capacity of the wind farm, and  $a$  is the annuity factor:

$$a = \frac{1}{\sum_{t=1}^n (1+r)^t} = \frac{1-(1+r)^{-n}}{r} \quad (1.3)$$

where  $a$  is the annuity factor,  $r$  is the discount rate and  $n$  is the lifetime of the offshore wind farm.

**Table 1.2** Example calculation of LCOE for three characteristic cases.

Case	A	B	C
FLH (h)	3767	3942	4200
Capacity factor (%)	43	45	48
Investment (EUR/kW)	4185	3555	1800
Discount rate (%)	10.0	8.0	8.0
Lifetime (yr)	25	25	25
Annuity factor	9.1	10.7	10.7
Investment (EURc/kWh)	12	8	4
Annual O&M (EUR/kW)	127	71	42
O&M (EURc/kWh)	3	2	1
<b>LCOE (EURc/kWh)</b>	<b>15</b>	<b>10</b>	<b>5</b>

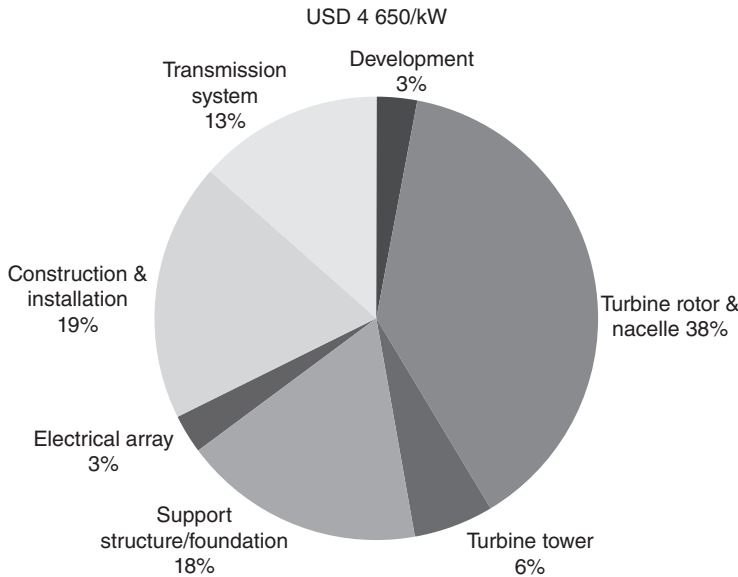
Applying these formulas (Equations 1.2 and 1.3), Table 1.2 sums up assumed input parameters and resulting LCOE for three characteristic cases. Cases A and B are applying input data as given by IRENA (2016), converting from USD to EUR assuming 9 EUR = 10 USD. The two cases mimic the central LCOE estimates for offshore wind in 2015 and 2025 (IRENA, 2016), stating that cost could be reduced from USD 0.17/kWh in 2015 to USD 0.11/kWh in 2025.

Case C illustrates a possible combination of parameters to give a LCOE of EUR 0.05/kWh, taking information from Vattenfall (2016) as the starting point. The full load hours and the capacity factors are for sites with good wind resources, although there will be offshore wind projects with both higher and lower production. The investment expenditure for cases A and B include significant costs for transmission to shore, whereas for case C no such transmission costs are assumed.

Distribution of investment expenditures for a ‘representative’ offshore wind farm is shown in Figure 1.7. It should be noted to this that with the given USD 4650/kW, the wind turbines only (44 %) would cost EUR 1841/kW, that is about two times the cost of land-based wind turbines, and seems a bit on the high side. Certainly, the investment expenditure for case C can only be achieved with turbine cost being close to that of land-based wind turbines. The O&M cost of case C is approaching that of land-based windfarms, and would be truly astonishing to achieve.

## 1.4 Future Offshore Wind Development

The offshore wind potential is tremendous. Assuming resources within 50 nautical miles of shore with a maximum water depth of 200 m, and omitting areas with low wind resources, the global offshore potential is estimated to 192 800 TWh (Arent *et al.*, 2012), that is eight times global electricity generation in 2014, which was 23 816 TWh (IEA, 2016a). Exactly how much of the potential will be realized is hard to say, but to reach climate targets renewable energy will play a central role. In the 450 Scenario by the International Energy Agency (IEA), the global operating wind capacity is expected to be 2312 GW in 2040, delivering 6127 TWh annually (IEA, 2016b). Exactly how much of this will



**Figure 1.7** Distribution of investment expenditures for a 'representative' offshore wind farm.  
 Source: IRENA (2016).

be offshore is not depicted but about 10% is indicated for a number of regions/countries. With the current trend providing continued reduced cost of energy from new offshore wind projects, this seems realistic. It requires though sustained strong efforts in developing market and technology.

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