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# Review of Technical Assumptions and Generation Costs

## Floating Offshore Wind Levelised Cost of Energy Review

March 2023

**017344**

**54821R Issue: 1.1**

**Prepared for: Department for Energy Security and Net Zero**

**SYSTEMS ● ENGINEERING ● TECHNOLOGY**

# Review of Technical Assumptions and Generation Costs

## Floating Offshore Wind Levelised Cost of Energy Review

**Client:** Department for Energy Security and Net Zero

**Client Ref.:** PS22124

**Date:** March 2023

**Classification:**

| | | | |
|---|---|---|---|
| **Project No.:** | 017344 | **Compiled By:** | Thomas Helfer |
| **Document No.:** | 54821R | **Verified By:** | Kate Ward |
| **Issue No.:** | 1.1 | **Approved By:** | David McNaught |

## Distribution

| Copy | Recipient | Organisation |
|---|---|---|
| 1 | Clara Jarvis | Department for Energy Security & Net Zero |
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## Revision History

| Issue | Date | Description |
|---|---|---|
| 1 | March 2023 | First issue |
| 1.1 | April 2023 | Clarifications reflecting client feedback on assumptions, project pipelines, and referencing. |

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# Contents

# 1 Introduction

The last decade has seen a major change in the energy landscape in the UK. Driven by the need to decarbonise and shaped by consideration of supply security and consumer affordability, our national generation portfolio has diversified to comprise a mix of traditional and renewable technologies at various stages in their lifecycles. This diversity in generation method provides us with a vital mix in supply profiles across baseload, variable and peak lopping, alongside fluctuating energy imports and exports through interconnection. Looking to the future, the UK government's recent Powering up Britain policy paper which follows the "British Energy Security Strategy" (BESS), sets out how the UK will further accelerate the deployment of wind, new nuclear, solar and hydrogen (Department for Energy Security and Net Zero, 2023) (Department for Business, Energy & Industrial Strategy (BEIS), 2022). The BESS strongly aligns to the wider 'Net Zero Strategy' (Department for Business, Energy & Industrial Strategy (BEIS), 2022), which is recognised as fundamental to energy security, and could lead to 95% of British electricity being low carbon by 2030.

Floating offshore wind (FOW) is an evolution of traditional ("fixed") offshore wind that uses floating foundations instead of rigid foundations fixed to the seabed. This enables generation from offshore sites in deeper waters with good wind resources that are otherwise impractical to access using fixed offshore wind. FOW is likely to play an increasingly significant role in the future energy mix. Rapid growth rates are possible based on forecast cost reductions and supported by recent and upcoming seabed auctions. As a result of the ScotWind seabed tender alone, Scotland could see an increase from the 80 MW of FOW currently operational to 17.8 GW by the mid-2030s (The Crown Estate, 2023) (Crown Estate Scotland, 2022).

## 1.1 Project Overview

Frazer-Nash Consultancy Ltd have been requested by the Department for Energy Security and Net Zero (DESNZ) to review the technical assumptions and generating costs relating to the levelised cost of electricity (LCOE) for floating offshore wind (FOW). This report presents the outcome of this review and provides a forecast of the LCOE for various maturities of FOW between now and 2050, considering recent industry developments.

From conversations with DESNZ, it is understood that this data will be used as an input to various energy sector models by DESNZ, such as power sector optimisation and analysis underpinning administrative strike price (ASP) calculations for the Contracts for Difference scheme.

The LCOE is the discounted lifetime cost of building and operating a generation asset, expressed as a cost per unit of electricity generated (£/MWh). It covers all relevant costs faced by the generator, including pre-development, capital, operating, fuel (where relevant), and financing costs. This is sometimes called a life-cycle cost, which emphasises the "cradle to grave" aspect of the definition. The levelised cost of a generation technology is the ratio of the total costs of a generic plant to the total amount of electricity expected to be generated over the plant's lifetime. Both are expressed in net present value terms. This means that future costs and outputs are discounted, when compared to costs and outputs today.

This analysis is Frazer-Nash's independent view but informed by the views of the industry and reviews of publicly available literature. Where sources are not provided it should be assumed that the statements are provided based on Frazer-Nash's experience in the industry.

## 1.2 Exclusions

The following aspects are out of the scope of this study:

1. Consideration of costs and technical assumptions as an input to Enhanced LCOE calculations, which capture wider system impacts of individual generation units. This includes impacts on the wholesale market, capacity market, balancing and ancillary service markets, and networks (Department for Business, Energy & Industrial Strategy (BEIS), 2020).
2. A review of the methodology that DESNZ use to calculate the LCOE. The methodology applied is consistent with the DESNZ approach outlined in (Department for Business, Energy & Industrial Strategy (BEIS), 2020).
3. A comparison with the LCOE inputs and assumptions applicable to other generation technologies. As such, direct comparison of the LCOE estimates presented in this report with other technologies is not considered representative.
4. Evaluation of the cost of capital (hurdle rates) is out of the project scope. The hurdle rates used within the LCOE calculation are as provided by DESNZ.
5. Evaluation of the impacts of recent short-term macroeconomic effects (refer to section 3.2 Limitations for further details).
6. Accounting for site-specific factors within the LOCE.

Additional assumptions made and limitations of the approach are noted in the report.

## 1.3 Report Structure

This report is structured in three main parts:

- Section 2 provides context for the report, including an overview of the current FOW landscape, a brief history of the industry's development, and an overview of FOW technology.
- Section 3 describes the methodology we have used for the study, including assumptions made and notable limitations.
- Section 4 describes the main findings from our study. It includes LCOE forecasts and drivers as well as highlighting opportunities for cost reduction in each area and a discussion of influencing factors.

In addition, Sections 5 summarises our findings. This report is supported by a separate Excel spreadsheet (document reference 017344-136659V "FOW LCOE Review-Data") which contains an aggregated and anonymised breakdown of LCOE cost components in a format better suited to modelling. This template is in the format provided by DESNZ (Department for Business, Energy & Industrial Strategy (BEIS), 2023).

# 2 Floating Offshore Wind Landscape

To deliver Net Zero goals, both in the UK and globally, a large expansion of renewable generation capacity is needed. This is outlined in the UK government's recent 'British Energy Security Strategy' (BESS) (Department for Business, Energy & Industrial Strategy (BEIS), 2022) which strongly aligns to the wider 'Net Zero Strategy' (Department for Business, Energy & Industrial Strategy (BEIS), 2022). Wind power is a mature and low-cost renewable technology that offers a viable route to rapid increases in low carbon generating capacity. As shortages of suitable sites and planning constraints limit opportunities for new onshore wind farms, offshore projects will be required to meet the scale of national and international ambitions.

The first offshore windfarm was Vindeby, a fixed installation of eleven 450 kW turbines, commissioned in Denmark in 1991. Since then, the industry has grown rapidly. Current worldwide operational capacity of offshore wind is around 60 GW, of which 22% is in the UK, and wind turbines are currently rated around 15 MW (Williams, et al., 2022). This installed offshore wind capacity is almost all fixed turbines, exploiting favourable sites with relatively shallow water: currently, only around 120 MW of offshore wind is floating globally (Williams, et al., 2022).

Wide-scale deployment of FOW has been limited to date, mainly due to higher costs compared to fixed offshore wind, and availability of shallow water sites which do not require floating foundations. However, many offshore sites (both in the UK and globally) are unsuitable for fixed wind farms due to the water depths and associated engineering challenges. This includes both near-shore areas and sites further from coastlines. There are no definitive indicators that distinguish when floating wind is more feasible than fixed, but it is estimated that around 80% of the world's offshore wind resource would be more suited to floating wind farms (Global Wind Energy Council (GWEC), 2022). Many of these potential floating sites also have the advantage of being in areas with better wind resource (e.g. higher wind speeds).

The feasibility of the concept of floating wind turbines is largely proven through existing demonstration floating wind farms. The world's first commercial floating offshore wind farm was Hywind Scotland. Hywind Scotland consists of 5 wind turbines with spar-design foundations, has an installed capacity of 30 MW, was commissioned in 2017, and operates in water depths of between 95m and 120m (Equinor, 2022). The wind farm has achieved long-term average capacity factors[1] of around 54% (including 57.1% within one 12-month period) and is frequently the best performing (by capacity factor) wind farm in the UK. These higher capacity factors are a combination favourable wind conditions and reliable system availability[2]. In combination with other sites, by demonstrating the potential of FOW, these sites have accelerated plans for FOW globally. Projections for deployment of floating wind in the UK look promising:

- 17.8 GW of floating wind projects were awarded seabed leasing options in Crown Estate Scotland's ScotWind leasing round (Crown Estate Scotland, 2022).
- In March 2023, 13 INTOG (Innovation and Targeted Oil and Gas) projects were also offered Exclusivity Agreements, totalling an additional 5.5GW of projects: all of these are floating (Crown Estate Scotland, 2023).
- Two future leasing rounds: The Crown Estate's Celtic Sea leasing round (ca. 4 GW) as well as the ScotWind 2 leasing round (The Crown Estate, n.d.) (Department for Business & Trade, 2023).

These seabed leasing rounds are in addition to ca. 400 MW of test and demonstration projects which are already under development (The Crown Estate, 2023), and total more than 25 GW of potential capacity. Although not all of

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[1] Capacity factor can also be referred to as the "load factor": it is the ratio of the energy generated within a given period to the hypothetical maximum energy generation that could have been generated (i.e. the installed capacity multiplied by the number of hours within the period).

[2] System availability: the proportion of time the system (in this instance including the electrical transmission system) is available to generate and not undergoing maintenance or in a fault condition (or otherwise unavailable).

these leases may be developed, this represents a significant development pipeline of projects and is an approximate 200-times increase compared to the ca. 80 MW of current installed FOW capacity in the UK.

By the end of 2030, it is anticipated that Europe will account for most floating installations, with the UK maintaining a global lead, followed by Asia and North America. Early floating offshore developments will help give rise to global uptake as costs decrease, supply chain capacity increases and enhanced capabilities result in mass production of components (Williams, et al., 2022).

## 2.1 FOW Technology

Most of the equipment needs for floating offshore wind farms are similar to the requirements for fixed wind farms (i.e. both have wind turbines, inter-array cables, substations, and export cables). The principal difference is in the foundations, which enable the wind turbines to float (substations may also float, or be subsea, or may continue to use fixed foundations). There are many alternative designs for floating foundations (based on experience there are more than 50), although these typically fall into one of four generic types: spar, semi-submersible, barge, and tension leg platforms (see Figure 1 below). These floating foundations require mooring systems and dynamic electrical cables, which further differentiates them from fixed wind sites. A floating wind turbine also necessitates some changes in the design of the turbines and towers to account for the floating motions and additional degrees of freedom.

Due to its nascent nature, there is not yet a standard foundation type within the FOW industry; each of the four types of foundation are being actively designed within the supply chain. Foundations are typically constructed from concrete or steel, and selecting the most appropriate foundation design for a project is influenced by many factors. These include the design maturity, site meteorological conditions, the wind turbine selected, the availability of manufacturing and logistical capabilities, material prices, health and safety considerations, O&M challenges, and ease of decommissioning.

Mooring systems for floating wind turbines share many similarities with other floating offshore structures, such as those used in the oil and gas industry. Figure 2 below illustrates several types. The most appropriate type of mooring is dependent on several factors, notably the site's meteorological conditions, geotechnics, and water depths. Catenary, taut and semi-taut moorings consist of steel, synthetic materials, or chains, whilst tendons typically consist of steel cylinders or solid rods. Anchor selection is primarily determined by the load, seabed conditions and mooring arrangement and includes dragging anchors, gravity anchors, suction buckets, or driven piles. For further reading refer to (Ramboll, 2021), (Iberdrola, 2023), (Myhr, et al., 2014), or (Taboada, 2016).

Dynamic power cables are designed to flex and bend to tolerate bending stresses during their lifetime and are required due to additional movements from the floating structure and deeper water. Figure 3 below shows the shapes that dynamic cables are designed to have: either take a free hanging catenary curve or form the "lazy wave" shape due to added buoyancy modules to reduce loading. For further reading refer to (Ramboll, 2021) or (Toulotte, 2021).

There are additional challenges to locating wind farms further from the shore. These are not unique to floating wind but will likely affect a high proportion of FOW sites, given its suitability for deep-water locations. Required adaptations include:

- the use of high voltage direct current (HVDC) technology instead of high voltage alternating current (HVAC),
- difference in the operation and maintenance (O&M) strategy adopted, and
- additional challenges resulting from the harsher metocean conditions typical of far-offshore locations.

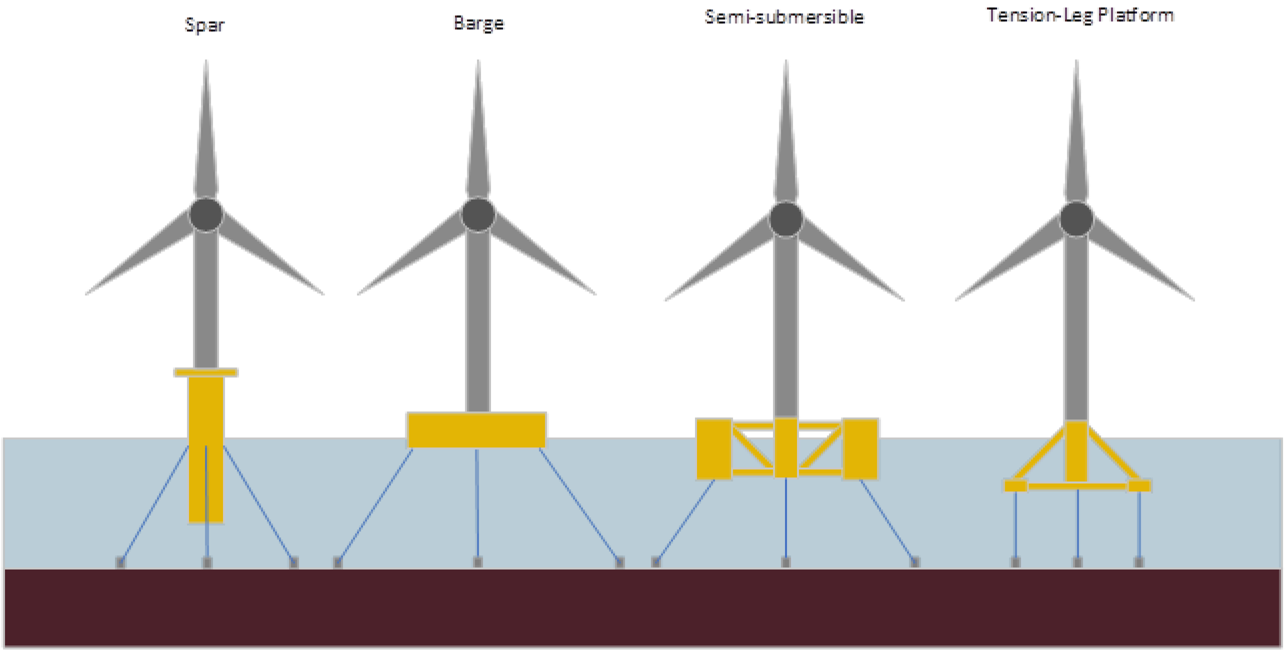
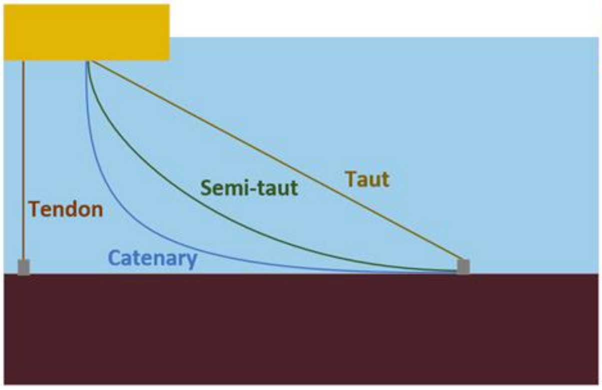


Figure 1: Type of floating foundation.



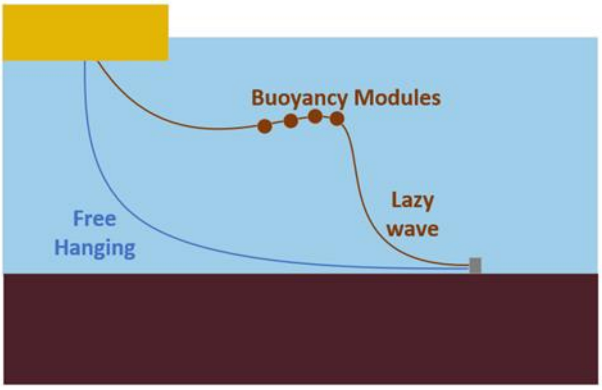


Figure 2 (left): illustration of mooring systems.

Figure 3 (right): illustration of dynamic power cables.

# 3 Methodology

Figure 4 shows the six-step approach used to obtain data and model the LCOE for FOW. This approach was developed based upon previous expertise obtaining, combining, modelling, analysing, and presenting industry data.

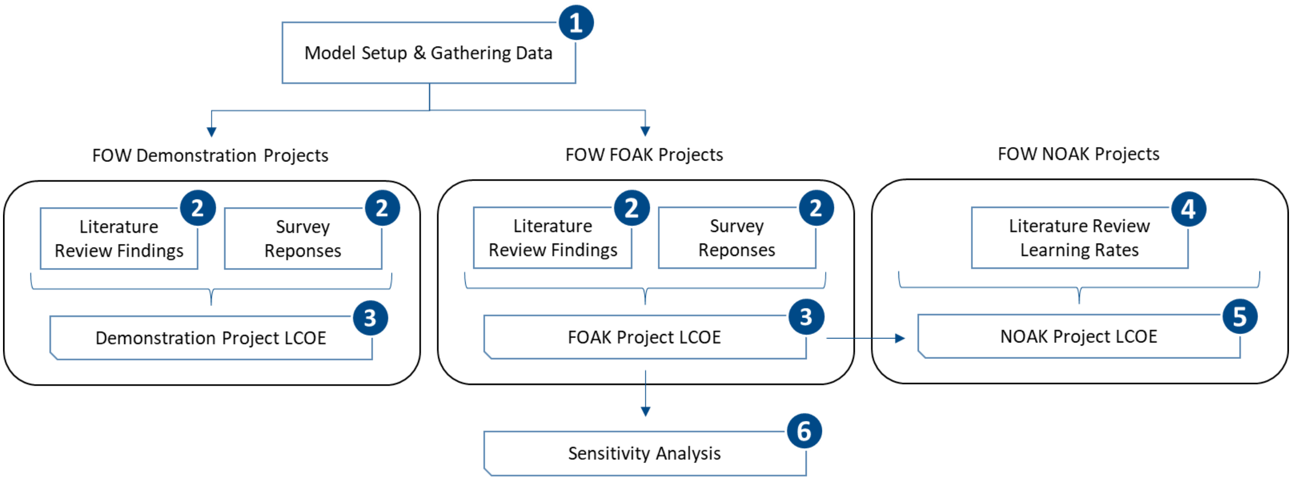


Figure 4: An overview of the methodology chosen. The numbers refer to the bullet-points below.

The following steps are described in more detail in Annex A.1:

1. Model set-up and gathering data: this included a literature review and engaging with the industry through surveys and interviews.
2. Categorising data according to project type (demonstration (Demo) or first of a kind (FOAK)) and initial modelling of the data, keeping literature review data and survey response data separate.
3. Modelling LCOE for Demo and FOAK FOW projects by combining results from the literature review data with survey responses.
4. Obtaining appropriate learning rates by analysing literature review data.
5. Modelling LCOE for NOAK FOW projects by combining the learning rates with the FOAK LCOE model results.
6. Conducting a sensitivity analysis on key variables to understand their impact on the LCOE using the FOAK LCOE results as the baseline.

## 3.1 Assumptions

The following parameters and assumptions have been used to inform the LCOE modelling:

- Distributions:
  - Where the number of available data points was limited, meaning there was insufficient data to accurately assume an alternative distribution, cost data was inputted to the model as a uniform distribution with the lowest and highest point of the distribution corresponding to the lowest and highest data points respectively from the survey data received or extracted from literature. The resulting output distributions may therefore infer a narrower range than may be realistic.

  - Where additional data was available, for example literature review data on fixed OPEX and CAPEX costs for FOAK projects, an appropriate distribution was selected to represent the data in the model. For both fixed OPEX and CAPEX costs, a triangular distribution was selected with the distribution median corresponding to the mean of the available data and the upper and lower bounds selected based on the datapoints.

  - The capacity factor information received across data sources was evenly distributed throughout the lifetime of projects which justified the use of a constant uniform distribution in the model. In practice (for example, since this includes system availability which is impacted by variations in failure rates over the life of the asset) the capacity factor will vary across the asset's lifetime. However, the data provided by developers suggests that projects are at an early stage where lifetime variability in capacity factor is not considered.
  - Constant values, based on the industry responses, were assumed for the project design and consenting period, pre-construction and construction period, asset operational lifetime and decommissioning period. The number of turbines and capacity of each turbine were also held constant. Together these allowed representative cases to be defined for each stage of project.
- As specified by DESNZ, a constant hurdle rate of 7.8% was applied across each of the simulations modelled.
- Cost figures provided have been aligned to 2020 prices in GBP. To achieve this, where appropriate, Frazer-Nash have first converted foreign currency costs to GBP using foreign exchange rates for the year provided (Exchange Rates, 2023), and then inflated or deflated to 2020 costs using GDP deflators at market prices as provided by HM Treasury (HM Treasury, 2023). Where is it unclear from the source which year costs refer to, the year of publication has been used. It has been assumed that all industry survey responses, which were obtained in early 2023, are in 2023 money, and therefore these have been deflated using the latest available data (i.e. from 2022 prices).
- It has been assumed that current government policies, and the principal of running regular Contract for Difference (CfD) support auctions, are unchanged throughout the analysis period. In addition, due to timescales, any announcements made within the 2023 March budget or subsequent Powering up Britain policy papers (Department for Energy Security and Net Zero, 2023) have not been considered. Potential policy changes which could affect the LCOE of FOW are discussed in section 4.3 and include:
  - changes to energy market strategy or policies, including those affecting:
    - access to seabed (and the rate of access), and the structure of seabed leasing auctions and option fees
    - consenting and planning
    - securing or paying for grid connections
    - support regimes (CfD auctions)
    - local supply chain content requirements
    - Offshore Transmission Owner (OFTO) regulations
  - changes to fiscal, trade or foreign policy (within or outside of the UK)
- It has been assumed that the growth of FOW in the UK is not constrained by infrastructure (e.g. ports or grid connections) or the supply chain. As discussed further in section 4.3, a shortage of manufacturing, transportation, assembly, or installation facilities and vessels, or grid connections, could delay the growth in FOW or lead to increased costs due to competition. Capacity growth rates for projects up to 2050 are discussed in section 4.2.3.

## 3.2 Limitations

The following limitations are noted.

### 3.2.1 Data availability and accuracy

As is typical with industry engagement, the response rates reflect a minority of the industry. The number of available data points was further reduced by the need to categorise projects as either Demo or FOAK projects. Feedback from the industry suggested that uncertainty as to how the data would be used, concerns that data may be misrepresented, limited benefits from participation, commercial sensitivity, and having limited data available at the early stage of project development were all factors in not responding.

The model is only as accurate as the data it contains, and the associated uncertainties are not fully known. Although other distributions could be used within the model to account for uncertainty, there was insufficient information to justify their use. As the output distribution for LCOE is calculated using the input data distributions, the uncertainty presented in the output calculations of LCOE may not be reflective of the actual uncertainty in the data.

To some extent, the effects of this are illustrated through the sensitivity analysis which models a wider distribution for several variables.

### 3.2.2 Short-term Macroeconomic Uncertainty

Costs are provided on a 2020 basis and have been inflated or deflated to align with this year. There have been significant macroeconomic changes between 2020 and present, predominantly driven by the COVID-19 pandemic and Russia’s invasion of Ukraine. These macroeconomic changes will impact costs differently and the full extent of these short-term effects is unknown, although there are signs of notable impacts on major capital projects both within the offshore wind industry (for example press articles on the Hornsea 3 wind farm (Twidale, 2023)) and more broadly (for example recent announcements concerning cost increases to the HS2 rail project (BBC News, 2023)).

Therefore, the regression of recent costs to 2020 prices (which includes the industry survey responses) is subject to increased uncertainty. For clarity, specific increases in the costs of materials (e.g. steel and concrete) or interest rates have not been assessed.

### 3.2.3 Site Dependency

Offshore wind farm design is site specific. Not only is the wind resource not consistent between sites, but metocean conditions, the seabed and water depth, distances to shore, ports and grid connections, other offshore stakeholders, and consenting and planning considerations are all site dependent (this is not an exhaustive list). This site variability impacts on the wind farm design and cost, and these more granular effects are not within the scope of this study.

For the purposes of this study, sites have been categorised predominantly by their installed capacity and year of construction. Although there is some correlation between these factors and site conditions (i.e. more favourable sites are likely to be developed earlier), significant differences remain between sites within each categorisation (i.e. within Demo, FOAK or NOAK projects).

Site dependency is not unique to FOW, but some of these effects have a larger impact than for other forms of power generation. These site differences, and thus LCOE differences, are captured to an extent by the LCOE distributions, but care should be taken to avoid assuming a single cost for the technology irrespective of sites.

### 3.2.4 Material Costs

Material costs can significantly affect project costs. Although a sensitivity analysis has been carried out on material costs, the sensitivity analysis relies upon assumptions around the proportion of costs which are driven by materials and a single percentage cost increase and decrease. Specific research into material prices, e.g. concrete & steel, has not been carried out.

### 3.2.5 Bias (including Optimism Bias)

The industry survey responses received from FOW developers may be subject to bias, including optimism bias.

Optimism bias is the documented tendency to underestimate costs and overestimate benefits for a project or programme during the planning stages. To better understand and quantify optimism bias, in 2002 HM Treasury commissioned Mott MacDonald to undertake a study to review the initial business case cost estimates and the outcomes of large public procurement projects in the UK over the previous 20 years (Mott MacDonald, 2002). This study revealed high levels of optimism bias across all industries, project types and expenditure types. The output from this study was incorporated into the Treasury's Green Book guidance on how to account for optimism bias in capital costs and works duration when developing a business case (HM Treasury, 2003).

Optimism bias estimates are not recommended to be added to a project's budget, as this might lead to overspending. A more suitable use for optimism bias adjustment values is to confirm that a business case remains robust if costs rise to this level. Another use is to check if risk and mitigations are appropriately considered. In addition to comparisons with Green Book Guidance, optimism bias can also be estimated by considering evidence of past similar projects.

The offshore wind industry (floating or fixed) is driven by the private sector. There is therefore insufficient publicly available evidence for Frazer-Nash to attempt to use historical data to inform of appropriate levels of optimism bias. An attempt could be made to adjust the industry survey responses to account for optimism bias based on the Green Book. However, this is subject to uncertainties, including:

- It is unclear how applicable the Green Book is to these projects, which are delivered by the private sector and differ from the projects analysed by Mott MacDonald (which inform the Green Book).
- It is difficult to determine suitable values for the criteria set out in the Green Book due to having limited information.
- It is unclear whether the developers have already applied their own, internal, optimism bias based on their experience of delivering similar projects. Methods for compensating for optimism bias are likely to vary significantly between developers and are linked to the effectiveness of developers' project management controls as well as the competence of project teams.

The survey responses and industry interviews may be subject to other sources of bias which could include:

- A desire to artificially inflate the projected cost of FOW, or of their own projects. This could be done to help obscure confidential data, influence government policy (e.g. increasing future budgets made available for CfD allocation rounds), influence supply chain negotiations by emphasising cost pressures, or otherwise secure more support for the sector.
- A desire to artificially deflate the projected cost of FOW, or of their own projects. This could be done to help obscure confidential data or to help influence public opinion by making FOW appear less expensive.
- A conservative approach to projecting costs at the early stage of projects utilising novel technology (over-compensating for optimism bias).
- Incomplete knowledge and incorrect assumptions.

Each developer who engaged with this project came across as frank and open. All are viewed, in the absence of any indication otherwise, as a reliable source. In light of the conflicting considerations above, it was therefore decided that no attempt would be made to correct for bias or weight responses differently. The range of values considered for each model input covers to some extent the effects that bias will have on the results.

# 4 LCOE for FOW

Results from reviewing literature and industry engagement, including both the component costs of LCOE and LCOE distributions, are provided as follows:

- Section 4.1 provides percentage breakdowns of the component costs of LCOE by lifecycle stage.
- An accompanying spreadsheet ("017344-136659V FOW LCOE Review-Data") provides component costs of LCOE for FOAK and NOAK projects at different confidence intervals.
- Section 4.2 provides the modelled LCOE distributions for Demo, FOAK and NOAK projects. These results are consistent with the components costs provided in the accompanying spreadsheet ("017344-136659V FOW LCOE Review-Data").
- Section 4.3 discusses LCOE cost drivers and includes modelled sensitivity analysis.

Although LCOE is a widespread metric in the energy industry, making direct comparisons between technologies can lead to unintended consequences. For example:

- Intermittent generation, such as FOW, has less value to the electricity system owner than dispatchable (power stations that can be turned on to meet demand) generation as its use requires a combination of additional storage, demand management, and stand-by generation. These costs are typically excluded from LCOE calculations.
- Indirect costs arising from a generation type, including societal costs such as impacts to health or the environment, are typically not included in LCOE calculations
- Different countries define the boundaries of a wind farm differently: for example, whether the cost of connecting to the existing electricity grid borne by the wind farm developer or by another company. Although these costs will always be required, they may not be included in the LCOE for the generating technology.

## 4.1 LCOE by Lifecycle Stage

Table 1 shows the range of each lifecycle stage's (DEVEX (development expenditure), CAPEX (capital expenditure), OPEX (operating expenditure) and DECEX (decommissioning expenditure)) contribution to LCOE based on industry survey responses and literature reviews. This shows that the majority of the LCOE is driven by CAPEX and OPEX.

It should be noted that these likely do not fully account for the recent short-term and ongoing macroeconomic conditions, which may significantly affect some lifecycle stages more than others, thus altering the percentage contributions.

Table 1: Percentage Breakdown of LCOE by Lifecycle Stage

| Component | % Contribution to LCOE – Range* | % Contribution to LCOE - Average value |
|---|---:|---:|
| DEVEX | 1 – 10 | 3 |
| CAPEX | 35 - 70 | 52 |
| OPEX | 25 - 60 | 41 |
| DECEX | 1 - 5 | 4 |

*rounded to nearest 5%.

A breakdown of each of the four lifecycle stages (DEVEX, CAPEX, OPEX and DEXEX) is provided in the following subsections where data is available. These indicate how the different components during each lifecycle stage contribute to the overall cost. The figures in the following sub-sections are informed from literature reviews and do not consider the results from industry engagement: therefore they are not consistent with the data in the accompanying spreadsheet (“017344-136659V FOW LCOE Review-Data”) or subsequent sections.

### 4.1.1 DEVEX Cost Breakdown

Development Expenditure (DEVEX) covers design and consenting costs prior to the main financial investment decision (FID) and start of construction, relating to technical, engineering and design elements of the plant. This also includes seabed option fees which, due to demand significantly outstripping supply, can be considerable (e.g. Crown Estate Leasing Round 4 results). It includes the costs of obtaining any licences required and meeting regulatory requirements prior to the start of the construction phase.

DEVEX is largely influenced by regulatory requirements or processes, meaning DEVEX likely presents the largest opportunities and risks for cost changes due to changes in government policy.

A detailed breakdown of these costs was not requested from the industry, but Table 2 shows the results from the literature review. The notable absence is seabed auctions and resultant option costs which could dominate DEVEX costs in future (see sensitivity analysis).

Table 2: Percentage Breakdown of DEVEX Costs

| Component | % Contribution to DEVEX – range* | % Contribution to DEVEX - average |
|---|---:|---:|
| Environmental Surveys | 5 - 10 | 7 |
| Seabed surveys | 5 - 20 | 14 |
| Meteorological Surveys | 5 – 10 | 7 |
| Seabed option fees | Notable absence in literature | |
| Front-End Engineering Design (FEED), project management, and other development services | 65 - 80 | 73 |

*rounded to nearest 5%.

### 4.1.2 CAPEX Cost Breakdown

Capital Expenditure (CAPEX) covers the procurement costs, materials, transport, assembly, installation and commissioning of the windfarm. It covers the expenditure that is incurred in the pre-construction period (the time from the signoff of the FID to the first installation of components on site) and the construction period (time from first installation on site to final commissioning (the date at which all turbines have supplied power to the grid on a commercial basis)).

The pre-construction & construction periods vary in length depending on the size and complexity of the individual project, but in total last typically 3 to 5 years.

A detailed breakdown of CAPEX costs was not requested from the industry, but Table 3 shows the results from the literature review. It should be noted that these do not account for the recent short-term macroeconomic conditions, which may significantly affect some of these aspects more than others.

Table 3: Percentage Breakdown of CAPEX Costs

| Category | Component | % Contribution to CAPEX – range* | % Contribution to CAPEX - average |
|---|---|---|---|
| Materials | Turbine & Tower | 40-50 | 44 |
| | Foundation, Mooring & Anchors | 35 | 35 |
| | Electrical substation, inter-array & export cables | 10 - 15 | 13 |
| Labour, transport & logistics | | 5 - 10 | 7 |
| Other | | 1 - 5 | 3 |

*rounded to nearest 5%.

### 4.1.3 OPEX Cost Breakdown

Operational Expenditure (OPEX) covers the costs incurred during the lifetime of the FOW asset.

There is limited information on the breakdown of OPEX figures within literature and therefore no table has been included. Katsouris & Marina (Katsouris & Marina, 2016) break maintenance costs into approximate shares of 60% corrective turbine maintenance; 30% fixed annual maintenance; 5% preventative maintenance and 5% BoP (balance of plant) corrective maintenance. Another source (BVG Associates, 2019) gives an OPEX split of 60:30:10 between maintenance, operational expenditure, and support & administration. The operational lifetime of future FOW is likely to be between 25 and 35 years.

For dispatchable power generation (i.e. power generation which you do not simply run as often as possible, such as fossil-fuel fired power stations), it is typical to separate OPEX costs into fixed and variable costs. Fixed costs are those incurred irrespective of whether the power station is generating (e.g. CAPEX costs or salaries), and variable costs are those that vary with generation (e.g. fuel or some maintenance costs). It is then possible to make an informed decision about whether to operate the power station at any given time, and it is possible to calculate an average cost based on assumptions around the proportion of time the power station is in operation. However, for FOW which has no fuel costs and will typically be run continuously, the distinction between fixed and variable OPEX is both more difficult to determine and has less value.

There is little in the literature to indicate the typical split between fixed and variable OPEX for FOW, and from industry the engagement there is clear ambiguity between these categories. Based on this, and the discussion in the previous paragraph, all FOW OPEX will be treated as a fixed OPEX cost, with negligible variable OPEX costs.

OPEX can vary between projects due to differences in:

- the distance from the project to the maintenance facilities
- site meteorological conditions
- port constraints
- grid connection costs
- seabed leases
- maintenance strategy and use of digitalisation

- equipment failure rates
- labour rates
- contracting strategy (e.g. whether to in-house or contract O&M tasks)
- synergies with nearby projects
- corporate organisation, including degree of centralisation and levels of available support from back-office functions

An additional area of OPEX risk affecting FOW that does not apply to fixed sites is the consideration of how to handle a major component failure (the failure of a component that cannot be addressed using usual maintenance personnel and equipment, e.g. a blade failure). Fixed sites are in waters sufficiently shallow to utilise a jack-up vessel, for which there is now an established market. These are the same vessels used during installation and decommissioning, and thus the process is conceptually relatively straightforward. However, this is not a feasible approach for FOW due to the increased water depths.

There are generally two options for handling a major component failure in FOW: tow to (near) shore, or repair offshore (using either a floating crane, or a self-erecting crane mounted on the foundation or wind turbine). Unfortunately, both are higher risk and more expensive than using a jack-up vessel in shallow water. It is likely that the chosen approach will evolve as the industry matures.

### 4.1.4 DECEX Cost Breakdown

Decommissioning costs (DECEX) cover the cost of decommissioning the plant at end of life and removal of materials for reuse, recycling or as waste. Under current decommissioning guidance (Department for Business, Energy & Industrial Strategy (BEIS), 2019), income from scrap values is not included in decommissioning costs due to the variability in scrap prices, which also makes them difficult to meaningfully estimate.

Decommissioning is expected to take between 2 and 3 years at the end of the windfarm’s operational life.

There is no operational data on FOW DECEX as no FOW projects have been decommissioned. DECEX is however expected to be a small proportion of the overall project cost and have a minimal impact on LCOE. Spyroudi (Spyroudi, 2021) indicates the split of DECEX for a fixed offshore wind is: 40% offshore preparation; 35% foundation removal; 19% vessels; and 6% disassembly, amounting to 1.5% of the LCOE. An alternative way of splitting the costs in the same reference indicates that the turbine accounts for 30% of the decommissioning cost, the foundation accounts for 46% and the array cables 24%. However, as these figures are for fixed offshore wind projects the percentage split will be different for FOW.

FOW projects will be in deeper waters compared to fixed offshore wind projects, and may also be situated in harsher environmental conditions, which would likely increase DECEX. However, these cost increases may be offset by the relative ease of removing the mooring system and anchoring as compared to removing foundations on fixed offshore wind projects (although sites with high mooring loads and therefore larger anchors may be more challenging to remove than fixed foundations). Requirements to remove equipment vs. leaving it in situ may also differ between sites.

## 4.2 LCOE Distributions

For Demo, FOAK and NOAK projects, different LCOE distributions are shown. The Demo and FOAK results show the results from literature review findings, industry survey findings, and the combined findings. For NOAK projects there are no direct literature review or survey data and therefore costs were extrapolated from FOAK projects using learning rates and capacity growth rates (see methodology section 3 above). Therefore, for NOAK projects a discussion on learning rates and capacity growth rates is provided and LCOE distributions are shown for each modelled scenario.

The results presented are based on the data available from the literature review and industry responses. The industry responses represent a minority of the industry, and therefore caution should be taken when inferring from these figures.

Results in this section are given as cumulative density plots, with points added to indicate the 10th (P10), 50th (P50) and 90th (P90) percentile values.

### 4.2.1 LCOE for Demo Projects

There was limited information in the literature review providing costs for Demo projects. The LCOE distribution for Demo projects was therefore predominantly based on results from industry surveys and is shown in Figure 5 below. The most comprehensive cost data from literature was sourced from a report by BVG Associates (BVG Associates, 2019) which has been shown as a single point on Figure 5.

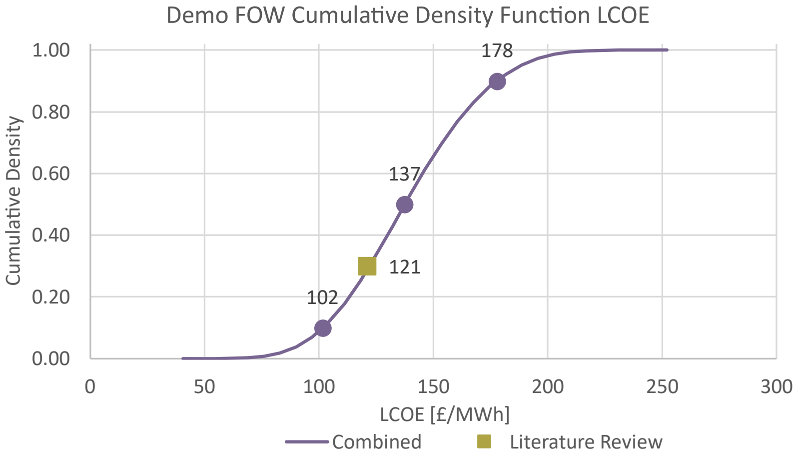


Figure 5: LCOE Distribution for Demo FOW Projects

Figure 5 shows that the literature review Demo project costs were below the median (around P30) compared to the combined LCOE distribution which is predominantly based on industry surveys. The main differences are lower DEVEX costs and OPEX costs in the BVG Associates data compared to the industry survey responses, although BVG costs are also below the median across most categories.

There are several possible explanations for this. This could be evidence of data bias, which is discussed in 3.2.5 above. Alternatively, the BVG Associates data is dated 2020 so the DEVEX difference could reflect the recent higher DEVEX costs experienced due to additional seabed option fees (driven by demand outstripping supply). Similarly, some OPEX costs have increased significantly in recent years (such as grid connection fees). The general difference in costs could be explained by site-specific factors or could be as a result of recent macroeconomic conditions not being fully accounted for when deflating the industry survey responses to 2020 prices (see section 3.2.2 above).

During the CfD allocation round four (AR4) auction (in 2022) one floating wind project was successful with a price of £104/MWh (£87.30/MWh in 2012 prices) (Department for Business, Energy & Industrial Strategy (BEIS), 2022). This project, TwinHub by Wave Hub Limited, has a capacity of 32 MW, and would therefore be categorised as a Demo project. This is a particularly interesting project as the foundation design supports two wind turbines, instead of the customary single wind turbine. Consideration was given as to whether this result could be considered an accurate representation of the project's LCOE and therefore be included in the modelling. However, based on experience, it was deemed that the CfD price awarded was likely insufficient to fully cover the project's costs and that it was therefore not representative of the project's LCOE. Due to the project's novel foundation design, which is a significant deviation from industry norms, the likely primary motivation for the project is in demonstrating the foundation's potential.

### 4.2.2 LCOE for FOAK Projects

More data was available in the literature for FOAK scale projects and therefore LCOE distributions are presented for literature review data, survey responses, and the combined distribution. The most comprehensive cost data in the literature was sourced from (Lerch, 2019), (Martinez & Iglesias, 2022), (Myhr, et al., 2014), and (Pennock, et al., 2022).

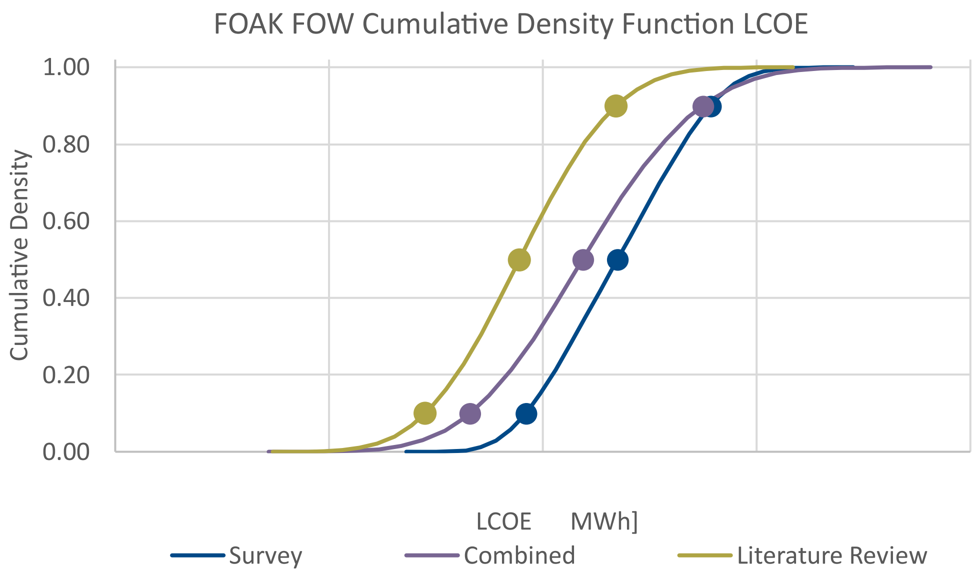


Figure 6: LCOE Distribution for Demo FOW Projects

As would be expected, there is a considerable reduction in LCOE from the demo scale to FOAK scale, with median LCOEs for the combined data reducing from £137/MWh to £109/MWh (20%).

Figure 6 shows that the literature review FOAK project costs tended to be lower than the industry survey results, which is similar to the FOW Demo project LCOE findings but more pronounced. It is difficult to attribute any particular factor to this although site-specific conditions, recent changes to cost drivers, macroeconomic effects, or potential data bias (as discussed for Demo projects in section 4.2.1 above) may account for the differences. The combined LCOE distribution lies between the two distributions.

### 4.2.3 Learning Rates and Capacity Growth for FOW up to 2050

Extrapolating the LCOE distribution for FOAK projects to NOAK projects requires learning rates. Learning rates aim to capture the changes in costs (typically, but not always, reductions in costs) observed when technologies are deployed repeatedly and at greater scales.

A literature review was carried out to determine appropriate learning rates for FOW. One of the sources, the US National Renewable Energy Laboratory (NREL) (Shields, et al., 2022) considers the different methods for determining suitable cost projections for emerging technology and discusses the advantages and disadvantages of each. That summary is shown in Table 4 below.

Table 4: Advantages and Limitations of Cost Projection Methodologies

| Methodology | Resolution | Advantages | Limitations |
|---|---|---|---|
| Learning Curve | Low | Empirical data basis | Top-down model |
| Expert Elicitation | Medium | Contextual data | Subject to survey biases |
| Bottom-up Assessment | High | Clearly Documented | High data requirement |
| Auction Results Analysis | Low | Public & commercial data | High data requirement |

NREL note that "There is reasonable agreement in the trends depicted by the different models; however, the methodologies used to derive these projections are typically opaque, making it difficult to determine the source of the variance in the results. Often, it is also unclear as to which scenarios or assumptions are implicit for deriving these projections. As a result, it is difficult to disentangle technological, financial, or supply chain drivers and to replicate the projections."

Taking account of this, the advantages and limitations of each approach discussed above, and the fact that as, a relatively new industry, there is limited historical data to rely upon, they propose a learning rate model which is "intended to capture the combined effects from (1) single innovations; (2) learning, standardization, and economies of scale in the supply chain and manufacturing; (3) wind turbine upscaling; and (4) interaction effects…[ and which] avoids any complications that might arise from "double-counting" any factors that might not be captured by the learning rate."

The 'learning rate' (LR) is defined as the cost reduction that can be expected for a doubling of the installed capacity of the technology. In the NREL case, the capacity growth rate used is the global one – this allows a greater range of project datasets to feed into the analysis. It also reflects the industry's global supply chain, where learning will disseminate throughout the world.

As a developing industry, there is limited learning rate data on FOW. Much of the literature focuses on applying the learning rates observed in other industries, particularly onshore wind and fixed offshore wind, to FOW. Learning rates assumed in the literature for FOW projects range between 5% and 20%, with some studies assigning different (higher) learning rates to individual wind farm components. As noted above however, this latter 'bottom-up' assessment requires high data availability to be used with any confidence, and such data are not yet available for FOW due to the limited number of projects and the relatively short timescales over which they have been operational.

After consideration of the sources, NREL's approach was deemed to be the most thorough and well justified (it is noted that the UK's Offshore Renewable Energy Catapult is acknowledged "for their input to the modelling approach and helpful discussions"). Therefore the rates generated by the NREL regression model have been used for this analysis, as they are considered the most robust and transparent figures available, and they fall within the range of values outlined in other literature.

The learning rates are summarised in Table 5. These learning rates apply to CAPEX only, but as this is a significant proportion of costs and the best available source of data it will be applied across all costs for FOW.

Table 5: FOW learning rates for CAPEX (Shields, et al., 2022)

| Description | CAPEX Learning Rate |
|---|---|
| **Conservative** | 8.7% |
| **Average** | 11.5% |
| **Advanced** | 14.3% |

The NREL approach for capacity growth (using global figures instead of country-specific or regional figures) has been used. There are limited forecasts for FOW growth rates up to 2050, however IRENA (IRENA, 2019) shows global installed FOW capacity doubling ca. five times in the period from early 2030s (when FOAK projects are likely to generate first power) to 2050. Therefore, two growth forecasts were modelled: four doublings (lower growth) and six doublings (higher growth).

Based on this analysis, four 'simple' scenarios and one 'profiled' scenario were modelled. The 'simple' scenarios applied a single capacity growth rate and a single learning rate across the period, whilst the 'profiled' scenario attempted to allow for the literature review finding that most learning is likely to be in the early years of the industry, reducing over time as the industry embraces increased standardisation of proven technology as it matures. These scenarios are described in the Table 6 and Table 7 below.

Table 6: Simple Capacity Growth and Learning Rate Scenarios

| Scenario | Years | Learning Rate (LR) | No. of times capacity doubles during the period | Comments |
|---|---|---|---|---|
| S1 | 2025-2050 | 11.5% | 6 | Central LR, higher growth |
| S2 | 2025-2050 | 11.5% | 4 | Central LR, higher growth |
| S3 | 2025-2050 | 14.3% | 6 | High LR, higher growth |
| S4 | 2025-2050 | 8.7% | 4 | Low LR, lower growth |

Table 7: Profiled Capacity Growth and Learning Rate Scenario

| Scenario | Years | Learning Rate (LR) | No. of times capacity doubles during the period | Comments |
|---|---|---|---|---|
| S5 | 2025-2030 | 14.3% | 2 | Higher growth, LR decreases as sector matures |
|  | 2030-2045 | 11.5% | 3 |  |
|  | 2045-2050 | 8.7% | 1 |  |

## 4.2.4 LCOE for NOAK Projects up to 2050

To generate LCOE distributions for NOAK projects in 2050, each scenario capacity growth and learning rate scenario identified in the previous section (4.2.3) was modelled using the combined FOAK LCOE distribution presented in section 4.2.2 above as the base case. The results are presented in Figure 7 below.

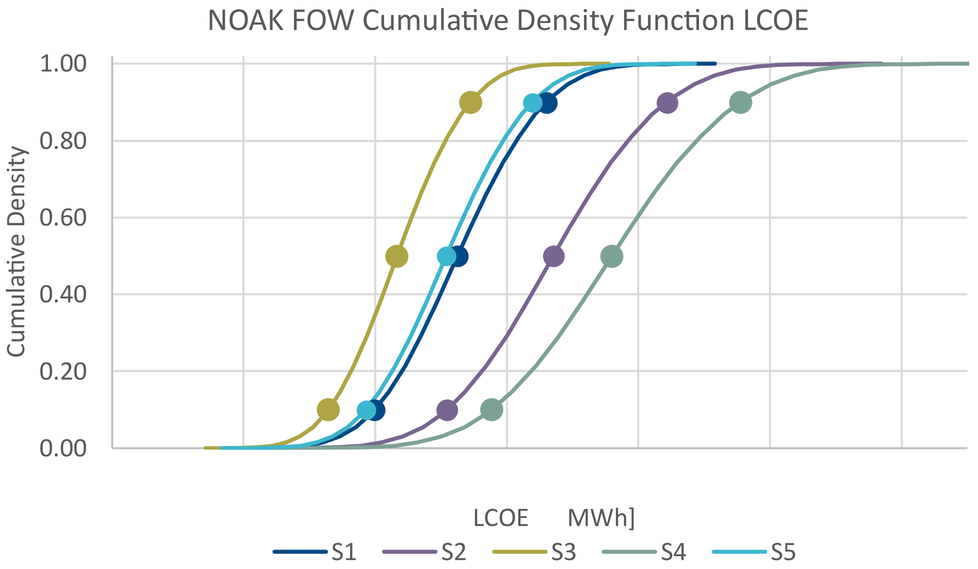


Figure 7: LCOE Distribution for NOAK FOW Projects

The cheapest award in the latest CfD auction (Department for Business, Energy & Industrial Strategy (BEIS), 2022) was for fixed offshore wind projects at a price of £45/MWh (£37.35/MWh in 2012 prices). These projects (at least the first phase) are to be completed in 2026/2027. £45/MWh is comparable to the Great Britain average electricity price between 2011 and 2021 (as per monthly averaged day ahead baseload contracts) (Ofgem, n.d.), which indicates that fixed offshore wind is cost competitive with other forms of generation. Electricity prices since 2021 have increased significantly due to the current macroeconomic conditions, and although these are not considered representative of long-term prices, electricity prices may not fall to the previous averages observed.

Nonetheless, taking £45/MWh as a relevant comparison to fixed offshore wind, Figure 7 shows that all scenarios except for S2 and S4 achieve cost parity with fixed offshore wind by 2050 at a P10 interval. Using the median P50 values, the forecasted LCOE for NOAK FOW projects only achieves parity with fixed offshore wind prices by 2050 in one scenario (scenario S3, P50 of £43/MWh). In no scenarios is there cost parity at a P90 interval. Of course, such a direct comparison has limited relevance and should be treated with caution because:

- There is a finite amount of seabed suitable for fixed wind (and similarly for other generation technologies), so a societal demand for low carbon and secure generation may necessitate the construction of FOW prior to achieving cost parity with fixed wind or other forms of generation.
- This modelling is dependent on numerous assumptions, not least the global growth rates for FOW. These global growth rates are particularly difficult to forecast with any precision and are outside the control of any single organisation or government.
- The recent significant increases in energy prices, which have had widespread impacts across society, are driven in the UK predominantly by increases in wholesale prices of gas and the relative shortage of storage. FOW is likely already cheaper than these short-term high prices.

## 4.3 LCOE Cost Drivers

Cost drivers have been identified from the literature review, interviews with industry, and in-house expertise. To quantify some effects, several factors have been modelled in a sensitivity analysis. Quantifying the potential of these areas is difficult, not least due to interdependencies between them and the limited relevant prior experience to learn from, and therefore cost drivers are discussed qualitatively in section 4.3.2.

### 4.3.1 Sensitivity Analysis

A sensitivity analysis was performed to give an indication of the sensitivity of the results to cost drivers. The analysis was applied against the baseline of the LCOE distributions for the FOAK combined scenario. It therefore provides a view of the range of FOAK project costs as opposed to future changes that will apply to NOAK projects because of learning. Table 8 shows the variables modelled.

Table 8: Sensitivity Analysis Variables

| Variable | Value | Comment |
|---|---|---|
| **Hurdle Rate** | 5% | Indicative range to illustrate the effect of changes to the hurdle rate. |
| **Hurdle Rate** | 13% | |
| **Material Costs (CAPEX)** | -20% | Percentage change from current CAPEX costs. Assumed to apply to 50% of CAPEX costs.<br>Indicative range to illustrate the effect of changes to material costs. |
| **Material Costs (CAPEX)** | +20% | |
| **Capacity Factor** | 53% | Indicative of capacity factors achieved by Hywind Scotland wind farm, which frequently achieves the highest capacity factor of any offshore wind farm in the UK (Equinor, 2022) |
| **Capacity Factor** | 57% | An increase in capacity factor to illustrate the effects of any further increases (e.g. due to greater wind turbine size, more favourable sites, or improvements in system availability) |
| **Lifetime** | 35 years | Indicative value based on experience of industry |
| **Grid connection costs (OPEX)** | + £80k/MW | Indicative additional value based on extrapolation of recent trends in Transmission Network Use of System (TNUoS) charges. This is an indicative value and not a forecast. |
| **Seabed Options Fees (DEVEX)** | £145k/MW/year for 3 years | Indicative additional value based on results from offshore wind leasing round four by The Crown Estate (The Crown Estate, 2023) |

Figure 8 presents the results of the sensitivity analysis. Where relevant, the baseline value which is adjusted under each sensitivity is presented in brackets. The figure shows the P10 to P90 range as well as the median point for each sensitivity.

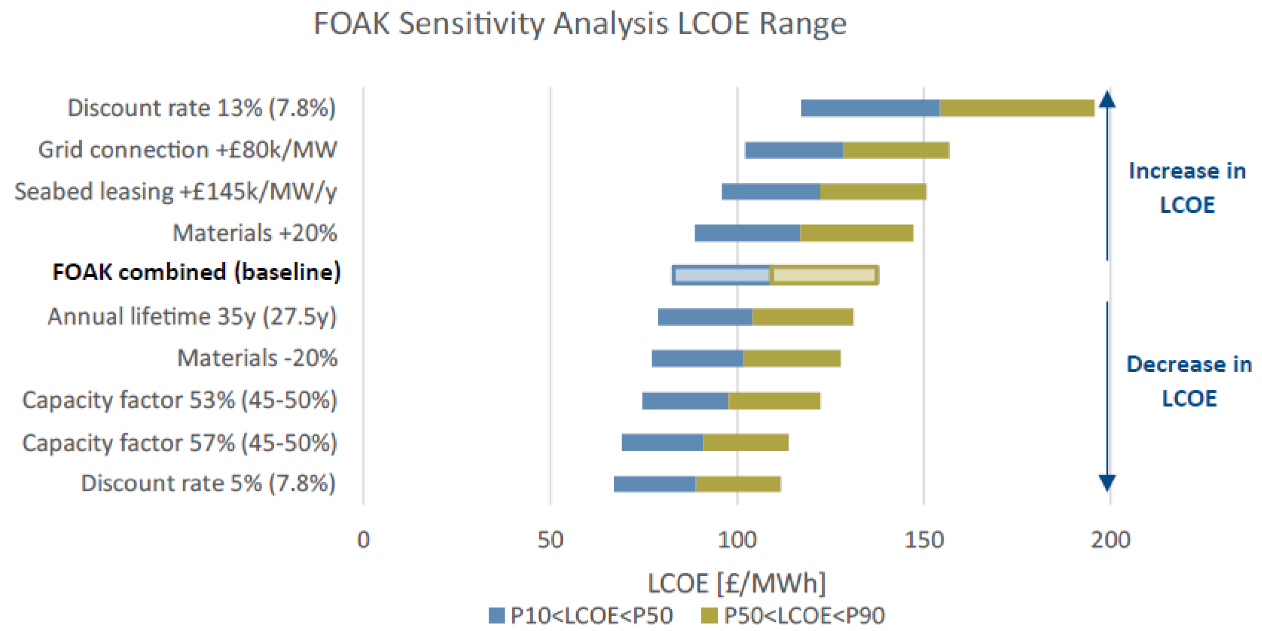


Figure 8: Sensitivities of variables using the FOAK LCOE distribution as the baseline.

#### 4.3.1.1 Combined Sensitivity Scenarios

To better understand sensitivities, adjusted variables were combined into an optimistic scenario and a pessimistic scenario as outlined in Table 9. These scenarios where then modelled, again using the FOAK LCOE distributions as the baseline.

Table 9: Combined Sensitivity Scenarios

| Variable | Optimistic Scenario | Pessimistic Scenario |
|---|---|---|
| **Hurdle rate** | 5% | 13% |
| **Grid costs** | £0/MW | £80,000/MW |
| **Capacity Factor** | 57% | No change |
| **Seabed option fees (DEVEX)** | No change | Additional £145,000 per MW every year for three years |
| **Asset Lifetime** | 35 years | 27.5 years |
| **Material Costs** | -20% | +20% |

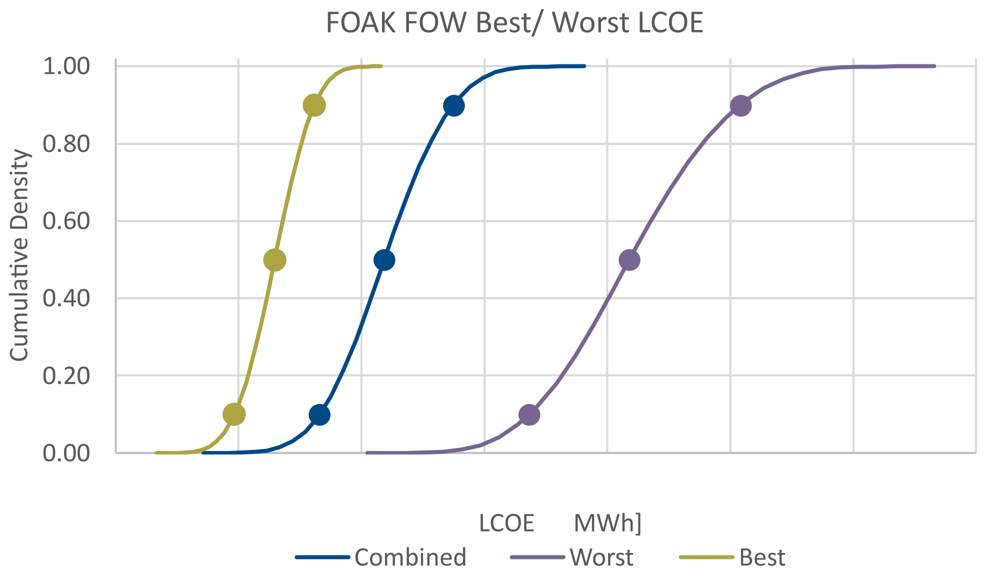


Figure 9: Sensitivity Scenarios, based on FOAK projects.

Figure 9 shows that the differences between these combined scenarios and the baseline FOAK LCOE distributions are significant: approximately halving or doubling the LCOE. This illustrates the current levels of uncertainty with forecasting LCOE figures for a nascent industry and indicates the scale of the opportunities and risks. Executing projects contributes to learning (which drives costs down), and more projects are executed when there are policy incentives and when costs are reduced: cost changes over time are likely to be self-reinforcing.

### 4.3.2 Discussion on Cost Drivers

Prior to discussing potential cost changes, it is worth putting the potential goal of achieving the lowest LCOE in context. Low energy prices have significant societal benefits, perhaps best highlighted by the widespread impacts to families and the economy observed during the current “cost of living crisis” which in part results from the recent abnormally high energy prices. However, “levelling up” communities, achieving Net Zero, and ensuring security of supply are also clearly beneficial.

Requirements for local content tend to increase the LCOE, whilst contributing to levelling up the economy and supporting UK businesses. The rate of deployment of low-carbon generation, such as FOW, can also be adversely impacted by focussing too much on driving down LCOE: lower rates of deployment will most likely lead to reduced carbon emission savings and reduce energy security. A relentless focus on reducing LCOE also increases supply chain stresses (supply chain risks are also increasing as individual components and projects increase in size and cost) which may in-turn lead to reduced deployment rates of FOW. For these reasons, and others, a desire to achieve the lowest LCOE should therefore be a considered goal.

The literature review and supplier discussions have indicated that key focus areas for cost reduction are:

1. Foundation design improvements, focusing on standardisation and material weight reduction
2. Economies of scale, allowing reduced costs across the board for all FOW components
3. Financing improvements – primarily reduction in hurdle rate, driven by increasing confidence in the technology and better understanding of the risks involved in FOW

These, and other, factors are discussed in the following sub-sections.

#### 4.3.2.1 Design Improvements & Innovation

Some equipment within FOW shares many similarities with fixed offshore wind or other offshore industries, and as such, there is less potential for technology design improvements. Other areas, such as the floating foundations and dynamic cables, are more novel and therefore notable cost reductions can be expected through innovation and learning.

Currently the FOW industry has not achieved a consensus on floating foundation design for the wind turbines. Foundation designs are project-specific, but the current high number (more than 50) of foundation designs is not viewed as sustainable and it is expected that there will be consolidation around a few leading designs. It is likely that the choice between using concrete or steel as the primary material for foundations will be region-specific, as this is influenced by regional material costs as well as the availability of manufacturing and assembly facilities and skilled workforces. Significant, and likely prohibitive, investment is required to establish entire industries in new regions of the world.

There are multiple designs for the offshore substations required by wind farms, both for the foundations and the top-side equipment. As water depths increase, floating substation foundations and subsea substations may become more favourable than the usual bottom-fixed jacket foundation.

Similarly, as projects are located further from grid connection points, the use of high voltage direct current (HVDC) as opposed to high voltage alternating current (HVAC) is more favourable due to the lower electrical losses with HVDC. Fixed wind farms currently under construction are using HVDC technology, and the use of HVDC technology is also increasing in use across electricity networks (for example long-distance interconnectors between countries); it is likely that this will lead to learning and reductions in costs.

Power cable designs are likely to improve, both for dynamic and static cables. This includes efforts to reduce failure rates, increase condition monitoring, and design for higher voltages. Subsea connections, which help enable turbines and their foundations to be disconnected from an array whilst remaining wind turbines continue to export power, are also expected to see innovation.

Although wind turbines are considered relatively mature in concept, the size of wind turbines continues to increase. This size increase is responsible for many of the reductions in cost observed over the last decade in fixed wind as larger turbines require fewer turbines for the same installed capacity which reduces the number of foundations required and other ‘balance of plant’ costs such as inter-array cables. In addition, larger wind turbines are exposed to the faster, less turbulent, and more reliable wind speeds observed at greater heights. Both FOW and fixed wind will benefit from these technology advances.

There are, however, disadvantages to striving for larger wind turbines to reduce cost. It puts considerable stress on the supply chain as designs (for wind turbines, towers, and foundations) have a short “shelf life” in-which to return a profit. Similarly, necessary investments (e.g. in manufacturing, transportation, assembly, and installation facilities and vessels) must be recouped over a shorter period. In extremis, increasing component size too rapidly could reduce cost saving opportunities by volume manufacture, which would reduce investment and in turn slow down the industry’s growth.

As discussed in section 4.1.3 above, major component exchange options are generally more expensive for FOW compared to fixed offshore wind. This is likely another area where innovation and scale will drive cost reductions.

#### 4.3.2.2 Economies of Scale

FOW is expected to benefit from significant economies of scale. As well as proportionally reducing costs which do not scale with project size (such as many DEVEX costs), larger projects incentivise manufacturing and logistical investments which lead to cost reductions. As projects increase in size, the relative importance of FOW projects compared to fixed offshore wind will also increase, further increasing attention from the supply chain and likely leading to additional cost reductions.

Synergies from scale during operations, for example by centralising functions or sharing O&M facilities and equipment with neighbouring sites, are likely to reduce LCOE. This may lead to consolidation in the operator market.

#### 4.3.2.3 Costs of Finance

The cost of finance is generally represented within LCOE models using a hurdle rate. As understanding of, and confidence in, the FOW industry improves the risks will decrease leading to reduced financing costs. This will reduce the cost of finance. The cost of borrowing appears to be a competitive advantage for some developers, with industry responses indicating that larger companies view this as less of a concern than those with smaller balance sheets.

The cost of finance is also influenced by macroeconomic factors which are not FOW specific.

#### 4.3.2.4 Infrastructure Investment

The FOW industry is dependent on the results of support auctions prior to making final investment decisions (FIDs) on projects. However, investment in manufacturing or logistical infrastructure takes many years and therefore is required prior to the support award. Smaller projects also may not be sufficiently large to justify investment on their own. As projects will not make investment decisions at the same time (and may not all be sanctioned), and future design evolutions may require additional works, there is limited incentive within the industry to make the necessary investments. This slows investment and creates a “race to be second” culture.

An example of necessary investment is ports. Currently, port facilities are a significant constraint for the FOW industry with UK ports having insufficient water depths, insufficiently reinforced quaysides, and/or insufficient space to assemble or store multiple foundations. Multiple port upgrades will likely be required in each region due to the number of planned wind farms. Resolving this requires significant investment which would benefit multiple projects in a region, lead to job creation, and help level-up communities.

#### 4.3.2.5 Project Lifetime

Life-extension activities, either during the design stage or through improved understanding of equipment integrity during operations, have the potential to increase the average lifetime of floating wind farms, which would likely reduce the LCOE. Some companies are actively considering designing floating wind farms for in-life re-powering: some equipment (e.g. the electrical infrastructure) would be designed for a longer lifetime than the wind turbines and foundations, which could be replaced at intervals during the lifecycle of the wind farm.

#### 4.3.2.6 Site Dependent Factors

Many LCOE cost drivers are site-specific and therefore more favourable sites with a lower LCOE will likely be developed first. This leads to a negative learning rate effect, where future sites are more challenging to develop and, in the absence of other factors, could have a higher LCOE.

#### 4.3.2.7 Regulatory Constraints

The current market is constrained by several highly regulated processes, most notably seabed leasing, grid connections, and support (CfD) auctions. Whilst these processes have led to significant growth of fixed offshore wind and brought significant cost reductions, if these become too restrictive they will negatively impact industry growth and the LCOE. Companies must bear the costs of unsuccessful projects, which materialises as either higher costs of finance or additional DEVEX in LCOE models. If there is insufficient long-term planning, and these processes are spread too far apart, a “feast and famine” industry will result, with limited incentives for long-term investment and further increasing supply chain stress.

#### 4.3.2.8 Auction Incentives

Currently, seabed lease and support auctions are awarded based on price. For seabed lease option fees, demand is outstripping supply, leading to very high prices (The Crown Estate, 2023) which is driving up LCOE. In other jurisdictions, bidding credits are used, which can be used to incentivise other goals such as sustainability, local content, supply chain and infrastructure investment, innovation, and workforce training (for example as outlined in recent auctions in the United States (United States Bureau of Ocean Energy Management, 2022)). Bidding credits could apply to seabed lease or support auctions, and adjustments to these criteria could increase or decrease the LCOE.

#### 4.3.2.9 Duration of Project Development

Reducing the length of time required for securing grid connections, consenting, and planning processes has been identified as an opportunity for increasing the growth rates of offshore wind projects. Streamlining these processes may also reduce costs directly.

#### 4.3.2.10 Grid Connections

From engagement with industry, there are concerns that two areas of the grid connection process could negatively impact the LCOE: uncertainty whilst securing a grid connection and costs during operations.

When securing a grid connection, delays and price uncertainty risk delaying investment decisions and cause subsequent cost increases elsewhere in the project.

During operations, the Transmission Network Use of System (TNUoS) charges are paid by generators to contribute to grid costs. These are currently regional, and financially incentivise connections in regions which do not have an excess of supply compared to demand. As sites with favourable conditions for offshore wind cannot be moved, and the locations of favourable offshore wind sites are generally situated near less populated areas of the UK, a comparative lack of grid infrastructure investment (i.e. HVDC links) could cause regional cost variations to increase significantly. As regional grid cost differences increase, sites in certain regions may be uncompetitive compared to sites in other regions during auctions. Region-specific auctions or changing how TNUoS costs are paid for by generators could help address this.

#### 4.3.2.11 Capacity Factor

Capacity factors for future sites may increase from a combination of larger wind turbines, accessing sites with improved wind resource and any improvements in system availability. System availability is likely to improve due to greater use of digitalisation, predictive maintenance, and planning optimisation but may reduce if sites are less accessible or equipment maintenance requirements increase.

## 4.4 Technological Changes out to 2050

As there is no ‘standard site’ for FOW, it is not expected that a single combination of technologies will become the standard design for all projects (in the UK, or worldwide). Foundation designs will continue to evolve and although a considerable consolidation in the supply chain is anticipated, designs with either concrete or steel as the primary material are expected to be developed dependent on the relative benefits of these materials in different regions of the world. Mooring systems will also remain site-dependent, and although significant advances in dynamic power cable designs and subsea connections are expected, it is unlikely that one cable design solution will suit all sites.

The TwinHub project in the Celtic Sea and the Nezzy$^2$ project in the Baltic Sea utilise two wind turbines on a single foundation. These will be interesting demonstrations of a novel approach to foundations. The potential drivers are significant, including reduced foundation, mooring, and inter-array cable costs. However, concerns over aerodynamic effects, the ability to utilise the latest generations of wind turbine design, and O&M challenges remain. Another area of potentially significant innovation relates to offshore substations, which in future will likely be based on subsea or floating concepts rather than the usual jacket structures.

The current model of building individual grid connections for each offshore wind farm (fixed or floating) may evolve into an “offshore grid” with shared infrastructure and more centralised ownership. Whilst this may reduce overall costs, it would increase interface risks and could lead to concerns that wind farm projects are dependent on grid infrastructure that is outside the control of the wind farm developer.

Evolutions in vessel and foundation design, the increased use of digitalisation, and operational synergies between wind farms (both fixed and floating) are likely to lead to safer and more efficient operations. Whilst these improvements are likely to reduce the LCOE, they may decrease the relative number of ‘front-line’ jobs within the industry.

FOW will likely be increasingly used to power offshore structures or remote islands (“island mode”) where space is a premium, carbon emissions make fossil-fuel powered generators uncompetitive, and connecting to national electricity grids is cost prohibitive. Examples of this include the Hywind Tampen wind farm as well as the recent INTOG leasing round. Some proponents believe that FOW will increasingly be used to generate green hydrogen. However, it is not currently evident that situating hydrogen production equipment offshore and connecting it to an intermittent electricity source is beneficial compared to producing the hydrogen onshore.

It is considered probable that FOW will be considered a mature technology by 2050, and it is likely that this journey will involve significant investment in associated manufacturing and logistical infrastructure. In the UK, these investments will likely be made in more remote regions which will have additional societal benefits. Although it is expected that there will continue to be efforts to focus development investment within the UK through local content requirements, it is unclear how much this will be possible, beyond necessary investments in local port infrastructure.

Improving affordability of energy, decarbonising electricity generation, increasing energy security, and ensuring investment in the UK, will remain competing priorities. However, the UK’s favourable sites means the FOW industry in the UK will likely continue its rapid growth and that FOW will be a key part of the electricity generation mix up to 2050 and beyond.

# 5 Summary

Component costs of LCOE for FOW and resultant LCOE distributions have been determined based on a review of literature and industry engagement. A sensitivity analysis has been carried out to demonstrate the impact of uncertainty in key variables, and a qualitative description of cost drivers is provided. These findings are provided in a combination of this report and its accompanying spreadsheet ("017344-136659V FOW LCOE Review-Data").

The LCOE for FOW is expected to rapidly decrease due to a combination of factors, most notably the cost of finance, foundation design improvements, and economies of scale. However, there are numerous influencing factors which could increase or decrease this rate of cost reduction, including the rate of FOW growth. Several of these factors are controlled by legislation and therefore government policies have significant influence over the LCOE.

Overall, there is significant uncertainty over future LCOE for FOW, as demonstrated by Figure 9, which shows a potential decrease of 50% or an increase of 100% to the LCOE based on two sensitivity scenarios. This indicates the scale of the opportunities and risks for this technology.

The Offshore Renewable Energy Catapult report "FOW cost reduction pathways to subsidy -free" (Catapult Offshore Renewable Energy, 2021) gives a comprehensive summary of technical innovations that are being developed.

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# Annex A - Supporting Information

# A.1 Methodology Details

Details of the approach chosen.

## A.1.1 Model Setup & Data Gathering

Prior to starting any data gathering, a draft model was setup to clarify the inputs required, and to ensure that data obtained would be at a relevant level of detail. Data was then gathered from a literature review of publicly available information, including previous work carried out for DESNZ, as well as through industry engagement.

### A.1.1.1 Model Setup

An Excel-based probabilistic graphical framework model was developed to calculate LCOE and align with the granular inputs required for the associated spreadsheet provided by DESNZ (Department for Business, Energy & Industrial Strategy (BEIS), 2023). To aid with model transparency, a dependency map was first drawn. Figure 10 shows the dependency map; this provides a visual description of the relationships between all the factors which inform the output (LCOE). This dependency map was replicated within our model, with probability distributions assigned to inputs and relationships captured as calculations.

The key advantage to the probabilistic graphical framework approach is it allows the inherent uncertainty in input assumptions to be captured via probability distributions. Each input is expressed as a range of values in a probability distribution. For each calculated relationship within the model, the model calculates the range of input distributions to create a probability distribution for the output. This is repeated throughout the model for each relationship, ultimately resulting in the calculated distribution for the LCOE. The distributions for each relationship node in the model can be extracted, analysed, and presented. In this report, distributions are shown as cumulative density functions, which values for the P10 (10%), P50 (50%) and P90 (90%) highlighted. The probabilistic graphical framework also enables us to perform Sobol analysis. Sobol analysis is a form of variance-based sensitivity analysis which allows the variance of the model outputs to be decomposed into fractions which can be attributed to inputs. This lets us quickly identify sensitive variables.

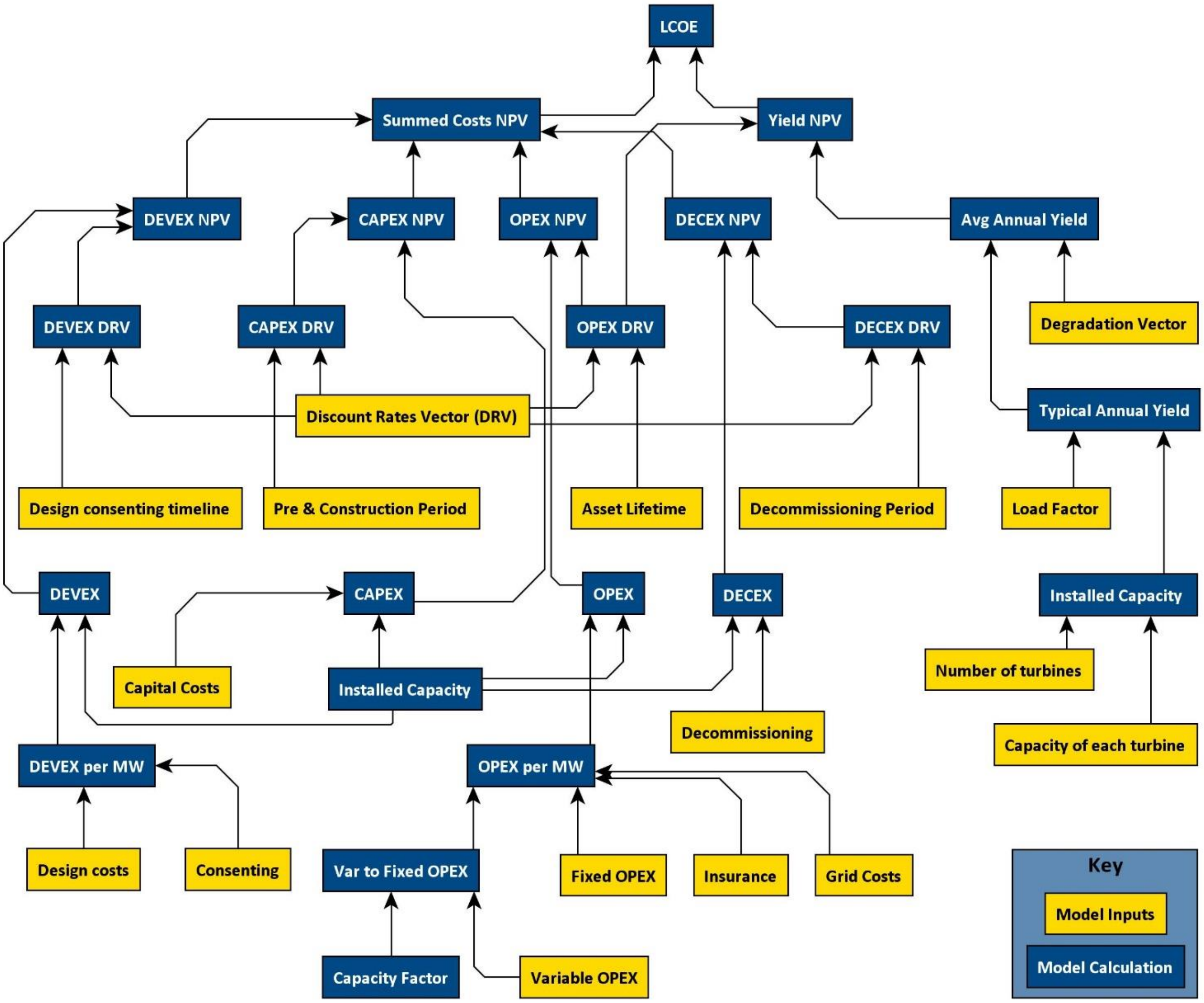

Figure 10: Dependency map providing a visual representation of the model and showing how inputs and calculations are combined.

### A.1.1.2 Literature Review

Around 30 reports and papers on offshore wind were reviewed (see References section). Approximately half of these were FOW specific, with the remainder either considering both floating and fixed, or just considering fixed offshore wind. Various data were extracted including costs, sensitivity and variability information, and barriers and cost reduction opportunities.

### A.1.1.3 Industry Engagement

Due to the level of data required, and the immaturity of FOW supply chain and projects, it was decided that the most appropriate industry sources were developers of FOW projects. Developers must consider and select the most appropriate of the novel designs for floating foundations (and associated mooring systems and dynamic cables), as well as consider the costs throughout the wind farm's lifecycle.

A survey was sent out to around 20 FOW project developers. These developers were selected based on those with at least one FOW project operational or under development, with the vast majority involved in UK projects. As most FOW projects are at an early stage of development, developers do not have access to a detailed breakdown of costs and the survey was designed accordingly. In addition, the survey was aligned with the inputs required by the LCOE model developed, ensuring sufficient detail for LCOE modelling.

To encourage responses, effort was made to ensure the survey was simple to use and focussed on the information required. Data relating to FOW costs is highly commercially sensitive, particularly in the current industry climate of competitive auctions and the wide range of potential designs and strategies. Reassurances were therefore provided that any industry data received would be anonymised and aggregated, and additional internal data security precautions taken. Where non-disclosure agreements were used it was ensured that they enabled the data to be used for this project, including presenting the findings in this report. There were also some concerns from the industry over how the data might be used, and whether it would be kept in context.

As well as including cost information, the survey included questions to enable categorisation of the responses into Demo, FOAK, or NOAK projects and to understand some of the cost drivers and reasons for cost differences.

Some developers were reluctant to complete the survey (either due to commercial sensitivities or as they did not feel they had sufficiently reliable data to share) but were nonetheless happy to share their perspectives of the FOW industry. For these developers, as well as all the developers who submitted completed surveys, interviews were carried out. These discussions were focussed on how costs could evolve in future and industry challenges and opportunities, this mainly input into the modelling of LCOE for NOAK projects. The interviews additionally enabled any potential anomalies or surprising results in the surveys to be corrected or contextualised.

### A.1.2 Data Categorisation & Initial Modelling

Both the literature review data and the industry survey responses were categorised according to whether they applied to Demo, FOAK, or NOAK project according to the following definitions:

1. Demo: Demonstration stage projects. These were those that were deemed (based on our industry experience) to be a project primarily aimed at learning about the FOW industry, proving and/or marketing a specific novel technology or capability, or projects that are not grid-connected (and therefore do not need to be cost competitive with grid-connected generation). These projects tend to be relatively close to shore, have a capacity less than ~200 MW, and are planned to achieve first power before 2030. Due to their relatively small size and therefore reduced overall cost, they enable technology development and learning with reduced financial risk. The Hywind Scotland and Hywind Tampen projects mentioned in Section 2 would fall into this category.
2. FOAK: First of a kind commercial stage projects. These are an order of magnitude larger than Demo projects and will be of a similar size to the latest fixed offshore wind farms. These typically have installed capacities in the order of 1 GW and will achieve first power after 2030.
3. NOAK: nth of a kind commercial stage projects. These are not necessarily larger in scale when compared to FOAK projects but have been developed after the FOAK projects. This enables lessons to be learnt and supply chains to be established, potentially driving down costs (see later discussion on learning rates). No industry survey responses came into this category, and NOAK projects are considered to achieve first power towards the end of the 2030s.

A note on “commercial” projects: with the availability of sufficient subsidies, it is possible for any projects (whether Demo, FOAK or NOAK projects) to be run on a commercial basis (i.e. to be run with the aim of being profitable). Wind farm owners may be more willing to take more financial risk on smaller-scale (Demo) projects, and some Demo projects may deliberately be sanctioned despite likely being unprofitable due to other drivers (for example marketing a specific technology). It is considerably less likely, due to the larger volumes of money required, for FOAK or NOAK scale projects to be sanctioned on a non-profitable basis.

After the survey responses and literature review findings had been categorised into either Demo or FOAK, they were input into the LCOE model individually. This initial modelling enabled a comparison of both the inputs, and the modelled LCOE, to be compared for each distinct project. By analysing the results on a project-by-project basis, and comparing with each project's specific characteristics, this helped verify the model, identify any anomalous data, and provided an indication of LCOE drivers.

Following this, four LCOE distributions, each based on multiple sources, where then modelled:

- Demo from survey responses,
- FOAK from survey responses,
- Demo from literature review data, and
- FOAK from literature review data.

This enabled a comparison between survey responses and literature review data and provided an insight into areas of potential bias (see section 3.2.4. below).

### A.1.3 Modelling LCOE for Demo and FOAK Projects

To determine the LCOE distribution for both Demo FOW projects and FOAK FOW projects, both survey response data and literature review data was combined. Using a balance of expertise from FOW experts and economic modellers, consideration was given as to how to best combine the different data sources as each value could be input using a different probability distribution, weighting some sources above others.

### A.1.4 Obtaining Learning Rates

Calculating an LCOE distribution for NOAK projects for an immature technology and therefore in the absence of literature data or industry data relies upon applying suitable learning rates. A literature review to identify FOW learning rates was carried out and the findings analysed to determine the most suitable source.

### A.1.5 Modelling LCOE for NOAK Projects

To model the LCOE distribution for NOAK projects, the FOAK LCOE distribution was modelled after applying learning rates obtained from the literature review. A series of different scenarios were modelled, applying different learning rates to different capacity growth forecasts.

### A.1.6 Sensitivity Analysis

By adjusting specific model inputs, it is possible to carry out a sensitivity analysis of potential developments to the FOW industry. From industry interviews, literature review findings, industry experience and Sobel analysis of the LCOE model, a range of factors were identified. These were input into the FOAK LCOE model, and the results analysed.

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