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Future renewable energy costs: Offshore wind

57 technology innovations that will have greater impact on reducing the cost of electricity from European offshore wind farms

BVGassociates

BVG Associates

BVG Associates is a technical consultancy with expertise in wind and marine energy technologies. The team probably has the best independent knowledge of the supply chain and market for wind turbines in the UK. BVG Associates has over 150 combined years of experience in the wind industry, many of these being "hands on" with wind turbine manufacturers, leading RD&D, purchasing and production departments. BVG Associates has consistently delivered to customers in many areas of the wind energy sector, including:

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- Market leaders and new entrants in wind farm component design and supply
- New and established players within the wind industry of all sizes, in the UK and on most continents, and
- The Department of Energy and Climate Change (DECC), RenewableUK, The Crown Estate, the Energy Technologies Institute, the Carbon Trust, Scottish Enterprise and other similar enabling bodies.

InnoEnergy

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We support and invest in innovation at every stage of the journey – from classroom to end-customer.

With our network of partners we build connections across Europe, bringing together inventors and industry, graduates and employers, researchers and entrepreneurs, businesses and markets.

We work in three essential areas of the innovation mix:

- **Education** to help create an informed and ambitious workforce that understands the demands of sustainability and the needs of industry.
- **Innovation Projects** to bring together ideas, inventors and industry to create commercially attractive technologies that deliver real results to customers.
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Bringing these disciplines together maximises the impact of each, accelerates the development of market-ready solutions, and creates a fertile environment in which we can sell the innovative results of our work.

InnoEnergy was established in 2010 and is supported by the European Institute of Innovation and Technology (EIT).

InnoEnergy

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Executive summary

InnoEnergy has developed credible future technology cost models for four renewable energy generation technologies using a consistent and robust methodology. The purpose of these cost models is to explore and track the impact of innovations on the levelised cost of energy (LCOE) in a consistent way across the four technologies. This report examines how technology innovation is anticipated to reduce the cost of energy from European offshore wind farms up to 2030.

Methodology

This report is an update of previous reports published by InnoEnergy in June 2014 and September 2016 and uses the same input data structure. The analysis has been expanded, extended and updated, including via fresh engagement with industry.

At the heart of this study is a cost model in which a range of technology innovations impact on the cost elements of baseline wind farms. These wind farms are defined in terms of the Turbine Size (6, 8, 10 and 12MW) (see Table 0.1), Site Types (see Table 0.2), and four points in time at which the projects reach the final investment decision (FID) (2017 (the baseline), 2020, 2025 and 2030). Innovations in electrical transmission are not considered individually but are included in the overall LCOE calculations along with supply chain and finance costs as 'Other Effects'.

Table 0.1. Different combinations of Turbine Sizes and years of FID investigated.

Turbine Size	2017 FID	2020 FID	2025 FID	2030 FID
6MW	○	○		
8MW	○	○	○	
10MW		○	○	○
12MW			○	○

Table 0.2. Site Type definitions.

Parameter	Site Type A[1]	Site Type D
Distance from shore (km)	40	125
Water depth (m)	25	35
Wind speed at 100m (m/s)	9.0	10.0
Farm size (MW)	500	500

Results

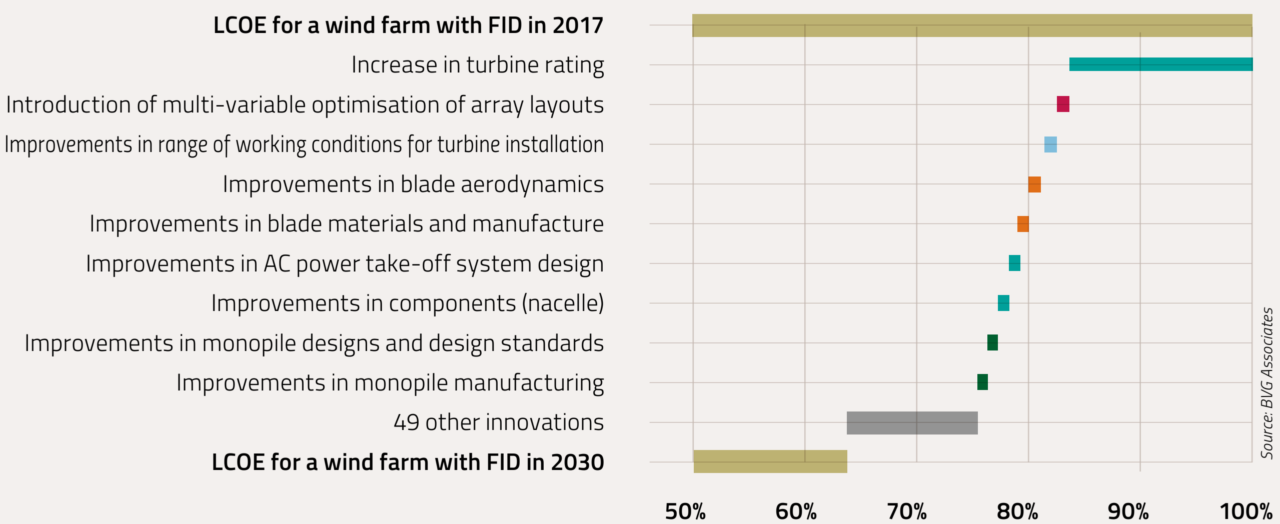
More than 50 technology innovations were identified as having the potential to cause a substantial reduction in LCOE through a change in the design of hardware, software or process. Many more technical innovations are in development, so some of those described in this report may be superseded by others.

The wind farm technology innovations (excluding Other Effects) contribute an anticipated 36% reduction in the LCOE from FID in 2017 to FID in 2030. Figure 0.1 shows that two-thirds of the total anticipated technology impact is achieved through nine areas of innovation, the largest of which is the increase in turbine size from 6MW to 12MW. By virtue of having fewer turbines for a given wind farm rated power, there are significant savings in the cost of foundations and construction, and in operational expenditure (OPEX). All of the next generation turbines (Turbine Size of 6MW or greater) operational and under development today have more optimum-sized rotors than the

1 The Site Type names are the same as in 2012 The Crown Estate Cost Reductions Pathways Study. Site Types B and C were not considered in this analysis.

previous generation and, because of a higher hub height, access wind further above sea level. They therefore have higher gross AEP per megawatt, even before taking into account increased reliability and maintainability, which is being demonstrated by the current generation of large turbines designed for the offshore market. The combined anticipated decrease in LCOE from larger turbines with optimum-sized rotors, improved aerodynamics and control and next generation drive-train designs is about 18%.

Figure 0.1. Anticipated impact of technology innovations for a wind farm using 10MW-Size Turbines with FID in 2030, compared with a wind farm with 6MW-Size Turbines with FID in 2017, both on Site Type D (no Other Effects incorporated).[2]



Impact of innovations in each wind farm element

In wind farm development, through upfront investments in engineering and site characterisation, the LCOE is anticipated to reduce by about 3% in the period. The principal innovations relate to greater levels of analysis and optimisation for array layout and during the front-end engineering design studies (FEED).

An increase in the turbine power rating has an anticipated impact on the LCOE of 17% in the period. Other innovations in the turbine nacelle are anticipated to reduce the LCOE by about 7%. Benefits come from the introduction of a number of next-generation drive trains, including improved direct-drive and mid-speed generator solutions, which are anticipated to reduce OPEX through greater reliability. Improvements in verification testing and increased knowledge sharing are critical to achieve the reliability of these next-generation designs.

2 Negative values indicate a reduction in the item and positive values indicate an increase in the item. All OPEX figures are per year, from year six. The LCOE calculations are based on the capital expenditure (CAPEX), operational expenditure (OPEX) and annual energy production (AEP) values presented. This is in order to present accurate relative cost changes while only showing the impact of technology innovations. Appendix B provides data behind all figures in this report.

Innovations in rotor components offer a 6% reduction in the LCOE in the period, delivered mainly via increases in energy production, rather than decreases in costs. Key innovations relate to improved blade aerodynamics, blade manufacture and the introduction of inflow wind measurement.

Changes in balance of plant LCOE are dominated by innovations in the support structure. The move from support structures initially suited to shallow waters to those suited to deeper ones has been slower than expected due to better than expected progress in the design and manufacturing of monopiles. By FID in 2030, the impact of innovations in balance of plant will be strengthened by improvements in jacket foundation design and manufacturing, through new processes that move from bespoke one-off structures for the oil and gas sector to series-produced, standardised foundations for offshore wind. Also significant are developments in holistic tower design and the introduction of array cables with higher operating voltages. Combined, innovations in balance of plant are anticipated to reduce the LCOE by approximately 3% in the period.

The introduction of installation vessels that can operate in a wider range of conditions will bring benefits because costs can be reduced through the introduction of large, heavy lift vessels designed for offshore wind foundation installation. The industry is anticipated to benefit from oil and gas sector experience and the entrance of major players from this sector is a positive sign that the potential savings can be realised. Overall, the anticipated reduction in the LCOE due to innovations in wind farm construction is about 3% in the period.

The three biggest innovations in OMS are: improvements in OMS strategy for far–from-shore wind farms; the introduction of condition-based maintenance for turbines and improvements in personnel access. Each will have the biggest impact on far-from-shore projects which involve greater transit distances and more severe sea states. We anticipate the reduction in the LCOE due to such innovations to be approximately 4% in the period.

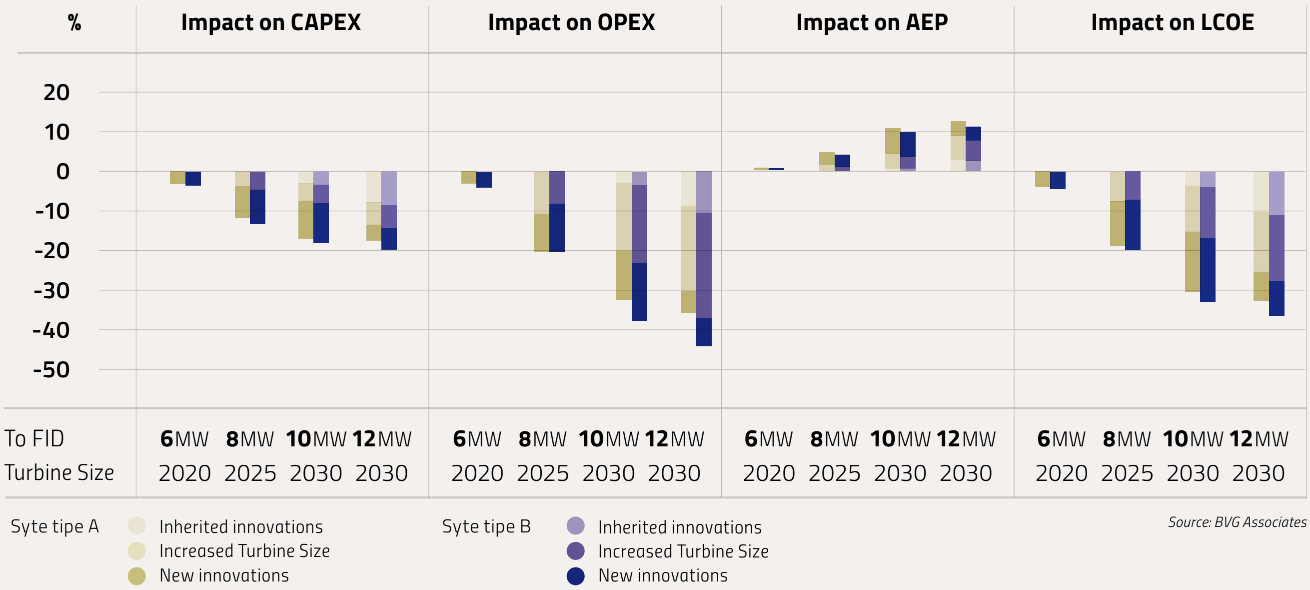
Source of innovation impact

The combined impact that technology innovations over the period are anticipated to have on projects with different combinations of Turbine Sizes and Site Type is presented in Figure 0.2. The aggregate impact of all innovations is shown over the FID range for each Turbine Size, all compared with the same wind farm, that is, one with 6MW-Size Turbines on Site Type A and FID of 2017. Showing the impact with respect to the same starting wind farm allows the effect of changes in Turbine Size and Site Type to be compared directly.

CAPEX, OPEX, AEP and LCOE all improve with increasing Turbine Size: CAPEX and OPEX fall and the AEP rises, resulting in LCOE savings. Figure 0.2 also breaks down each of the changes in CAPEX, OPEX, AEP and LCOE by the source of the change. The sources considered are gains through:

1. Inherited innovations (impact of innovations already incorporated in baseline project for given Turbine Size, ref. Table 2.2)
2. Increased Turbine Size
3. New innovations (impact of innovations coming in after baseline project for given Turbine Size)

Figure 0.2. Anticipated impact of all innovations by Turbine Size and Site Type over the periods shown (no Other Effects incorporated).



Source: BVG Associates

For wind farms on Site Type A, the aggregate impact of all innovations and the change to 12MW-Size Turbines over the period FID 2017-2030 is a 18% reduction in CAPEX, a 36% reduction in OPEX and a 13% increase in AEP, giving an overall 43% reduction in LCOE. For wind farms on Site Type D, using 12MW-Size Turbines decreases CAPEX by 20%, decreases OPEX by 44% and increases AEP by 12%, giving an overall reduction in LCOE of 45%.

When Other Effects are incorporated, the LCOE reduction for wind farms on Site Type A with Turbine Size of 12MW for FID in 2030 is 52%, while for Site Type D the reduction is 51%, both in comparison with 6MW-Size Turbines on Site Type A with FID in 2017.

Glossary

AEP. Annual energy production.

Anticipated impact. Term used in this report to quantify the anticipated market impact of a given innovation. This figure has been derived by moderating the potential impact through applying various real-world factors. For details of methodology, see Section 2.

Balance of plant. Support structure and array electrical, see Appendix A.

Baseline. Term used in this report to refer to "today's" technology, as would be incorporated into a project.

Capacity factor (CF). Ratio of annual energy production to annual energy production if all turbines are generating continuously at rated power.

CAPEX. Capital expenditure.

DECEX. Decommissioning expenditure.

FEED. Front end engineering and design.

FID. Final investment decision, defined here as that point of a project life cycle at which all consents, agreements and contracts that are required in order to commence a project construction have been signed (or are at or near execution form) and there is a firm commitment by equity holders and, in the case of debt finance, debt funders, to provide or mobilise funding to cover the majority of construction costs.

Generic WACC. Weighted average cost of capital applied to generate LCOE-based comparisons of technical innovations across scenarios. Different from Scenario-specific WACC.

Gross AEP. Predicted annual energy production based on turbine power curve, excluding losses.

Hs. Significant wave height.

Inherited innovations. Innovations already incorporated in baseline project for given Turbine Size.

LCOE. Levelised cost of energy, considered here as pre-tax and real in end 2016 terms. For details of methodology, see Section 2.

MHWS. Mean high water springs, the average throughout the year (when the average maximium declination of the moon is 23.5°) of two successive high waters during those periods of 24 hours when the range of the tide is at its greatest.

MSL. Mean sea level.

MW. Megawatt.

MWh. Megawatt hour.

Net AEP. Metered annual energy production at the offshore substation, including wind farm losses.

New innovations. Innovations which come in after baseline project for given Turbine Size.

OMS. Operation, planned maintenance and unplanned service in response to a fault.

OPEX. Operational expenditure.

Other Effects. Effects other than from wind farm technology innovations, such as supply chain competition and changes in financing costs.

Potential impact. Term used in this report to quantify the maximum potential technical impact by FID in 2030 of a given innovation. This impact is then moderated through application of various real-world factors. For details of methodology, see Section 2.

RD&D. Research, development and demonstration.

Site Type. Term used in this report to describe a representative set of physical parameters for a location where a project may be developed. For details of methodology, see Section 2.

Scenario-specific WACC. Weighted average cost of capital associated with a specific combination of Site Type, Turbine Size and year of FID . Used to calculate real-world LCOE incorporating Other Effects, (Section 2.4).

Technology Type. Used in this study to describe Turbine Size

Turbine Size Term used in this report to describe a representative turbine size (rated power) for which baseline costs are derived and to which innovations are applied. For details of methodology, see Section 2.

WACC. Weighted average cost of capital, considered here as real and pre-tax.

WCD. Works completion date.

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1. Introduction

1.1. Framework

As an innovation promoter, InnoEnergy is interested in identifying and evaluating the impact of visible innovations on the cost of energy from various renewable energy technologies. This analysis is critical in understanding where the biggest opportunities and challenges are, from a technology point of view.

InnoEnergy has already published a set of consistent analyses for various technologies to help in the understanding and definition of innovation pathways that industries could follow to maintain the competitiveness of the European renewable energy sector worldwide. These technologies include onshore and offshore wind, solar PV and solar thermal electricity and gas and coal. These analyses all contribute to the DELPHOS online cost of energy tool. In 2014 InnoEnergy first published *Future renewable energy costs: offshore wind (2014)* [3] .

In this report, InnoEnergy updates the baseline turbine size to 6MW and the baseline FID date to 2017, to capture the major changes that have occurred in offshore wind cost and LCOE through 2016 and the first half of 2017. It also increases the turbine capacity to 12MW to look at longer-term trends in the innovation pathways and acknowledge updated expectations about turbine size growth. This is clearly a longer-term approach, but is complementary to the InnoEnergy technology mapping focusing on innovations reaching the market in the short/mid-term (up to five years ahead).

1.2. Purpose and background

The purpose of this report is to document the cost of energy for offshore wind projects reaching financial investment decision (FID) up to 2030, by modelling of the impact of a range of technical innovations and Other Effects including financing and supply chain impacts. The methodology follows that of the previous report. Additional industry engagement has been used in the production of this report.

3 InnoEnergy, available online at www.innoenergy.com

1.3. Structure of this report

Following this introduction, this report is structured as follows:

Section 2 Methodology: This section describes the scope of the model, project terminology and assumptions, the process of technology innovation modelling, industry engagement and the treatment of risk and health and safety.

Section 3 Baseline wind farms: This section summarises the parameters relating to the eight baseline wind farms for which results are presented. Assumptions relating to these wind farms are presented in Section 2.

The following six sections consider each element of the wind farm in turn, exploring the impact of innovations in that element.

- **Section 4 Innovations in wind farm development:** This section incorporates the wind farm design, consenting, contracting and developer's project management activities through to the works completion date (WCD).
- **Section 5 Innovations in wind turbine nacelle:** This section incorporates the drive train, power take-off and auxiliary systems, including those that may be located in the tower.
- **Section 6 Innovations in wind turbine rotor:** This section incorporates the blades, hub and any pitch or other aerodynamic control system.
- **Section 7 Innovations in balance of plant:** This section incorporates the support structure, the tower and foundation. It includes the sea bed connection and also the secondary steel work to provide personnel and equipment access and array cable support. It also considers subsea cables connecting turbines to any substation. Cable protection is covered under innovations in wind farm construction. Offshore and onshore substations and export cables are not considered among the innovations, but these transmission costs are included in the Other Effects discussed in Section 2.4.
- **Section 8 Innovations in wind farm construction:** This section incorporates transportation of components from the port nearest to the component supplier, plus all installation and commissioning activities for the support structure, turbine and array cables. Decommissioning is also discussed in this section. It excludes installation of the offshore substation, the export cables and onshore transmission assets, which are modelled as transmission charges.
- **Section 9 Innovations in operation, maintenance and service (OMS):** This section incorporates all activities after the WCD until decommissioning.
- **Section 10 Summary of the impact of innovations:** This section presents the aggregate impact of all innovations, exploring the relative impact of innovations in different wind farm elements.

Section 11 Conclusions: This section includes both technology-related conclusions and conclusions regarding Other Effects.

Appendix A Details of methodology: This appendix discusses project assumptions and provides examples of methodology use.

Appendix B Data tables: This appendix provides tables of data behind figures presented in the report.

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2. Methodology

The main innovations were selected and described through engagement with industry. This led to 57 innovations and their effects on cost pathways being modelled. The model uses the maximum technical potential impact of the innovations on the cost and energy elements of the baseline wind farms, which were developed from a combination of deeper modelling and engagement with industry. Site relevance, commercial readiness and market shares are used to modify this maximum so as to give the anticipated impact of each innovation. The innovations are then combined to give an overall innovation trajectory, with additional (non-innovation) effects included separately.

2.1. Scope of model

The basis of the model is a set of baseline elements of capital expenditure (CAPEX), operational expenditure (OPEX) and annual energy production (AEP) for a range of representative Turbine Sizes on two Site Types (see Table 2.1), impacted on by a range of technology innovations. Analysis is carried out at a number of points in time (years of FID) (see Table 2.2), thus describing various potential pathways that the industry could follow, each with an associated LCOE trajectory. The tick in brackets in Table 2.2 shows the baseline used to compare individual innovations over the whole period from FID in 2017 to FID in 2030, as used in Figure 4.2, Figure 5.2, Figure 6.2, Figure 7.2, Figure 8.2 and Figure 9.2.

The study does not consider the market share of the different Turbine Sizes and Site Types The actual average levelised cost of energy (LCOE) in a given year will depend on the mix of such parameters for projects reaching FID in that year.

Table 2.1. Site Type definitions[4]

Parameter	Site Type A	Site Type D
Distance from shore (km)	40	125
Water depth (m)	25	35
Wind speed at 100m (m/s)	9.0	10.0
Farm size (MW)	500	500

Table 2.2. Different combinations of Turbine Sizes and years of FID used as baselines.

Turbine Size	2017 FID	2020 FID	2025 FID	2030 FID
6MW	O			
8MW	O			
10MW	(O)	O		
12MW	(O)		O	

2.2. Project terminology and assumptions

2.2.1. Definitions

A detailed set of project assumptions were established in advance of modelling. These are presented in Appendix A, and cover technical and other global considerations and wind farm-specific parameters.

2.2.2. Terminology

For clarity, when referring to the impact of an innovation that lowers costs or the LCOE, terms such as reduction or saving are used and the changes are quantified as positive numbers. When these reductions are represented graphically or in tables, reductions are expressed as negative numbers as they are intuitively associated with downward trends. An increase in gross AEP results in a lower LCOE, so a positive number is used to show the effect of an innovation increasing gross AEP. Changes in percentages (for example, losses) are expressed as a relative change. For example, if losses are decreased by 0.5% from 10% to 9.5%, then there is a 5% reduction in losses.

4 The Site Types have been named to be consistent with The Crown Estate Offshore Wind Cost Reduction Pathways Study (2012). Site Types B and C were not considered in this analysis.

2.3. Technology innovation modelling

The model assesses the impact of technology innovations on each of the wind farm elements on each of the baseline wind farms, as outlined in Figure 2.1. This section describes the methodology analysing each innovation. An example is given in Appendix A.

Figure 2.1. Process to derive impact of innovations on the LCOE. Note that Technology Type in this study means Turbine Size.

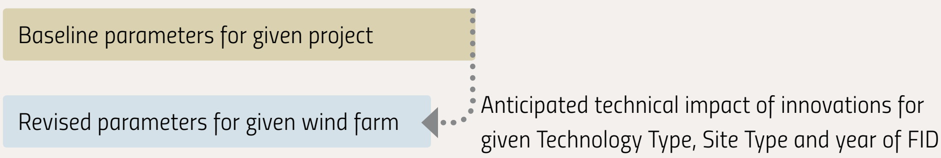
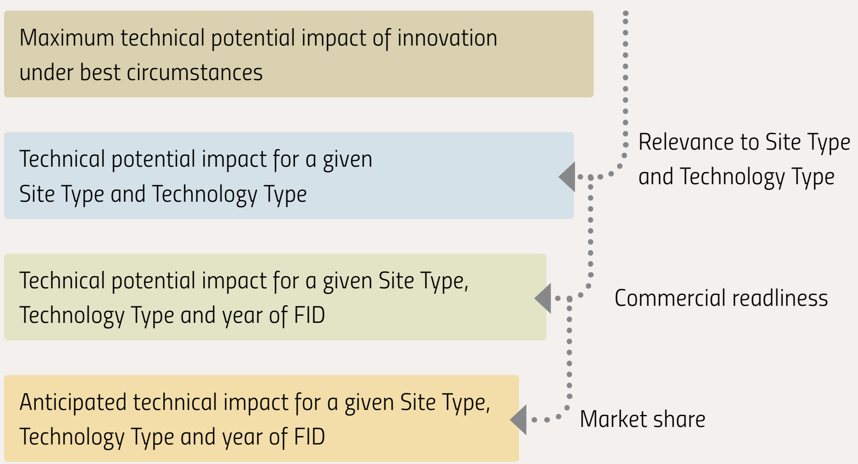


Figure 2.2 summarises this process of moderation.

Figure 2.2. Four stage process of moderation applied to the maximum potential technical impact of an innovation to derive anticipated impact on the LCOE. Note that Technology Type in this study means Turbine Size.



2.3.1. Baselines

The baselines were developed based on industry experience, historical records, bottom-up understanding of costs and the specific site conditions. Bottom-up estimates are rationalised against top-down viewpoints from industry experts and literature for the overall cost and energy balance and for each cost or energy element. There is significant variability in costs between projects, due to both supply chain and technology effects, even within the portfolio of a given wind farm developer.

2.3.2. Maximum technical potential impact by FID in 2030

Each innovation may impact a range of different costs and / or the gross AEP (calculated from the power curve) and net AEP (reflecting losses) of the wind farm, as listed in Table 2.3. The maximum technical potential impact by FID in 2030 on each of these is recorded separately for the Turbine Size and Site Type most suited to the given innovation. The maximum technical potential impact is the maximum impact expected to be available by FID in 2030 for the site and turbine combination for which it is most favourable[5] . Anticipated impact is then the fraction of this impact that is expected to be realised for the specific Turbine Size, Site Type and date in question. An innovation may change any combination of CAPEX, OPEX or AEP. The analysis uses the implementation resulting in the largest reduction in the LCOE, which is a combination of CAPEX, OPEX and AEP.

Table 2.3. Information recorded for each innovation.

% impact on cost of

- Wind farm development
- Wind turbine
- Support structure
- Array electrical
- Construction
- Planned wind farm operation, maintenance and service
- Unplanned service and other OPEX

% impact on

- Gross AEP, and
- Losses

In some cases, there is more potential for a given innovation to be realised even after projects reaching FID in 2030. This may be for a number of reasons:

- Long research, development and demonstration period for an innovation, which will not be completely ready for use on a project with FID in 2030
- The technical potential can only be realised through an ongoing evolution of the design based on feedback from commercial-scale manufacture and operation, or
- The technical potential impact of one innovation is decreased by the subsequent introduction of another innovation.

For this study, technical potential has been adjusted to that realisable by FID 2030.

2.3.3. Relevance to Site Types and Turbine Sizes

This maximum technical potential impact of an innovation on the baseline may not be realised on both Site Types with all four Turbine Sizes. In some cases, an innovation may not be relevant to a given Site Type and Turbine Size combination at all. For example, high-temperature superconducting generators are unlikely to be of benefit on smaller turbines, so the relevance of this innovation to

5 This is slightly different to previous versions of this modelling. Previously, this maximum technical impact considered timescales beyond the final year of FID considered in the study.

6MW-Size Turbines is 0%. In other cases, the maximum technical potential may be different for each Site Type. For example, using feeder vessels in support structure installation is most applicable to sites far from port, such as those characterised by Site Type D. In this case, the impact on Site Type A may be only 80% of that on Site Type D. This relevance is modelled by applying a factor specific to each combination of Site Type and Turbine Size independently for each innovation.

2.3.4. Commercial readiness

Commercial readiness is defined by how much of the technical potential of the innovation is available to projects reaching FID in a given year. For this study, commercial readiness in FID 2030 is set as 100%, with the maximum technical potential taken as for the commercial readiness at this FID date. If the commercial readiness at a given FID date is 50%, this means that half of the FID 2030 technical potential can be realised by that year of FID.

The factor relates to how much of the technical potential is commercially ready for deployment in a project of the scale defined in the baseline. Reaching this point is likely to have required full-scale demonstration. This moderation does not relate to the share of the market that the innovation has taken but rather how much of the full benefit of the innovation is available for a given Site Turbine or Turbine Size.

2.3.5. Market share

Not all innovations are compatible. For example, innovations relating to monopiles or jackets are not compatible, nor are those which are only valid for either geared or gearless drive train solutions.

For those innovations which are not compatible with others, the market share must be assessed with this in mind. For example, a market share is assigned to each of the foundation technology options, for each Turbine Size and FID. For each innovation that is dependent on a particular foundation option, its share of the market within that foundation option is combined with that option's share of the total market to give an overall market share for the innovation.

The resulting anticipated impact of a given innovation, because it takes into account the anticipated market share on a given Turbine Size in a given year of FID, can be combined with the anticipated impact of all other innovations to give an overall anticipated impact for a given Turbine Size, Site Type and year of FID. At this stage, the impact of a given innovation is still captured in terms of its anticipated impact on each capital, operational and energy-related parameter, as listed in Table 2.3.

2.3.6. Impact for a single innovation

The relevance, commercial readiness and market share impacts are then applied to the baseline costs and operational parameters shown in Table 2.3 to derive the impact of each innovation on LCOE for each Turbine Size, Site Type and year of FID, using a generic weighted average cost of capital (WACC).

An example of this procedure is given in Appendix A.

2.3.7. Impact for a group of innovations

The aggregate impact of all innovations on each operational and energy-related parameter in Table 2.3 is also derived, enabling a technology-only LCOE to be derived for each Turbine Size, Site Type and FID year combination. To look at the group or overall effect, the combined effect of the individual innovations on the cost and energy elements is used to produce an overall value for the impact of CAPEX, OPEX and AEP. These are then combined to give the new LCOE.

2.3.8. Innovation impacts

To compare the individual innovations over the time period, a project using 10MW-Size Turbines on Site Type D with FID in 2017 is used as the baseline. This means that the innovations can be compared over the whole time period from 2017 to 2030. Obviously, this 10MW-Size Turbine was not available for use in projects with FID in 2017, but using it as a theoretical comparison point is helpful. The CAPEX, OPEX and AEP values for such a project are shown in Table A.6.

2.4. Treatment of Other Effects

To derive a real-world LCOE, this technology-only LCOE is factored to account for the impact of various Other Effects, defined for each for each combination of Turbine Size, Site Type and year of FID as follows:

- Scenario-specific WACC and lifetime combinations, taking into account risk (or contingency).
- Transmission and land cost, covering transmission CAPEX and OPEX and charges related to the onshore transmission network and sea bed lease fees. The transmission cost is based on an HVAC transmission system for Site Type A and HVDC system (or HVAC system with reactor station) for Site Type D. The distance at which a developer would choose an HVDC system over an HVAC system is currently quite uncertain, due to dynamic changes in technology and supply chain. In some markets, transmission is a socialised cost, transparent to the wind farm owner; in other markets, the developer constructs the transmission system then sells it to an operator and pays a rental for its use. As the focus of this study is wind farm generating assets, transmission is treated simply as an Other Effect.
- Supply chain dynamics, simplifying the impact of the supply chain levers such as competition and collaboration, first discussed in EC Harris's *Offshore Wind Cost Reduction Pathways: Supply chain work stream*[6]. Between 2015 and 2017, winning bids for auctions for pre-developed offshore wind farms in Europe have indicated important further cost reductions for projects commissioned from 2020. These are likely to be mainly due to:
    - Increased competition at developer level for the same site,
    - Benefit of anticipated savings due to having a pipeline of projects over a number of years, enabling savings in the supply chain due to the expectation of higher utilisation of vessels and facilities, depreciation of investment over more activity, increased learning through repetition and the facilitation of new investment, and
    - Inclusion of benefits from likely future savings in OMS that are not available at FID.
- Insurance and contingency costs, both relating to construction and operation insurance and typical spend of construction phase contingency.
- The risk that some projects are terminated prior to FID, thereby inflating the equivalent cost of work carried out in this phase on a project that is constructed. For example, if only one in three projects reaches FID, then the effective contribution to the cost of energy of work carried out on projects prior to FID is modelled as three times the actual cost for the project that is successful, and
- Decommissioning costs.

A factor for each of these effects was derived from a range of sources and a trend was used across each combination of Turbine Size, Site Type and FID year, as presented in Appendix A.

The factors are applied as follows:

- Scenario-specific WACC and operating life are used in place of the generic WACC to calculate a revised LCOE, and
- Each factor is applied in turn to this LCOE to derive the real-world LCOE.

6 (May 2012), available online at www.thecrownestate.co.uk/media/305090/echarris_owcrp_supply_chain_workstream.pdf

These factors are kept separate from the impact of technology innovations in order to clearly identify the impact of innovations, but they are needed in order to be able to compare LCOE for different scenarios rationally.

The effects of changes in construction time are not modelled.

2.5. Treatment of health and safety

The health and safety of staff working on both onshore and offshore operations is important to the offshore wind industry. This study incorporates into the cost of innovations any mitigation required in order to at least preserve existing levels of health and safety. It is difficult to quantify health and safety impacts but in some cases, preserving similar levels of health and safety precluded some innovations. This is evident in, for example, offshore operations. Many of the innovations that are considered to reduce the LCOE over time have an intrinsic benefit to health and safety performance. These include:

- The increased rated capacity of turbines, hence fewer turbines to transfer to per gigawatt installed. All other things being equal, reducing the number of transfers reduces the risk of incidents during transfer.
- Turbine design with increased onshore assembly. All other things being equal, reducing the amount of offshore activity decreases the risk of incidents.
- The increased reliability of turbines and hence fewer transfers to turbines and less time working in the offshore environment.
- Condition monitoring and remote diagnostics, which enable a more effective and proactive service and hence result in fewer complex retrofits or repairs, and
- The introduction of systems that allow for easier access to turbines, for example walk-to-work access systems and crane-less transfer systems.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3. Baseline wind farms

Section 2 described the modelling process as the following:

- Define a set of baseline wind farms and derive costs, and energy-related parameters for each.
- For each of a range of innovations, derive the anticipated impact on these same parameters, for each baseline wind farm, for a given year of FID, and
- Combine the impact of a range of innovations to derive costs and energy-related parameters for each of the baseline wind farms for each year of FID.

In this section, the costs and other parameters for the baseline wind farms are summarised.

The baseline costs presented in Figure 3.1 and Figure 3.2 are nominal contract values, rather than outturn values. As such, they incorporate real-life supply chain effects such as the impact of competition. They are for the combinations of Turbine Size and Site Type shown in Table 2.2.

All results presented in this report incorporate the impact of technology innovations only, except for when the LCOE is presented in Figure 3.3 and in Section 10.3, which also incorporates the Other Effects discussed in Section 2.4.

For the purposes of this study, the 10MW turbines are modelled first in projects with FIDs in 2020 onwards (rather than with FIDs in 2017). Projects auctioned during 2017 may use 10MW turbines, but FID will not be until after 2017.The first 12MW turbines are assumed to be used on projects with FIDs in 2025 onwards. 6MW and especially 8MW turbines will continue to be used into the 2020's if the market goes through optimisation of existing turbines rather than the innovation of new turbines. No assumptions are made in this report about the market share of the different Turbine Sizes.

The baseline wind farm used in the innovation comparisons in Sections 4-9 is described in Table A.6.

Table 3.1. Baseline parameters

Type	Parameter	Units	6-A-17	8-A-17	10-A-20	12-A-25	6-D-17	8-D-17	10-D-20	12-D-25
CAPEX	Development	€k/MW	96	92	90	88	102	97	94	93
	Turbine	€k/MW	966	1,003	1,030	1,049	986	1,023	1,051	1,070
	Support structure	€k/MW	517	489	449	379	648	590	531	476
	Array electrical	€k/MW	54	50	44	37	54	51	46	37
	Construction	€k/MW	422	341	279	212	441	360	295	221
OPEX	Operations and planned maintenance	€k/MW/yr	36	33	31	29	40	36	32	30
	Unplanned service and other OPEX	€k/MW/yr	49	43	36	29	62	57	44	32
AEP	Gross AEP	MWh/yr/MW	4,528	4,599	4,692	4,842	5,058	5,119	5,209	5,363
	Losses	-	17.6%	17.5%	16.9%	15.9%	16.2%	16.1%	15.5%	14.6%
	Net AEP	MWh/yr/MW	3,730	3,794	3,901	4,072	4,237	4,294	4,402	4,582
	Net capacity factor	-	42.5%	43.3%	44.5%	46.4%	48.3%	49.0%	50.2%	52.3%

Figure 3.1. Baseline CAPEX by element.

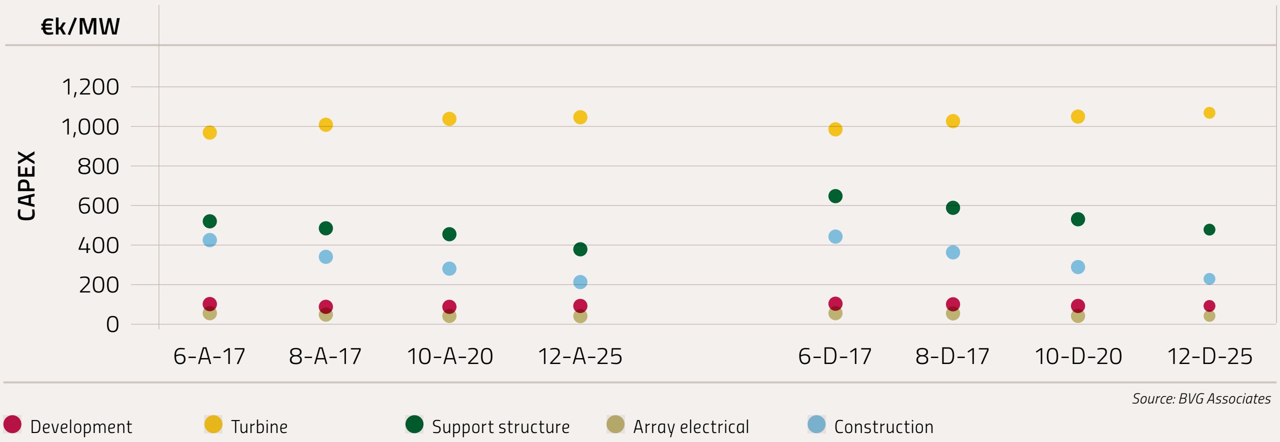
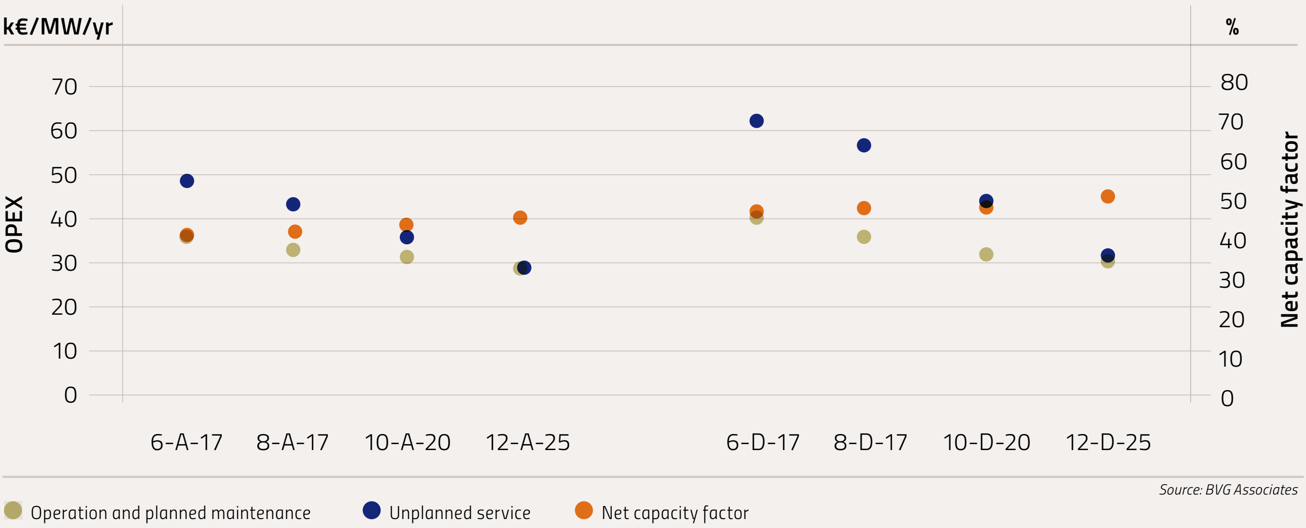


Figure 3.2. Baseline OPEX and net capacity factor.

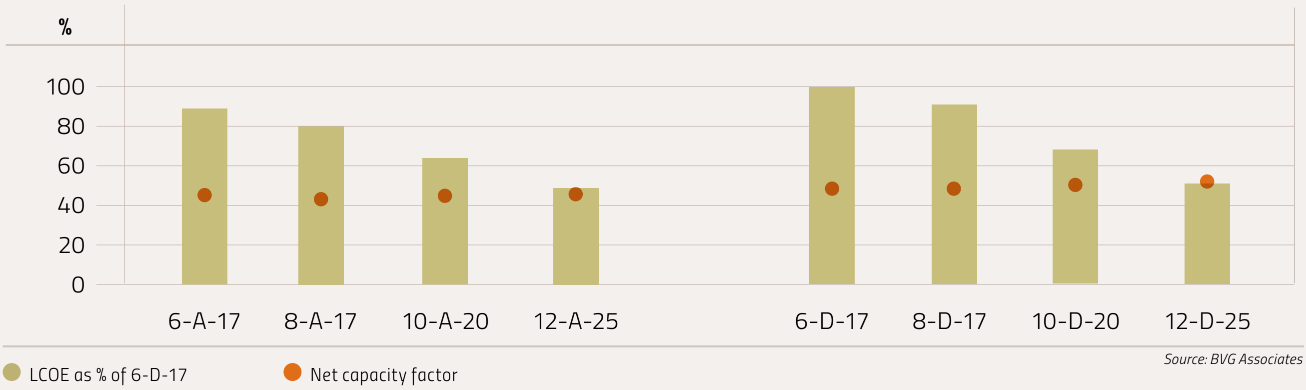


The timing profile of CAPEX and OPEX spend, which is important in deriving the LCOE, is presented in Appendix A.

These baseline parameters are used to derive the LCOE for the four baseline Site Type and Turbine Size combinations. A comparison of the relative LCOE for each of the baseline wind farms is presented in Figure 3.3 with a wind farm of 6MW-Size Turbines on Site Type D used as the comparator.

The trend is for higher LCOE for Site Type D than Site Type A because the increased costs outweigh the increased energy production. For the 2017 FID, there is more risk for an 8MW turbine than for a 6MW turbine, which leads to LCOEs which are closer together than just the cost and energy elements would suggest. For the later FIDs, there is no difference in risk between turbine sizes, although there is more risk for Site Type D than for Site Type A.

Figure 3.3. Relative LCOE and net capacity factor for baseline wind farms with Other Effects incorporated, ref. Section 2.4.



Source: BVG Associates

4. Innovations in wind farm development

4.1. Overview

Innovations in wind farm development are anticipated to reduce the LCOE by 0.3-2.6% over the course of the whole study duration depending on the turbine capacity and Site Type. The largest savings are anticipated for projects using larger turbines on Site Type D. The savings come from improvements in CAPEX and OPEX, especially post development, rather than in AEP.

Figure 4.1 shows the impact on LCOE for all the Turbine Sizes and Site Types. The aggregate impact of innovations in this element actually increases the spend on wind farm development marginally but, through this, reduces the cost of other elements of the wind farm, primarily the support structure and construction.

Figure 4.1. Anticipated impact of wind farm development innovations by Turbine Size and Site Type, compared with a wind farm with the same MW-Size Turbines over the range of FIDs stated for each Turbine Size (no Other Effects incorporated).

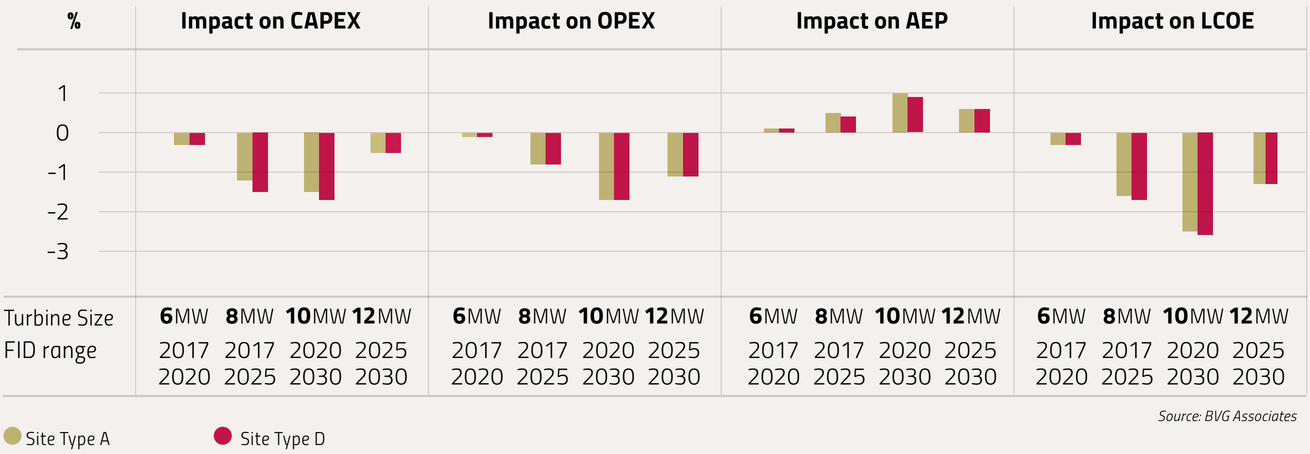


Figure 4.2 and Table 4.1 show that the individual innovation with the largest anticipated impact by FID 2030 is the optimisation of array layouts. Array layout optimisation promises significant reductions in overall cost of energy by finding balances between competing factors such as wake minimisation, electrical losses and foundation costs in array layout design. This is also the innovation in this area with the greatest potential impact.

Figure 4.2. Anticipated impact of all innovations by element for a wind farm using 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm using 6MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).

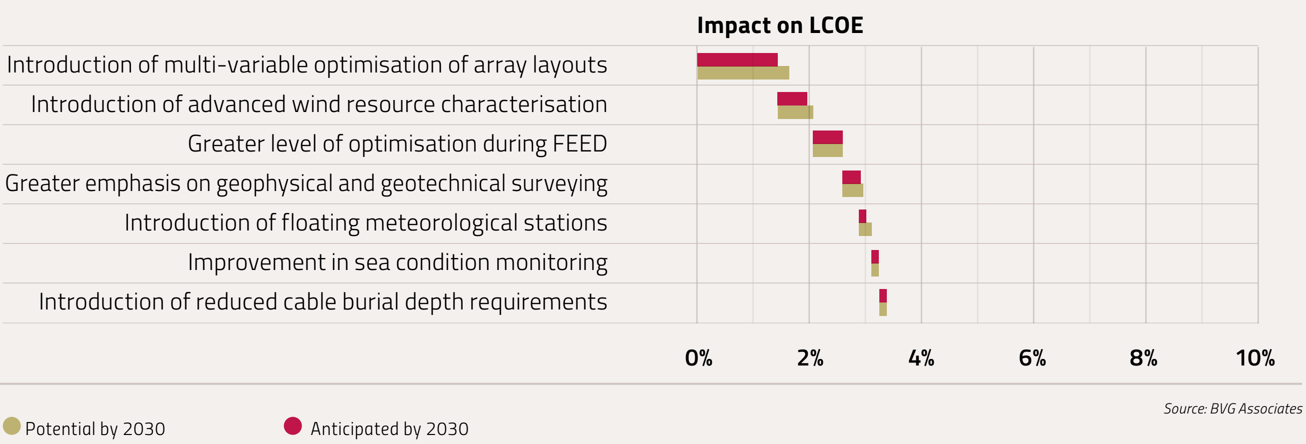


Table 4.1. Anticipated and potential impact of wind farm development innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).

Innovation	Maximum technical potential impact by FID in 2030				Anticipated impact by FID 2030			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Introduction of multi-variable optimisation of array layouts	-0.6%	-1.5%	0.7%	-1.6%	-0.5%	-1.3%	0.7%	-1.4%
Introduction of advanced wind resource characterisation	0.0%	-0.7%	0.4%	-0.6%	0.0%	-0.5%	0.3%	-0.5%
Greater level of optimisation during FEED	-0.8%	0.0%	0.0%	-0.5%	-0.8%	0.0%	0.0%	-0.5%
Greater emphasis on geophysical and geotechnical surveying	-0.5%	0.0%	0.0%	-0.3%	-0.4%	0.0%	0.0%	-0.3%
Introduction of floating meteorological stations	-0.2%	0.0%	0.0%	-0.2%	-0.2%	0.0%	0.0%	-0.1%
Improvement in sea condition monitoring	0.0%	-0.1%	0.1%	-0.1%	0.0%	0.0%	0.1%	-0.1%
Introduction of reduced cable burial depth requirements	-0.2%	0.0%	0.0%	-0.1%	-0.1%	0.0%	0.0%	-0.1%

4.2. Innovations

Innovations in wind farm development span a range of technical modelling and optimisation improvements in the design of a wind farm. A subset of the more important of these has been modelled here.

Introduction of multi-variable optimisation of array layouts

Practice today: Developers use an iterative process involving multiple engineering teams and design loops occurring through the pre-FEED and FEED periods due to the relatively benign and uniform conditions in which early wind farms were deployed, the lack of accurate cost of energy modelling data and the constraints imposed on the sites. Multidisciplinary optimisation tools for this purpose are now beginning to be used.

Innovation: The introduction of multi-variable optimisation of array layouts includes using fast and reliable optimisation software that allows for the constraints required by multiple technical disciplines. The wind farm array layout is optimised, for example, for the combination of wake effects, array electrical cost, support structure cost, consenting constraints and construction and operational costs. The overall benefit of this innovation is to reduce the LCOE through improving the choice of turbine, foundation design and location of turbines and cables while accounting for the constraints of multiple design criteria, completing iterative loops in minutes where these currently take weeks.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: 15% of the benefit of this innovation is anticipated to be available for projects with FID in 2020 rising to around 50% for projects with FID in 2025.

Market share: Market share is anticipated to be about two-thirds of projects with FID in 2020. It is anticipated that it will be used almost universally for projects with FID in 2025 and 2030.

Introduction of advanced wind resource characterisation

Practice today: Wind resource characterisation for projects being installed today is often based on data from a single met mast, correlated to one or more 'virtual' data sources.

Innovation: The quality and number of 'virtual' and remote data sources will increase, allowing for greater understanding of the variation of wind speeds across a site and increased certainty. The ability to model wake effects will also increase. This means that wind farms can be designed with more sensitivity to local wind resource and inter-turbine effects, thereby increasing the energy yield. Installation and OMS solutions can also be better optimised with improved characterisation of the conditions.

Relevance: The innovation is equally relevant to all Turbine Sizes and both Site Types.

Commercial readiness: Less than 5% of the benefit of this innovation is anticipated to be available for projects with FID in 2020. By 2025, this will rise to about one third.

Market share: In the 2020 market, less than 5% of projects will use this innovation. However, by 2025 the share will be 50%, rising to 75% by 2030.

Greater level of optimisation during FEED

Practice today: Detailed design and optimisation occur during FEED studies that are delivered via a mix of developer in-house expertise and contracted services. Currently, FEED studies enable the basic concept and component size to be chosen based on simplified design activities. Usually, this is completed for a variety of design options to compare economically viable solutions. At this stage, design options remain relatively flexible.

Innovation: Developers indicate that a greater level of optimisation during FEED could offer substantial reductions in the LCOE. This includes the undertaking of additional detailed design studies at the FEED stage. It involves the use of additional survey data, such as those gathered through a greater level of geotechnical and geophysical surveying, and increased depth of design for the foundation and installation methods for a number of turbine and foundation designs, which are usually completed later in the development process. A greater level of optimisation during FEED allows some of the detailed aspects of design to be brought forward, enhancing the accuracy of cost estimates for wind farm design solutions with variables such as water depth, soil conditions and wind speed, as well as choice of turbine. This enables improved decision making.

Relevance: The innovation is more relevant to wind farms in deeper water and further from shore where support structure and construction costs are higher.

Commercial readiness: Over half of the benefit of this innovation is anticipated to be available to projects with FID in 2020, with almost all of the remainder available for projects with FID in 2025.

Market share: Market share is anticipated to be about 70% of projects with FID, rising to almost 100% by FID 2025.

Greater emphasis on geophysical and geotechnical surveying

Practice today: Historically, sea bed (geotechnical and geophysical) surveys and data collection start many years before the planned operation of the wind farm. Often, pre-FID geotechnical and geophysical data are available only at turbine locations and with a focus on properties far below the sea bed, leading to significant uncertainties relating to cable design and installation.

Innovation: An improved knowledge of sea bed conditions and of soil conditions closer to the surface of the sea bed can lead to cost reductions in array electrical and construction CAPEX. This is because it can prevent conservative overdesign or late design changes. It can also reduce costs in construction because the soil conditions are known beforehand in places where jack-up legs will be sited and the correct cable installation tools can be chosen. Support structure CAPEX savings are also possible with an increased number of core samples taken at turbine locations resulting in reduced uncertainty about sea bed conditions. Additional data have the added benefit of reducing the uncertainties relating to installation methods and costs, thus leading to an eventual reduction in both the allocated contingency and the cost of finance. It is also relevant to work on reducing the costs of the geotechnical campaigns, defining low-cost survey strategies and lowering the cost of material and tools, provided this does not materially impact the quality of results.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: About 60% of the benefit of this innovation is anticipated to be available for projects with FID in 2020, rising to almost 100% for projects with FID in 2025.

Market share: Market share is anticipated to be about half of projects with FID in 2020. This is anticipated to rise to about two-thirds of projects with FID in 2025 and four-fifths of projects with FID in 2030.

Introduction of floating meteorological stations

Practice today: Fixed meteorological stations are erected at a proposed wind farm site prior to FID to monitor meteorological and oceanographic conditions at the site, generally with conventional anemometry and light detecting and ranging (LiDAR) units. These LiDAR units have been favourably compared, in terms of cost and accuracy, with meteorological masts when situated on fixed offshore platforms. Floating LiDAR systems have started to be deployed to verify their performance rather than to replace existing measurement methods.

Innovation: The introduction of floating LiDAR units for wind resource data collection instead of a fixed meteorological station reduces wind farm development CAPEX and can increase the period of collection before FID. The use of floating meteorological stations is not anticipated to increase the certainty of wind resource estimates for a few years but, eventually, benefits in this regard will be seen. Benefits also come from the ability to measure relatively cheaply above hub height and in multiple locations for short campaigns. Another scenario anticipated by some developers is to use floating meteorological stations in conjunction with a fixed meteorological mast to maximise confidence in the wind resource, even if this results in increased CAPEX.

Relevance: The innovation is more relevant to wind farms in deeper water and further from shore where fixed meteorological station and related installation costs are higher.

Commercial readiness: About 20% of the benefit of this innovation will be available for projects with FID in 2020, rising to about 50% for projects with FID in 2025.

Market share: Market share is anticipated to be about a third of projects with FID in 2020. This is anticipated to double to 60% for projects with FID in 2025 and increase a little more for projects with FID in 2030.

Improvement in sea condition monitoring

Practice today: Sea condition characterisation for projects being installed today is often based on data from a small collection of wave buoys alongside pre-FID hydrodynamic measurement and supported by oceanic data modelling.

Innovation: Improved knowledge of sea conditions can lead to cost reductions in support structure design, manufacture and maintenance. The quality and number of measurement devices, oceanic data sets and modelling methods will increase, allowing for greater understanding of sea conditions at the project site. This means that support structures can be designed in line with specific site conditions, thereby optimising structure selection, design and manufacture. Installation and OMS strategies can also be honed with improved characterisation of the conditions.

Relevance: The innovation is more relevant to wind farms in deeper water and further from shore where support structure and maintenance costs are higher.

Commercial readiness: About 40% of the benefit of this innovation is anticipated to be available for projects with FID in 2020 rising to about 80% for projects with FID in 2025.

Market share: Market share is anticipated to be around 5% of projects with FID in 2020, 20% for projects with FID in 2025 and 50% for projects with FID in 2030.

Introduction of reduced cable burial depth requirements

Practice today: There is concern across the industry that cable burial requirements are frequently arbitrary and do not fully reflect site conditions or the risk of cable damage. This issue has a significant effect on cable installation costs.

Innovation: The cable burial depth requirement typically exceeds 1m because standard fishing equipment and anchors would not normally make disturbances beyond this depth. With due consideration of soil conditions and the penetration risk of other sea bed uses, cable burial depth can safely be reduced. A cable buried shallower in clay, for example, can still be better protected than a cable buried deeper in sand; this is a reality often not taken into account in specifying cable burial depths to date.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: About one-third of the benefit of this innovation is anticipated to be available for projects with FID in 2020 rising to about three quarters for projects with FID in 2025.

Market share: Market share is anticipated to be about 25% of projects with FID in 2020, 50% for projects with FID in 2025 and reaching around 60% by 2030.

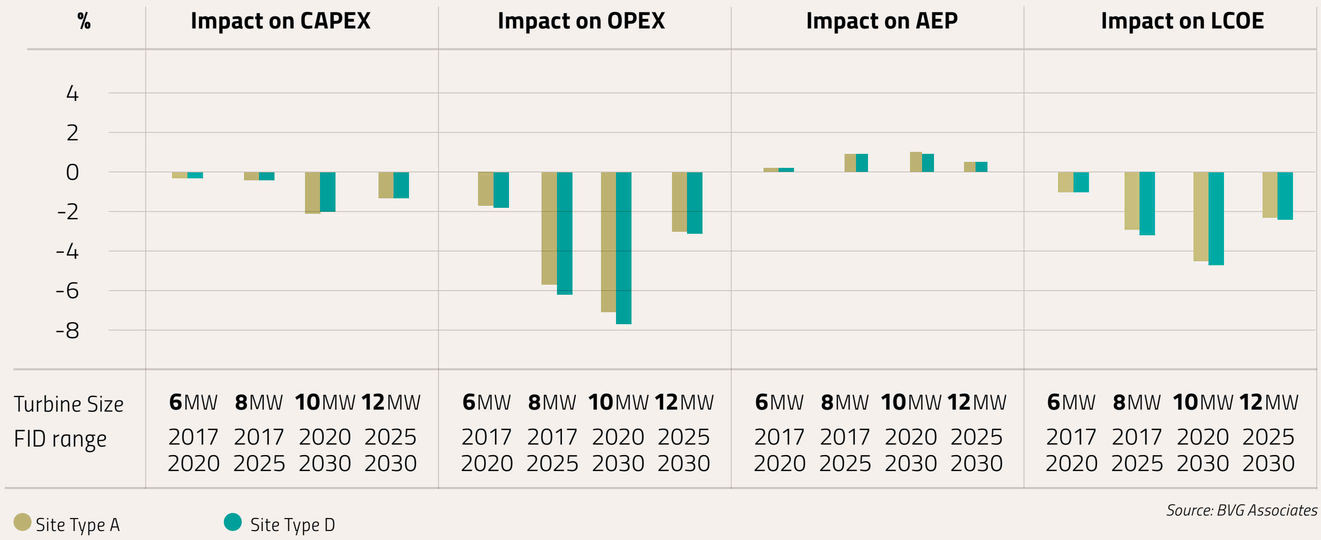
5. Innovations in the wind turbine nacelle

5.1. Overview

Innovations in the turbine nacelle are anticipated to reduce the LCOE by between 1.0% and 4.7% between FID 2017 and 2030. The savings are dominated by improvements in OPEX, rather than CAPEX or AEP.

Figure 5.1 shows that the impact on OPEX and LCOE is greatest for a wind farm using 10MW-Size Turbines on Site Type D. This is because many of the most significant innovations in this area are only anticipated to be applied to larger sizes of turbines and the impact of improved reliability on OPEX is greatest on Site Type D. The 6MW-Size Turbines primarily benefit from evolutionary changes to current practice and hence see smaller improvements. The small CAPEX impact shown here for 6MW- and 8MW-Size Turbines is due to the high proportion of direct-drive machines at those scales. On average, this increases CAPEX slightly, but with benefits elsewhere that balance this, compared to other drive train concepts.

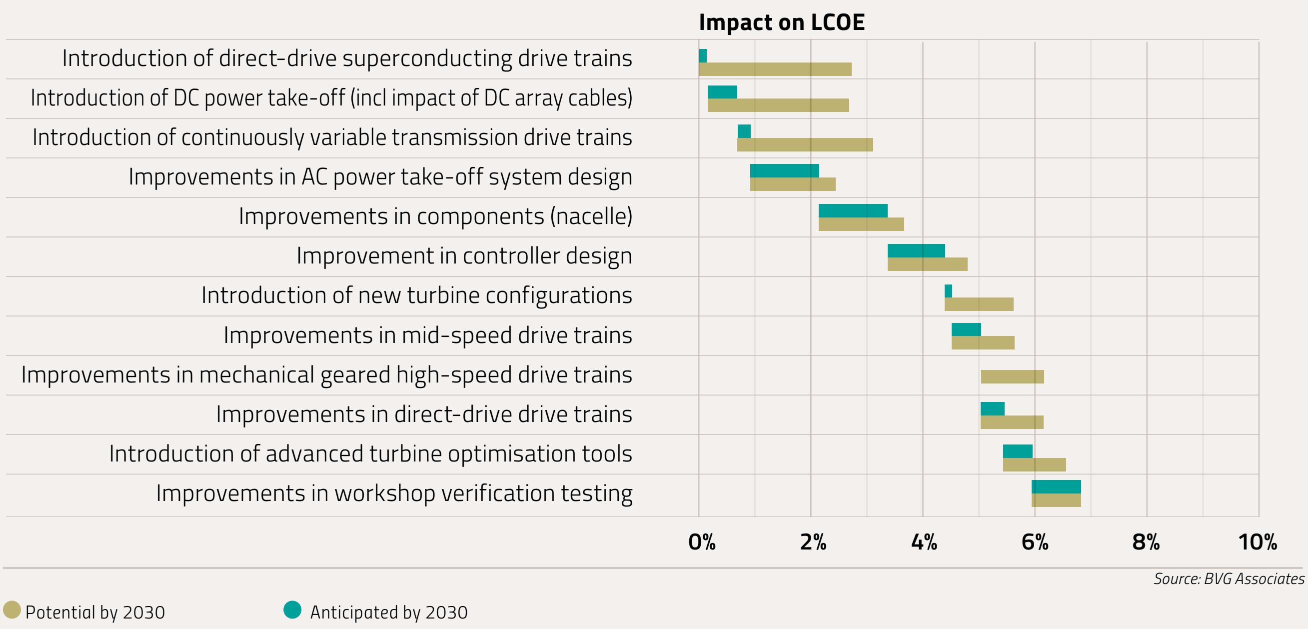
Figure 5.1. Anticipated impact of turbine nacelle innovations by Turbine Size and Site Type, compared with a wind farm with the same MW-Size Turbines over the range of FIDs stated for each Turbine Size (no Other Effects incorporated).



Source: BVG Associates

Figure 5.2 and Table 5.1 show that the innovations anticipated to have the biggest impact are improvements in AC power take-off, nacelle components and controller design. The innovation with the greatest potential impact on LCOE is the introduction of superconducting drive trains, but these are anticipated to only have 10% of the market by 2030. Many of the innovations have large potential, but low anticipated impacts. This is because they are mutually exclusive: there is only one type of drive-train per turbine.

Figure 5.2. Anticipated and potential impact of turbine nacelle innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).



Source: BVG Associates

Table 5.1. Anticipated and potential impact of turbine nacelle innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).

Innovation	Maximum technical potential impact by FID in 2030				Anticipated impact by FID 2030			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Introduction of direct-drive superconducting drive trains	-0.5%	-3.3%	1.4%	-2.7%	0.0%	-0.1%	0.1%	-0.1%
Introduction of DC power take-off (incl impact of DC array cables)	-1.2%	-2.2%	1.1%	-2.5%	-0.2%	-0.4%	0.2%	-0.5%
Introduction of continuously variable transmission drive trains	-2.0%	-4.6%	-0.4%	-2.4%	-0.2%	-0.5%	0.0%	-0.2%
Improvements in AC power take-off system design	-0.3%	-3.6%	0.2%	-1.5%	-0.3%	-2.9%	0.1%	-1.2%
Improvements in components (nacelle)	-0.5%	-3.3%	0.2%	-1.5%	-0.4%	-2.6%	0.1%	-1.2%
Improvement in controller design	-0.6%	-2.0%	0.4%	-1.4%	-0.4%	-1.4%	0.3%	-1.0%
Introduction of new turbine configurations	0.0%	0.0%	1.2%	-1.2%	0.0%	0.0%	0.1%	-0.1%
Improvements in mid-speed drive trains	-0.5%	-1.6%	0.3%	-1.1%	-0.2%	-0.7%	0.1%	-0.5%
Improvements in mechanical geared high-speed drive trains	-0.6%	-1.8%	0.1%	-1.1%	0.0%	0.0%	0.0%	0.0%
Improvements in direct-drive drive trains	0.3%	-2.2%	0.6%	-1.1%	0.1%	-0.9%	0.2%	-0.4%
Introduction of advanced turbine optimisation tools	-1.5%	0.0%	0.0%	-1.1%	-0.8%	0.0%	0.0%	-0.5%
Improvements in workshop verification testing	0.0%	-1.7%	0.1%	-0.7%	0.0%	-1.7%	0.1%	-0.7%

5.2. Innovations

Innovations in the turbine nacelle are primarily focused on the drive train and power take-off arrangements. The more important of these have been modelled.

Introduction of direct-drive superconducting drive trains

Practice today: At present, there are no commercial scale demonstration wind turbines featuring superconducting drive trains. Prototype designs have been produced for other sectors.

Innovation: This innovation involves replacing copper in the generator with superconducting wire that has zero electrical resistance when cooled below the 'critical' temperature of the material. Technical advances in recent years have increased the critical temperature to above 77K, meaning that cooling can be provided via the use of liquid nitrogen. This is anticipated to reduce generator mass by about 50% compared with a conventional system and to increase efficiency.

Relevance: The innovation is more relevant to larger turbines, but does not depend on Site Type. This innovation is not relevant to the smaller turbines due to the cost of cooling systems and the reduced benefits of lower generator mass.

Commercial readiness: High temperature superconducting (HTS) wire is currently manufactured in small quantities although second generation HTS wire producers have been scaling up production. Due to the immaturity of this innovation, it is anticipated that commercial readiness will remain low for projects with FID in 2020 but that most of the benefit will be available for projects reaching FID in 2025.

Market share: A move to superconductivity is a large technical leap which brings supply chain challenges. It is anticipated that this innovation will only begin to be implemented on a small proportion of projects by the end of the period of interest, with up to 10% of the two largest turbines sizes having direct-drive superconducting drive-trains by FID 2030.

Introduction of DC power take-off

Practice today: Current practice is to convert variable frequency alternating current (AC) to direct current (DC) then back to AC at 50Hz for collection through the site array cabling.

Innovation: In this innovation, the second half of the power converter that converts back to AC is removed. Moving to DC collection reduces the number of array cable cores from three to two and material by 20-30% which results in savings on array electrical CAPEX. Increased reliability drives a reduction of unplanned service OPEX and losses are reduced.

Relevance: The innovation is equally relevant to all Turbine Sizes. Projects on Site Type A will only realise 90% of the maximum potential benefit because these do not also use high voltage direct current (HVDC) transmission.

Commercial readiness: About one-third of the benefit of this innovation is anticipated to be available to sites reaching FID in 2020 rising to half for sites reaching FID in 2025.

Market share: DC take-off is not anticipated to have significant market impact on projects with FID in 2020, but it is anticipated to have about a 10% market share for projects with FID in 2025, rising to 20% by FID in 2030.

Introduction of continuously variable transmission drive trains

Practice today: At present, there are no commercially available wind turbines featuring continuously variable transmission drive trains. MHI Vestas owns two prototypes, the design of which was developed by MHI before the joint venture was formed .

Innovation: A hydraulic or mechanical device provides a variable ratio of input to output speed between the rotor and a synchronous generator. The need for a power converter is removed as compliance and generator speed control is provided by the variable transmission device. A reduction in gross AEP due to drive inefficiency is anticipated to be offset by a decrease in turbine CAPEX and improved reliability, resulting in a reduced unplanned OPEX and availability losses.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: Given the current state of development, it is anticipated that about a quarter of the benefit of this innovation will be technically available for projects with FID in 2020 increasing to about 60% for projects with FID in 2025.

Market share: It is anticipated that this innovation will be implemented on 10% of projects using 12MW-Size Turbines with FID in 2025, rising to 15% by 2030, with 10% of the 10MW-Size Turbines in use in 2030 having such drive-trains. It is not anticipated that this innovation will be implemented on the smaller turbines. If this innovation is prioritised by manufacturers, the innovation will be more widely adopted than stated here, but it is also possible that the market share will be 0%. This is because the way of assessing market share is probabilistic.

Improvements in AC power take-off system design

Practice today: Converters currently in use rely primarily on silicon components and have limited prognostic and diagnostic capability. Power electronics are a common cause of turbine failure although wind turbine manufacturers and tier 1 suppliers are continually improving designs.

Innovation: Improvements include the use of advanced materials such as silicon carbide or diamond to achieve greater reliability of smaller, more efficient and faster switching power conditioning units with greater health monitoring capabilities. Also included are modularisation and redundancy strategies to limit downtime and improve maintainability. This trend is anticipated to continue and to deliver reductions in turbine CAPEX, unplanned service OPEX and losses.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: Two-thirds of the benefits of this innovation are anticipated to be available to projects reaching FID in 2020 and almost all of the benefits are anticipated to be available for projects with FID in 2025.

Market share: It is anticipated that this innovation will be implemented on about half of 6MW-Size Turbines with FID in 2020, rising to 80% for 10MW-Size Turbines, This increases for FID in 2025. By FID in 2030, all the wind farms using AC power take-off will use this innovation, but as DC power take-off becomes more common, this will limit the market share of improvements in AC power take-off system design to 80% for both 10MW- and 12MW-Size Turbines.

Improvements in components (nacelle)

Practice today: Many components within the turbine nacelle use technologies developed in a range of other industries, which are in some cases adapted for use in offshore wind.

Innovation: Component-level progress in industries such as heavy automotive, marine transport, aerospace and industrial machines will continue to be applied in the offshore wind industry. Examples areas include metallurgy (science of metals), tribology (the science of moving surfaces). Such innovations are generally evolutionary (resulting in small steps of improvement and are incorporated into new components almost as a matter of course. They are not seen as a wind industry innovation. The benefits are seen in increased reliability through decreasing unplanned maintenance costs and downtime losses. It is recognised that it is hard to define and quantify the impact of innovations in this area, but for completeness, an estimate has been made.

Relevance: This type of innovation applies equally to all Turbine Sizes and Site Types.

Commercial readiness: Only around 3% of the benefit of this innovation is available to sites reaching FID in 2020. This rises to nearly 60% by FID in 2025.

Market share: The market share for 6MW-Size Turbines in 2020 is around a third, rising to over three-quarters for turbines with FID in 2030.

Improvements in controller design

Practice today: Controllers are used to operate the turbine to generate maximum power while ensuring drive-train safety and reliability. Control strategies are designed in advance based on expected operating parameters and to cater for turbine-to-turbine variation in manufacture. The control strategies are therefore conservative and drive trains are sized to withstand the worst-case extreme and fatigue loads.

Innovation: As more data is generated from operational turbines, and computing power improves, controllers may become more sophisticated, taking information about loading history, actual operating conditions and data from the turbine sensors to calculate what loading the drive-train can experience. In certain conditions, the controller may allow the drive-train to perform at higher than rated capacity, increasing energy production.

Relevance: These innovations apply equally to all Turbine Sizes and Site Types.

Commercial readiness: Around 50% of the benefit of this innovation will be available for projects with FID in 2020, rising to over 90% by 2025.

Market share: It is anticipated that for FID in 2030 around 70% of the market will use this innovation, up from under half of the market in 2020.

Introduction of new turbine configurations

Practice today: Current commercially produced offshore wind turbines are three-bladed, horizontal-axis, pitch-regulated and upwind, mounted on a tubular tower and with yaw system designed to keep the turbine facing the wind during operation.

Innovation: Some of the limitations for design of onshore wind turbines do not apply offshore; and offshore, the costs (and hence the design drivers) are different. Thus, a wider range of turbine configurations is available. Longer-term, there are possibilities to implement 2-bladed, down-wind, multi-rotor turbine or vertical-axis solutions. Examples of innovation in this area include those from 2B-Energy (2-bladed, downwind, lattice tower), Hitachi (downwind), Nenuphar (vertical axis), Seawind Ocean Technology (2-bladed, active yaw-control to regulate power by yawing out of the wind), Vestas (multi-rotor). Such innovations generally aim to improve AEP without significantly increasing CAPEX and OPEX, though some tend to impact LCOE through reductions in costs.

Relevance: These innovations apply equally to all Turbine Sizes and Site Types.

Commercial readiness: The benefits only begin to be available for FID in 2025, with around 40% of the benefit available by this point.

Market share: It is anticipated that around 10% of the market will use this innovation for FID in 2030, with none of the market using the innovation before this.

Improvements in mid-speed drive trains

Practice today: 8MW-Size Turbines from Adwen and MHI Vestas feature a 'first generation' mid-speed drive train with a relatively close-coupled generator.

Innovation: Removal of the high-speed stage in the gearbox reduces the gearbox size and mechanical losses. These benefits are somewhat offset by the increased size and inefficiencies associated with the move to a multipole generator. The generator and gearbox become more similar in size and may be close-coupled with a potential improvement in reliability, although some argue that part of this increase will be offset by the reliability of the more complex multipole generator. Increases in reliability offer an improvement to OPEX and AEP.

Relevance: The innovation is equally relevant to all Turbine Sizes and both Site Types.

Commercial readiness: As first generation designs are already in production, it is anticipated that half of the benefit will be technically available for projects with FID in 2020 and over 80% for projects with FID in 2025.

Market share: It is anticipated that around half of projects using 10MW-Size Turbines and a small proportion of projects using 8MW-Size Turbines that reach FID in 2020 will use this innovation and that this will remain the case for projects with FID in 2025. By FID 2030, the market share will be just under half for 10MW-Size Turbines and a third for 12MW-Size Turbines.

Improvements in mechanical geared high-speed drive trains

Practice today: Generally, the wind turbine manufacturer specifies gearbox loading to the supplier after limited whole drive train modelling. The gearbox, when designed, is tested under torque loads only by the supplier, rather than on a whole nacelle test rig under dynamic loads.

Innovation: Improvements through more holistic drive train design and developments in bearing design, manufacture and lubrication have the potential to decrease operational costs by reducing unplanned service events. Similarly, ongoing improvements in the design of gearboxes to further optimise gear mesh loadings, accommodate higher rated but slower rotating machines, and reduce relative gearbox mass will enable a reduction in CAPEX and a decrease in unplanned service OPEX. Innovation in this field has been continuous since the start of the wind turbine industry and impact is anticipated to continue at a gradually decreasing pace, partly dependent on the number of suppliers that stay with the technology for both offshore and onshore applications.

Relevance: The innovation is equally relevant to all Turbine Sizes and both Site Types.

Commercial readiness: Around one-third of the benefit of this innovation will be available for projects with FID in 2020, rising to half by 2025.

Market share: Market share is anticipated to be 50% for projects with 6MW-Size Turbines with FID in 2020. For 8MW-Size Turbines, this drops to 30%. By 2025, the market share is less than 10% and by 2030, the market share is almost negligible as other drive types come into the market.

Improvements in direct-drive drive trains

Practice today: GE and Siemens have adopted direct-drive drive trains for offshore turbines. Full-scale test machines are currently operational at a number of European sites with full-scale commercial deployment commencing. This drive train design has also been applied to 4MW-Size Turbines in commercial onshore wind farms.

Innovation: Removal of the gearbox results in a simpler drive train with fewer mechanical parts and an anticipated increase in reliability, although some argue that part of this increase will be offset by the reliability of the more complex multipole generator. It is anticipated that a slight increase in CAPEX will be more than offset by the anticipated reduction in unplanned service OPEX and losses.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: As first generation designs are already in production, it is anticipated that over half of the benefit will be technically available for projects with FID in 2020 and over 80% of the benefit will be available for projects with FID in 2025.

Market share: It is anticipated that less than 5% of wind farms using 6MW-Size Turbines and reaching FID in 2020 will use this solution. For 8MW-Size Turbines, the market size is anticipated to be around 50% for 10MW-Size Turbines by FID 2025 due to competition from other options. By FID 2030, it is anticipated that around 40% of the wind farms with both 10MW- and 12MW-Size Turbines will use this solution.

Introduction of advanced turbine optimisation

Practice today: Current turbines have been designed with good optimisation of each component, but a varying amount of optimisation between different components and little optimisation of the turbine system as a whole. Much of the component optimisation is based on experience at smaller-scale.

Innovation: As the industry improves its dynamic aeroelastic and hydrodynamic modelling tools and improves the correlation between predicted and measured behaviour, there is an increasing opportunity to optimise the whole system through changes in the sub-systems. This requires further use of analytical software and optimisation tools that are being used also in other sectors. In addition, as larger components are required, there is more opportunity (and motivation) for re-thinking the design of some components, enabling optimisation to different local maxima.

Relevance: The innovation applies equally to all Turbine Sizes and Site Types.

Commercial readiness: The benefit of this innovation only begins to be available by FID in 2025, with nearly two-thirds of the benefit available by this point.

Market share: It is anticipated that for FID in 2030 around half of the market will use this innovation, with usage dominated by new turbine platforms that have the opportunity to use such optimisation tools.

Improvements in workshop verification testing

Practice today: Workshop verification testing, which is the verification and approval of turbines or turbine components in laboratory conditions rather than in field trials, has occurred for turbines used on projects reaching FID today, but it is not standardised and has been limited in scope and in the ability to simulate accurate loading regimes. Newer, larger and more dynamic rigs are being commissioned but standards are still absent.

Innovation: The development of standardised functional and highly accelerated life tests (HALTs) for components and systems up to complete drive trains is widely viewed by industry as a route to deliver increased reliability, especially when combined with monitoring turbines under deployment.

Relevance: The innovation is equally relevant to all Turbine Sizes. Sites close to shore and in shallow water will benefit less than harsher sites due to the increased OPEX for harsher sites.

Commercial readiness: 40% of the benefit of this innovation is anticipated to be available for projects with FID in 2020, with almost all available for projects with FID in 2025.

Market share: Because the types of drive used for the larger turbines will be developed later, it is anticipated that this innovation will have a larger share for larger turbines for which manufacturers will have seen greater benefits from workshop testing. For a 6MW-Size Turbine with FID in 2017, the share is around a third, rising to over two-thirds for a 10MW-Size Turbine. This market share increases somewhat for FID in 2025. By FID in 2030, the innovation is used for almost all Turbine Sizes.

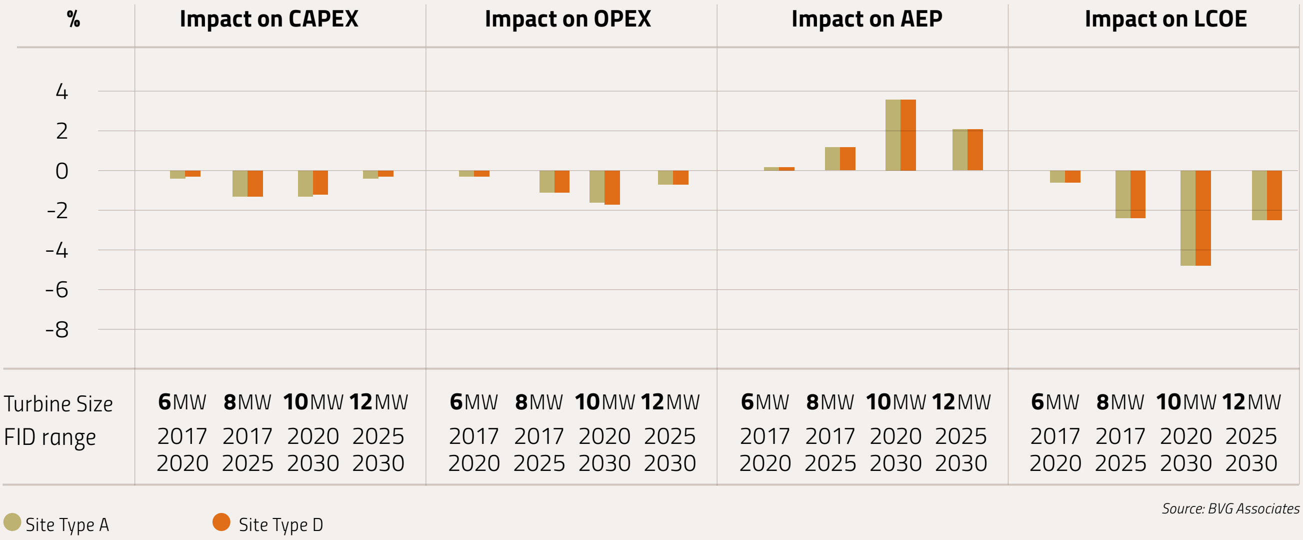
6. Innovations in the wind turbine rotor

6.1. Overview

Innovations in the turbine rotor are anticipated to reduce the LCOE by between 0.6% and 4.8% between FID 2017 and 2030. The savings are driven by improvements in CAPEX and AEP with limited changes to OPEX.

Figure 6.1 shows that the impacts on CAPEX, OPEX are broadly consistent between Site Types but are different with respect to Turbine Size. As Turbine Size increases, there are many innovations aimed at increasing AEP. Some of these innovations require increases in CAPEX or OPEX in order to increase AEP. Overall the impact on LCOE is larger for larger turbines due to the AEP gains.

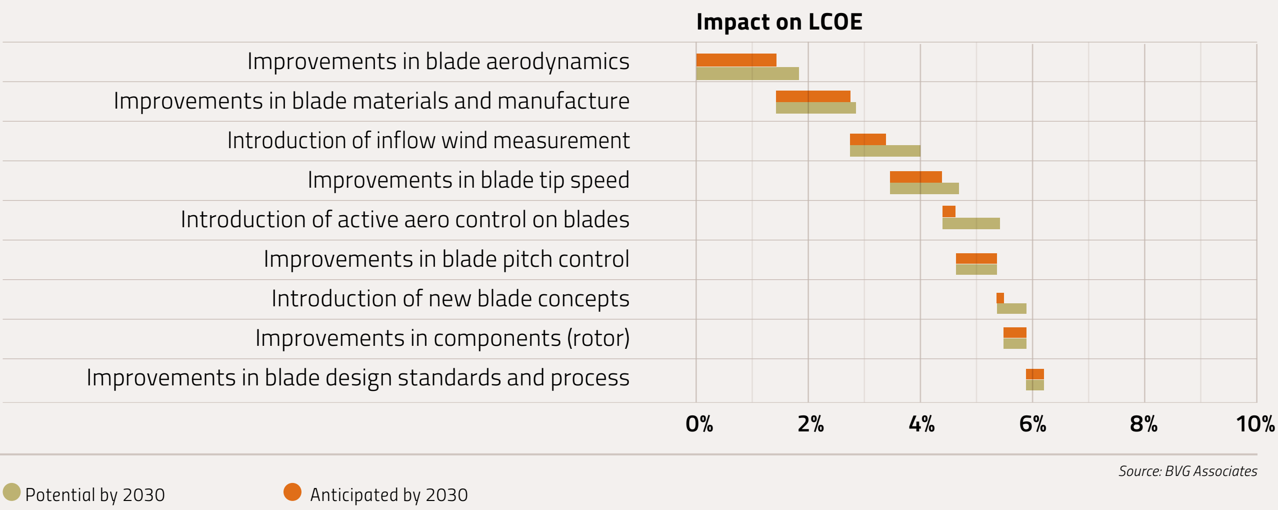
Figure 6.1. Anticipated impact of turbine rotor innovations by Turbine Size and Site Type, compared with a wind farm with the same MW-Size Turbines over the range of FIDs stated for each Turbine Size (no Other Effects incorporated).



Source: BVG Associates

Figure 6.2 and Table 6.1 show that the individual innovations anticipated to deliver the greatest savings in this area are improvements in blade aerodynamics and improvement of blade materials and manufacture.

Figure 6.2. Anticipated and potential impact of turbine rotor innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).



Source: BVG Associates

Table 6.1. Anticipated and potential impact of turbine rotor innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).

Innovation	Maximum technical potential impact by FID in 2030				Anticipated impact by FID 2030			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Improvements in blade aerodynamics	-0.4%	0.2%	1.6%	-1.8%	-0.3%	0.2%	1.2%	-1.4%
Improvements in blade materials and manufacture	-1.6%	-0.9%	0.1%	-1.4%	-1.4%	-0.8%	0.1%	-1.3%
Introduction of inflow wind measurement	0.4%	0.5%	1.8%	-1.4%	0.2%	0.3%	0.9%	-0.7%
Improvements in blade tip speed	0.1%	-1.8%	0.7%	-1.2%	0.1%	-1.4%	0.5%	-0.9%
Introduction of active aero control on blades	0.9%	1.5%	2.2%	-1.0%	0.1%	0.2%	0.3%	-0.2%
Improvements in blade pitch control	-0.3%	0.1%	0.5%	-0.7%	-0.3%	0.1%	0.5%	-0.7%
Introduction of new blade concepts	1.3%	0.1%	1.5%	-0.5%	0.3%	0.0%	0.3%	-0.1%
Improvements in components (rotor)	-0.3%	-0.8%	0.1%	-0.5%	-0.3%	-0.8%	0.1%	-0.5%
Improvements in blade design standards and process	-0.2%	-0.1%	0.2%	-0.4%	-0.2%	-0.1%	0.2%	-0.4%

6.2. Innovations

Innovations in turbine rotors encompass a range of improvements around the design and manufacture of blades and the algorithms and systems which control the blades in operation. The more important of these have been modelled here.

Improvements in blade aerodynamics

Practice today: Blade manufacturers use cutting edge computational fluid dynamics (CFD) modelling and wind tunnel testing to improve design. Passive aerodynamic elements (for example, trailing edge flow modifiers) are being developed and optimised.

Innovation: This innovation includes a range of possibilities from evolutionary developments and fine-tuning of existing designs through to more radical changes such as new aerofoil concepts and the passive aerodynamic enhancements, such as those now being offered by Siemens. Overall, an increase in gross AEP is modelled alongside a small increase in turbine CAPEX, reflecting additional costs in the manufacture of the rotor and additional OPEX to care for passive blade modifications. Reduced support structure costs will result from lower thrust fatigue loading.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: This innovation will have around 20% of the benefits available for projects reaching FID in 2020 rising to around 70% by FID in 2025. There has already been a strong history of innovation in blade aerodynamics and it is anticipated that the pace of progress will gradually slow.

Market share: Market share is anticipated to be greater for larger turbines. Less than 20% of projects using 6MW-Size Turbines reaching FID in 2020 will use this innovation. By FID in 2025, around a third of 8MW-Size Turbines will feature this, rising to slightly below two-thirds of 10MW-Size Turbines and slightly above two-thirds of 12MW-Size Turbines. By FID in 2030, around 80% of the market will use this innovation.

Improvements in blade materials and manufacture

Practice today: Most offshore wind turbine blades use glass fibre as the main structural material, along with epoxy-based resins and adhesives. Carbon fibre is used by some to decrease mass and increase stiffness, but at extra material cost. Manufacture of blades generally involves a significant element of resin-infusion moulding, with structural elements either built into the shell of the blade or into a spar, bonded to the aerodynamic shells.

Innovation: Many novel materials and manufacturing processes are in development to produce stiffer, lighter, lower cost and higher quality blades with improved radar, lightning, environmental resistance and aerodynamic performance. In some cases, aerospace innovations are now starting to be incorporated. There is greater potential for the use of such aerospace techniques. This innovation includes those processes that enable lighter and longer blades to be manufactured.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: Some aspects of this innovation may be available relatively quickly; others are at an early stage and may require more development and commercialisation. Overall, around one-third of the benefits are anticipated to be available for projects reaching FID in 2020 with 80% by FID in 2025.

Market share: The market share is anticipated to be larger for projects using larger turbines. For 6MW-Size Turbines with FID in 2020, it is anticipated to be around a third, rising to a half for 8MW-Size Turbines. For FID in 2025, the market share for 8MW-Size Turbines is expected to be around two-thirds. This rises to around 90% for 12MW-Size Turbines. By FID in 2030, over 90% of turbines use this innovation.

Introduction of inflow wind measurement

Practice today: Current turbine designs use anemometry mounted at the rear of the nacelle to infer inflow wind conditions. Forward-looking wind measurement devices, typically LiDAR, are now being trialled as a potential alternative with additional benefits.

Innovation: Forward-looking LiDAR has the ability to characterise the inflow wind field more completely and earlier than an anemometer downwind of the rotor. The best way to take advantage of the resulting reduced fatigue loading is to increase the diameter of the rotor, thereby increasing AEP with only marginal changes in load and OPEX. It is critical to develop LiDAR units suited to this application, with high reliability and robustness to different environmental conditions. Simultaneously, costs must be reduced significantly compared with the units currently used for resource assessment where accurate measurement of absolute wind speed is more important. The anticipated increase in gross AEP comes at the cost of an increase in turbine CAPEX to account for equipment and integration costs and an increase in unplanned OPEX.

Relevance: The innovation is equally relevant to all Site Types, but is less relevant for smaller Turbine Sizes, with 6MW-Size Turbines having around 70% of the benefits available as for 10MW-Size Turbines.

Commercial readiness: The relatively high upfront cost of LiDAR in comparison to an anemometer and the complexity of the necessary integrated control system mean that only around 10% of the technical potential of this innovation is anticipated to be available for projects reaching FID in 2020, but this is anticipated to double for projects with FID in 2025.

Market share: This innovation is not anticipated to be deployed in large quantities on smaller turbines or in large scales until reaching the 10MW- and 12MW-Size Turbines for FID in 2025, where about a third of the market will use this innovation. By FID in 2030 market share is anticipated to reach about half.

Improvements in blade tip speed

Practice today: The highest tip speeds are 90m/s, limited by fatigue loading, blade erosion and uncertainty about slender blade aerodynamic performance. Typically, blade leading edge erosion is mitigated by the use of tape, which is applied after manufacture of the blade and then repaired at least twice during the life of the blade.

Innovation: Increasing tip speed has the potential to increase AEP and reduce turbine CAPEX, although some of this benefit is anticipated to be offset by increases in the support structure CAPEX. Increased aerodynamic noise is less of an issue offshore than onshore, but erosion remains critical and work is underway to develop and test long-term robust solutions with less aerodynamic impact which, in some cases, are built into the blade during manufacture. Increases in tip speed can be linked to decreases in solidity (blade planform area) and changes in aerofoil shape to reduce fatigue loads.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: Around 10% of the benefit will be available to projects with FID in 2020 and over half by FID in 2025.

Market share: Market share is anticipated to be below 20% for projects using 6MW-Size Turbines reaching FID in 2020, with 8MW-Size Turbines higher. This market share rises to over 50% for projects using 10MW-Size Turbines for FID in 2025, with around 80% of the market using this innovation by FID in 2030.

Introduction of active aero control on blades

Practice today: Active control surfaces are commonly used in the aerospace industry. At present this approach is not yet used in the wind industry, although there has been an upturn in the use of passive aerodynamic enhancement devices.

Innovation: This innovation encompasses many potential advances, including micro-actuated surfaces, air-jet boundary layer control, active flaps, trailing edge modifiers and plasma aerodynamic control effectors. The industry expects some to be commercialised but it is unclear which ones. Robustness and reliability of any solution in the tough environmental conditions experienced by the outer sections of blades is critical. Uplift in gross AEP is anticipated, combined with an increase in turbine CAPEX and unplanned service cost to account for increased failure rates of these advanced control solutions. This reduced reliability is also reflected in a modelled increase in losses. This innovation does not include wind farm wide control strategies. These are included as an OMS innovation in Section 9.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: The limited interest currently shown by mainstream manufacturers and the relatively early stage in development mean that only around a 10% of the technical potential of this innovation will be available for projects with FID in 2020. This will reach around two-thirds by FID in 2025.

Market share: Uptake of this technology is anticipated to be slow. Market share is anticipated to be very low for projects with FID in 2020 and to rise to around 15% for FID in 2025 for 12MW-Size Turbines. By FID in 2030, only around 20% of the market is anticipated to use this innovation.

Improvements in blade pitch control

Practice today: Most commercial turbines use collective pitch control to control the rotor speed and loads, with drive train torque controlled by the converter, although some use individual pitch control to address aerodynamic imbalances between blades. Manufacturers are beginning to develop more advanced algorithms to balance wake and turbulence loads on turbines to improve energy production.

Innovation: Continuing improvements in both collective and individual pitch control, in both routine and turbulent or wake affected operating conditions, have the potential to reduce lifetime turbine loads on some components by up to 30% as well as increasing energy production. Savings in support structure and turbine CAPEX are anticipated but are offset to some extent by increased duty cycles on the pitch system, which leads to an increase in turbine CAPEX and unplanned OPEX. Gross AEP is anticipated to increase due to improved aerodynamic performance. This innovation does not include wind farm wide control strategies. These are included as an OMS innovation in Section 9.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: Work is ongoing in this area, although some improvements are at a relatively early stage. Overall, one-third of the benefits are anticipated to be available for projects with FID in 2020 with 75% available for projects with FID in 2025.

Market share: For projects using 6MW-Size Turbines with FID in 2020 market share is anticipated to be over two-thirds. This rises with Turbine Size and FID. For 12MW-Size Turbines and for FID in 2030, this innovation will be universally adopted.

Introduction of new blade concepts

Practice today: Blades used in offshore wind today use either a central structural spar with aerodynamic shells or aerodynamic shells with structural spar caps and webs to connect the shells. Aerodynamic shells are moulded in one or two pieces and the whole blade is manufactured at a coastal site.

Innovation: This innovation includes modular blades assembled from pre-manufactured components, including aerodynamic surfaces moulded in multiple pieces, or provided by textiles. The benefits include the ability to better control the quality of components, reduced manufacturing facility costs and increased design and supply flexibility. Together these offer reductions in CAPEX and increases in AEP.

Relevance: The innovation is more relevant to larger Turbine Sizes, with Site Type not having an effect.

Commercial readiness: Over half of the anticipated benefit is available for projects with FID in 2025 (with no benefit available for projects with FID in 2020).

Market share: Around 10% of the 10MW- and 12MW-Size Turbines with FID in 2025 will use new blade concepts. This rises to 20% by FID in 2030.

Improvements in components (rotor)

Practice today: Pitch systems and blade bearings are significant sources of downtime. Innovations that increase the load cycles on pitch systems risk compounding this problem. Designs have only evolved slowly over the last 10 years and hub castings have continued to be scaled upwards for larger turbines, which can create problems in manufacture.

Innovation: This innovation includes improved bearing concepts and lubrication, improved hydraulic and electric systems, improved backup energy sources for emergency response and grid fault ride-through. It also includes improved hub design through better design methods and improved material properties that are necessary for larger castings. Better design is anticipated to reduce turbine CAPEX and improve reliability, reducing unplanned OPEX and increasing availability.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: One-third of the technical potential of these innovations will be available for projects with FID in 2020, with 75% available by FID in 2025.

Market share: This innovation is anticipated to have around three-quarters of the market for projects using 6MW-Size Turbines reaching FID in 2020, with a little more for 8MW-Size Turbines. There is then no change for 8MW-Size Turbines with FID in 2025. For projects using 10MW-Size Turbines, the market share is anticipated to be higher, at around 90%, rising gradually to become almost universal. For 12MW-Size Turbines, almost all projects will use improved hub assembly components.

Improvements in blade design standards and process

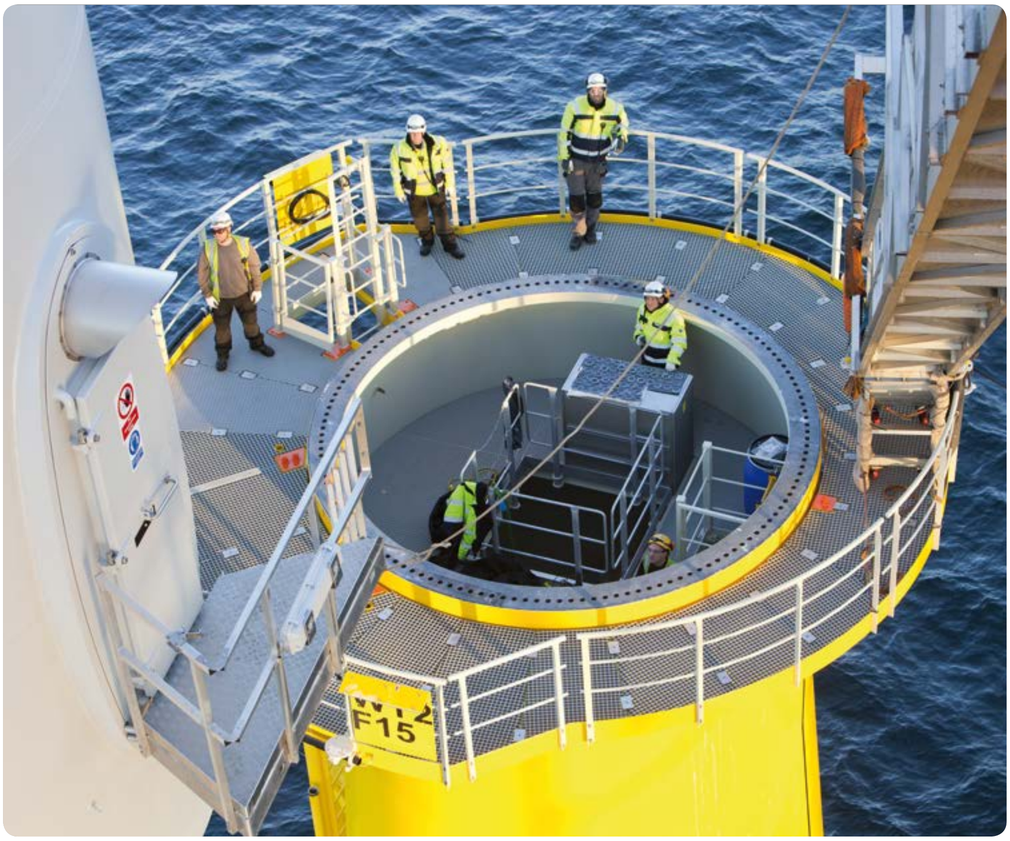
Practice today: Blades and blade components are tested before use. The quality of this testing has increased in recent years, but design is still suboptimal. Holistic multi-objective design processes balance the aerodynamic and structural requirements of blades and CFD is used to explore specific effects.

Innovation: Further progress via the use of more advanced tools and modelling techniques will continue to improve aerodynamic performance, decrease CAPEX (of the blades and also the rest of the turbine) or decrease OPEX (due to increased reliability). Progress in this area is anticipated to have a small impact on turbine CAPEX, a saving on OPEX associated with unplanned service and an associated reduction in losses due to blade related issues. A small increase is also anticipated in gross AEP.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: Given the good progress already made by the industry, it is anticipated that around 75% of the benefits of this innovation will be available for projects with FID in 2020, with almost 100% by FID in 2025.

Market share: The market share is anticipated to be larger for projects using larger turbines. For 6MW-Size Turbines with FID in 2020 the market share is anticipated to be around a third, rising to a half for 8MW-Size Turbines. For FID in 2025, the market share for 8MW-Size Turbines is anticipated to be around two-thirds. This rises to being almost universal for 10MW- and 12MW-Size Turbines for 2025 FID. By FID in 2030, almost all turbines use this innovation.



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7. Innovations in balance of plant

7.1. Overview

Innovations in balance of plant are anticipated to reduce LCOE by up to 2.2% between FID 2017 and 2030. The savings are dominated by improvements in CAPEX with only minor changes anticipated in OPEX and AEP.

Figure 7.1 shows that the impact on CAPEX is greater for wind farms on Site Type D, where jacket foundations are anticipated to be used. The impact is likely to be greater for smaller turbines, where balance of plant makes up a larger section of the baseline.

Figure 7.1. Anticipated impact of balance of plant innovations by Turbine Size and Site Type, compared with a wind farm with the same MW-Size Turbines over the range of FIDs stated for each Turbine Size (no Other Effects incorporated).

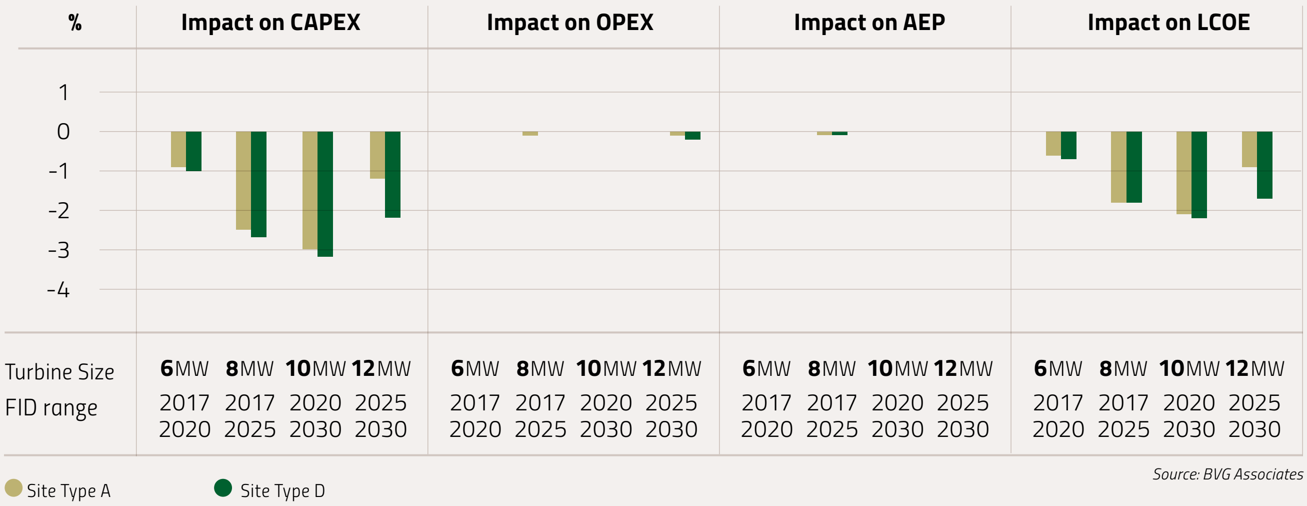
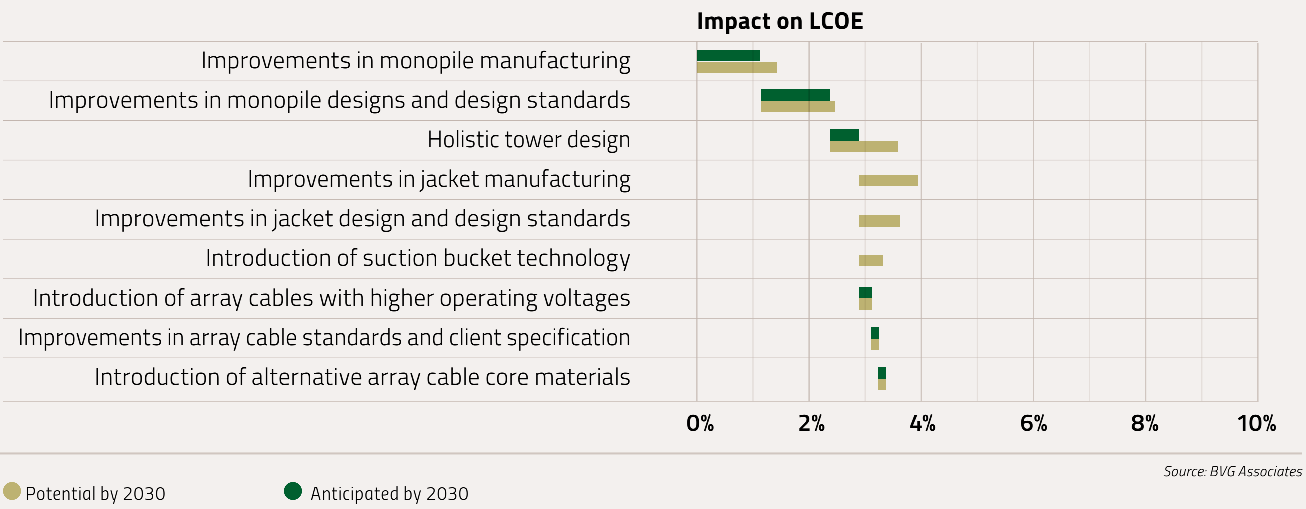


Figure 7.2 and Table 7.1 show that the individual innovation with the largest anticipated impact by FID in 2030 is improvements in monopile manufacturing, followed by improvements in monopile design. The innovation with the largest potential impact however, is improvements in jacket manufacturing. No anticipated impact is shown in the figure due to it being anticipated that monopiles can be used on projects with 10MW-Size Turbines but not on projects with 12MW turbines on Site Type D. Innovations relating to array cables have a lower potential impact on LCOE compared with foundations and towers, but more progress is anticipated in realising this potential in time for projects with FID in 2030.

Figure 7.2. Anticipated and potential impact of balance of plant innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated). There is no anticipated impact in jacket design as it is anticipated that jackets will not be used on projects with 10MW-Size Turbines on Site Type D.



Source: BVG Associates

Table 7.1 Anticipated and potential impact of balance of plant innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).

Innovation	Maximum technical potential impact by FID in 2030				Anticipated impact by FID 2030			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Improvements in monopile manufacturing	-2.0%	0.0%	0.0%	-1.4%	-1.6%	0.0%	0.0%	-1.1%
Improvements in monopile designs and design standards	-1.8%	-0.2%	0.0%	-1.3%	-1.6%	-0.2%	0.0%	-1.2%
Holistic tower design	-1.6%	-0.2%	0.0%	-1.2%	-0.6%	-0.1%	0.0%	-0.5%
Improvements in jacket manufacturing	-1.4%	-0.3%	0.0%	-1.1%	0.0%	0.0%	0.0%	0.0%
Improvements in jacket design and design standards	-1.1%	0.0%	0.0%	-0.7%	0.0%	0.0%	0.0%	0.0%
Introduction of suction bucket technology	-0.6%	0.0%	0.0%	-0.4%	0.0%	0.0%	0.0%	0.0%
Introduction of array cables with higher operating voltages	-0.2%	0.0%	0.1%	-0.2%	-0.2%	0.0%	0.1%	-0.2%
Improvements in array cable standards and client specification	-0.2%	0.0%	0.0%	-0.1%	-0.2%	0.0%	0.0%	-0.1%
Introduction of alternative array cable core materials	-0.3%	0.2%	0.0%	-0.1%	-0.3%	0.2%	0.0%	-0.1%

7.2. Innovations

Innovations in balance of plant are mostly centred on the foundation and relate to improvements in the manufacture and design of this main structure. The most important of these have been modelled here. Offshore and onshore substations and export cables have been modelled separately in this study (see Section 2.4). Solutions involving permanently floating foundations in deeper water are not modelled as it is unlikely that there will be benefits in 35m water depth, as for projects on Site Type D.

Improvements in monopile manufacturing

Practice today: Monopiles are manufactured in large sections in facilities previously used for smaller batch-production.

Innovation: Monopiles will continue to be manufactured in larger sizes and in increasing numbers. This will require dedicated manufacturing facilities and equipment that can handle thicker steels and larger equipment. The process will also change from batch to more rapid, serial manufacture, even for large structures. Quality will need to remain high so automation of quality control procedures will be necessary to keep pace with streamlined manufacture.

Relevance: The innovation is relevant to all projects except those using 12MW-Size Turbines on Site Type D, where jackets are anticipated to be used.

Commercial readiness: 65% of the benefit of innovation in this area is anticipated to be available for projects with FID in 2020, increasing to 85% for projects with FID in 2025.

Market share: It is anticipated that, where relevant, more than 40% of the projects with FID in 2020 will use these innovations and that this will increase to about 60% for projects with FID in 2025 and 80% for FID in 2030. Due to the mix of support structure types in the market the increase will not rise beyond this value.

Improvements in monopile design and design standards

Practice today: Monopile design is largely optimised but a refinement of design standards and further improvements (including to the transmission piece and connection with the monopile) are still possible. The design standards use an empirical approach to soil interaction based on data from the oil and gas sector, which is considered to be out of date and unrepresentative of the larger piles used in the offshore wind industry today. Fatigue properties and safety factors are also not ideally suited to the application.

Innovation: Improvements in the design of the transmission piece, the suitability of design standards to soil interaction for offshore wind monopiles and in the design of J-tubes offer savings in both support structure and construction CAPEX.

Relevance: The innovation is relevant to all projects except those using 12MW-Size Turbines on Site Type D, where jackets are anticipated to be used.

Commercial readiness: Around 40% of the benefit of innovation in this area is anticipated to be available for projects with FID in 2020, increasing to 60% for projects with FID in 2025.

Market share: It is anticipated that, where relevant, more than 50% of the projects with FID in 2020 will use these innovations and that this will increase to about 80% for projects with FID in 2025 and

90% for FID in 2030. Due to the mix of support structure types in the market the increase will not rise beyond this value.

Holistic tower design

Practice today: The tower is generally a standard design for a given turbine and the design and supply responsibility has always been within the scope of the wind turbine manufacturer. Conversely, the foundation is project- and generally location-specific. Towers consist of two or three flanged sections that are pre-assembled at a local construction port before installation.

Innovation: By considering the stiffness performance requirement of the combined tower and foundation, a slight increase in the mass of the tower would enable a more substantial decrease in the mass of the foundation. This innovation includes more sophisticated tower dampers. It also includes production of single section towers which require fewer flanges and allow a more streamlined manufacturing approach. Such changes reduce both support structure and construction CAPEX. Single section towers would also reduce inspection requirements for bolted flange joints and hence OPEX.

Relevance: The innovation is relevant to all Turbine Size and Site Types but the impact is reduced by a half on wind farms using 12MW-Size Turbines on Site Type D as this combination will use jackets, where the challenges relating to natural frequency are less significant.

Commercial readiness: It is anticipated that 10% of the benefit of this innovation will be available for projects with FID in 2020 and around three-quarters will be available for projects with FID in 2025.

Market share: Market share is anticipated to be around 10% for projects with FID in 2020 increasing to 30% for projects with FID in 2025 and 40% for projects with FID in 2030.

Improvements in jacket manufacturing

Practice today: Jacket production is based on the manufacturing practices of the oil and gas sector, with tubulars added to a static structure with manually welded joints. Corrosion protection is applied to the completed structure in a large paint shop.

Innovation: New fabrication facilities will be developed that are optimised for the serial fabrication of jacket foundations with more advanced handling and welding equipment and pre-fabricated nodes reducing support structure CAPEX and OPEX by increasing reliability. Increasingly, activity may also take place away from the main fabrication facility with the modular assembly of sections by sub-suppliers and the pre-painting of tubulars.

Relevance: The innovation is only relevant to projects using jacket support structures, hence 12MW-Size Turbines on Site Type D.

Commercial readiness: More than a quarter of the benefit of these innovations is anticipated to be available for projects with FID in 2020 rising to around three quarters for projects with FID in 2025.

Market share: Where relevant, around 90% of the projects with 12MW-Size Turbines are anticipated to use these innovations.

Improvements in jacket design and design standards

Practice today: Jacket design is optimised for oil and gas structures but not for serial production for offshore wind. Current design standards for structure-soil interaction and material fatigue are also considered to be excessively conservative because they are based on dated oil and gas standards for manned structures.

Innovation: The development of semi-standardised jacket designs capable of accommodating some variation in water depth will facilitate higher levels of automated fabrication, reducing labour, production time and installation time. As with monopiles, savings on secondary steel design and J-tube placement will also be applicable. Although jackets are less sensitive to fatigue loads than monopiles, it is anticipated that the development of offshore wind-specific design standards will allow a saving on material costs.

Relevance: These innovations are relevant to projects using jacket support structures, hence projects using 12MW-Size Turbines on Site Type D.

Commercial readiness: More than 40% of the benefit is anticipated to be available for projects with FID in 2020 rising further to over half for projects with FID in 2025.

Market share: Where relevant, around 90% of the projects with 12MW-Size Turbines are anticipated to use these innovations.

Introduction of suction bucket technology

Practice today: Suction bucket technology has been demonstrated on smaller turbines. It has not yet been used with "next generation" turbines in a commercial or full-scale test environment.

Innovation: The pile-driven foundation is replaced by a suction bucket which is drawn into the sea bed by a combination of its own weight and applied hydrostatic pressure. The structure can be vertically aligned during installation. The installation process is quieter than piling and thus noise abatement costs are lowered. A small rise in development costs is anticipated due to the need for increased geotechnical surveying. It can be used with both monopile and jacket-type structures.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types, though not all ground conditions are suitable for sites types not considered in this analysis.

Commercial readiness: Almost one-third of the benefit of this innovation is anticipated to be available for projects with FID in 2020, rising to three-quarters for projects with FID in 2025.

Market share: Less than 5% of projects with FID in 2020 are anticipated to use this innovation but this is anticipated to increase to almost 10% of projects with FID in 2030.

Introduction of array cables with higher operating voltages

Practice today: Today, 33kV three-core subsea AC cable is the universal solution for array cabling but this means that the number of turbines that can be connected to a single cable run is limited by the rated capacity of the cable, which is supplied in a number of steps of core size. This limits the number of turbines on a run to five or six depending on Turbine Size.

Innovation: The introduction of array cables with higher operating voltages means capacity can be increased and electrical losses reduced. The first 66kV subsea inter-array cables are now being demonstrated offshore.. and as the industry moves towards larger turbines, the need for even higher capacity array cables becomes more critical to minimise the total cable length and the number of substations required.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: It is anticipated that almost all of the benefit of this innovation will be available for projects with FID in 2020 with the full benefit available for projects with FID in 2025.

Market share: It is anticipated that for the 8MW- and 10MW-Size Turbines, 60% and 75% of projects respectively with FID in 2020 will use this innovation. This market share rises to over 80% for 10MW- and 12MW-Size Turbines for projects with FID in 2025. For the 8MW-Size Turbines, the market share will be a little lower, at 70%. For FID in 2030, the market share will not increase above 80% as DC array cabling will be available as an alternative.

Improvements in array cable standards and client specification

Practice today: Developers conventionally regularly require cable manufacturers to produce cables to a higher specification than the minimum accepted by recognised standards, even though the integrity of operating cable has generally been good, excluding externally-caused mechanical damage.

Innovation: This innovation will involve the selection of the most suitable cable core size, insulation thicknesses and mechanical protection based on a greater understanding of site conditions and the specification of cable delivery lengths to fit with the manufacturer's capability. Small increases in development CAPEX are anticipated to be dominated by large savings on array electrical CAPEX and smaller savings on construction CAPEX.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: It is anticipated that more than one-third of the benefit of this innovation will be available for projects with FID in 2020 with a little under half of the benefit available for projects with FID in 2025.

Market share: It is anticipated that more than a third of projects with FID in 2020 will use this innovation. This is anticipated to increase to about three-quarters for projects with FID in 2025, with almost all for FID in 2030. It is anticipated that the projects with smaller turbines are more likely to take up this innovation due to cabling being a larger fraction of the cost in these cases.

Introduction of alternative array cable core materials

Practice today: Most array cables installed in offshore wind farms have copper cores. Aluminium is also being used in offshore array cables and has been utilised in other sectors for both onshore and offshore links.

Innovation: The introduction of alternative array cable core materials could offer significant CAPEX savings. Copper prices have increased rapidly over recent years and are currently significantly higher than aluminium. An increased core size is required but there is an overall saving in material costs leading to significant savings in array electrical CAPEX. Installation costs do increase due the difficulty of handling and burying cables with aluminium cores due to lower density and increased susceptibility to work hardening. Some increase in unplanned OPEX and losses due to unavailability of the electrical system are anticipated in the early years.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: 20% of this innovation is anticipated to be available for projects with FID in 2020 with almost all of the benefit available for projects with FID in 2025.

Market share: It is anticipated that almost 80% of projects with FID in 2020 will use this innovation and that this market share will only increase very slowly to 85% for FID in 2030.

8. Innovations in wind farm construction

8.1. Overview

Innovations in construction are anticipated to reduce the LCOE by up to 2.3% between FID 2017 and 2030. The savings are exclusively from improvements in CAPEX, rather than OPEX or AEP.

Figure 8.1 shows that the impact on CAPEX is greater for a wind farm on Site Type D. This is because many of the innovations cause improvements in the working conditions for installation and these have the biggest impact on Site Type D. The innovations have a greater impact on the 8MW- and 10MW-Size Turbines, as the majority of these innovations come in between FID 2020 and 2025.

Figure 8.1. Anticipated impact of construction innovations by Turbine Size and Site Type, compared with a wind farm with the same MW-Size Turbines over the range of FIDs stated for each Turbine Size (no Other Effects incorporated).

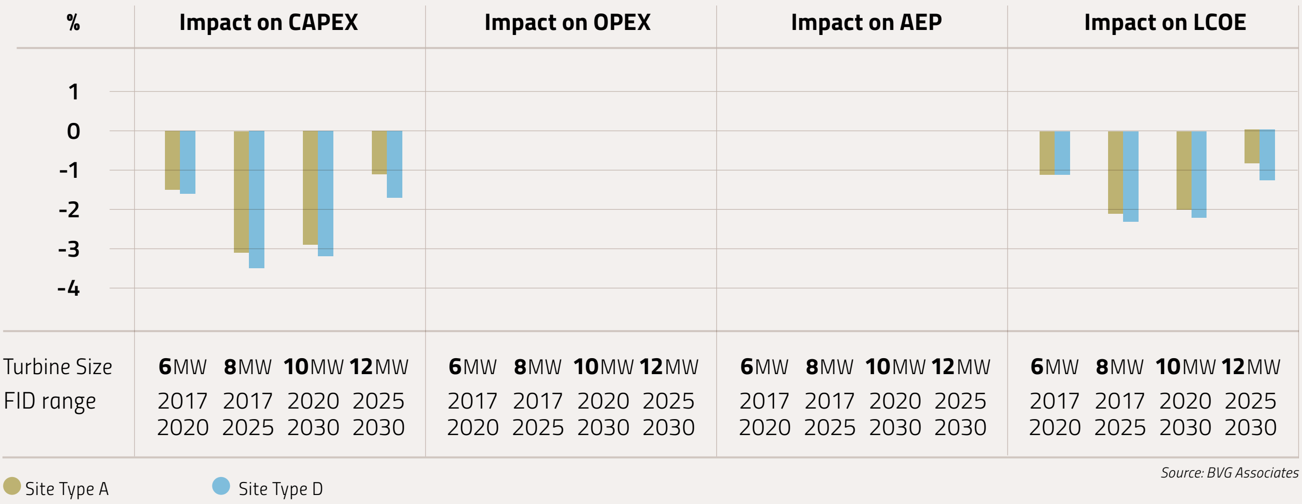
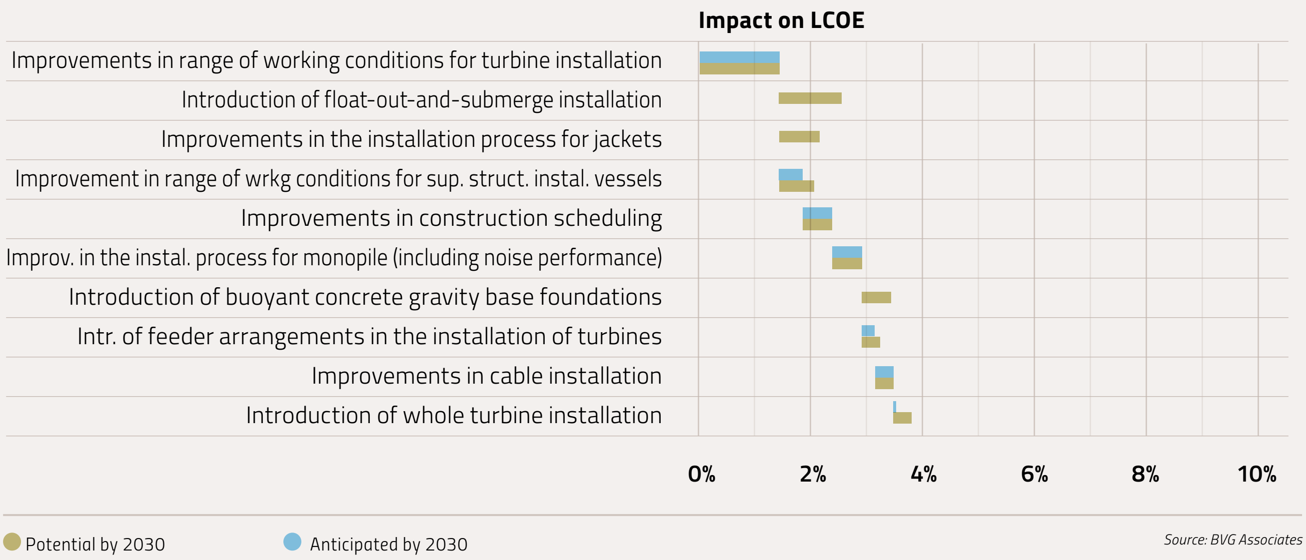


Figure 8.2 and Table 8.1 show that the individual innovation with the largest anticipated impact for projects reaching FID in 2030 relates to improvements in the range of working conditions for turbine. The innovation with by far the greatest potential impact is the introduction of float-out-and-sink installation but, even by projects with FID in 2030, market share is anticipated to be low. The overall impact of innovation in construction may seem lower than expected. This is because the benefits of moving to larger Turbine Size have already been included in the starting point, making the difference appear low.

Figure 8.2. Anticipated and potential impact of construction innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).



Source: BVG Associates

Table 8.1. Anticipated and potential impact of construction innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).

Innovation	Maximum technical potential impact by FID in 2030				Anticipated impact by FID 2030			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Improvements in range of working conditions for turbine installation	-2.1%	0.0%	0.0%	-1.4%	-2.1%	0.0%	0.0%	-1.4%
Introduction of float-out-and-submerge installation	-1.7%	0.0%	0.0%	-1.1%	0.0%	0.0%	0.0%	0.0%
Improvements in the installation process for jackets	-1.0%	0.0%	0.0%	-0.7%	0.0%	0.0%	0.0%	0.0%
Impr. in range of working conditions for support struct. instal. vessels	-0.8%	0.0%	0.0%	-0.6%	-0.6%	0.0%	0.0%	-0.4%
Improvements in construction scheduling	-0.8%	0.0%	0.0%	-0.5%	-0.8%	0.0%	0.0%	-0.5%
Impr. in the instal. process for monopile (includ. noise performance)	-0.7%	0.0%	0.0%	-0.5%	-0.7%	0.0%	0.0%	-0.5%
Introduction of buoyant concrete gravity base foundations	-0.7%	0.0%	0.0%	-0.5%	0.0%	0.0%	0.0%	0.0%
Introduction of feeder arrangements in the installation of turbines	-0.5%	0.0%	0.0%	-0.3%	-0.3%	0.0%	0.0%	-0.2%
Improvements in cable installation	-0.4%	0.0%	0.0%	-0.3%	-0.4%	0.0%	0.0%	-0.3%
Introduction of whole turbine installation	-0.4%	0.0%	0.0%	-0.3%	0.0%	0.0%	0.0%	0.0%

8.2. Innovations

Innovations in wind farm construction span foundations, cables and turbines. A subset of the more important of these has been modelled here. Transmission system installation in this study is modelled separately: see Section 2.4. Solutions involving permanently floating foundations in deeper water are not modelled as it is unlikely at this stage that there will be benefits in 35m water depth, as for projects on Site Type D.

Improvements in range of working conditions for turbine installation

Practice today: The amount of installation downtime caused and the risk introduced by weather have a significant impact on the installation costs of offshore wind turbines. The wait for jack-up vessels to be able to place legs down onto the sea bed and time spent away from site bringing towers, nacelles and blades to site are critical.

Innovation: An increase in the average Hs working limit from 1.4m to 2.5m represents a significant but achievable target. New technology in dynamic positioning of vessels will allow them to continue operations in rough environmental conditions. The use of feeder barges maximises the utilisation of the installation vessel on core installation tasks, hence decreasing construction costs at the cost of additional offshore lifts and increased costs in the case of critical path delays. Innovations in component lifting, especially for blades, will also reduce time lost wait for wind speeds to drop below current thresholds of around 12m/s.

Relevance: The full impact of these innovations is anticipated to be realised for projects using Site Type D, with lower benefit available for projects using the more benign Site Type A.

Commercial readiness: Almost half of the benefit of these innovations will be available for projects with FID in 2020, with 80% available for projects with FID in 2025.

Market share: It is anticipated that this innovation will be used on a third of projects with FID in 2020 rising to 70% of projects by FID in 2025. By FID in 2030 it is anticipated that full market share will be achieved.

Introduction of float-out-and-submerge installation

Practice today: The foundation is installed at site.The turbine is transported to site as separate main components and installed on the foundation.

Innovation: The complete structure is assembled at the quayside and floated out using tugs, with or without a dedicated transport and installation barge to provide buoyancy and stability, depending on the concept. As long as stability and turbine loading issues can be addressed cost-effectively, this has the potential to result in significant savings in construction CAPEX. The approach can be applied to concrete gravity base foundations or steel structures with a suction bucket sea bed connection and also offers an associated saving in support structure costs

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: It is anticipated that under 10% of the benefits of float-out-and-sink solutions will be available to the market for a project achieving FID in 2020, rising to around 70% for projects reaching FID in 2025.

Market share: It is anticipated this innovation will be used on a tiny number of projects with FID in 2020, rising to only around 5% by FID in 2025 and 2030.

Improvements in the installation process for jackets

Practice today: Jackets have been installed using sheerleg crane vessels, heavy lift vessels and jack-up vessels. None of these are optimally specified for space frame installation, due to weather sensitivity, vessel cost or carrying capacity.

Innovation: Developers anticipate significant savings from the development of a fleet of specialised vessels able to perform discrete installation steps more efficiently. Where vessels transport both foundations and turbines, the introduction of flexible sea fastenings capable of holding both components could reduce mobilisation time and hence construction costs. Advances in pre-piling technology and innovative drilling processes could reduce cost in the installation process for jackets.

Relevance: This innovation is relevant only for projects using jacket support structures, hence using 12MW-Size Turbines on Site Type D.

Commercial readiness: A quarter of the benefit of this innovation is anticipated to be available for projects with FID in 2020, with over 80% available for projects with FID in 2025.

Market share: This innovation is anticipated to capture market share of 90% on relevant projects for FID in 2030.

Improvements in the range of working conditions for support structure installation vessels

Practice today: The amount of installation downtime caused and the risk introduced by weather have a significant impact on the installation costs of support structures, being typically over 30% even on projects on Site Type A. The wait for jack-up vessels to be able to place legs down onto the sea bed and time spent away from site bringing foundations to site are critical.

Innovation: An increase in the average Hs working limit from 1.4m to 2.5m represents a significant but achievable target. New technology in dynamic positioning of vessels will allow them to continue operations in rough environmental conditions. The use of feeder barges maximises the utilisation of the installation vessel on core installation tasks, hence decreasing construction costs at the cost of additional offshore lifts and increased costs in the case of critical path delays.

Relevance: The full impact of these innovations is anticipated to be realised for projects using Site Type D, with lower benefit available for projects using the more benign Site Type A.

Commercial readiness: Around one-third of the benefit of these innovations will be available for projects with FID in 2020, with most of the remainder available for projects with FID in 2025.

Market share: It is anticipated that this innovation will be used on over 80% of projects with FID in 2020. By FID in 2030, the market share is slightly down, at 70%, due to alternative installation strategies being used.

Improvements in construction scheduling

Practice today: Construction planning is undertaken to optimise wind farm installation, minimising both contractor time spent offshore and risk. It is aided by construction modelling tools and procedures to ensure high levels of safety and efficiency.

Innovation: Enhanced modelling tools that make use of extensive wind farm construction vessel and weather data and smoother procedures that allow for faster reactive responses to on-site challenges will lead to better scheduling of tasks.

Relevance: The full impact of these innovations is anticipated to be realised for projects using Site Type D, with lower benefit available for projects using the more benign Site Type A.

Commercial readiness: Half of the benefit of these innovations will be available for projects with FID in 2020, with the majority of the remainder available for projects with FID in 2025.

Market share: It is anticipated that this innovation will be used on a quarter of projects with FID in 2020. By FID in 2025, the market share will rise to two-thirds before reaching full adoption for projects with FID in 2030.

Improvements in the installation process for monopile (including noise performance)

Practice today: Monopiles are installed by driving the piled structures into the seabed using hydraulic powered hammers. This is carried out by sheerleg crane vessels or jack-up vessels and generates large amounts of underwater construction noise.

Innovation: Developers anticipate significant savings from the development of a fleet of specialised vessels able to perform discrete installation steps more efficiently. Where vessels transport both foundations and turbines, the introduction of flexible sea fastenings capable of holding both components could reduce mobilisation time and hence construction costs. Advances in piling technology and innovative installation processes could allow for faster, more accurate and quieter installation of monopiles.

Relevance: The full impact of these innovations is anticipated to be realised for projects using Site Type D with the exception of projects using 12MW-SIze Turbines, with lower benefit available for projects using the more benign Site Type A.

Commercial readiness: It is anticipated that two-thirds of the benefits will be available to the market for a project achieving FID in 2020, rising to over 80% for projects reaching FID in 2025.

Market share: It is anticipated that this innovation will be used on 60% of projects with FID in 2020 rising to 90% of projects by FID in 2025. By FID in 2030 it is anticipated that full market share will be achieved.

Introduction of buoyant concrete gravity base foundations

Practice today: The concrete gravity base foundations at offshore wind farms have been installed using crane vessels with relatively small environmental operating windows.

Innovation: The introduction of buoyant concrete gravity base foundations reduces installation costs by removing the need for specialist vessels because these designs can be towed to site using standard tugs then positioned and sunk without the use of an expensive installation vessel. These foundations are also anticipated to deliver a saving on support structure costs on some sites, depending on ground conditions and relatively volatile steel prices. Decommissioning is simplified, consisting of the reversal of the installation process, although there are concerns over the dredging and rock dumping requirements for some concepts.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: It is anticipated that 40% of the benefit will be available to projects reaching FID in 2020 and around two-thirds available by FID in 2025.

Market share: It is anticipated this innovation will be used on a tiny number of projects with FID in 2020, rising to only around 5% by FID in 2025 and 2030.

Improvements in installation through feeder vessel use

Practice today: Generally, turbine components are transported from port to the wind farm site by the specialised installation vessel. This reduces the proportion of time this vessel is available for use lifting components into position. The practice of utilising feeder vessels to bring foundation and turbine components to the installation vessel on site has been demonstrated to work in offshore wind, but is not optimised.

Innovation: The use of feeder barges to transport turbine components to the installation vessel reduces the installation time. This saving is offset by the marginal increase in risk associated with the additional at-sea lifts and increased per-day costs due for the feeder vessels, especially in the event of project delays.

Relevance: The full impact of this innovation is for projects using Site Type D, with little available for projects using the Site Type A, with a shorter distance from port.

Commercial readiness: It is anticipated that 50% of the benefit from this innovation will be available for projects reaching FID in 2020, increasing to 100% by FID in 2025.

Market share: This innovation is anticipated to be used on three quarters of projects with FID in 2020 and 2025. For projects using 8MW-Size Turbines, this is anticipated to rise further to over 80% for those reaching FID in 2025. Competition from other methods is anticipated to slightly reduce the share for projects using 10MW- and 12MW-Size Turbines with FID in 2030.

Improvements in cable installation

Practice today: The cable is pulled in through a J-tube or equivalent at the first turbine position before being laid between turbine positions then pulled in at the second position. Array cable installation can be undertaken using either a single lay and burial process with a plough or a separate surface lay with subsequent burial, using a jetting tool operated from a remotely operated vehicle (ROV).

Innovation: Early engagement between cable installers and support structure designers allows the optimisation of the cable-pull in process and reduces the use of specialist vessels. A move to more advanced, bespoke cable laying vessels will increase the range of working conditions for array cable installation, maximising vessel utilisation and further reducing the cost of installing cables.

Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.

Commercial readiness: Over half of the benefit of these innovations is anticipated to be available for projects with FID in 2020, with almost all of the remaining benefit available by FID in 2025.

Market share: Most projects with FID in 2020 and all projects with FID in 2025 and 2030 are anticipated to use these innovations.

Introduction of whole turbine installation

Practice today: After the foundation is installed, the turbine is transported to site as separate main components and installed on the foundation.

Innovation: The turbine is fully assembled and partly commissioned in the construction port then transported to site and installed in one lift onto the foundation. This requires the use of a different design of installation vessel but reduces installation time and weather downtime.

Relevance: The full impact of this innovation is anticipated to be realised for projects using 12MW-Size Turbines on Site Type D, with somewhat lower benefit available for projects using Site Type A and lower benefits for projects using smaller turbines. For the 6MW-Size Turbines on Site Type A, the relevance is just over half.

Commercial readiness: None of the benefit of this innovation will be available for FID in 2020. About 60% of the benefit of this innovation will be available for projects with FID in 2025.

Market share: This innovation is not anticipated to capture significant market share for projects reaching FID in 2020 but is anticipated to rise to account for around a tenth of the market for projects reaching FID in 2025 and 2030.

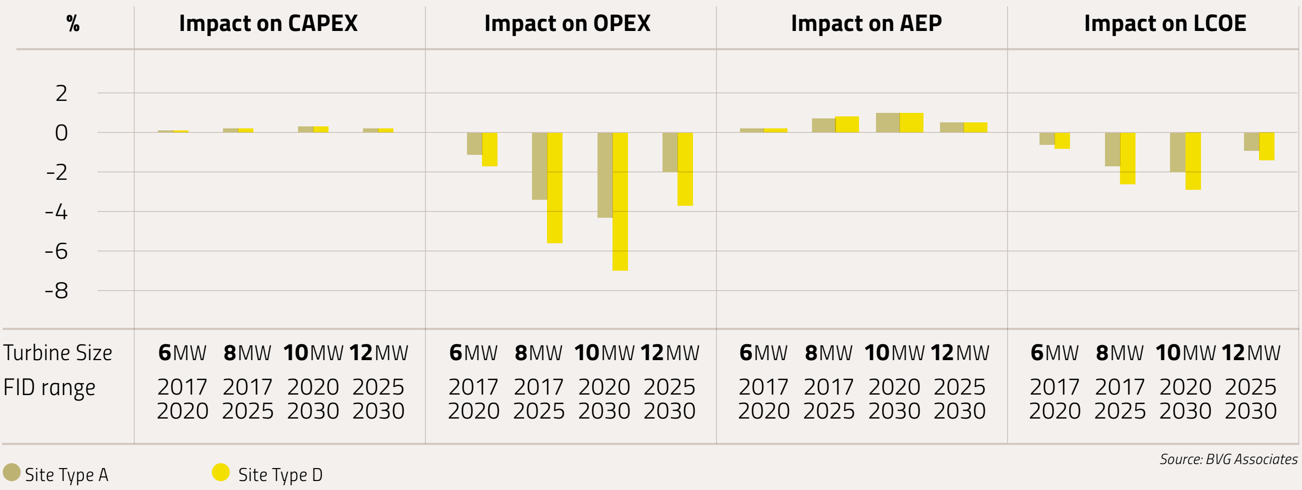
9. Innovations in wind farm operation, maintenance and service

9.1. Overview

Innovations in operations, maintenance and service (OMS) are anticipated to reduce the LCOE by 0.6-2.9% between FID in 2017 and 2030, with the largest savings anticipated for projects using 8MW and 10MW-Size Turbines on Site Type D. The savings are dominated by improvements in OPEX, although there is some benefit to wind farm availability and hence to net AEP.

Figure 9.1 shows that the impact on OPEX is much greater for projects on Site Type D. This is because there is more potential to address the challenges of operating wind farms far from shore.

Figure 9.1. Anticipated impact of OMS innovations by Turbine Size and Site Type, compared with a wind farm with the same MW-Size Turbines over the range of FIDs stated for each Turbine Size (no Other Effects incorporated).

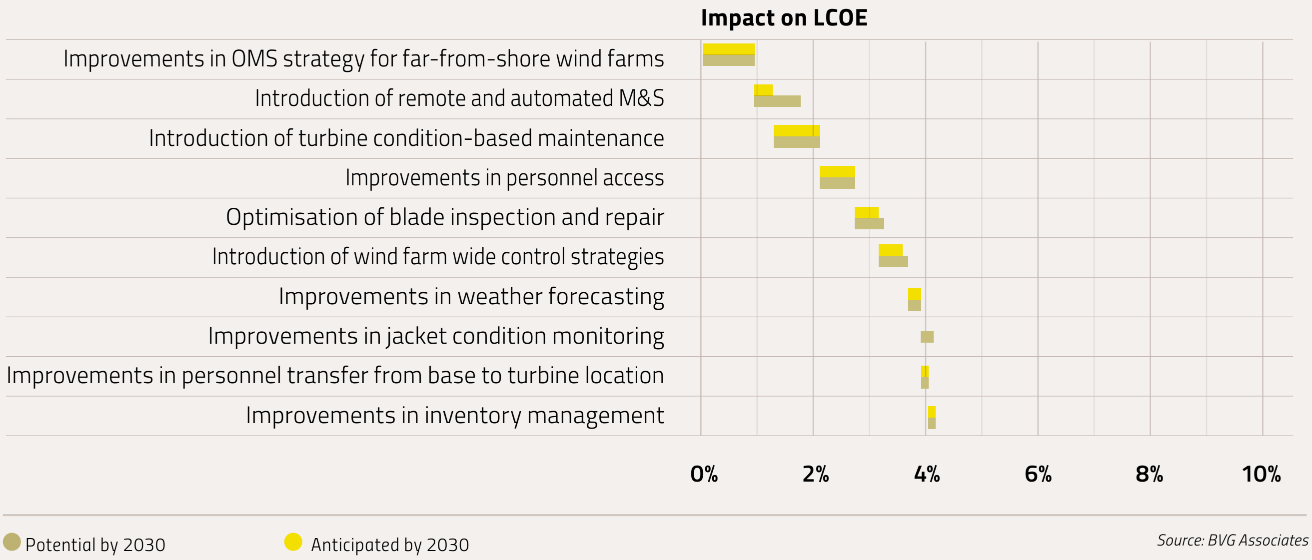


Source: BVG Associates

Figure 9.2 and Table 9.1 show that the innovations with the largest anticipated impact by FID in 2030 are far-from-shore operational strategies, the introduction of condition based maintenance (CBM) and improvements in personnel transfer to turbines. Clearly, far-from-shore operational strategies apply only to Site Type D. Investment in the development of sensors and algorithms that provide estimates of the remaining useful life of turbine components will support the introduction of CBM strategies. This, when combined with wind farm level control algorithms, has the potential to reduce the number of technician visits and increase the efficiency of turbine maintenance and service.

It is anticipated that most of the potential of innovations in this element will be achieved by projects with FID in 2020. This depends on the industry being willing to take the long view, learn from other industries in terms of CBM, and ensure that relevant systems and services are specified at FEED and provided for in CAPEX budgets. In addition to the innovations with early (pre-FID-2020) impact, remote and automated OMS has a large potential impact later in the period.

Figure 9.2. Anticipated and potential impact of OMS innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).



Source: BVG Associates

Table 9.1. Anticipated and potential impact of OMS innovations for a wind farm with 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).

Innovation	Maximum technical potential impact by FID in 2030				Anticipated impact by FID 2030			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Improvements in OMS strategy for far-from-shore wind farms	0.0%	-2.9%	0.0%	-0.9%	0.0%	-2.8%	0.0%	-0.9%
Introduction of remote and automated M&S	0.0%	-2.0%	0.2%	-0.8%	0.0%	-0.8%	0.1%	-0.3%
Introduction of turbine condition-based maintenance	0.1%	-2.1%	0.2%	-0.8%	0.1%	-2.0%	0.2%	-0.8%
Improvements in personnel access	0.0%	-0.9%	0.3%	-0.6%	0.0%	-0.9%	0.3%	-0.6%
Optimisation of blade inspection and repair	0.0%	-1.0%	0.1%	-0.5%	0.0%	-0.9%	0.1%	-0.4%
Introduction of wind farm wide control strategies	0.2%	-0.5%	0.5%	-0.5%	0.2%	-0.5%	0.4%	-0.4%
Improvements in weather forecasting	0.0%	-0.5%	0.0%	-0.2%	0.0%	-0.5%	0.0%	-0.2%
Improvements in jacket condition monitoring	0.1%	-0.7%	0.0%	-0.2%	0.0%	0.0%	0.0%	0.0%
Improvements in personnel transfer from base to turbine location	0.0%	-0.3%	0.1%	-0.1%	0.0%	-0.2%	0.0%	-0.1%
Improvements in inventory management	0.0%	-0.3%	0.0%	-0.1%	0.0%	-0.3%	0.0%	-0.1%

9.2. Innovations

Innovations in wind farm OMS vary widely from highly practical to deeply technical. The most important of these have been modelled here.

Improvements in OMS strategy for far-from-shore wind farms

Practice today: Floatel accommodation vessels have seen limited deployment on a number of operational sites to allow service personnel to remain in the field for extended periods during retrofits, thus reducing travel times.

Innovation: Motherships will provide accommodation, office space, workshops and welfare facilities for technicians and operations staff. Dock facilities, stores and loading facilities will allow these ships to support a number of daughter vessels. Improvements to Health and Safety systems may allow 24/7 working to be adopted. Significant OPEX savings are anticipated to result from this innovation.

Relevance: This innovation is anticipated to be only relevant to projects on Site Type D. Future application to near-shore sites is possible but not modelled in this report as the industry appetite, and therefore likelihood, remains low at present.

Commercial readiness: 20% of the benefit of this innovation is anticipated to be available for projects with FID in 2020 rising to around 70% for projects with FID in 2025.

Market share: This innovation is anticipated to be implemented on three-quarters of projects with FID in 2020 and almost all projects with FID in 2025, with implementation almost universal by FID in 2030.

Introduction of remote and automated maintenance and service

Practice today: Today, most wind farm planned maintenance and unplanned service in response to failures is undertaken on site by technicians.

Innovation: Automated and remote maintenance systems are developing rapidly in other sectors and are being adapted to use in offshore wind, for example the aerial inspection of blades using drones. In future, it is anticipated that remote or automated interventions will also include service operations. Remote service also includes the increased use of redundant,- remotely diagnosable and configurable systems enabling remote intervention to facilitate ongoing operation of the turbine.

Innovations reduce the cost of energy through lower personnel costs and potentially through lower downtime if the technologies' operating window is greater than the current method.

Relevance: The benefits of this innovation are equally relevant for all Site and Turbine Types.

Commercial readiness: Around half of the benefit of this innovation is anticipated to be available for projects with FID in 2025, with no benefit available before that date.

Market share: It is anticipated that around 40% of the market will use this innovation by FID in 2030, with around 25% for FID in 2025. Almost no projects will use this innovation for FID in 2020.

Introduction of turbine condition-based maintenance

Practice today: In order to comply with manufacturer warranty conditions, operators are required to adhere to time-based planned maintenance strategies. There is evidence that, as turbines come out of the initial warranty periods, some operators are taking ownership of some of the risk and implementing condition-based maintenance (CBM) strategies on some projects, improving AEP and reducing OPEX.

Innovation: Condition-based maintenance instead allows maintenance to be based on information from condition monitoring equipment and inspections across a fleet of turbines, thereby reducing the need for routine activity on systems that do not need it, whilst focussing effort in areas where the benefits are greatest. With the successful deployment of CBM strategies in other industries and some initial success stories from the wind industry, CBM is anticipated to become more sophisticated and more widely accepted from project FID. New and improved prognostic and diagnostic systems and processes allow operators to improve turbine availability and target inspections and maintenance. This would reduce OPEX and losses with a small increase in turbine CAPEX by targeting maintenance on key issues and improved monitoring of changes in behaviour system, rather than by carrying out a wide range of standard maintenance activities.

Relevance: It is anticipated that all of the value of this innovation will be realised on projects using Site Type D, with most available also for projects using Site Type A.

Commercial readiness: One-third of the benefit of this innovation is anticipated to be available for projects with FID in 2020 with three-quarters available for projects with FID in 2025.

Market share: This innovation is anticipated to be implemented on three-quarters of projects with FID in 2020 and almost all projects with FID in 2025, with implementation almost universal by FID in 2030.

Improvements in personnel access

Practice today: Currently used crew transfer vessels (CTVs) and personnel access methods enable access only in wave conditions below 1.4m Hs with reductions in technician utilisation of 30% to 40% due to this restriction.

Innovation: The use of larger, more capable support vessels fitted with systems such as passive or heave compensated walkways or lifting pods that allow safe transfer of technicians to turbines for Hs up to 2.5m is anticipated. On a typical North Sea site, this innovation is anticipated to increase accessibility from 70% to 95%, as such, it is anticipated to deliver a significant reduction in availability losses as well as savings in planned and unplanned OPEX.

Relevance: As transfer vessel is a larger fraction of the Site Type A operations cost than the Site Type D cost, the relevance is smaller for Site Type D. It is still anticipated that most of the value will also be captured by projects using Site Type D.

Commercial readiness: Over 40% of the benefit of this innovation is anticipated to be available for projects with FID in 2020 and close to 80% of the benefit is available for projects with FID in 2025.

Market share: This innovation is anticipated to be implemented on three-quarters of projects with FID in 2020 and almost all projects with FID in 2025, with implementation almost universal by FID in 2030.

Optimisation of blade inspection and repair

Practice today: Maintenance and servicing of turbine blades is predominantly carried out by technicians via rope access methods. Blade inspection tasks have begun to be supported by the use drone and remote visual technology but this practice offshore is still in its infancy.

Innovation: Inspection techniques such as the use of high performance cameras or drones can lead to blade inspections being carried out three times faster than by conventional rope access methods and allows for technician resource to be better spent on investigation and repair. Techniques to support blade repairs, such as through automation and improvements in safe technician access, will further optimise servicing.

Relevance: It is anticipated that all of the value of this innovation will be realised on projects using Site Type D, with most available also for projects using Site Type A.

Commercial readiness: 30% of the benefit of this innovation is anticipated to be available for projects with FID in 2020 rising to over 80% for projects with FID in 2025.

Market share: This innovation is anticipated to be implemented on 30% of projects with FID in 2020, 80% of projects with FID in 2025, and almost all projects with FID in 2030.

Introduction of wind farm wide control strategies

Practice today: Automatic control of wind turbines is carried out by individual wind turbine controls systems that cannot be co-ordinated to optimise performance across a wind farm. Any intervention to change the turbine operational parameters based on wind farm wide or local operating conditions is generally only by human operators. All wind turbine control systems provide for automatic curtailment (reduction of maximum power) which may in some cases already be managed by simple wind farm level control algorithms.

Innovation: Development of more holistic control strategies using systems able to measure residual useful life and hold an understanding of the income drivers (for example, market spot prices) has the potential to provide multi-objective optimal control of wind farms to minimise LCOE. This innovation will slightly increase turbine CAPEX but is anticipated to reduce unplanned OPEX and losses, and to increase AEP. This innovation does not include individual wind turbine control strategies. These are included as innovations in Section 6.

Relevance: The full impact of this innovation is anticipated to be realised for projects using 12MW-Size Turbines. The benefits for projects using smaller turbines are lower. For the 6MW-Size Turbines on Site Type A and Site Type D the relevance is just over 80%.

Commercial readiness: Around 20% of the benefit of this innovation is anticipated to be available for projects with FID in 2020, increasing to over half for projects with FID in 2025.

Market share: This innovation is anticipated to be implemented on three-quarters of projects with FID in 2020 and almost all projects with FID in 2025, with implementation almost universal by FID in 2030.

Improvements in weather forecasting

Practice today: Owners of offshore wind farms can subscribe to one or more weather forecasting feeds provided by organisations such as MeteoGroup or the UK Meteorological Office. Forecasts are generally updated up to four times a day, to a granularity of half-hourly intervals out to six days ahead. The most advanced services provide hourly updates.

Innovation: Improvements in weather forecasting will increase the efficient use of staff and vessels by maximising activity during weather windows. This requires advances both in the accuracy and the granularity of forecasts. Currently, accuracy drops significantly for forecasts beyond five days ahead for an area of approximately 100km2. In order to make the most efficient use of resources, and especially heavy equipment such as jack-up vessels, reasonable accuracy will need to be extended to a 21-day forecast.

Relevance: It is anticipated that all of the value of this innovation will be realised on projects using Site Type D, with most available also for projects using Site Type A.

Commercial readiness: Around a quarter of the benefit of this innovation is anticipated to be available for projects with FID in 2020 rising to around 60% for projects with FID in 2025.

Market share: This innovation is anticipated to be implemented on three-quarters of projects with FID in 2020 and almost all projects with FID in 2025, with implementation almost universal by FID in 2030.

Improvements in jacket condition monitoring

Practice today: Currently there are over 200 jackets installed on offshore wind farms. Trial sites such as Alpha Ventus and Beatrice have been used to evaluate a variety of jacket condition monitoring systems. As more complex sites are developed, jacket use is anticipated to increase. Industry advises that, typically, 60 person-hours of annual inspection visits is required for a jacket compared with 20 person-hours for a monopile foundation.

Innovation: The remaining life of the foundation will be measured by installing permanent sensors at critical points and implementing remote monitoring and subsea inspections using autonomous systems. Improvements in jacket condition monitoring will increase in foundation CAPEX marginally, but reduce unplanned OPEX, and losses due to unavailability.

Relevance: The full value of this innovation is anticipated to be realised on all projects using jacket foundations, that is, 12MW-Size Turbines on Site Type D.

Commercial readiness: One-third of the benefit of this innovation is anticipated to be available for projects with FID in 2020 with three-quarters available for projects with FID in 2025.

Market share: This innovation is anticipated to be implemented on 90% of relevant projects (12MW-Size Turbines) with FID 2030.

Improvements in personnel transfer from base to turbine location

Practice today: The majority of offshore wind farms currently ooperating have a shore-based operating base. Transit from the base to the wind turbine is routinely by small (15m-26m) crew transfer vessels. Some more recent wind farms have had provision for helicopter access for both operational and health and safety functions.

Innovation: Improved transfer vessels will deliver crews in larger numbers and greater comfort from their onshore or offshore base, maximising technician productivity on arrival. These vessels will also have greater payload capacities enabling a greater stock of material and tooling to be transported. Industry anticipates reduced staff churn (and hence increased knowledge retention) as working conditions improve. This is anticipated to improve both planned and unplanned OPEX and to reduce availability losses.

Relevance: The harsher conditions and shorter transit times from the offshore base on projects on Site Type A are anticipated to allow the maximum value to be extracted from this innovation, but it is still anticipated that most of the value will also be captured by projects using Site Type D.

Commercial readiness: Just under 40% of the benefit of this innovation is anticipated to be available for projects with FID in 2020 and almost all is available for projects with FID in 2025.

Market share: This innovation is anticipated to be implemented on three-quarters of projects with FID in 2020 and almost all projects with FID in 2025, with implementation almost universal by FID in 2030.

Improvements in inventory management

Practice today: Some wind turbine manufacturers have adopted systems such as radio frequency identification (RFID) component tagging and electronic configuration management; however, tracking of turbine operational spares holding and use, and the clarity of recording turbine configuration are suboptimal.

Innovation: Adopting and further developing inventory management systems and processes has the potential to reduce the cost of both planned and unplanned OPEX by increasing knowledge of the configuration of the turbines, allowing appropriate parts to be dispatched. Such systems will also allow proactive management of inventory levels and the ability to better characterise and analyse turbine fault patterns. More efficient dispatch is also anticipated to reduce the mean time to repair and hence unavailability losses.

Relevance: It is anticipated that all of the value of this innovation will be realised on projects using Site Type D, with most available also for projects using Site Type A.

Commercial readiness: Around 70% of the benefit of this innovation is anticipated to be available for projects with FID in 2020 and 2025.

Market share: This innovation is anticipated to be implemented on three-quarters of projects with FID in 2020 and almost all projects with FID in 2025, with implementation almost universal by FID in 2030.

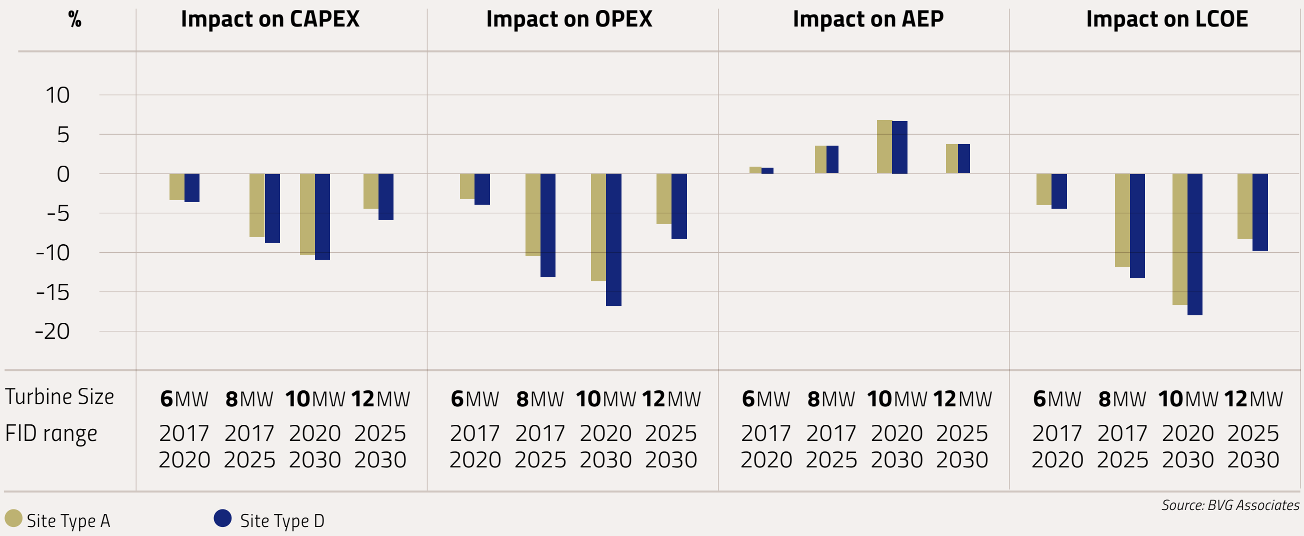
10. Summary of the impact of innovations

10.1. Combined impact of innovations

Innovations across all elements of the wind farm are anticipated to reduce the LCOE by 4% to 18% for projects with FID between 2017 and 2030. Figure 10.1 shows that the savings are generated through a balanced contribution of reduced CAPEX and OPEX, and increased AEP. Figure 10.1 shows changes for a given Turbine Size and Site Type. The comparisons are over different time frames. For 6MW-Size Turbines, FID 2017-2025; 8MW-Size Turbines, FID 2017-2030; 10MW-Size Turbines, FID 2020-2030 and 12MW-Size Turbines, FID 2025-2030. No impact of a change in Turbine Size is thus shown. It is important to note that the impact shown in Figure 10.1 is an aggregate of the impacts shown in Figure 4.1 to Figure 9.1 and as such excludes any Other Effects: financing and lifetime effects, transmission and land cost, supply chain dynamics, insurance and contingency, project risk and decommissioning costs. The impacts of Other Effects are discussed in Section 10.3.

The largest available like-for-like reductions for the same Turbine Size and Site Type are for projects using 10MW-Size Turbines. This is because the impact of innovation is larger during the FID range 2020-2030 than over the range available for any of the other Turbine Sizes. The impacts are larger for Site Type D due to the additional opportunities for innovation provided by working further from shore.

Figure 10.1. Anticipated impact of all innovations by Turbine Size and Site Type over the periods shown (no Other Effects incorporated).



For each Turbine Size in Figure 10.1, the FID range is different. This means that changes for each Turbine Size cannot be compared directly. Figure 10.2 shows the aggregate impact of all innovations over the FID range for each Turbine Size, all compared with the same wind farm, that is one with 6MW-Size Turbines on Site Type A and FID of 2017. Showing the impact with respect to the same starting wind farm allows the effect of changes in Turbine Size and Site Type to be compared directly.

Figure 10.2 shows that CAPEX, OPEX, AEP and LCOE all improve with increasing Turbine Size: CAPEX and OPEX fall and the AEP rises, resulting in LCOE savings. As with Figure 10.1, these impacts are an aggregate of those shown in Figure 4.1 to Figure 9.1 and, as such, exclude any Other Effects such as supply chain competition. These Other Effects are discussed in Section 10.3.

Figure 10.2 shows the overall change in comparison to a wind farm with 6MW-Size Turbines on Site Type A for FID 2017 for CAPEX, OPEX, AEP and LCOE. It also breaks each of these changes down by the source of the change. The sources considered are gains through:

1. Inherited innovations (impact of innovations already incorporated in baseline project for given Turbine Size, ref. Table 2.2)
2. Increased Turbine Size
3. New innovations (impact of innovations coming in after baseline project for given Turbine Size)

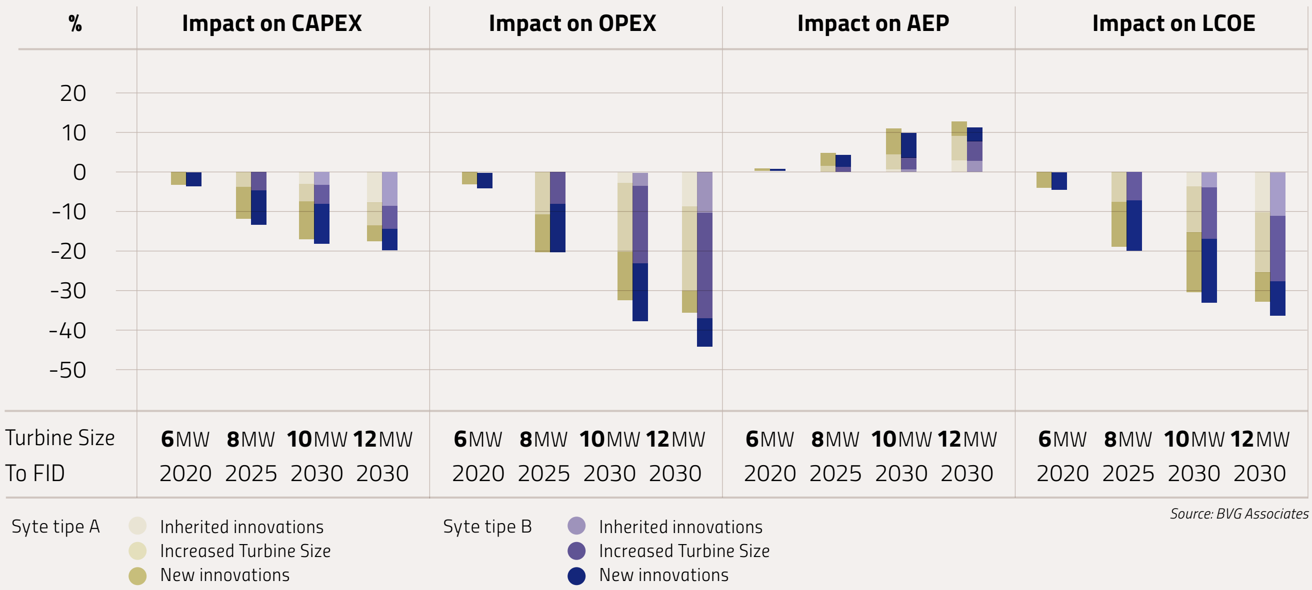
For example looking at 12MW size turbines, this is:

1. Innovations on projects using 6MW turbines between projects with FID in 2017 and FID in 2025 (giving 11% reduction in LCOE for Site Type A)
2. Increasing turbine size from 6MW to 12MW for projects with FID in 2025 (giving 15% reduction in LCOE for Site Type A), and;
3. Innovations on projects with 12MW turbines between projects with FID in 2025 and FID in 2030 (giving 16.5% reduction in LCOE for Site Type A).

For wind farms on Site Type A, the aggregate impact of all innovations and the change to 12MW-Size Turbines over the period FID 2017-2030 drives a 18% reduction in CAPEX, a 36% reduction in OPEX and a 13% increase in AEP, giving an overall 43% reduction in LCOE. For wind farms on Site Type D, using 12MW-Size Turbines decreases CAPEX by 20%, OPEX by 44% and increases AEP by 12%, giving an overall reduction in LCOE of 45%.

Section 10.3 shows that when the other effects are incorporated, the LCOE reduction for wind farms on Site Type A with Turbine Size of 12MW for FID in 2030 is 52%, while for Site Type D, the reduction is 51%, both in comparison to 6MW-Size Turbines on Site Type A with FID in 2017.

Figure 10.2. Anticipated impact of all innovations by Turbine Size and Site Type from a wind farm with 6MW-Size Turbines on Site Type A with FID in 2017 to Turbine Size and year of FID shown (no Other Effects incorporated). The labels 1, 2, 3 match the sources of innovation described above.



CAPEX, OPEX, AEP and LCOE show different trends.

For 6MW-Size Turbines, all of the impact is from new innovation (source 3). This is because for this Turbine Size, by definition, there is no Turbine Size change from the 6MW starting point (source 2) and no FID date change from the 2017 starting point (source 1).

For 8MW-Size Turbines, more than half of the CAPEX impact for both Site Types comes from increases in new innovation (source 3) with the rest from Turbine Size (source 2). None of the impact comes from inherited innovation (source 1), as the starting point for 8MW-Size Turbines is also FID 2017.

For 10MW-Size Turbines, the main source of CAPEX impact is new innovations applying in the period FID 2020-2030 (source 3). The effect on CAPEX of innovations that have come online before the 2020 FID starting point (source 1) and from the impact of Turbine Size increase (source 2) make up just under half of the change.

For 12MW-Size Turbines, the opportunity for improvement in CAPEX costs for the FID period 2025-2030 (source 3) is smaller than for FID period 2017-2025 (source 1). The proportion of the breakdown due to new innovations is thus smaller in the case of the 12MW-Size Turbines than for the 10MW-Size Turbines.

For OPEX, the main source of change is in Turbine Size increase (source 2). This is because the number of components per MW needed to maintain, and to service in the event of failures is significantly smaller. In comparison to the absolute % value in CAPEX, the OPEX absolute % numbers are larger.

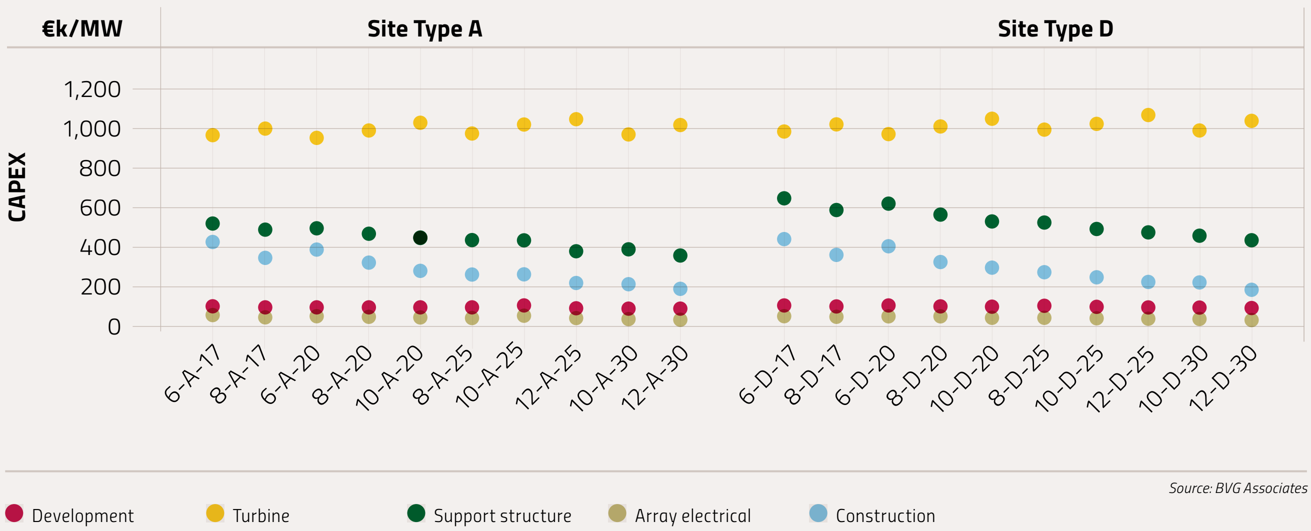
For the AEP impact, the increase in Turbine Size (especially with increasing hub-height) is important (source 2), but not as important as for OPEX. Inherited innovations (source 1) have relatively little impact on AEP particularly compared to the impact on CAPEX, while the new innovations (source 3) contribute a larger proportion of the split by source than for OPEX.

The effects of new innovations on LCOE are particularly important for the 10MW-Size Turbines; there is also a strong effect for the 12MW-Size Turbines but these are less than for 10MW-Size Turbines because they are available for a shorter period. The isolated effect of increasing Turbine Size from 6MW to 12MW (without the effect of inherited or new innovations (sources 1 and 3) over the period) is responsible for an LCOE saving of 16%.

10.2. Relative impact of cost of each wind farm element

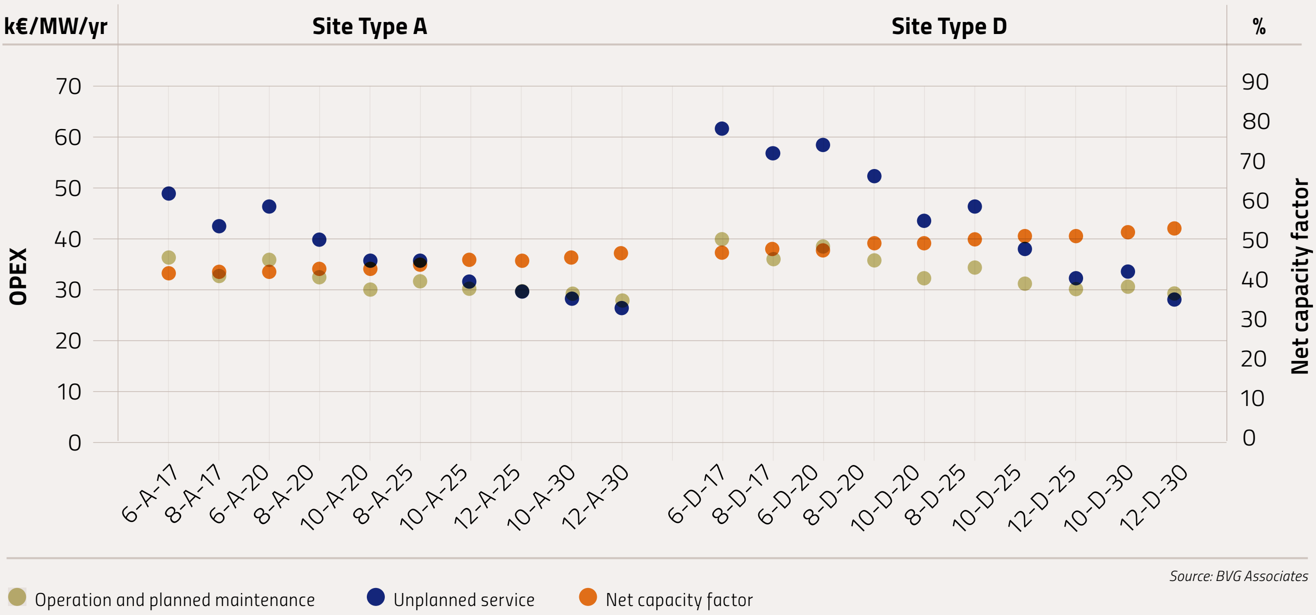
Figure 10.3 shows the cost of all CAPEX elements for all combinations of Turbine Size, Site Type and FID date and Figure 10.4 shows the same for OPEX and net capacity factor. These figures show the reduction in costs and increases in capacity factor over time for a given combination of Turbine Size and Site Type, as well as the relative costs between different Turbine Sizes and Site Types.

Figure 10.3. CAPEX for wind farms with FID 2017, 2020, 2025 and 2030.



Source: BVG Associates

Figure 10.4. OPEX and net capacity factor for wind farms with FID 2017, 2020, 2025 and 2030.

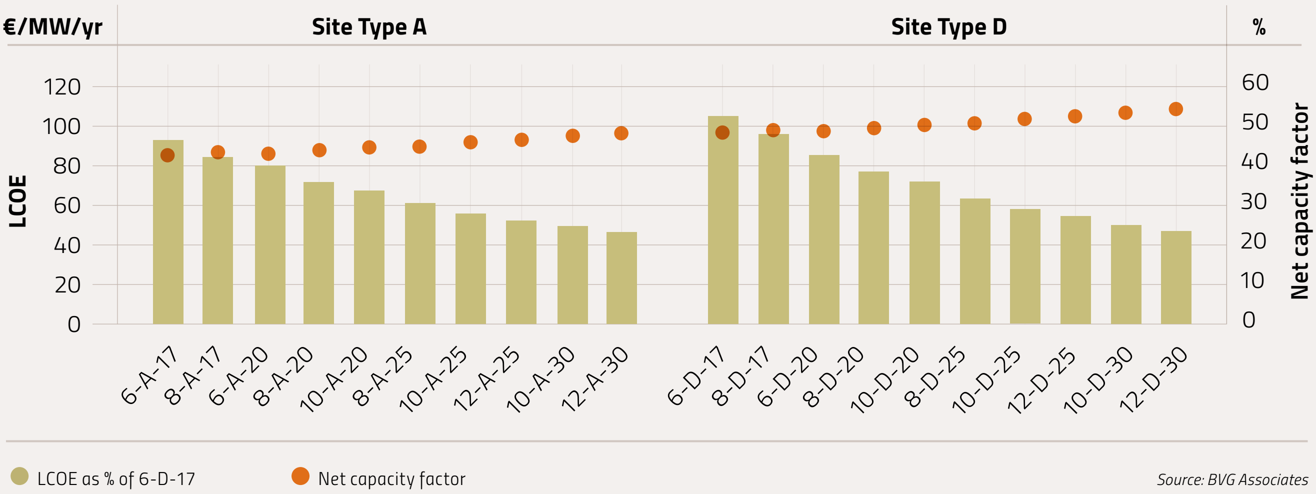


Source: BVG Associates

10.3. Levelised cost of energy including the impact of Other Effects

In order to compare LCOE, Figure 10.5 incorporates the Other Effects (financing and lifetime effects, transmission and land cost, supply chain dynamics, insurance and contingency, project risk and decommissioning costs) discussed in Section 2.4. It shows that, with the benefit of increasing capacity factor over time and with the move towards larger turbines, LCOE decreases.

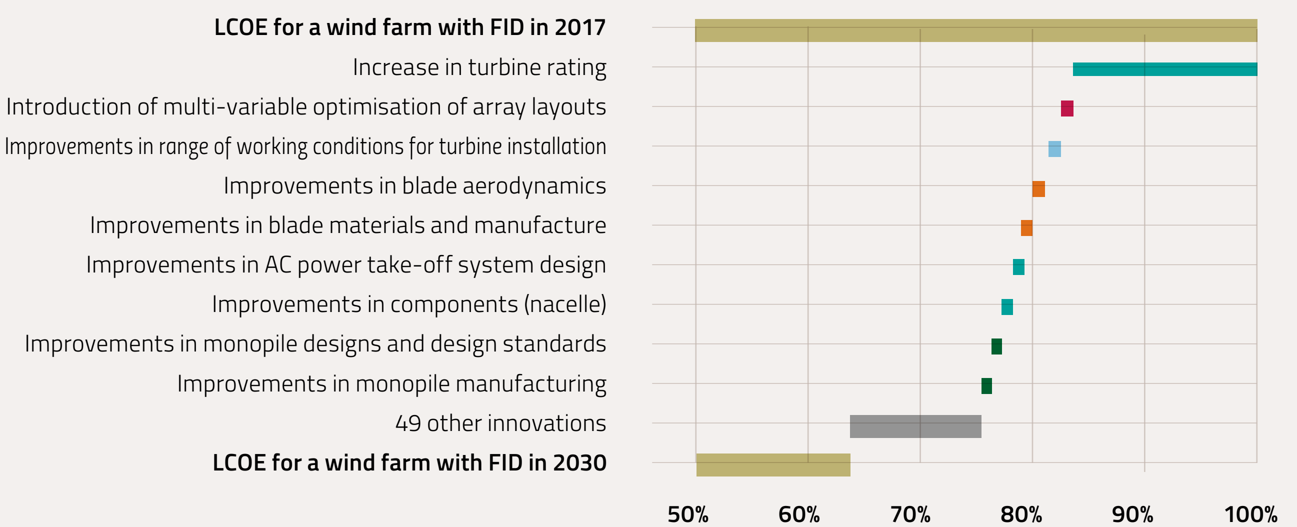
Figure 10.5. LCOE for the wind farms *with* other effects incorporated, ref. Section 2.4.



Source: BVG Associates

The contribution of innovations in each element to this LCOE reduction is presented in Figure 10.6. It shows that individual innovations in the turbine dominate the LCOE impact, but that the combined effects of smaller innovations in many other elements also make a sizable contribution.

Figure 10.6. Anticipated impact of all innovations by element for a wind farm using 10MW-Size Turbines on Site Type D with FID in 2030, compared with a wind farm using 6MW-Size Turbines on the same Site Type with FID in 2017 (no Other Effects incorporated).



Source: BVG Associates

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11. Conclusions

In Section 4.1 to Section 9.1, a large number of innovations with the potential to reduce the LCOE by FID 2030 are considered. Within these, a number of themes emerge, which will be the focus of the industry's efforts to reduce costs:

- The introduction of turbines with a higher rated capacity and more efficient rotors that are more reliable and deliver increased energy production
- The introduction of mass-produced support structures for use in deeper water with larger turbines
- Enhanced construction and OMS methods using bespoke vessels and equipment which can operate in a wider range of conditions, and
- Greater upfront investment in wind farm development, both in terms of site investigations and engineering studies.

Although we have treated larger turbines, increased reliability and optimised rotors under a range of distinct innovations, they are closely linked. Turbine manufacturers have recognised the value of these and are working to optimise the current generation of turbines, as well as bring the next generation of turbines to market with significant progress in all of these areas.

Developers recognise the impact that these next generation turbines can have and, in particular, the wide-ranging impact that turbines with higher rated power have on the balance of plant, construction and OPEX costs. While several of these next generation turbines (10MW- to 12MW-Size Turbines) are at an advanced stage of development, developers face a dilemma about what turbines to use. Some developers have chosen to use smaller turbines with an established track record; others have jumped early to the use of 8MW-Size Turbines and enhanced power variants of these with a significantly shorter track record but offering the possibility of significantly increased project returns.

A prerequisite in making a successful step to 10MW- to 12MW-Size Turbines is a step change in the levels of component, system and turbine-level design for reliability, testing and verification to build confidence that designs are suitable for use on a commercial scale. This will need to be accompanied by an increase in the quality assurance and quality control processes right through the supply chain, including low-cost turbine components. This activity needs to be further opened to wind farm developer scrutiny to build confidence in manufacturers' commitment to reliability.

This focus on larger turbines and the increase in water depth of projects in development beyond 35m dictates a shift away from the monopile foundations that have dominated the market to date. Recent experience has been that this trend has been slower than initially expected due to greater understanding of monopile design and development of larger-scale manufacturing and installation tooling. Several decades of offshore oil and gas extraction and large bridge-building projects have delivered proven technologies in the form of space-frame structures such as jackets and concrete gravity bases. The offshore wind industry will use these technologies more, but recognises that changes to the design are needed to reflect the increased quantities of similar structures required, the higher focus on cost, the changed design margins and the greater importance of fatigue loading.

For novel foundation designs, test sites are needed to prove the concept and, as importantly, the installation methods. For example, the underlying technology for concrete gravity bases is sound, but developers will need confidence that they can be manufactured and installed efficiently in volume. This drives additional requirements in terms of demonstrating new technology using multiple units.

Offshore wind vessel practices, both during construction and OMS, are still not fully developed and future projects in deeper water and further from shore increase the scale and complexity of the work. A key element in maturing this area is investing in new fit-for-purpose vessels and equipment. This process is underway for turbine installation, aided by a relatively clear view of the physical parameters of next generation hardware. This is less true for foundation installation. While there is widespread recognition that jack-up vessels may not be the best solution, there is less certainty about what should replace them. Feedback from industry is that jacket structures are generally the preferred solution where monopiles cannot be used cost effectively and installation contractors should be in a position to refine vessel design concepts while retaining flexibility with new designs of sea fastenings.

Another recurring theme in this study has been the value in greater upfront investment in wind farm development, both in terms of site investigations and engineering studies. For example, a focus on optimising layout not only based on energy production but also taking into account the impact on CAPEX of different ground conditions and water depths, along with an improved understanding of wake effects, will reduce the LCOE. In addition, more extensive cable route characterisation on average will reduce quoted costs and, in all cases, reduce the risks associated with cable-laying. Much progress in these areas has already been made, but there is more to do.

57 technology innovations have been identified as having the potential to cause a substantive change in the design of hardware, software or process, with an impact on the cost of energy. Many more technical innovations are in development and so some of those described in this report may well be superseded by others. Overall, however, industry expectation is that the level of cost of energy reduction is consistent with the findings of this analysis. Indeed, in most cases, the anticipated impact of each innovation has been significantly moderated downwards in order to give overall levels of cost of energy reduction in line with industry expectations. The availability of such a range of innovations with the potential to impact LCOE more than shown gives confidence that the picture described is achievable.

In addition, large LCOE reductions are available through some of the Other Effects considered in Section 2.4. Improved financing arrangements and reduced risk can have significant effects as can competition in the supply chain.

12. About InnoEnergy

InnoEnergy is a European company driving innovation and entrepreneurship in the sustainable energy field, by bringing together academics, business and research sectors.

- We provide acceleration services to startups and ventures by supporting entrepreneurs with their business ideas, strengthening their business models, building expert teams, and providing access to finance.
- We support innovation in the field and bring innovative ideas to life that have a positive impact on sustainable energy in Europe.
- We provide Master and PhD educational programmes that deliver knowledge and skills to students and managers that will shape the future of the energy sector.

InnoEnergy is one of the first three Knowledge and Innovation Communities (KICs) created under the leadership of the European Institute of Innovation and Technology (EIT). We are a commercial company with 27 shareholders that include top ranking industries, research centres and universities - all of them key players in the energy field. (See Figure 12.1)

We are headquartered in the Netherlands, and manage our activities through offices across Europe in Belgium, France, Germany, the Netherlands, Poland, Portugal, Spain and Sweden.

We are committed to reducing costs in the energy value chain, increasing security and reducing CO_2 and other greenhouse gas emissions. To achieve this, we focus our activities around eight thematic areas:

- **Energy Storage**
- **Energy from Chemical Fuels**
- **Sustainable Nuclear and Renewable Energy Convergence**
- **Smart and Efficient Cities and Buildings**
- **Clean Coal Technologies**
- **Smart Electric Grid**
- **Renewable Energies,** and
- **Energy Efficiency.**

Figure 12.1. InnoEnergy partners over Europe.

Supported by the EIT

InnoEnergy is funded by the EIT. The EIT is an independent body of the European Union established in March 2008, with the mission to increase European sustainable growth and competitiveness by reinforcing the innovation capacity within the European Union.

For more information on InnoEnergy please visit: www.innoenergy.com

European Institute of
Innovation & Technology

Appendix A

Further details of methodology

A detailed set of project assumptions was distributed to project participants in advance of their involvement in interviews and workshops. Assumptions that are relevant to the Technology work stream are provided below.

A.1 Definitions

Definitions of the scope of each element are provided in Sections 4 to 9 and summarised in Table A.1, below

Table A.1. Definitions of the scope of each element.

Parameter	Definition	Unit
CAPEX		
Development	Development and consenting work paid for by the developer up to the point of WCD. INCLUDES ▪ Internal and external activities such as environmental and wildlife surveys met mast (including installation) and engineering (pre-FEED) and planning studies up to FID ▪ Further site investigations and surveys after FID ▪ Engineering (FEED) studies ▪ Environmental monitoring during construction ▪ Project management (work undertaken or contracted by the developer up to WCD) ▪ Other administrative and professional services such as accountancy and legal advice ▪ Any reservation payments to suppliers EXCLUDES ▪ Construction phase insurance, ▪ Suppliers own project management.	€/MW
Turbine	Payment to wind turbine manufacturer for the supply of the nacelle and its sub-systems, the blades and hub, and the turbine electrical systems to the point of connection to the array cables. INCLUDES ▪ Delivery to nearest port to supplier ▪ 5-year warranty, and ▪ Commissioning costs. EXCLUDES ▪ Tower ▪ OMS costs, and ▪ RD&D costs.	€/MW
Support structure (including tower)	INCLUDES ▪ Payment to suppliers for the supply of the support structure comprising the foundation (including any piles, transition piece and secondary steelwork such as J-tubes and personnel access ladders and platforms) and the tower ▪ Delivery to nearest port to supplier, ▪ Warranty. EXCLUDES ▪ OMS costs ▪ RD&D costs. *Innovations in support structure and array electrical elements are reported together under balance of plant.*	€/MW

Array electrical	INCLUDES ▪ Delivery to nearest port to supplier ▪ Warranty EXCLUDES ▪ OMS costs, and ▪ RD&D costs. *Innovations in support structure and array electrical elements are reported together under balance of plant.*	€/MW
Construction	INCLUDES ▪ Transportation of all from each supplier's nearest port ▪ Pre-assembly work completed at a construction port before the components are taken offshore ▪ All installation work for support structures, turbines and array cables ▪ Commissioning work for all but turbine (including snagging post-WCD) ▪ Scour protection (for support structure and cable array), and ▪ Subsea cable protection mats etc., as required. Excludes installation of offshore substation / transmission assets.	€/MW
OPEX		
Operation and planned maintenance	Starts once first turbine is commissioned. INCLUDES ▪ Operational costs relating to the day-to-day control of the wind farm including the costs of port facilities, buildings and personnel on long-term hire. ▪ Condition monitoring ▪ Planned preventative maintenance, health and safety inspections.	€/MW/yr
Unplanned service and other OPEX	Starts once the first turbine is commissioned. Includes reactive service in response to unplanned systems failure in the turbine or electrical systems. Other OPEX covers fixed cost elements that are unaffected by technology innovations, including: ▪ Contributions to community funds, and ▪ Monitoring of the local environmental impact of the wind farm.	€/MW/yr
AEP		
Gross AEP	The gross AEP averaged over the wind farm life at the output of the turbines. Excludes aerodynamic array losses, electrical array losses and other losses. Includes any site air density adjustments from the standard turbine power curve	MWh/yr/MW
Losses	INCLUDES ▪ Lifetime energy loss from cut-in / cut-out hysteresis, power curve degradation, and power performance loss. ▪ Wake losses. ▪ Electrical array losses to the offshore metering point, and ▪ Losses due to lack of availability of wind farm elements. Excludes transmission losses.	%
Net AEP	The net AEP averaged over the wind farm life at the offshore metering point at entry to offshore substation.	MWh/yr/MW

A.2 Assumptions

Baseline costs and the impact of innovations are based on the following assumptions for offshore wind.

Global assumptions

- Real (2017) prices
- Commodity prices fixed at the average for 2016
- Market expectation "mid view"

Wind farm assumptions

General

The general assumptions are:

- A 500MW wind farm in an established Northern European market, using European supply chain
- Turbines are spaced at nine rotor diameters (downwind) and six rotor diameters (across-wind) in a rectangle
- A wind farm design is used that is certificated for an operational life of 25 years in 2017, rising to 30 years by 2030
- The lowest point of the rotor sweep is at least 22 metres above MHWS
- The development and construction costs are funded entirely by the project developer, and
- A multi-contract approach is used to contracting for construction.

Spend profile

Figure A.3. CAPEX spend profile

Year	-5	-4	-3	-2	-1	0
CAPEX Spend			6%	10%	34%	50%

Year 1 is defined as year of first full generation.
AEP and OPEX are assumed as 100% for each year within the operational lifetime.

Meteorological regime

The meteorological regime assumptions are:

- A wind shear exponent of 0.12
- Rayleigh wind speed distribution
- A mean annual average temperature of 10°C
- The tidal range of 4m and the Hs of 1.8m is exceeded on 15% of the days over a year at Site Type A and 25% of the days at Site Type D, and
- No storm surge is considered.

Turbine

The turbine assumptions are:

- The turbine is certified to Class IA to international offshore wind turbine design standard IEC 61400-3
    - The 6MW baseline turbine has a three-bladed upwind, three-stage gearbox, a partial-span power converter, a doubly-fed induction generator, 1500 rpm 690VAC output, and 90 m/s tip speed. It has a rotor of 154m diameter, and a specific rating of around 325W/m^2 (which is representative of the products at this scale available for FID in 2017, namely the SWP 6MW, Senvion 6.2M126/152 and GE Haliade 6MW turbines).
    - The 8MW, 10MW and 12MW turbines have a low-ratio gearbox mid speed, mid-voltage AC generator. The rotor diameters are 164m, 190m and 205m, respectively, and hence they have the same specific rating as the 6MW turbine.

Support structure

The support structure assumptions are:

- A monopile with separate transition piece and tower is used for wind farms on Site Type A and for 6MW, 8MW and 10MW turbines on site type D; and a four-legged piled jacket with a separate tower is used for 12MW-Size Turbines on Site Type D, and
- Ground conditions are "typical", namely 10m dense sand on 15m stiff clay, only occasionally with locations with lower bearing pressure, the presence of boulders or significant gradients.

Array electrical

The array electrical assumption is that a three core 33kV AC cable in fully flexible strings is used, that is, with provision to isolate an individual turbine.

Construction

The construction assumptions are:

- Construction is carried out sequentially by the foundation, array cable, then the pre-assembled tower and turbine together
- A jack-up vessel collects components from the construction port for turbine installation
- A single jack-up is used to install the monopile and transition pieces
- Two jack-ups are used for jacket installation and pre-piling, collecting components from the construction port, and
- Array cables are installed via J-tubes, with separate cable lay and survey and burial.
- Decommissioning reverses the assembly process to result in construction taking one year. Piles and cables are cut off at a depth below the sea bed, which is unlikely to lead to uncovering. Environmental monitoring is conducted at the end. The residual value and cost of scrapping are ignored.

OMS

Baseline access is by work boats for Site Type A and mother ships or accommodation platforms for Site Type D, while jack-ups are used for major component replacement.

A.3 Other Effects

The table below corresponds to definitions made in Section 2.4. These figures are derived from internal BVGA modelling, first used in the Offshore Wind Cost Reduction Pathways Study and are provided for completeness. They do not form an integral part of the study.

DECEX includes:

- Planning work and design of any additional equipment required
- Removal of the turbine and support structure to meet legal obligations, and
- Further environmental work and monitoring.

Table A.4. Summary of the impact of other effects.

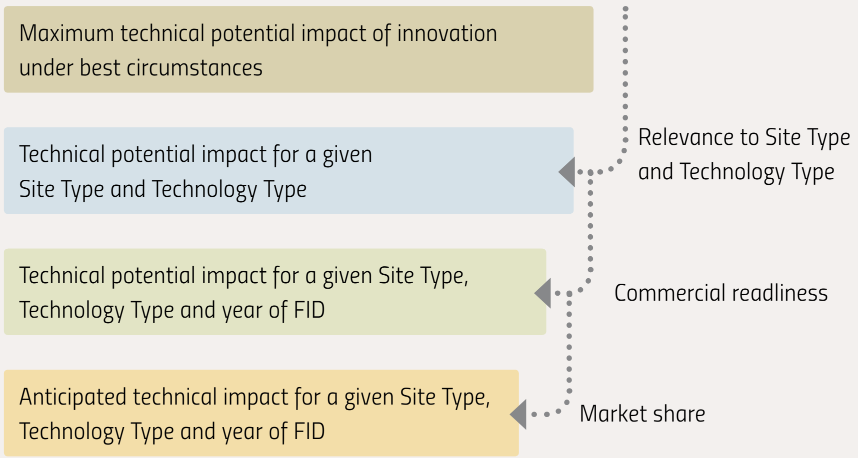
Tech-Site-FID	Transmission land rent	Insurance and contingency	Pre-FID risk	Supply chain	Decommissioning costs	WACC	Lifetime
6-A-17	29.8%	6.7%	1.6%	-6.0%	1.8%	6.3%	25
8-A-17	31.8%	6.9%	1.6%	-9.0%	1.6%	6.3%	25
6-D-17	46.9%	6.5%	1.5%	-5.0%	1.7%	6.3%	25
8-D-17	50.0%	6.6%	1.5%	-8.0%	1.5%	6.3%	25
6-A-20	23.6%	6.3%	1.5%	-8.0%	1.5%	6.0%	27
8-A-20	26.1%	6.5%	1.6%	-11.0%	1.3%	6.0%	27
10-A-20	27.8%	6.7%	1.6%	-13.0%	1.2%	6.0%	27
6-D-20	33.8%	6.1%	1.5%	-7.0%	1.4%	6.0%	27
8-D-20	36.1%	6.3%	1.5%	-10.0%	1.2%	6.0%	27
10-D-20	38.3%	6.5%	1.5%	-11.5%	1.2%	6.0%	27
8-A-25	23.2%	6.1%	1.5%	-12.0%	1.0%	5.7%	30
10-A-25	24.1%	6.2%	1.6%	-15.0%	0.9%	5.7%	30
12-A-25	24.8%	6.3%	1.6%	-17.5%	0.9%	5.7%	30
8-D-25	32.6%	5.9%	1.5%	-13.0%	0.9%	5.7%	30
10-D-25	34.7%	6.1%	1.5%	-15.0%	0.9%	5.7%	30
12-D-25	35.9%	6.3%	1.6%	-17.0%	0.8%	5.7%	30
10-A-30	24.1%	6.0%	1.6%	-18.0%	0.9%	5.4%	30
12-A-30	24.5%	6.1%	1.6%	-20.0%	0.8%	5.4%	30
10-D-30	34.4%	6.0%	1.5%	-18.0%	0.9%	5.4%	30
12-D-30	35.7%	6.2%	1.6%	-20.0%	0.8%	5.4%	30

A.4 Example calculation of change in LCOE for a given innovation

The following example is intended to show the process of derivation and moderation of the impact of an innovation. There is some explanation of the figures used, but the focus is on methodology rather than content. The example used is the impact of improvements in jacket design and design standards for a project using 12MW-Size Turbines on Site Type D.

To consider the impact of a technology innovation, a measure of LCOE is used, based on a fixed WACC. The CAPEX spend profile is annualised by applying a factor of 0.0992, which is based on a discount rate of 8.0%, as an average across the duration of interest.

Figure A.1. Four stage process of moderation applied to the maximum potential technical impact of an innovation to derive anticipated impact on the LCOE. Note that Technology Type in this study means Turbine Size.



Maximum technical potential impact. Based on work in the Offshore Wind Cost Reduction Pathways Study and updated to reflect current industry thinking, the combined potential effect of improvements in jacket design and design standards is a potential 3.64% reduction in support structure cost and a 0.61% reduction in construction cost. No potential impact on other CAPEX terms, OPEX or energy terms is modelled.

Relevance to Site Types and Turbine Size. Projects using 6MW-12MW-Size Turbines on Site Type A are modelled as using monopiles, hence this innovation is not relevant. Projects using 12MW-Size Turbines on Site Type D are modelled as using jacket support structures. The innovation is fully relevant to this Turbine Size and Site Type, so the relevance is modelled as 100%.

Commercial readiness. The development and introduction time for improving existing designs is relatively short. By definition, 100% of the potential of this innovation is modelled as available for wind farms reaching FID in 2030.

Market share. Based on industry feedback, the market share for this innovation for projects using 12MW-Size Turbines in 2030 is modelled as 90%.

The anticipated LCOE impact is evaluated by comparison of the LCOE calculated for the baseline case with the LCOE calculated for the target case. The target case includes the impact of the innovation on the costs for each element and AEP parameters, as well as the effects of relevance to Site Type and Turbine Size, commercial readiness and market share. Target case impacts are calculated as follows:
Impact for support structure CAPEX = Maximum potential impact (3.64%)
x Relevance to Site Type D and 12MW-Size Turbine (100%) = 3.64%
x Commercial readiness at FID in 2030 (100%) = 3.64%
x Market share for project using 12MW-Size Turbine with FID in 2030 (90%) = 3.28%

Impact for construction CAPEX = Maximum potential impact (0.61%)
x Relevance to Site Type D and 12MW-Size Turbine (100%) = 0.61%
x Commercial readiness at FID in 2030 (100%) = 0.61%
x Market share for project using 12MW-Size Turbine with FID in 2030 (90%) = 0.55%

The LCOE for the baseline and target cases then is calculated as in Table A.5. The anticipated impact of the innovation on the LCOE for this case is therefore (54.9 - 55.2) / 55.2 = -0.5% or a 0.5% reduction in the LCOE. For the 10MW- and 12MW-Size Turbines, a baseline scaled to FID 2017 is used so that the same innovations may be applied for all Turbine Sizes. These baselines are mathematical artefacts and should not be thought of as the real cost or energy values for real wind farms with FID in 2017.

Table A.5. Calculation of the LCOE from cost and AEP data.

Parameter	Units	Baseline case (Theoretical 10-D-14)	Target case 10-D-30
Support structure CAPEX	€k/MW	496	496 x (1 - 0.0328) = 480
Construction CAPEX	€k/MW	279	279 x (1 - 0.0055) = 278
Other CAPEX	€k/MW	1,263	1,263
Total CAPEX	€k/MW	2,039	2,021
OPEX	€k/MW/yr	72	72
Net AEP	MWh/yr/MW	4,381	4,381
LCOE	€/MWh	(2,039 x 0.0833 + 72) / 4381 = 55.2	(2,021 x 0.0833 + 72) / 4381 = 54.9

Table A.6. Theoretical baseline case for 12MW-Size Turbines on Site Type D with FID in 2017.

Element	Units	Theoretical 12-D-17
Development	€k/MW	93
Turbine	€k/MW	1,125
Support structure	€k/MW	496
Array electrical	€k/MW	45
Construction	€k/MW	279
Operations and planned maintenance	€k/MW/yr	31
Unplanned service and other OPEX	€k/MW/yr	41
Gross AEP	MWh/MW/yr	5,207
Losses	%	15.9

Appendix B

Data supporting tables

Table B.1. Data relating to Figure 3.1.

Element	Units	6-A-17	8-A-17	10-A-20	12-A-25	6-D-17	8-D-17	10-D-20	12-D-25
Development	€k/MW	96	92	90	88	102	97	94	93
Turbine	€k/MW	966	1,003	1,030	1,049	986	1,023	1,051	1,070
Support structure	€k/MW	517	489	449	379	648	590	531	476
Array electrical	€k/MW	54	50	44	37	54	51	46	37
Construction	€k/MW	422	341	279	211	441	360	295	221

Table B.2. Data relating to Figure 3.2.

Element	Units	6-A-17	8-A-17	10-A-20	12-A-25	6-D-17	8-D-17	10-D-20	12-D-25
Operations and planned maintenance	€k/MW/yr	36	33	31	29	40	36	32	30
Unplanned service and other OPEX	€k/MW/yr	49	43	36	29	62	57	44	32
Net capacity factor	%	42.5	43.3	44.5	46.4	48.3	49	50.2	52.3

Table B.3. Data relating to Figure 3.3.

Element	Units	6-A-17	8-A-17	10-A-20	12-A-25	6-D-17	8-D-17	10-D-20	12-D-25
LCOE including Other Effects	€/MWh	93.2	84.3	67.5	51.6	104.9	95.9	71.6	53.8
LCOE as % of 6-D-17	%	89	80	64	49	100	91	68	51
Net capacity factor	%	42.5	43.3	44.5	46.4	48.3	49	50.2	52.3

Table B.4. Data relating to Figure 4.1.

Impact of innovation on...	6-A	6-D	8-A	8-D	10-A	10-D	12-A	12-D
CAPEX	-0.3%	-0.3%	-1.2%	-1.5%	-1.5%	-1.7%	-0.5%	-0.5%
OPEX	-0.1%	-0.1%	-0.8%	-0.8%	-1.7%	-1.7%	-1.1%	-1.1%
Net AEP	0.1%	0.1%	0.5%	0.4%	1.0%	0.9%	0.6%	0.6%
LCOE	-0.3%	-0.3%	-1.6%	-1.7%	-2.5%	-2.6%	-1.3%	-1.3%

Table B.5. Data relating to Figure 5.1

Impact of innovation on...	6-A	6-D	8-A	8-D	10-A	10-D	12-A	12-D
CAPEX	-0.3%	-0.3%	-0.4%	-0.4%	-2.1%	-2.0%	-1.3%	-1.3%
OPEX	-1.7%	-1.8%	-5.7%	-6.2%	-7.1%	-7.7%	-3.0%	-3.1%
Net AEP	0.2%	0.2%	0.9%	0.9%	1.0%	0.9%	0.5%	0.5%
LCOE	-1.0%	-1.0%	-2.9%	-3.2%	-4.5%	-4.7%	-2.3%	-2.4%

Table B.6. Data relating to Figure 6.1.

Impact of innovation on...	6-A	6-D	8-A	8-D	10-A	10-D	12-A	12-D
CAPEX	-0.4%	-0.3%	-1.3%	-1.3%	-1.3%	-1.2%	-0.4%	-0.3%
OPEX	-0.3%	-0.3%	-1.1%	-1.1%	-1.6%	-1.7%	-0.7%	-0.7%
Net AEP	0.2%	0.2%	1.2%	1.2%	3.6%	3.6%	2.1%	2.1%
LCOE	-0.6%	-0.6%	-2.4%	-2.4%	-4.8%	-4.8%	-2.5%	-2.5%

Table B.7. Data relating to Figure 7.1.

Impact of innovation on...	6-A	6-D	8-A	8-D	10-A	10-D	12-A	12-D
CAPEX	-0.9%	-1.0%	-2.5%	-2.7%	-3.0%	-3.2%	-1.2%	-2.2%
OPEX	0.0%	0.0%	0.0%	0.0%	-0.1%	0.0%	-0.1%	-0.2%
Net AEP	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
LCOE	-0.6%	-0.7%	-1.8%	-1.8%	-2.1%	-2.2%	-0.9%	-1.7%

Table B.8. Data relating to Figure 8.1.

Impact of innovation on...	6-A	6-D	8-A	8-D	10-A	10-D	12-A	12-D
CAPEX	-1.5%	-1.6%	-3.1%	-3.5%	-2.9%	-3.2%	-1.1%	-1.7%
OPEX	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Net AEP	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LCOE	-1.0%	-1.1%	-2.1%	-2.3%	-2.0%	-2.2%	-0.8%	-1.2%

Table B.9. Data relating to Figure 9.1.

Impact of innovation on...	6-A	6-D	8-A	8-D	10-A	10-D	12-A	12-D
CAPEX	0.0%	0.0%	0.2%	0.2%	0.3%	0.3%	0.2%	0.2%
OPEX	-1.1%	-1.7%	-3.4%	-5.6%	-4.3%	-7.0%	-2.0%	-3.7%
Net AEP	0.2%	0.2%	0.7%	0.8%	1.0%	1.0%	0.5%	0.5%
LCOE	-0.6%	-0.8%	-1.7%	-2.6%	-2.0%	-2.9%	-0.9%	-1.4%

Table B.10. Data relating to Figure 10.1

Impact of innovation on...	6-A	6-D	8-A	8-D	10-A	10-D	12-A	12-D
CAPEX	-3.3%	-3.6%	-8.1%	-8.8%	-10.3%	-10.9%	-4.4%	-5.9%
OPEX	-3.2%	-3.9%	-10.5%	-13.1%	-13.7%	-16.8%	-6.4%	-8.3%
Net AEP	0.8%	0.7%	3.4%	3.4%	6.6%	6.5%	3.6%	3.6%
LCOE	-4.0%	-4.4%	-11.9%	-13.2%	-16.7%	-18.0%	-8.3%	-9.8%

Table B.11. Data relating to Figure 10.2.

Impact of innovation on...		6-A	6-D	8-A	8-D	10-A	10-D	12-A	12-D
CAPEX	**Inherited innovation**	0.0%	0.0%	-3.1%	-7.8%	0.0%	0.0%	-3.4%	-8.4%
	Power increase	0.0%	-3.8%	-4.5%	-6.0%	0.0%	-4.7%	-5.8%	-6.1%
	New innovation	-3.3%	-7.9%	-9.7%	-4.1%	-3.6%	-8.6%	-10.2%	-5.5%
OPEX	**Inherited innovation**	0.0%	0.0%	-2.9%	-8.6%	0.0%	0.0%	-3.4%	-10.5%
	Power increase	0.0%	-10.9%	-17.7%	-21.8%	0.0%	-8.3%	-19.7%	-26.8%
	New innovation	-3.2%	-9.9%	-12.4%	-5.7%	-3.9%	-12.4%	-14.8%	-7.2%
Net AEP	**Inherited innovation**	0.0%	0.0%	0.8%	3.1%	0.0%	0.0%	0.8%	3.0%
	Power increase	0.0%	1.7%	3.9%	6.3%	0.0%	1.4%	3.2%	5.3%
	New innovation	0.8%	3.5%	6.7%	3.8%	0.7%	3.4%	6.6%	3.8%
LCOE	**Inherited innovation**	0,0%	0,0%	-3,6%	-10,2%	0,0%	0,0%	-3,9%	-11,1%
	Power increase	0,0%	-7,6%	-11,8%	-15,3%	0,0%	-7,1%	-13,0%	-16,6%
	New innovation	-4,0%	-11,4%	-15,1%	-7,4%	-4,4%	-12,7%	-16,1%	-8,6%

Table B.12. Data relating to Figure 10.3 and Figure 10.4.

Element	Units	6-A-17	8-A-17	6-A-20	8-A-20	10-A-20	8-A-25	10-A-25	12-A-25	10-A-30	12-A-30
Development	€k/MW	96	92	96	92	90	92	90	88	89	87
Turbine	€k/MW	966	1003	955	992	1030	976	1005	1049	971	1020
Support structure	€k/MW	517	489	496	469	449	437	418	379	390	359
Array electrical	€k/MW	54	50	52	48	44	42	39	37	36	34
Construction	€k/MW	422	341	389	313	279	267	239	211	212	187
Operations, planned maintenance	€k/MW/yr	36.3	32.8	36.1	32.6	30.5	31.8	29.8	28.7	29.0	28.0
Unplanned service and other OPEX	€k/MW/yr	48.9	42.6	46.5	39.7	35.7	35.7	31.6	29.5	28.1	26.5
Net capacity factor	-	43%	43%	43%	44%	44%	45%	46%	46%	47%	48%

Element	Units	6-A-17	8-A-17	6-A-20	8-A-20	10-A-20	8-A-25	10-A-25	12-A-25	10-A-30	12-A-30
Development	€k/MW	102	97	102	98	94	98	95	93	93	92
Turbine	€k/MW	986	1023	974	1012	1051	996	1025	1070	991	1040
Support structure	€k/MW	648	590	621	566	531	526	492	476	459	435
Array electrical	€k/MW	54	51	52	48	46	43	41	37	38	34
Construction	€k/MW	441	360	401	326	295	273	248	221	217	184
Operations, planned maintenance	€k/MW/yr	40.0	36.1	39.5	35.7	32.1	34.3	30.8	29.5	29.7	28.5
Unplanned service and other OPEX	€k/MW/yr	61.6	56.6	58.2	52.5	43.7	46.3	38.0	32.1	33.4	28.0
Net capacity factor	-	48%	49%	49%	50%	50%	51%	52%	52%	53%	54%

Table B.13. Data relating to Figure 10.5.

	Units	6-A-17	8-A-17	6-A-20	8-A-20	10-A-20	8-A-25	10-A-25	12-A-25	10-A-30	12-A-30
Net capacity factor	-	42.5%	43.3%	42.9%	43.8%	44.5%	44.7%	45.8%	46.4%	47.4%	48.1%
LCOE including Other Effects	€/MWh	93.2	84.3	79.5	71.7	67.5	60.9	55.7	52.2	48.8	46.2
Net capacity factor	-	48.3%	49.0%	48.7%	49.5%	50.2%	50.6%	51.7%	52.3%	53.5%	54.2%
LCOE including Other Effects	€/MWh	104.9	95.9	85.2	77.0	71.6	63.4	57.8	54.4	50.3	47.0

Table B.14. Data relating to Figure 10.6.

Innovation	Relative impact of innovation on LCOE
LCOE for a wind farm with FID in 2017	100.0%
Increase in turbine rating	16.6%
Introduction of multi-variable optimisation of array layouts	1.1%
Improvements in range of working conditions for turbine installation	1.1%
Improvements in blade aerodynamics	1.1%
Improvements in blade materials and manufacture	1.0%
Improvements in AC power take-off system design	1.0%
Improvements in components (nacelle)	1.0%
Improvements in monopile designs and design standards	0.9%
Improvements in monopile manufacturing	0.9%
49 other innovations	11.7%
LCOE for a wind farm with FID in 2030	63.7%

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