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Renewable Energies

Future renewable energy costs: offshore wind

How technology innovation is anticipated to reduce the cost of energy from European offshore wind farms

BVGassociates

BVG Associates

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- Market leaders and new entrants in wind turbine supply and UK and EU wind farm development
- 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.

KIC InnoEnergy

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Executive summary

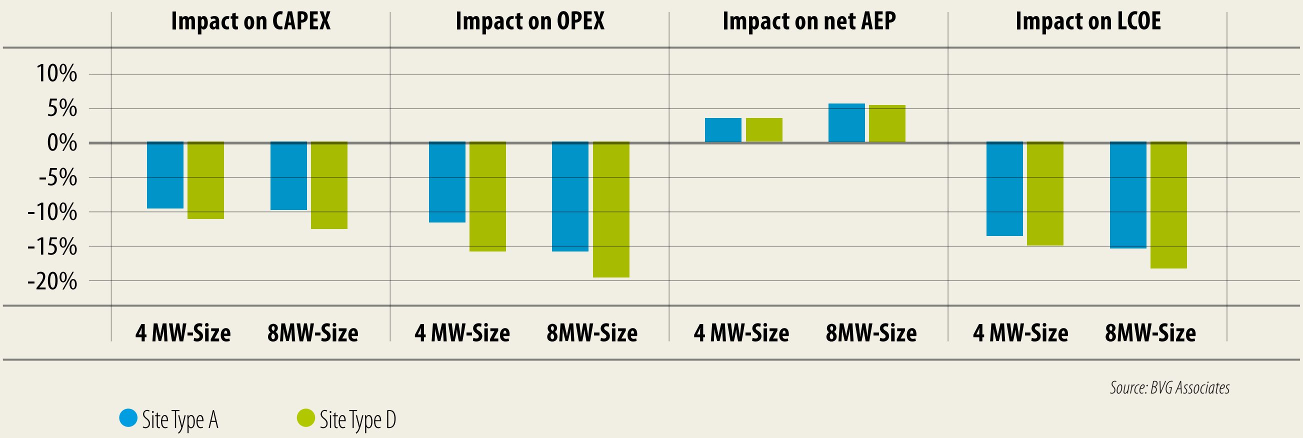
KIC InnoEnergy is developing credible future technology cost models for four renewable energy generation technologies using a consistent and robust methodology. The purpose of these cost models is to enable the impact of innovations on the levelised cost of energy (LCOE) to be explored and tracked in a consistent way across the four technologies. While the priority is to help focus on key innovations, credibility comes with a realistic overall LCOE trajectory.This report examines how technology innovation is anticipated to reduce the cost of energy from European offshore wind farms over the next 12-15 years.

For this offshore wind report, input data is closely based on the Technology work stream of The Crown Estate's *Offshore Wind Cost Reduction Pathways Study* published in June 2012. The output of that work was a comprehensive, transparent evidence base built through significant industry engagement, detailed benchmarking and modelling of costs and the definition and assessment of the impact of many discrete innovations. For this report, the analysis has been simplified and updated, including via fresh engagement with industry and extending the window of time within which the cost of energy is considered.

At the heart of this study is a cost model in which elements of baseline wind farms are impacted on by a range of technology innovations. These wind farms are defined in terms of the turbine size (rated power 4MW and 8MW), site conditions (Site Type A: 40km from construction port at 25m water depth, and Site Type D: 125km from port at 35m water depth, both with different wind conditions), and three points in time at which the projects reach the final investment decision (FID) (2014 (the baseline), 2020 and 2025), following the definitions of the *Offshore Wind Cost Reduction Pathways Study*.

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 0.1.

Figure 0.1 **Anticipated impact of all innovations by Turbine Size and Site Type with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**[1]

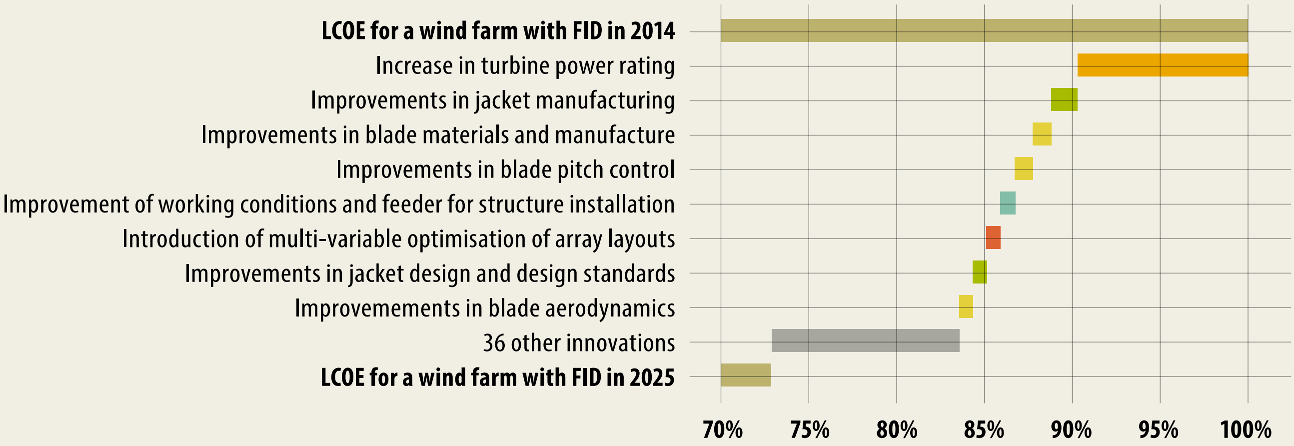


The study demonstrates that the key transition is from a typical wind farm with FID in 2014, which uses turbines with a rated power of 4MW, to the use of 8MW turbines for a project with FID in 2025. The figures used throughout this summary relate to this transition on a 500MW wind farm that is 125km from port and installed at 35m water depth.

The impacts from wind farm technology innovations (excluding transmission, decommissioning, supply chain and finance effects) contribute an anticipated 27% reduction in the LCOE. Figure 0.2 shows that well over half of the total anticipated technology impact is achieved through eight areas of innovation, of which the largest is the increase in turbine size from 4MW to 8MW. 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 operation, maintenance and service (OMS). All of the next generation turbines under development today have more optimum-sized rotors than used to date and therefore have higher gross energy production per megawatt, even before taking into account increased reliability and maintainability. The combined impact of larger turbines with optimum-sized rotors, improved aerodynamics and control and next generation drive train designs on the LCOE is about 13%.

1 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.

Figure 0.2 **Anticipated impact of technology innovations for a wind farm using 8MW-Size Turbines with FID in 2025, compared with a wind farm with 4MW-Size Turbines with FID in 2014.**[2]



Almost 50 technology innovations were identified as having the potential to cause a substantive reduction in LCOE through a change in the design of hardware, software or process. Technology innovations are distinguished from supply chain innovations, which are addressed separately. Many more technical innovations are in development, so some of those described in this report may be superseded by others. Overall, however, industry expectation is that the LCOE will reduce by the aggregate level described. In most cases, the anticipated impact of each innovation has been significantly moderated downwards in order to give overall LCOE reductions in line with industry expectations. The availability of this range of innovations with the potential to impact LCOE further gives confidence that the picture described is achievable.

To calculate a realistic LCOE for each scenario, real-world effects of supply chain dynamics, pre-FID risks, cost of finance, transmission and decommissioning are considered in addition to technology innovations.

In wind farm development, through investments in engineering and site characterisation, the LCOE is anticipated to reduce by about 2% in the period. The principal innovations relate to greater levels of analysis and optimisation during the front-end engineering design studies (FEED).

Aside from an increase in the turbine power rating, which has an anticipated impact on the LCOE of almost 10% in the period, other innovations within the turbine nacelle are anticipated to reduce the LCOE by about 3% in the period. The major benefit here comes from the introduction of next-generation drive trains, including direct-drive and mid-speed generator solutions, which are anticipated to reduce OPEX through greater reliability. A challenge for turbine manufacturers will be to demonstrate this reliability to customers with experience of operational issues to date. A step change in verification testing and increased openness is seen as critical to achieving this.

Together, all innovations in rotor components offer about a 5% 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 designs and manufacture and aerodynamic control.

2 Comparison is on Site Type D as defined in Section 2.

The impact of innovations in balance of plant is dominated by improvements in jacket foundation 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 jacket design, 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 4% in the period.

These savings do not include the introduction of concrete gravity base foundations. While these offer some benefit to support structure supply costs, especially in an environment of higher steel prices, their primary benefit is through reduced construction costs if installed as part of a float-out-and-sink strategy. The potential of such strategies is significant, minimising offshore construction, but it is anticipated that much of this benefit will be achieved only on projects reaching FID after 2025. Shorter term benefits will come from the introduction of installation vessels that can operate in a wider range of conditions and bespoke fleets of vessels for jacket foundation installation, where costs can be reduced through the introduction of large, floating heavy lift vessels designed for offshore wind. 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: a move to holistic, condition-based maintenance, with reduced downtime and the frequency of large component retrofits; improvements in the transfer of personnel from vessel to turbine; and improvements in holistic wind farm control. 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 3% in the period.

Overall, reductions in CAPEX per megawatt installed over the period are anticipated to be about 15%. OMS costs are anticipated to reduce by approximately 40% and AEP is anticipated to increase by about 8% per megawatt. From a higher baseline, CAPEX reductions are greater for the site further from shore. This is due to the relatively larger impact of the use of feeder solutions and innovations to increase the envelope of working conditions. OPEX reductions are also largest further from shore due to the greater opportunity for innovation when moving from today's state-of-the-art sites to sites with more severe conditions.

Reductions are also more significant for turbines with higher rated power, partly as innovations are anticipated to be more fully implemented on new, larger turbines than on existing platforms that are nearing the end of their product lifecycles.

There are a range of innovations not discussed in detail in this report because their anticipated impact is still negligible on projects reaching FID in 2025. Among these are new turbine concepts, such as two-bladed rotors, generally regarded as well suited to offshore conditions, and floating foundation solutions, enabling access to higher wind speed sites close to shore. At a wind farm level, centralised grid control and moving complexity from each turbine to the substation offers the prospect of further savings, along with changes to the wind farm design life. At a system level, it is anticipated that there will be significant further progress in terms of high voltage direct current (HVDC) networks for transmission. The unused potential at FID in 2025 of innovations modelled in the project, coupled with this further range of innovations not modelled, suggests there are significant further cost reduction opportunities when looking to 2030 and beyond.

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 application of 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 is all turbines 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 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.

Hs. Significant wave height

LCOE. Levelised cost of energy, considered here as pre-tax and real in end 2013 terms. For details of methodology, see Section 2.

MHWS. Mean high water springs.

MSL. Mean sea level.

MW. Megawatt.

MWh. Megawatt hour.

OMS. Operation, planned Maintenance and unplanned (proactive or reactive) Service in response to a fault.

OPEX. Operational expenditure.

Other Effects. Effects beyond those of wind farm 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 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.

Scenario. A specific combination of Site Type, Turbine Size and year of FID.

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 Scenario. Used to calculate real-world LCOE incorporating Other Effects.

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, KIC InnoEnergy is interested in 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.

In publishing a set of consistent analyses of various technologies, KIC InnoEnergy seeks 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. In addition, it seeks to help solve the existing challenges at the European level: reducing energy dependency, mitigating climate change effects and facilitating the smooth evolution of the generation mix for the final consumers.

With a temporal horizon out to 2025, this work includes a range of innovations that might be further from the market than normally expected from KIC InnoEnergy. This constitutes a longer term approach, complementary to the KIC 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 anticipated future offshore wind cost of energy to projects reaching their financial investment decision (FID) in 2025, by reference to robust modelling of the impact of a range of technical innovations and other effects. This work is based on *Offshore Wind Cost Reduction Pathways: Technology work stream*[3], published in June 2012, refreshed to bring it up to date. This earlier work involved significant industry engagement, as detailed in the above report. This has been augmented by continued dialogue with players across industry, right up until publication of this report.

3 The Crown Estate, (June 2012), available online at www.bvgassociates.co.uk/Publications/BVGAssociatespublications.aspx.

The study does not consider the market share of the different Turbine Sizes and Site Types considered. 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.

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 four 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, including the sea bed connection and secondary steel work to provide personnel and equipment access and array cable support. It also considers subsea cables connecting turbines to any substation only. Cable protection is covered under innovations in wind farm construction. Offshore and onshore substations and export cables are not considered. These transmission costs are including 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 up 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 technology-related conclusions.

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

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 different representative Turbine Sizes on given Site Types, impacted on by a range of technology innovations. Analysis is carried out at a number of points in time (years of FID), thus describing various potential pathways that the industry could follow, each with an associated progression of LCOE. The model has been somewhat simplified from that used in *Offshore Wind Cost Reduction Pathways: Technology work stream*.

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, covering technical and non-technical 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.

Changes in percentages (for example, losses) are expressed as a relative change. For example, if losses are decreased by 5% from a baseline of 10%, then the resultant losses are 9.5%.

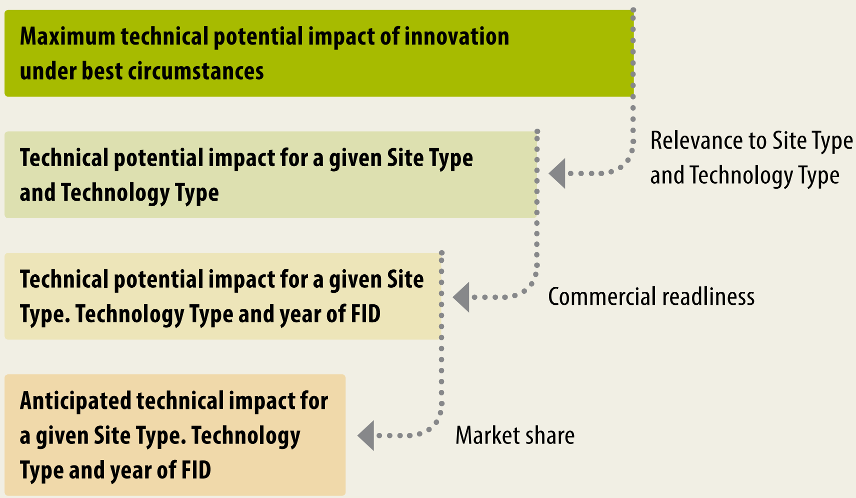
2.3. Technology innovation modelling

The basis of the model is an assessment of the differing impact of technology innovations in 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 in detail. 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. Maximum technical potential impact

Each innovation may impact a range of different costs or operational parameters, as listed in Table 2.1. The maximum technical potential impact on each of these is recorded separately for the Turbine Size and Site Type most suited to the given innovation. Where relevant and where possible, this maximum technical impact considers timescales that may be well beyond the final year of FID considered in this study.

Frequently, the potential impact of an innovation can be realised in a number of ways, for example, through reduced CAPEX or OPEX or increased AEP. The analysis uses the implementation resulting in the largest reduction in the LCOE, which is a combination of CAPEX, OPEX and AEP.

Table 2.1 **Information recorded for each innovation.** (%)	**Impact on cost of**	**Impact on**
	• Wind farm development • Wind turbine • Support structure • Array electrical • Construction, and • Wind farm operation, maintenance and service	• Gross AEP, and • Losses

2.3.2. Relevance to Site Types and Turbine Sizes

This maximum technical potential impact of an innovation compared with the baseline may not be realised on both Site Types with both 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 significant benefit on smaller turbines, so the relevance of this innovation to 4MW-Size Turbines is set to 0%. In other cases, the maximum technical potential may only be realised on some Site Types, with a lower technical potential realised on others. 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. In this way, relevance indicators for a given Turbine Size and Site Type may be between zero and 100%, with (in almost all cases) at least one Turbine Size and Site Type combination having 100% relevance.

This relevance is modelled by applying a factor specific to each combination of Site Type and Turbine Size independently for each innovation. The factor for a given Site Type and Turbine Size combination is applied uniformly to each of the technical potential impacts derived above.

2.3.3. Commercial readiness

In some cases, the technical potential of a given innovation will not be fully realised even on a project reaching FID in 2025. This may be for a number of reasons:

- Long research, development and demonstration period for an innovation
- 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.

This commercial readiness is modelled by defining a factor for each innovation specific to each year of FID, defining how much of the technical potential of the innovation is available to projects reaching FID in that year. If the figure is 100%, this means that the full technical potential is realised by the given 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, taking into account not only the supplier offering the innovation for sale but also the customer's appetite for purchase. 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 to the market.

2.3.4. Market share

Many innovations are compatible with others, but some are not. For example, innovations relating to monopiles and jackets are not compatible, nor are geared and gearless drive train solutions. Each innovation is assigned to one or more groups (combinations) of complementary innovations and each group is then assigned a market share for each Turbine Size and year of FID. This is a market share of a group of innovations for a given Turbine Size for projects reaching FID in a given year. It is not a market share of the innovation in the whole of the market that consists of a range of projects with different Turbine Sizes and Site Types.

The resulting anticipated impact of a given innovation, as 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 2.1.

These impacts are then applied to the baseline costs and operational parameters 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).

The aggregate impact of all innovations on each operational and energy-related parameter in Table 2.1 is also derived, enabling a technology-only LCOE to be derived for each Turbine Size, Site Type and FID year combination.

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, taking into account risk
- Transmission and land cost, covering transmission capital and operating costs and charges related to the infrastructure from input to offshore substation to the transmission network and typical sea bed lease fees
- Supply chain dynamics, simplifying the impact of the supply chain levers such as competition and collaboration discussed in EC Harris' *Offshore Wind Cost Reduction Pathways: Supply chain work stream*[4]
- 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 reach 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, as described in Appendix A.

A factor for each of these effects was derived from the results of the other work streams of the *Offshore Wind Cost Reduction Pathways Study* or each specific Turbine Size, Site Type and FID year, as presented in Appendix A.

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

The factors are applied as follows:

- Scenario-specific WACC is 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 WACC, that is, a 19.8% effect to account for transmission costs (the first factor in Table A.4) is applied as a factor of 1.198.

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 of primary importance 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. Although difficult to quantify whether fully captured in the assessments, in some cases, preserving similar levels of health and safety limited the range of innovations modelled. 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
- The increased reliability of turbines and hence fewer transfers to turbines and less time working in the offshore environment, and
- Condition monitoring / remote diagnostics, which provide a more effective and proactive service and hence result in fewer complex retrofits.


Courtesy of ABB

3. Baseline wind farms

The modelling process described in Section 2 is to:

- 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.

This section summarises the costs and other parameters for the baseline wind farms. The baselines were developed from the analysis undertaken to deliver *The Crown Estate Offshore Wind Cost Reduction Pathways Technology Work Stream* report, based on the technical parameters of the baseline wind farms (see Appendix A). Additional adjustments were applied to account for inflation and exchange rates.

It is recognised that 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.

The baseline costs presented in Table 3.1, Figure 3.1 and Figure 3.2 are nominal contract values, rather than outturn values, and are for projects reaching FID in 2014. As such, they incorporate real-life supply chain effects such as the impact of competition. All results presented in this report incorporate the impact of technology innovations only, except for when the LCOE are presented in Figure 3.3 and in Section 10.3, which also incorporate the other effects discussed in Section 2.4.

It is assumed that the first 8MW-Size Turbines will be commercially available to the market for projects with FID in 2014, as demonstrated by DONG Energy's commitment to use the V164-8.0MW turbine for its Burbo Bank extension offshore wind farm project. "Commercially available" means that it is technically possible to build such turbines in volume and that they have been sufficiently prototyped and demonstrated so they have a reasonable prospect of sale into a 500MW project. No assumptions are made in this report about the market share of 8MW-Size Turbines compared with 4MW-Size Turbines.

Table 3.1 **Baseline parameters.**

Type	Parameter	Units	4-A-14	4-D-14	8-A-14	8-D-14
CAPEX	Development	€k/MW	101	108	90	95
	Turbine	€k/MW	1,279	1,279	1,498	1,498
	Support structure	€k/MW	677	861	689	722
	Array electrical	€k/MW	98	99	89	91
	Construction	€k/MW	543	645	320	496
OPEX	Operations and planned maintenance	€k/MW/yr	31	37	23	28
	Unplanned service and other OPEX	€k/MW/yr	65	78	48	57
AEP	Gross AEP	MWh/yr/MW	4,459	5,022	4,551	5,089
	Losses	%	18.6	17.3	17.6	16.2
	Net AEP	MWh/yr/MW	3,628	4,154	3,750	4,263
	Net capacity factor	%	41.4	47.4	42.8	48.7

Source: BVG Associates

Figure 3.1 **Baseline CAPEX by element.**
Note: Development data points are partially overlapped by array electrical data points.

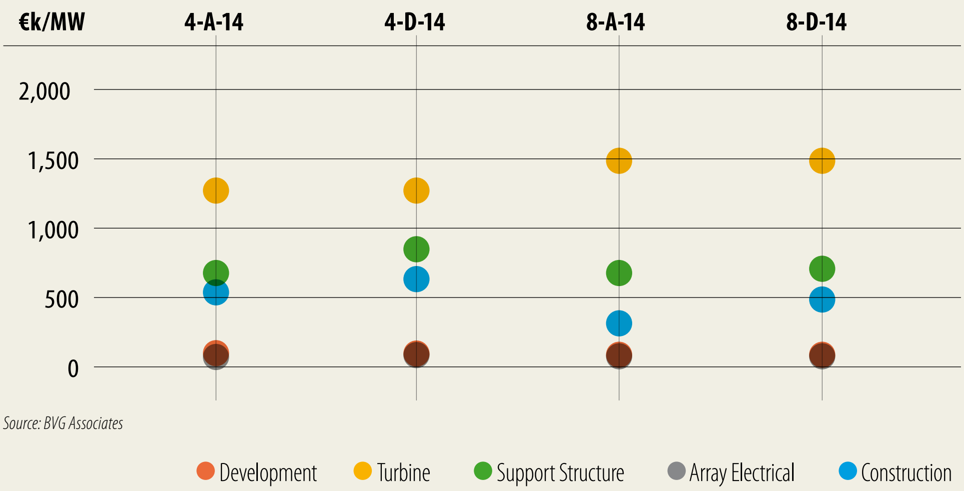
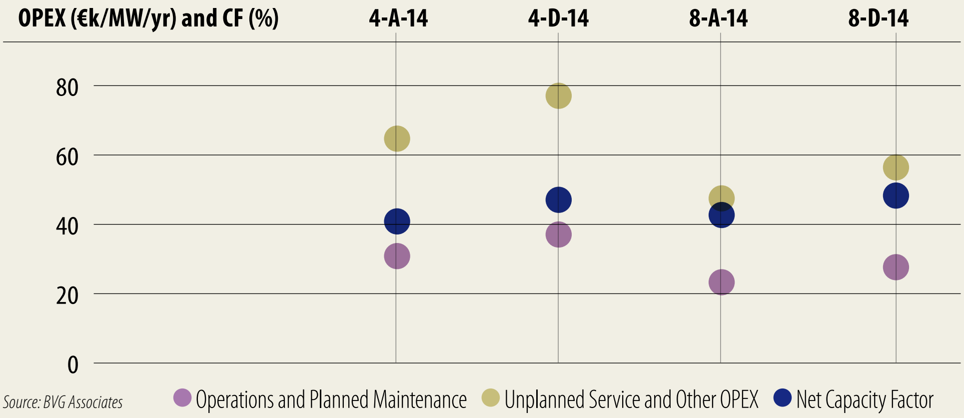


Figure 3.2 **Baseline OPEX and net capacity factor.**

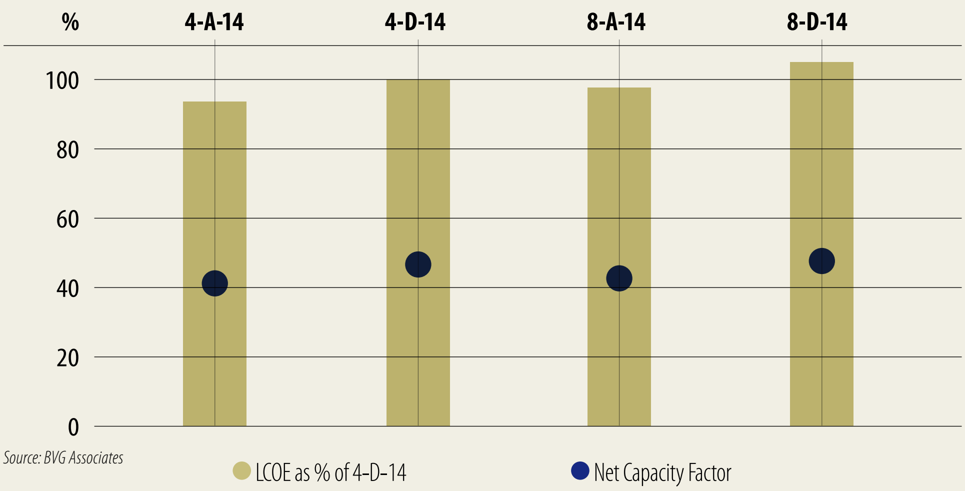


The timing profile of CAPEX and OPEX spend, which is important in deriving the LCOE, is presented in Appendix A.

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 4MW-Size Turbines on Site Type D used as the comparator.

The trend is for higher LCOE for Site Type D than A as the increased costs outweigh the increased energy production. The increased risk of a wind farm of 8MW-Size Turbines drives the increased LCOE compared with 4MW-Sized Turbines for projects with FID in 2014. In time, the analysis shows that this picture will change.

Figure 3.3 **Relative LCOE and net capacity factor for baseline wind farms with other effects incorporated, ref. Section 2.4.**



alpha ventus - North Sea © Doti / Matthias Ibeler

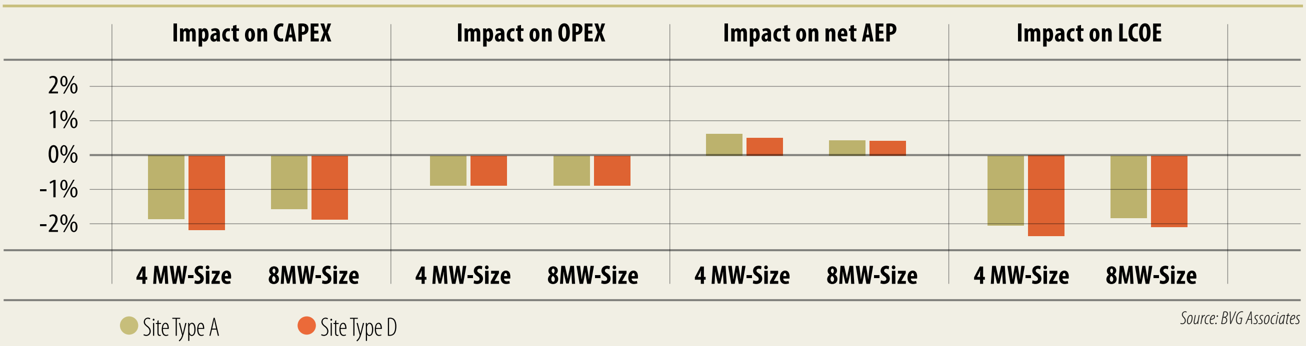
4. Innovations in wind farm development

4.1. Overview

Innovations in wind farm development are anticipated to reduce the LCOE by between 2% and 2.5% between FID 2014 and 2025, with the largest savings anticipated for projects using 4MW-Size Turbines on Site Type D. The savings are dominated by improvements in CAPEX, especially post development, rather than in OPEX or AEP.

Figure 4.1 shows that the impact on LCOE is greatest for a wind farm using 4MW-Size Turbines on Site Type D. The aggregate impact of innovations in this element actually increases the spend on wind farm development marginally but, through this, reduces costs of other elements of the wind farm, primarily the support structure and construction.

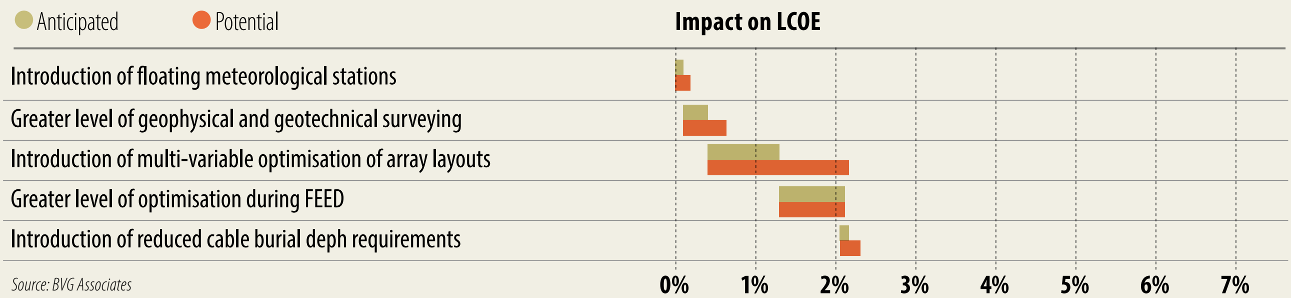
Figure 4.1 **Anticipated impact of wind farm development innovations by Turbine Size and Site Type with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



Source: BVG Associates

Figure 4.2 and Table 4.1 show that the individual innovation with the largest anticipated impact by FID 2025 is the optimisation of array layouts. Array layout optimisation promises significant reductions in overall cost of energy by finding Pareto optimal 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 and potential impact of wind farm development innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



Source: BVG Associates

Table 4.1 **Anticipated and potential impact of wind farm development innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Introduction of floating meteorological stations	0.2%	0.0%	0.0%	0.2%	0.1%	0.0%	0.0%	0.1%
Greater level of geophysical and geotechnical surveying	0.7%	0.0%	0.0%	0.6%	0.4%	0.0%	0.0%	0.3%
Introduction of multi-variable optimisation of array layouts	0.7%	1.7%	0.9%	1.7%	0.4%	0.9%	0.5%	0.9%
Greater level of optimisation during FEED	1.0%	0.0%	0.0%	0.8%	0.9%	0.0%	0.0%	0.8%
Introduction of reduced cable burial depth requirements	0.3%	0.0%	0.0%	0.2%	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 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 initially 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 ensue 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 at the cost of 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 half of the benefit of this innovation will be available for projects with FID in 2020, rising to about 70% 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 for projects with FID in 2025.

Greater level of 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, 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 from surveys that focus on other areas of the site and on soil conditions closer to the surface of the sea bed can lead to cost reductions in array electrical and construction CAPEX through earlier design work, and preventing conservative overdesign or late design changes. 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 measuring 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 all 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 70% of projects with FID in 2025.

Introduction of multi-variable optimisation of array layouts

Practice today: To date, multi-disciplinary optimisation tools have not been used on projects that have reached FID because of the relatively benign and uniform conditions in which the early wind farms were deployed, the lack of accurate cost of energy modelling data and the constraints imposed on the sites. Instead, developers have used the existing iterative process involving multiple engineering teams and design loops occurring through the pre-FEED and FEED periods.

Innovation: The introduction of multi-variable optimisation of array layouts includes developing and using fast and reliable optimisation software tools that account for the effects and constraints of multiple technical disciplines. This innovation includes incorporating improved models for offshore wind farm wakes. The wind farm array layout is optimised, for example, for the combination of wake effect, 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 location of turbines 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: About 30% of the benefit of this innovation is anticipated to be available for projects with FID in 2020 rising to about double this 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.

Greater level of optimisation during FEED

Practice today: Detailed design and optimisation occurs 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. An increased level of study allows some of the detailed aspects of design to be brought forward, enhancing the accuracy of cost estimates for solutions with varying parameters such as water depth, soil conditions and turbine choice. 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 all by FID 2025.

Introduction of reduced cable burial depth requirements

Practice today: There remains concern across the industry that cable burial requirements are frequently arbitrary and are neither based on the site conditions nor the risk of cable damage. This issue has a significant effect on cable installation costs.

Innovation: Cable burial depth typically exceeds 1m as 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 seabed 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 60% of the benefit of this innovation is anticipated to be available for projects with FID in 2020 rising to about 90% for projects with FID in 2025.

Market share: Market share is anticipated to be about a quarter of projects with FID in 2020, doubling for projects with FID in 2025.

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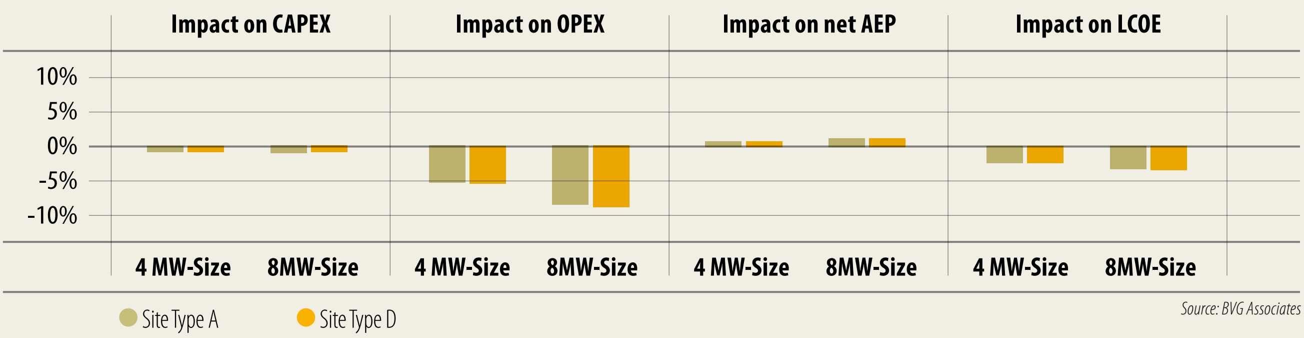
5. Innovations in the wind turbine nacelle

5.1. Overview

Innovations in the turbine nacelle are anticipated to reduce the LCOE by between 2% and 3.5% between FID 2014 and 2025. 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 8MW-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 4MW-Size Turbines primarily benefit from more modest, evolutionary changes to current practice and hence see smaller improvements.

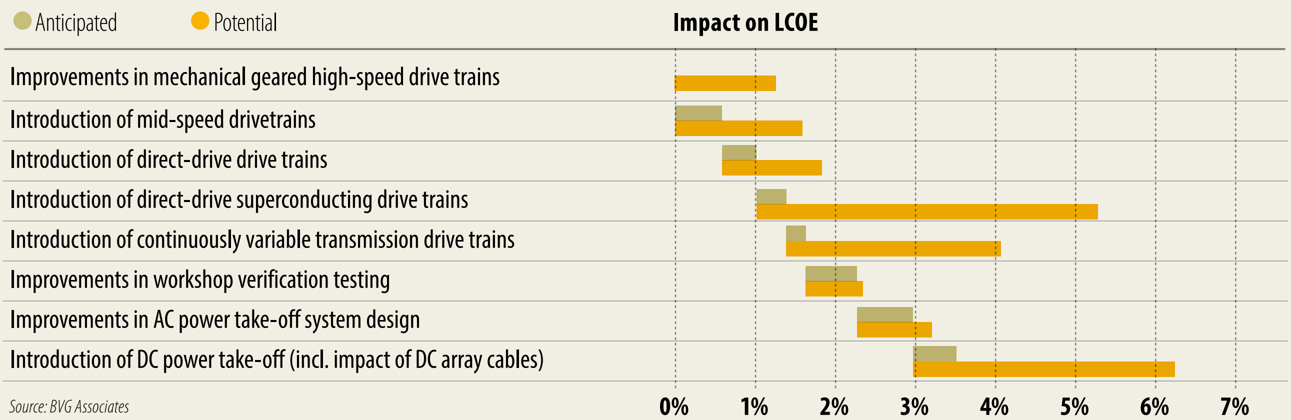
Figure 5.1 **Anticipated impact of turbine nacelle innovations by Turbine Size and Site Type with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



Source: BVG Associates

Figure 5.2 and Table 5.1 show that the innovation anticipated to have the biggest impact is the improvement of workshop verification and testing, including an increase in the amount of accelerated lifecycle testing which drives improvement in system reliability. The innovation with the greatest potential impact on LCOE is the introduction of superconducting drive trains, but these are anticipated to take significant time to develop.

Figure 5.2 **Anticipated and potential impact of turbine nacelle innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



Source: BVG Associates

Table 5.1 **Anticipated and potential impact of turbine nacelle innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Improvements in mechanical geared high-speed drive trains	0.7%	2.6%	0.2%	1.3%	0.0%	0.0%	0.0%	0.0%
Introduction of mid-speed drive trains	0.7%	2.7%	0.5%	1.6%	0.3%	1.0%	0.2%	0.6%
Introduction of direct-drive drive trains	-0.5%	3.9%	0.9%	1.2%	-0.2%	1.3%	0.3%	0.4%
Introduction of direct-drive superconducting drive trains	0.9%	6.4%	2.5%	4.3%	0.1%	0.6%	0.2%	0.4%
Introduction of continuously variable transmission drive trains	2.4%	6.4%	-0.5%	2.7%	0.2%	0.5%	0.0%	0.2%
Improvements in workshop verification testing	0.0%	2.8%	0.2%	0.7%	0.0%	2.6%	0.2%	0.7%
Improvements in AC power take-off system design	0.2%	3.1%	0.1%	0.9%	0.2%	2.3%	0.1%	0.7%
Introduction of DC power take-off (incl. impact of DC array cables)	1.6%	3.2%	1.4%	3.2%	0.3%	0.5%	0.2%	0.5%

5.2. Innovations

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

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 and 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 to bearing design, manufacture and lubrication have the potential to decrease through life operational costs by reducing unplanned service events. Similarly, ongoing improvements in the design of gear boxes 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 players that stay with the technology both offshore and onshore.

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

Commercial readiness: Most of the benefit of this innovation will be available for projects with FID in 2020 and 2025.

Market share: Market share is anticipated to be 70% for projects with 4MW-Size Turbines with FID in 2020 and 2025 but negligible for projects with 8MW-Size Turbines.

Introduction of mid-speed drive trains

Practice today: The 8MW-Size Turbines from Areva, Samsung and Vestas all feature a mid-speed drive train with relatively close-coupled generator. Only Areva has experience of such a concept, and then only in small-scale production.

Innovation: Removal of the high speed stage in the gearbox reduces the gearbox size and mechanical losses. These 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. Increases in reliability offer an improvement to OPEX and AEP.

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 most of the benefit will be technically available for projects with FID in 2020 and almost all for projects with FID in 2025.

Market share: It is anticipated that around half of projects using 8MW-Size Turbine and a small proportion of projects using 4MW-Size Turbines that reach FID in 2020 will use this innovation and that this will remain the case for projects with FID in 2025.

Introduction of direct-drive drive trains

Practice today: Alstom 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 deployments.

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 a 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 most of the benefit will be technically available for projects with FID in 2020 and almost all of the benefit will be available for projects with FID in 2025.
Market share: It is anticipated that around one quarter of wind farms using 4MW-Size Turbines and reaching FID in 2020 and 2025 will use this solution. It is anticipated that around half the wind farms using 8MW-Size Turbines and reaching FID in 2020 will use this solution, dropping to about a third in 2025 due to competition from superconducting direct-drive and other drive trains.

Introduction of direct-drive superconducting drive trains

Practice today: At present there are no commercial scale demonstration wind turbines featuring super conducting drive trains. Prototype designs have been produced for other sectors.
Innovation: This innovation involves replacing conventional copper in the generator with superconducting wire which has zero electrical resistance when cooled below a given temperature, known as the critical temperature of the material. Technical advances in recent years have increased the critical temperature to above 77K, so that cooling can be provided via the use of liquid nitrogen. This is anticipated to reduce generator mass by roughly 50% compared with that of a conventional system, as well as increasing efficiency.
Relevance: The innovation is relevant to 8MW-Size Turbines on all Site Types. This innovation is not relevant to any 4MW-Size Turbines due to the cost of implementing cooling and the reduced benefits of lower generator mass.
Commercial readiness: High temperature superconducting (HTS) wire is not in serial production although second generation HTS wire producers are continually 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 relatively large technical leap which brings supply chain challenges. It is anticipated that this innovation will be implemented on a small proportion of projects with FID in 2020 and still only on around 10% of projects with FID in 2025.

Introduction of continuously variable transmission drive trains

Practice today: There is presently a 2MW demonstration turbine developed by MHI running with a hydraulic drive, coupled with a synchronous generator, with a 7MW prototype to be installed this year. Few other wind turbine manufacturers are anticipated to adopt this technology in the near future and it is not anticipated that the Vestas-MHI joint venture will prioritise this technology.
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 half of the benefit of this innovation will be technically available for projects with FID in 2020 increasing to about three quarters for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on 10% of projects using 8MW-Size Turbines with FID in 2020 and 2025. It is not anticipated that this innovation will be implemented on 4MW-Size Turbines.

Improvements in workshop verification testing

Practice today: Workshop verification testing may have occurred for turbines used on projects reaching FID today, but is not standardised and may have 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 (HALT) 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 "head of the fleet" turbines.
Relevance: The innovation is equally relevant to all Turbine Sizes. Sites close to shore and in shallow water will benefit somewhat less than harsher sites due to the increased importance of OPEX for such harsher sites.
Commercial readiness: Three quarters 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: It is anticipated that this innovation will be implemented on all projects using 8MW-Size Turbines and 30% of projects using 4MW-Size Turbines from FID 2020 onwards.

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 on 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: Most 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 three quarters of projects using 8MW-Size Turbines with FID in 2020 and almost all such projects with FID in 2025. The market share on projects using 4MW-Size Turbines is anticipated to rise from about one half to two thirds over the same period as there is less incentive to implement the innovation on more mature products.

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 convertor that converts back to AC is removed. Moving to DC collection reduces the number of 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 as these do not also use high voltage direct current (HVDC) transmission.

Commercial readiness: About one half of the benefit of this innovation is anticipated to be available to sites reaching FID in 2020 rising to about three quarters 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 20% market share for projects with FID in 2025.

alpha ventus rotor installation © Doti / Matthias Ibeler

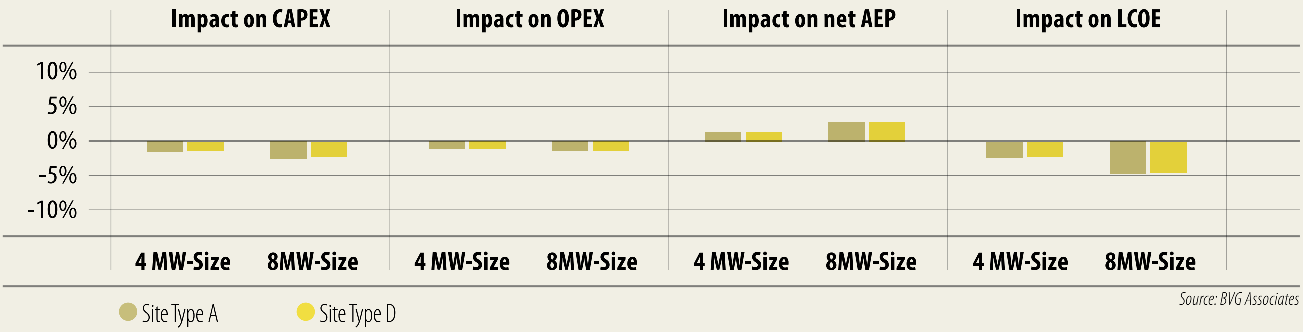
6. Innovations in the wind turbine rotor

6.1. Overview

Innovations in the turbine rotor are anticipated to reduce the LCOE by between 2.5% and 5% between FID 2014 and 2025. The savings are driven by improvements in CAPEX and AEP with limited improvements to OPEX.

Figure 6.1 shows that the impacts on CAPEX and AEP are broadly consistent between Site Types but all benefits are increased on the 8MW-Size Turbines. This increase is primarily due to a higher anticipated market share for innovations on projects using 8MW-Size Turbines.

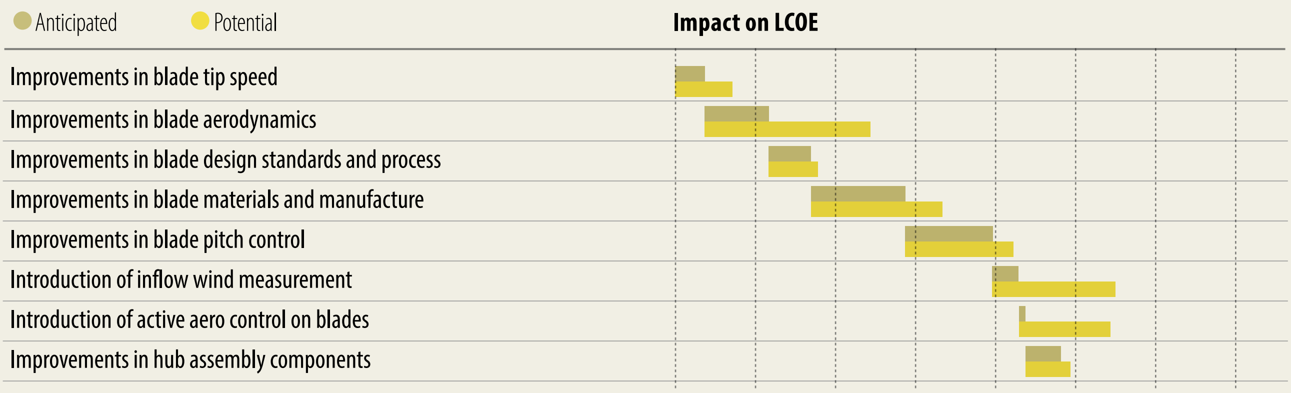
Figure 6.1 **Anticipated impact of turbine rotor innovations by Turbine Size and Site Type with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



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 the improvement of blade materials and manufacture and improvements in pitch control. The innovation with the greatest potential impact is improvements in blade aerodynamics.

Figure 6.2 **Anticipated and potential impact of turbine rotor innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



Source: BVG Associates

Table 6.1 **Anticipated and potential impact of turbine rotor innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Improvements in blade tip speed	0.0%	0.0%	0.7%	0.7%	0.0%	0.0%	0.4%	0.4%
Improvements in blade aerodynamics	0.5%	-0.3%	1.8%	2.1%	0.2%	-0.1%	0.7%	0.8%
Improvements in blade design standards and process	0.4%	0.2%	0.3%	0.6%	0.3%	0.1%	0.2%	0.5%
Improvements in blade materials and manufacture	1.7%	1.0%	0.1%	1.6%	1.2%	0.7%	0.1%	1.2%
Improvements in blade pitch control	0.6%	-0.3%	0.9%	1.3%	0.5%	-0.2%	0.8%	1.1%
Introduction of inflow wind measurement	-0.4%	-0.6%	2.0%	1.5%	-0.1%	-0.1%	0.4%	0.3%
Introduction of active aero control on blades	-1.1%	-1.9%	2.4%	1.1%	-0.1%	-0.1%	0.1%	0.1%
Improvements in hub assembly components	0.3%	1.0%	0.1%	0.5%	0.3%	0.8%	0.1%	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. A subset of the more important of these has been modelled here.

Improvements in blade tip speed

Practice today: The highest tip speeds are between 85m/s and 90m/s, limited by fatigue loading, blade erosion and uncertainty about slender blade aerodynamic performance. Typically, blade leading edge erosion is controlled 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 to, for example, 100m/s 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.
Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.
Commercial readiness: Advances to 100m/s are feasible relatively quickly with most of the benefit available for projects with FID in 2020 and almost all for projects with FID in 2025.
Market share: Market share is anticipated to be around 20% for projects using 4MW-Size Turbines reaching FID in 2020 and 2025 and around half for projects using 8MW-Size Turbines.

Improvements in blade aerodynamics

Practice today: Blade manufacturers are using 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 encompasses a range of possibilities from evolutionary developments and fine tuning of existing designs to 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 reflect an industry anticipation that these improvements will help reduce thrust fatigue loading.
Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.
Commercial readiness: This innovation will develop more slowly than most others in this area with around half of the benefits available for projects reaching FID in 2020 and rising to three quarters by FID in 2025. There has already been a strong history of innovation in this area and it is anticipated that the pace of progress will gradually slow.
Market share: Market share is anticipated to be around 20% for projects using 4MW-Size Turbines reaching FID in 2020 and 2025 and around half for projects using 8MW-Size Turbines.

Improvements in blade design standards and process

Practice today: In recent years there has been a marked increase in the quality of testing blades and blade components. 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 provide benefits in terms of increased aerodynamic performance, decreased CAPEX (of the blades and also the rest of the turbine) and OPEX (due to increased reliability). Progress in this area is anticipated to have a modest potential 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 envisaged that almost all of the benefits of this innovation will be available for projects with FID in 2020, with further benefit taken by FID 2025.

Market share: The market share for projects using 8MW-Size Turbines with FID in 2020 is anticipated to be around 75%. This is anticipated to continue to rise for FID in 2025. The market share for projects using 4MW-Size Turbines is less than half of this as the uptake of new innovations on these turbines generally is anticipated to be significantly less.

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 give a mix of 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.

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

Commercial readiness: Some innovations in this area may be available relatively quickly; others are at an early stage and may require more development and commercialisation. Overall, most of the benefits are anticipated to be available for projects reaching FID in 2020 with further gains by FID in 2025.

Market share: The market share for projects using 8MW-Size Turbines with FID in 2020 is anticipated to be around 75%. This is anticipated to continue to rise for projects with FID in 2025. The market share for projects using 4MW-Size Turbines is less than half of this as the uptake of new innovations on these turbines generally is anticipated to be significantly less.

Improvements in blade pitch control

Practice today: Currently, 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 with maximising energy production.

Innovation: Continuing improvements in both collective and individual pitch control, in both routine and turbulent or wake affected operational scenarios, have the potential to reduce lifetime turbine loads on some components by a further 20-30% 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, modelled as an increase in turbine CAPEX and unplanned OPEX. Gross AEP is anticipated to increase due to improved aerodynamic performance.
Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types.
Commercial readiness: Work is ongoing in this area, although some is at a relatively early stage. Overall, two thirds of the benefits are anticipated to be available for projects with FID in 2020 with almost all available for projects with FID in 2025.
Market share: The market share for projects using 8MW-Size Turbines with FD in 2020 is anticipated to be around 75%. This is anticipated to continue to rise for FID in 2025. The market share for projects using 4MW-Size Turbines is less than half of this as the uptake of new innovations generally on these turbines is anticipated to be significantly less.

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 Turbine Sizes and Site Types.
Commercial readiness: The relatively high cost of LiDAR and the complexity of the necessary integrated control system mean that only a quarter of the technical potential of this innovation is anticipated to be available for projects reaching FID in 2020, but this is anticipated to more than double for projects with FID in 2025.
Market share: This innovation is not anticipated to be deployed in large quantities on 4MW-Size Turbines. For projects using 8MW-Size Turbines, market share is anticipated to reach about 40% by FID in 2025.

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 approaches including micro actuated surfaces, air jet boundary layer control, active flaps, trailing edge modifiers and plasma aerodynamic control effectors. The industry expects some to come to fruition but it is currently unclear which ones will progress. Robustness and reliability of any solution in the tough environmental conditions experienced by the outer sections of blades is critical. Uplift in gross AEP, combined with an increase in turbine CAPEX and unplanned service cost to account for increased failure rates of these advanced control solutions, is anticipated. This reduced reliability is also reflected in a modelled increase in losses.

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

Commercial readiness: The limited interest currently shown by mainstream players and the relatively early stage in development mean that only around a quarter of the technical potential of this innovation will be available for projects with FID in 2020, doubling by 2025.

Market share: Uptake of this novel technical approach is anticipated to be slow. Market share is anticipated to be very low for projects using 8MW-Size Turbines with FID in 2020 and to rise modestly to around 15% in 2025. No significant deployment on 4MW-Size Turbines is anticipated.

Improvements in hub assembly components

Practice today: Pitch systems and blade bearings already represent significant sources of downtime. Innovations increasing 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.

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, and improved hub design methods and material properties. Better design is anticipated to drive a saving on turbine CAPEX and improved reliability, reducing unplanned OPEX and availability losses.

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

Commercial readiness: Most of the technical potential of these innovations will be available for projects with FID in 2020, with further gains by FID in 2025.

Market share: This innovation is anticipated to have around three quarters of the market for projects using 4MW-Size Turbines reaching FID in 2020, with little further change. For projects using 8MW-Size Turbines, the market share is anticipated to be higher still.

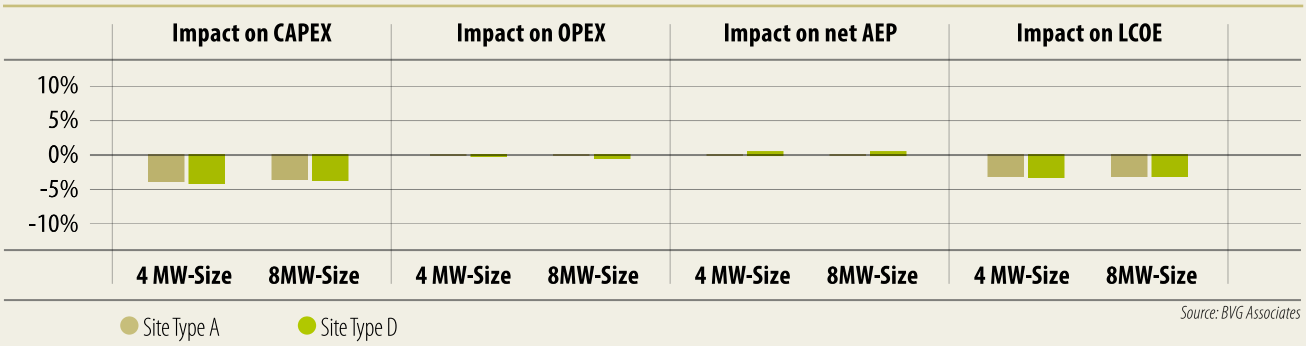
7. Innovations in balance of plant

7.1. Overview

Innovations in balance of plant are anticipated to reduce LCOE by approximately 4% between 2014 and 2025. The savings are dominated by improvements in CAPEX with only minor improvements anticipated in OPEX and AEP.

Figure 7.1 shows that the impact on CAPEX is greatest for a wind farm using 8MW-Size Turbines on Site Type D, because this combination is the only one where jacket foundations are anticipated to be used.

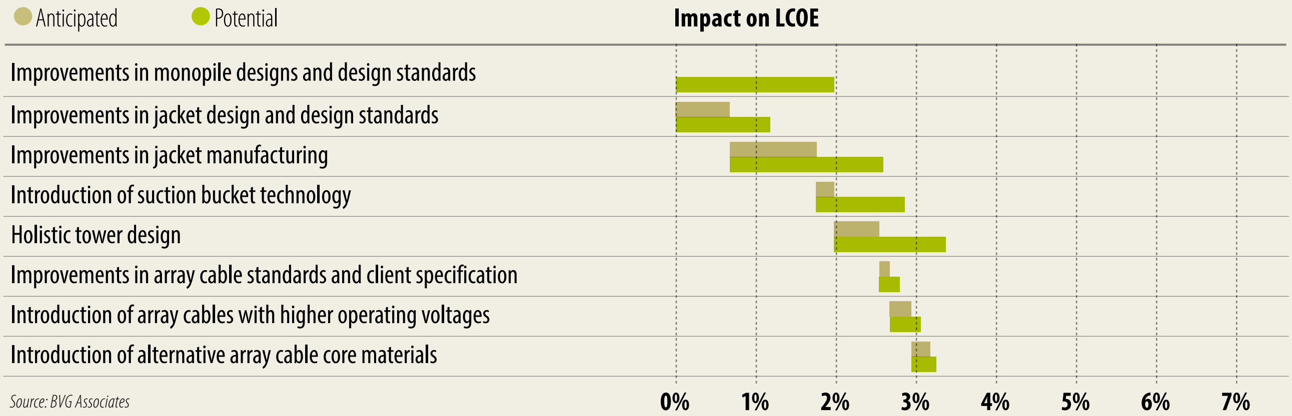
Figure 7.1 **Anticipated impact of balance of plant innovations by Turbine Size and Site Type with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



Source: BVG Associates

Figure 7.2 and Table 7.1 show that the individual innovation with the largest anticipated impact by FID in 2025 relates to improvements in jacket manufacturing. Improvements in monopile design and design standards also have a significant potential impact but none is shown in Figure 7.2 as it is anticipated that monopiles will not be used on projects with 8MW-Size 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 2025.

Figure 7.2 **Anticipated and potential impact of balance of plant innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



Source: BVG Associates

Table 7.1 **Anticipated and potential impact of balance of plant innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Improvements in monopile designs and design standards	2.3%	0.3%	0.0%	2.0%	0.0%	0.0%	0.0%	0.0%
Improvements in jacket design and design standards	1.4%	0.0%	0.0%	1.2%	0.8%	0.0%	0.0%	0.7%
Improvements in jacket manufacturing	2.2%	0.6%	0.0%	1.9%	1.2%	0.3%	0.0%	1.1%
Introduction of suction bucket technology	1.4%	0.0%	0.0%	1.1%	0.3%	0.0%	0.0%	0.2%
Holistic tower design	1.7%	0.2%	0.0%	1.4%	0.7%	0.1%	0.0%	0.6%
Improvements in array cable standards and client specification	0.3%	0.0%	0.0%	0.2%	0.2%	0.0%	0.0%	0.1%
Introduction of array cables with higher operating voltages	0.3%	0.0%	0.1%	0.4%	0.2%	0.0%	0.1%	0.3%
Introduction of alternative array cable core materials	0.5%	-0.3%	-0.1%	0.3%	0.4%	-0.2%	0.0%	0.2%

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. A subset of the more important of these has 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 at this stage that there will be benefits in 35m water depth, as for projects on Site Type D.

Improvements in monopile design and design standards

Practice today: Monopile design is already largely optimised but a refinement of design assumptions and further improvements (including to the transmission piece and connection with the monopile) are still available. 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 line with the areas of improvement suggested above 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 8MW-Size Turbines on Site Type D, where jackets are anticipated to be used.

Commercial readiness: Two thirds of the benefit of innovation in this area is anticipated to be available for projects with FID in 2020, increasing to three quarters for projects with FID in 2025.

Market share: It is anticipated that, where relevant, more than half the projects with FID in 2020 will use these innovations and that this will increase to about three quarters for projects with FID in 2025.

Improvements in jacket design and design standards

Practice today: Jacket design is optimised for manned 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 8MW-Size Turbines on Site Type D.

Commercial readiness: More than two thirds of the benefit is anticipated to be available for projects with FID in 2020 rising to three quarters for projects with FID in 2025.

Market share: Where relevant, almost half the projects with 8MW-Size Turbines with FID in 2020 are anticipated to use these innovations, rising to three quarters for projects with FID in 2025.

Improvements in jacket manufacturing

Practice today: Jacket production is heavily influenced by manufacturing practices inherited from 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. More 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 relevant to projects using jacket support structures, hence 8MW-Size Turbines on Site Type D.
Commercial readiness: More than half of the benefit of these innovations is anticipated to be available for projects with FID in 2020 rising to three quarters for projects with FID in 2025.
Market share: Almost half of relevant projects with 8MW-Size Turbines with FID in 2020 are anticipated to use these innovations, rising to three quarters for projects with FID in 2025.

Introduction of suction bucket technology

Practice today: Suction bucket technology has been demonstrated on smaller close-to-shore turbines and two offshore met stations with a further test planned at full-scale, but 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 pile driving 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 monopod and jacket-type structures.
Relevance: The innovation is equally relevant to all Turbine Sizes and Site Types, though not all ground conditions are suitable.
Commercial readiness: Almost than two thirds of the benefit of this innovation is anticipated to be available for projects with FID in 2020, rising to almost full availability for projects with FID in 2025.
Market share: Less than 15% of projects with FID in 2020 are anticipated to use this innovation but this is anticipated to increase to almost a quarter of projects with FID in 2025.

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. A move to waterside manufacturing facilities would enable production of single section towers which require fewer flanges and allow a more streamlined manufacturing approach, reducing both support structure

and construction CAPEX. This 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 8MW-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 most of the benefit of this innovation will be available for projects with FID in 2020 and will be fully available for projects with FID in 2025.

Market share: Market share is anticipated to be around two thirds of projects with FID in 2020 increasing to more than three quarters market share for projects with FID in 2025.

Improvements in array cable standards and client specification

Practice today: Conservative developers 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 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 more complete 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 two thirds of the benefit of this innovation will be available for projects with FID in 2020 with three quarters of the benefit available for projects with FID in 2025.

Market share: It is anticipated that more than one 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.

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.

Innovation: The introduction of array cables with higher operating voltages means capacity can be increased and electrical losses reduced. Studies have proved the feasibility of extending the operating voltage of wet cable designs to close to 66kV. As the industry moves towards turbines with higher megawatt ratings, the need for higher capacity array cables becomes more critical to minimise the total cable length and the number of substations required.

Relevance: All of the value of this innovation is anticipated to be realised on projects using 8MW-Size Turbines and over three quarters is anticipated to be realised on projects using 4MW-Size Turbines.

Commercial readiness: It is anticipated that more than two-thirds 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 more than a third of projects with FID in 2020 will use this innovation rising to around three quarters for projects with FID in 2025.

Introduction of alternative array cable core materials

Practice today: To date, all array cables installed in offshore wind farms have had copper cores, but aluminium is used in other sectors for both onshore and offshore interconnectors.

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 are also anticipated to 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: Half of the benefit 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 half of projects with FID in 2020 will use this innovation, increasing to more than 80% for projects with FID in 2025.

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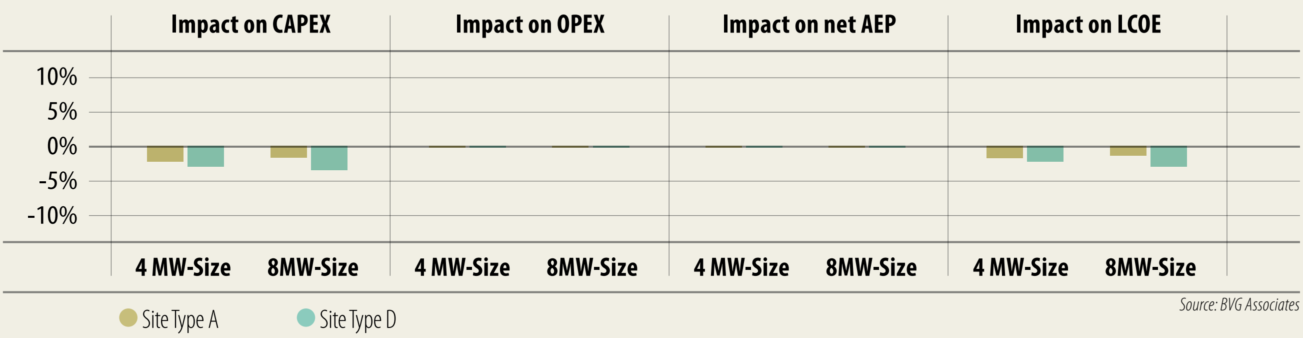
8. Innovations in wind farm construction

8.1. Overview

Innovations in construction are anticipated to reduce the LCOE by approximately 2.5% between 2014 and 2025. The savings are exclusively from improvements in CAPEX, rather than OPEX or AEP.

Figure 8.1 shows that the impact on CAPEX is greatest for a wind farm using 8MW-Size Turbines 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 apply almost equally to both 4MW- and 8MW-Size Turbines.

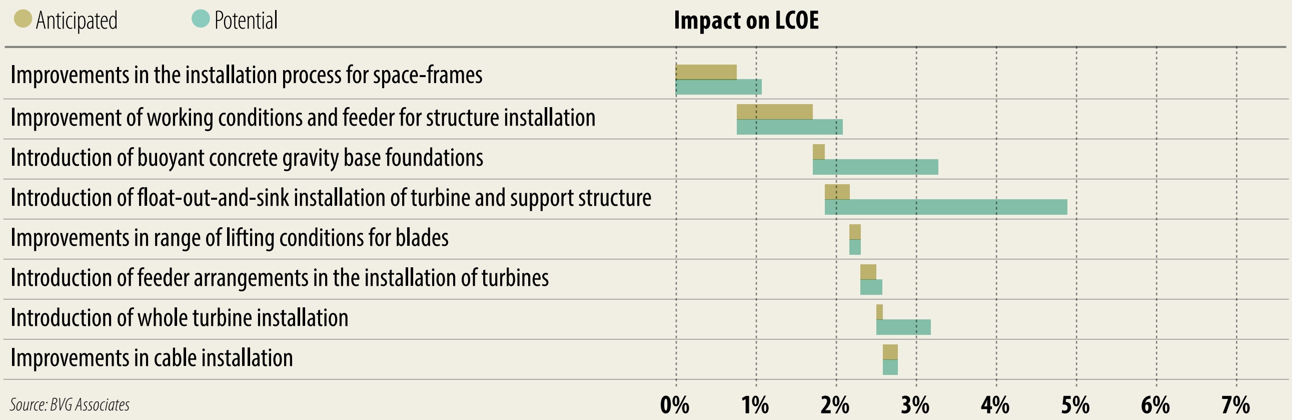
Figure 8.1 **Anticipated impact of construction innovations by Turbine Size and Site Type with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



Source: BVG Associates

Figure 8.2 and Table 8.1 show that the individual innovations with the largest anticipated impact for projects reaching FID in 2025 relate to improvements in the feeder arrangements and working conditions for support structure installation. The other innovation that is anticipated to impact significantly by FID in 2025 relates to improvements in space-frame installation. The innovation with by far the greatest potential impact is the introduction of float-out-and-sink installation of turbine and support structure together but, even by projects with FID in 2025, market share is anticipated to remain low.

Figure 8.2 **Anticipated and potential impact of construction innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



Source: BVG Associates

Table 8.1 **Anticipated and potential impact of construction innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Improvements in the installation process for space-frames	1.3%	0.0%	0.0%	1.1%	0.9%	0.0%	0.0%	0.8%
Improvements in the range of working conditions and feeder arrangements for support structure installation	1.6%	0.0%	0.0%	1.3%	1.2%	0.0%	0.0%	1.0%
Introduction of buoyant concrete gravity base foundations	1.9%	0.0%	0.0%	1.6%	0.2%	0.0%	0.0%	0.2%
Introduction of float-out-and-sink installation of turbine and support structure	3.7%	0.0%	0.0%	3.0%	0.4%	0.0%	0.0%	0.3%
Improvements in range of lifting conditions for blades	0.2%	0.0%	0.0%	0.2%	0.1%	0.0%	0.0%	0.1%
Introduction of feeder arrangements in the installation of turbines	0.4%	0.0%	0.0%	0.3%	0.3%	0.0%	0.0%	0.2%
Introduction of whole turbine installation	0.8%	0.0%	0.0%	0.7%	0.1%	0.0%	0.0%	0.1%
Improvements in cable installation	0.2%	0.0%	0.0%	0.2%	0.2%	0.0%	0.0%	0.2%

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 the installation process for space-frames

Practice today: Space frame structures have been installed in small quantities using weather-sensitive vessels but experience of serial installation of such structures is limited.
Innovation: Developers anticipate significant savings from the development of a fleet of specialised vessels able to perform discrete installation steps more efficiently than multi-purpose vessels. 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.
Relevance: This innovation is relevant only for projects using jacket support structures, hence using 8MW-Size Turbines on Site Type D.
Commercial readiness: Half of the benefit of this innovation is anticipated to be available for projects with FID in 2020, with much of the remainder available for projects with FID in 2025.
Market share: This innovation is anticipated to capture most of the market on relevant projects in 2020, although it is anticipated that this will drop slightly in 2025 as additional installation methods become available.

Improvements in the range of working conditions and feeder arrangements for support structure installation

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 be able to place legs down onto the seabed 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. 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 somewhat lower benefit available for projects using the more benign Site Type A.
Commercial readiness: Most of the benefit of these innovations will be available for projects with FID in 2020, with the remainder available for projects with FID in 2025.
Market share: It is anticipated that this innovation will be used on most projects with FID in 2020 and 2025.

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, as 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 most of the benefit will be available to projects reaching FID in 2020.

Market share: It is anticipated this innovation will be used on a small fraction of projects using 8MW-Size Turbines with FID in 2020, rising to around one tenth in 2025. It is not anticipated that this approach will be used on projects using 4MW-Size Turbines.

Introduction of float-out-and-sink installation of turbine and support structure

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

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 60% 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 80% for projects reaching FID in 2025.

Market share: It is anticipated that market uptake will be low for projects with FID in 2020, rising to account for around one tenth of the market in 2025.

Improvements in the range of lifting conditions for blades

Practice today: The blades are either lifted individually with the nacelle and hub in position or as a preinstalled rotor as a single "star" lift. This activity is generally the bottleneck in turbine installation due to weather dependency.

Innovation: Increasing the maximum wind speed for blade lifts from 8m/s to 12m/s would reduce weather downtime for such operations by around a third and deliver installation savings by increasing utilisation of the installation vessels.

Relevance: The full benefit of this innovation is available for projects on Site Type D. Lower wind speeds on projects on Site Type A are mean that it is anticipated that only three quarters of the potential benefit is available.

Commercial readiness: It is anticipated that the majority of benefits from this innovation will be available for projects reaching FID in 2020 and that the remainder will be available in 2025.

Market share: This innovation is anticipated to be used on most applicable projects regardless of Turbine Size or Site Type for FID in 2020. For projects using 4MW-Size Turbines, this is anticipated to rise further for projects reaching FID in 2025 but competition from other methods is anticipated to limit further rises for projects using 8MW-Size Turbines.

Introduction of feeder arrangements in the installation of turbines

Practice today: 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.

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 anticipated to be realised for projects using Site Type D, with somewhat lower benefit available for projects using the Site Type A, with a shorter distance from port.

Commercial readiness: This innovation is anticipated to be available to most projects with FID in 2020 and all projects with a FID in 2025.

Market share: This innovation is anticipated to be used on most applicable projects regardless of Turbine Size or Site Type for FID in 2020. For projects using 4MW-Size Turbines, this is anticipated to rise further for those reaching FID in 2025 but competition from other methods is anticipated to limit further rises for projects using 8MW-Size Turbines.

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 similarly to onshore.

Innovation: The turbine is fully assembled and part 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 and could be implemented using feeder vessels.

Relevance: The full impact of this innovation is anticipated to be realised for projects using 8MW-Size Turbines on Site Type D, with somewhat lower benefit available for projects using the Site Type A and still lower benefits for projects using 4MW-Size Turbines.

Commercial readiness: About 60% of the benefit of this innovation will be available for projects with FID in 2020, rising further 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.

Greater levels of optimised cable installation equipment and processes

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: Most of the benefit of these innovations is anticipated to be available for projects with FID in 2020.
Market share: Most projects with FID in 2020 and all projects with FID in 2025 are anticipated to use these innovations.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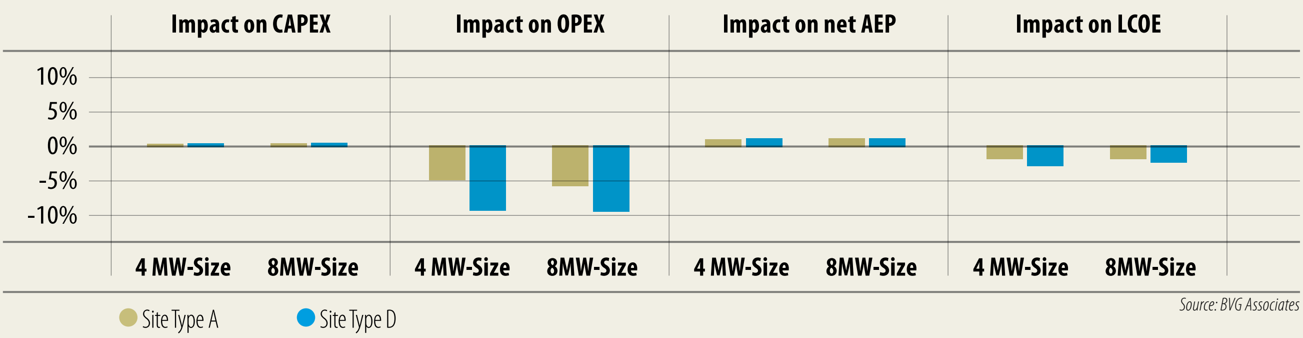
9. Innovations in wind farm operation, maintenance and service

9.1. Overview

Innovations in operations, maintenance and service (OMS) are anticipated to reduce the LCOE by approximately 2% between 2014 and 2025, with the largest savings anticipated for projects using 4MW-Size Turbines on Site Type D. The savings are dominated by improvements in OPEX and wind farm availability, and hence net AEP.

Figure 9.1 shows that the impact on OPEX is greater for projects with Site Type D, because hardware on sites far from shore have more challenges in terms of access to repair. The LCOE reduction is greater for projects using 4MW-Size Turbines because OPEX is a larger contribution to LCOE for projects using such turbines.

Figure 9.1 **Anticipated impact of OMS innovations by Turbine Size and Site Type with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**

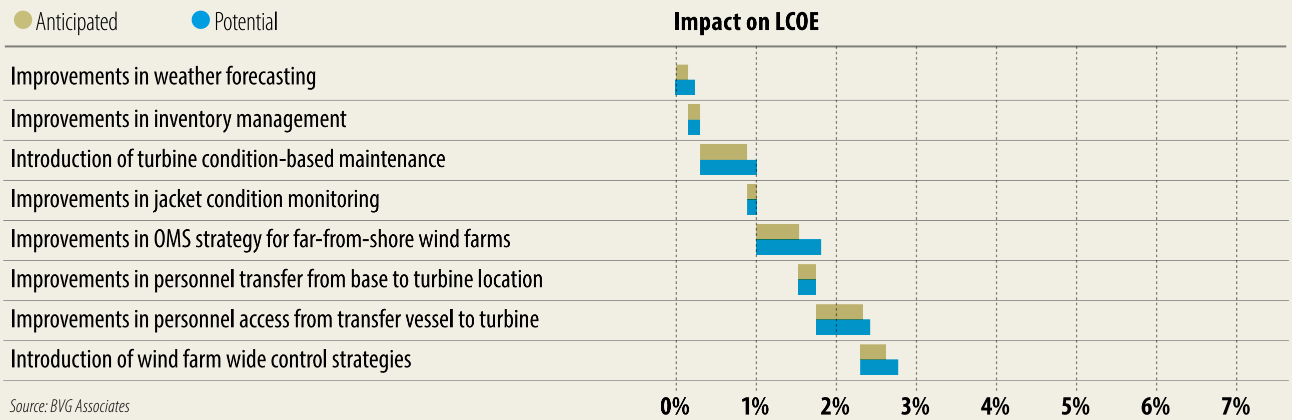


Source: BVG Associates

Figure 9.2 and Table 9.1 show that the individual innovations with the largest anticipated impact by FID 2025 relate to the introduction of condition based maintenance (CBM), far from shore operational strategies and improvements in personnel transfer to turbines. Investment in the development of sensors and algorithms that provide estimates of the remaining useful life of turbine components will support a proactive move to 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 are services are specified at FEED and provided for in CAPEX budgets.

Figure 9.2 **Anticipated and potential impact of OMS innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**



Source: BVG Associates

Table 9.1 **Anticipated and potential impact of OMS innovations for a wind farm with 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Improvements in weather forecasting	0.0%	0.7%	0.0%	0.2%	0.0%	0.5%	0.0%	0.1%
Improvements in inventory management	0.0%	0.5%	0.0%	0.1%	0.0%	0.4%	0.0%	0.1%
Introduction of turbine condition-based maintenance	-0.2%	3.0%	0.3%	0.7%	-0.1%	2.4%	0.3%	0.6%
Improvements in jacket condition monitoring	-0.1%	1.0%	0.0%	0.1%	-0.1%	0.8%	0.0%	0.1%
Improvements in OMS strategy for far-from-shore wind farms	0.0%	4.4%	0.0%	0.8%	0.0%	3.0%	0.0%	0.6%
Improvements in personnel transfer from base to turbine location	0.0%	0.5%	0.1%	0.2%	0.0%	0.5%	0.1%	0.2%
Improvements in personnel access from transfer vessel to turbine	0.0%	1.4%	0.4%	0.7%	0.0%	1.2%	0.4%	0.6%
Introduction of wind farm wide control strategies	-0.3%	0.7%	0.5%	0.5%	-0.2%	0.5%	0.4%	0.3%

9.2. Innovations

Innovations in wind farm OMS vary widely from highly practical to deeply technical. A subset of the more important of these has been modelled here.

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 Met Office. Forecasts are updated up to four times a day, to a granularity of half-hourly intervals out to six days ahead. Some enhanced services now provide hourly updates.

Innovation: There is general agreement in the industry that improvements in weather forecasting will increase the efficient use of staff and vessels by maximising activity during weather windows. This requires improvements both to 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 half of the benefit of this innovation is anticipated to be available for projects with FID in 2020 rising to around three quarters 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.

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 far from optimal in many cases.

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: Almost all of the benefit of this innovation is anticipated to be available for projects with FID in 2020.

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.

Introduction of turbine condition-based maintenance

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

Innovation: 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. New and improved prognostic and diagnostic systems and processes could allow operators to maximise 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: The full value of this innovation is anticipated to be captured on projects using 8MW-Size Turbines with most of the value also captured on projects using 4MW-Size Turbines.

Commercial readiness: Most of the benefit of this innovation is anticipated to be available for projects with FID in 2020 with much of the test 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.

Improvements in jacket condition monitoring

Practice today: In 2014, only a small number of offshore turbines are installed on jacket foundations. 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, a total of 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 scheduled inspections, including subsea inspections, using autonomous systems. At the cost of an anticipated increase in foundation CAPEX, both planned and unplanned OPEX is reduced, as are losses due to unavailability.

Relevance: The full value of this innovation is anticipated to be realised on all projects using jacket foundations.

Commercial readiness: Most of the benefit of this innovation is anticipated to be available for projects with FID in 2020, with a further increase for projects with FID in 2025.

Market share: This innovation is anticipated to be implemented on three quarters of relevant projects with FID in 2020 and almost all projects with FID in 2025.

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: Mother ships 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: Approximately half 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: This innovation is anticipated to be implemented on three quarters of relevant projects with FID in 2020 and almost all relevant projects with FID in 2025.

Improvements in personnel access from transfer vessel to turbine

Practice today: Currently used crew transfer vessel (CTV) designs require waves with Hs below 1.4m with asset owners reporting reductions in technician utilisation of up to 40% due to this restriction.

Innovation: The use of larger, more capable support vessels fitted with systems such as 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: The harsher conditions on projects on Site Type D 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 A.

Commercial readiness: Three quarters of the benefit of this innovation is anticipated to be available for projects with FID in 2020 and to be almost fully 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.

Improvements in personnel transfer from base to turbine location

Practice today: The majority of offshore wind farms operating in 2014 have a shore-based operating base. Transit from the base to the wind turbine is routinely by small (20m-30m) 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, 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 on projects on Site Type D 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 A.

Commercial readiness: Most of the benefit of this innovation is anticipated to be available for projects with FID in 2020 and to be almost fully 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.

Introduction of wind farm wide control strategies

Practice today: Automatic control of wind turbines is carried out by individual wind turbine controls systems. 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.

Relevance: The full value of this innovation is anticipated to be captured on projects using 8MW-Size Turbines with most of the value also captured on projects using 4MW-Size Turbines.

Commercial readiness: Around half of the benefit of this innovation is anticipated to be available for projects with FID in 2020, increasing to 75% 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.

Courtesy of EDP Renováveis

10. Summary of the impact of innovations

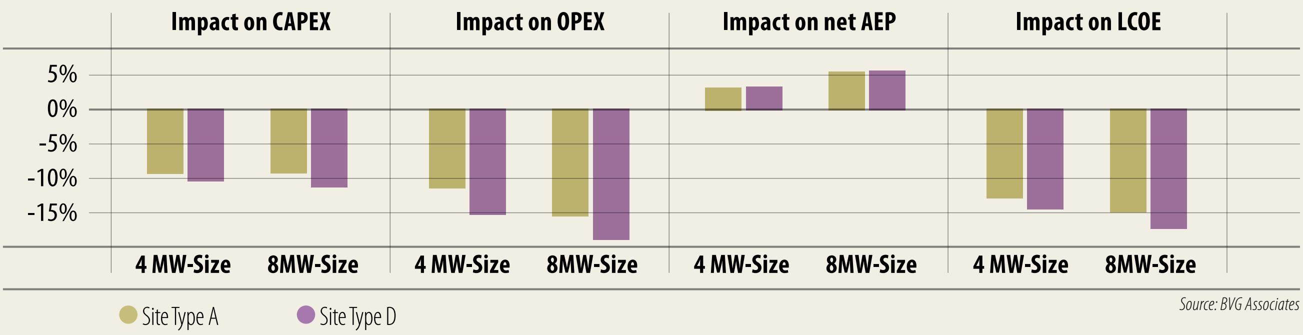
10.1. Combined impact of innovations

Innovations across all elements of the wind farm are anticipated to reduce the LCOE by 13% to 18% between projects with FID in 2014 and 2025. Figure 10.1 shows that the savings are generated through a balanced contribution of reduced CAPEX and OPEX and increased AEP.

It is important to note that the impact shown in Figure 10.1 is an aggregate of the impact shown in Figure 4.1 to Figure 9.1 and as such excludes any other effects such as supply chain competition. These are discussed in Section 10.3. The largest like-for-like reductions for the same Turbine Size and Site Type that are available are for projects using 8MW-Size Turbines on Site Type D. This is due to the increased market uptake of innovation on the larger turbines and the additional opportunities for innovation provided by working further from shore.

Figure 10.1 considers changes for a given Turbine Size and Site Type, so there is no impact of a change in turbine rating incorporated in any of the results shown.

Figure 10.1 **Anticipated impact of all innovations by Turbine Size and Site Type with FID in 2025, compared with a wind farm with the same MW-Size Turbines on the same Site Type with FID in 2014.**

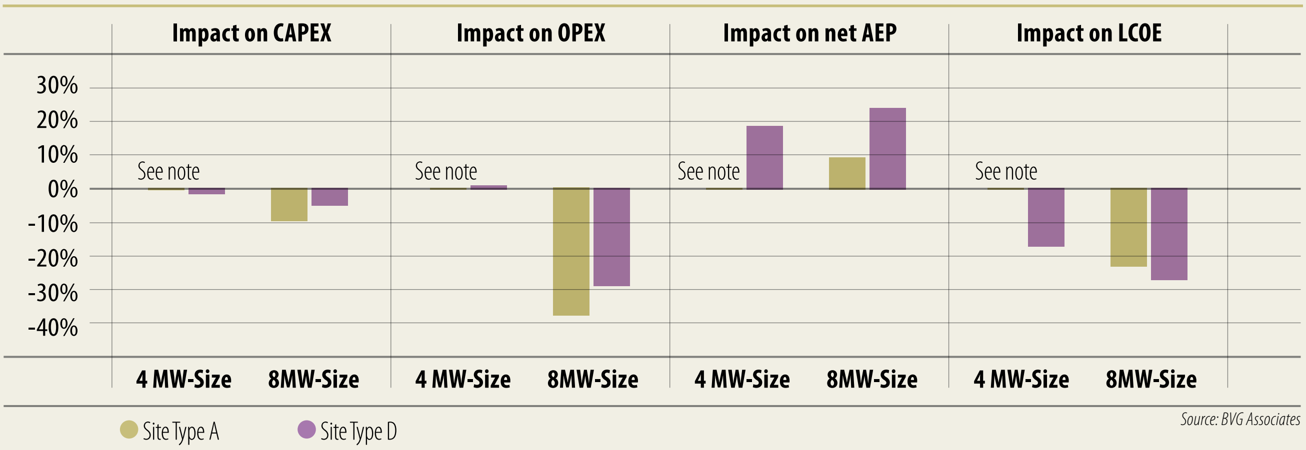


Source: BVG Associates

Figure 10.2 again shows the aggregate impact of all innovations for wind farms with FID in 2025, but this time all are compared with a wind farm using 4MW-Size Turbines on Site Type A with FID in 2014. This allows the effect of changes in Turbine MW-Size and Site Type to be compared. It shows that, even with the anticipated aggregate impact of all innovations, OPEX for a wind farm using 4MW-Size Turbines on Site Type D remains higher for FID in 2025 than for a 4MW-Size Turbines on Site Type A with FID in 2014 but, because CAPEX is slightly lower and AEP is so much higher, overall LCOE is reduced.

It also shows that, for wind farms on Site Type A, the aggregate impact of all innovations and the change to 8MW-Size Turbines over the period drives a 9% reduction in CAPEX, a 38% reduction in OPEX and a 9% increase in AEP, giving an overall 23% reduction in LCOE. Finally, for wind farms on Site Type D, using 8MW-Size Turbines decreases CAPEX by 5%, OPEX by almost 30% and increases AEP by 24%, giving an overall reduction in LCOE of 27%.It should be noted that these LCOE data exclude other effects such as transmission cost and variations in WACC, as discussed in Section 2.4.

Figure 10.2 **Anticipated impact of all innovations by Turbine Size and Site Type with FID in 2025, in each case compared with a wind farm with 4MW-Size Turbines on Site Type A with FID in 2014.**
Note that results for wind farm with 4MW-Size Turbines on Site Type A are not shown as the results are the same as in Figure 10.1.



10.2. Relative impact of cost of each wind farm element

In order to explore the relative cost of each wind farm element, Figure 10.3 shows the cost of all CAPEX elements for all scenarios and Figure 10.4 shows similar 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 2014, 2020 and 2025.** *Source: BVG Associates*

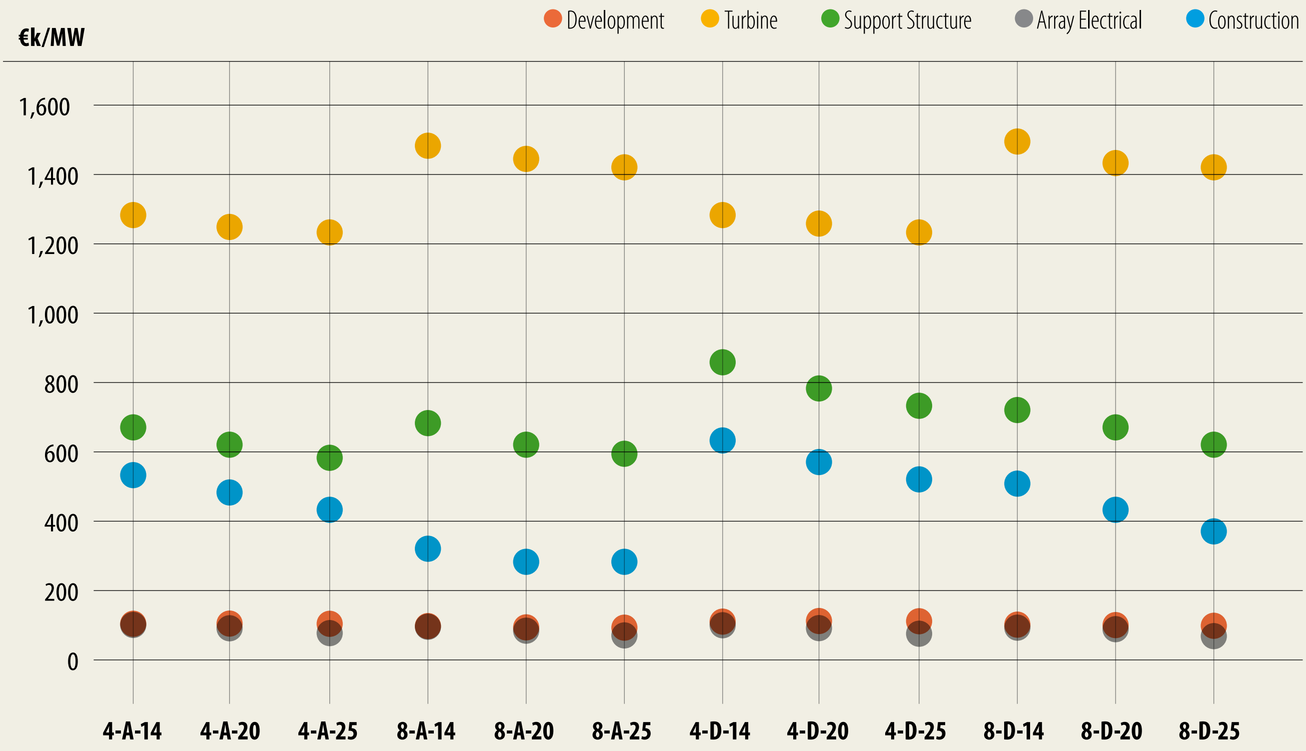
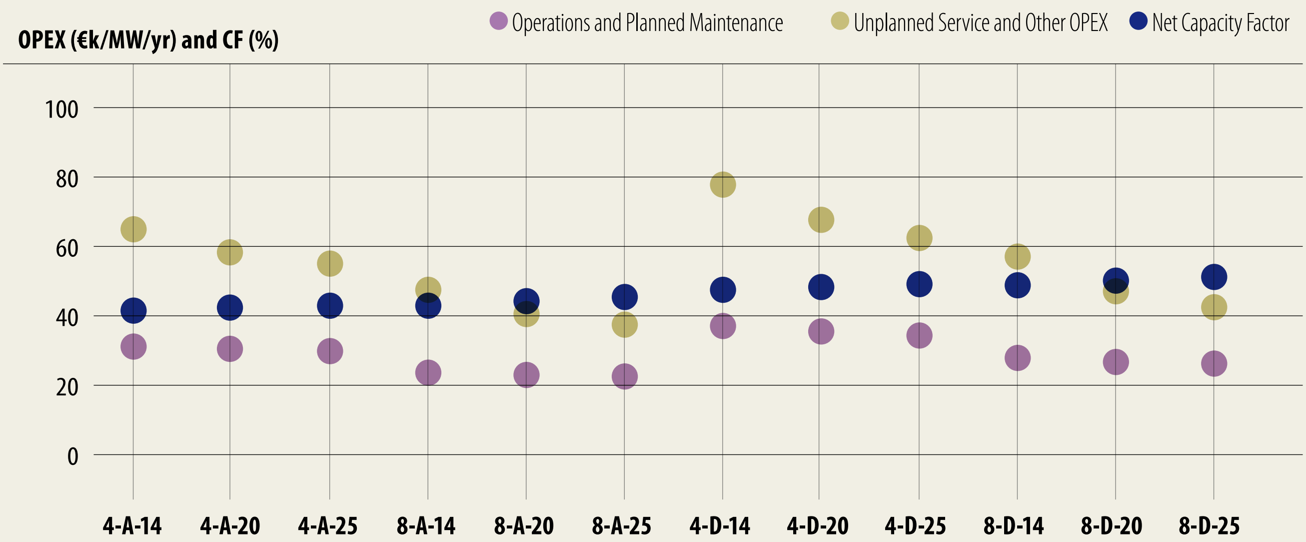


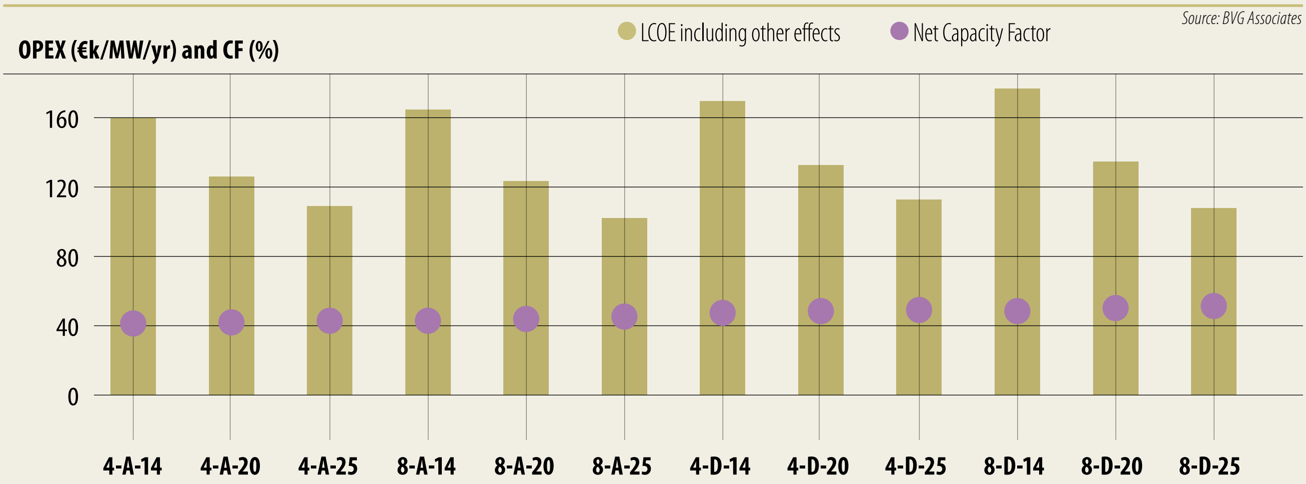
Figure 10.4 **OPEX and net capacity factor for wind farms with FID 2014, 2020 and 2025.** *Source: BVG Associates*



10.3. Levelised cost of energy including the impact of other effects

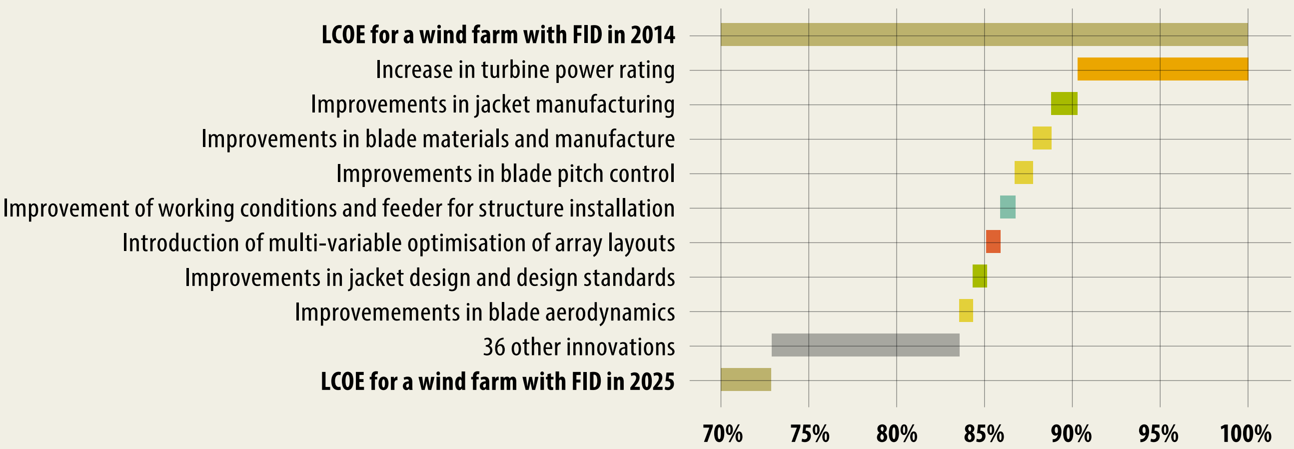
In order to compare LCOE, Figure 10.5incorporates also the other effects discussed in Section 2.4. It shows that, with the benefit of increasing capacity factor over time and with the move towards larger turbines, LCOE is lowest for projects reaching FID in 2014 using 4MW-Size Turbines on Site Type A, but for projects reaching FID in 2020 and 2025, the use of 8MW-Size Turbines offers an LCOE advantage.

Figure 10.5 **LCOE for wind farms with FID 2014, 2020 and 2025 with other effects incorporated, ref. Section 2.4.**



The contribution of innovations in each element to this LCOE reduction is presented in Figure 10.6. It shows that innovations in the turbine have the dominant effect on LCOE, but innovations in many other elements are also important.

Figure 10.6 **Anticipated impact of all innovations by element for a wind farm using 8MW-Size Turbines on Site Type D with FID in 2025, compared with a wind farm using 4MW-Size Turbines on the same Site Type with FID in 2014.**



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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 2025 are considered. Within these, a number of distinct 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 most next generation turbines at 8MW and above will come 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 and construction costs. While several of these next generation turbines are at an advanced stage of development, developers will face a dilemma for projects with FID in the period 2014 to 2017. Some developers face a choice between using 4MW-Size Turbines with an established, albeit not unblemished, track record and 8MW-Size Turbines with a significantly shorter track record but offering the possibility of significantly increased project returns.

A prerequisite in making a successful step to 8MW-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 for many low cost turbine components. This activity needs to be further opened to wind farm developer scrutiny to build confidence in manufacturers' commitment to reliability.

Essential is an increased acceptance among developers that the LCOE should be the key measure in evaluating turbine choices, hence including a more thorough assessment of OPEX to balance the assessment of CAPEX, recognising that the certain and immediate CAPEX will remain a more powerful driver than the uncertain OPEX over time. Larger turbines have an inherently higher CAPEX per megawatt, as discussed in the *Offshore Wind Cost Reduction Pathways Study* but turbine manufacturers report concerns that this is not fully appreciated by their customers.

Offshore wind turbine manufacturers have demanding requirements for their factories. There are limited cost-effective options for sites with good access to North Sea projects. Further sites will be needed if the full potential impact of turbine innovations on the LCOE is to be realised. Despite this, the lack of coastal infrastructure will be immaterial if there is not the demand, so the issue of market confidence is critical to unlock many of the technology savings that are in development through sufficient levels of supply chain competition.

This focus on larger turbines and the increase in water depth of projects in development to 35m and more dictates a shift away from the monopile foundations that have dominated the market to date. 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. Offshore wind is another potential application and changes to the design are required 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. The move to new foundation designs will require significant investment in manufacturing facilities to deliver the technical savings available.

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

Offshore wind operational practices, both during construction and OMS, are still relatively immature 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 are not the best solution looking forward, there is less certainty about what should replace them. Feedback from industry is that jacket structures are anticipated to be 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. A holistic approach to tower and foundation design is seen by many to also offer cost reductions. These measures require an increased investment in the development phase and the consolidation of experience from personnel from previous projects who can ensure that lessons are learnt.

Almost 50 technology innovations have been identified as having the potential to cause a substantive change in the design of hardware, software or process, with a resulting quantifiable 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 anticipated as described. 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, it is important to remember that LCOE reductions are available through the other effects considered in Section 2.4, although these are not anticipated to impact to the same degree as technology innovations.

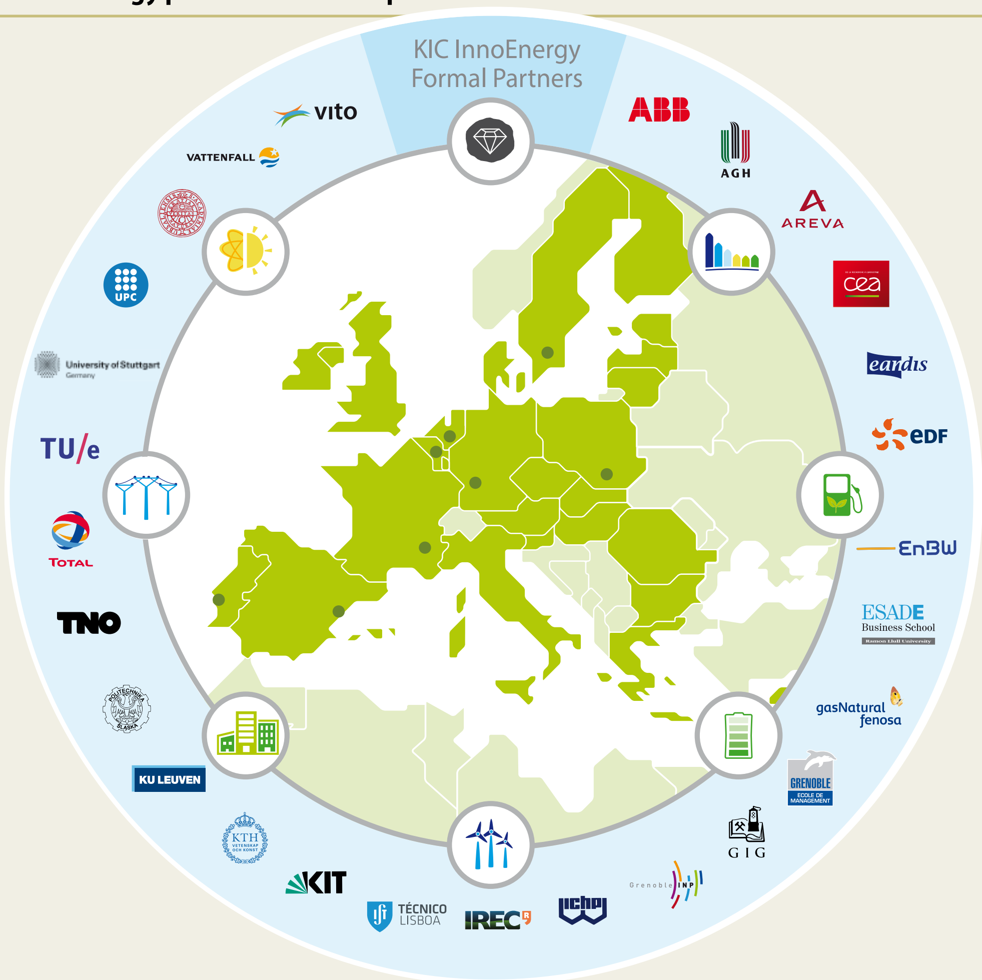
12. About KIC InnoEnergy

KIC InnoEnergy is a European company driving innovation, entrepreneurship and education in the sustainable energy field, by bringing together academics, business and research institutes. KIC InnoEnergy´s goal is to make a positive impact on sustainable energy in Europe by creating future game changers with a different mind-set, and bringing innovative products, services and successful companies to life.

KIC InnoEnergy is one of the first Knowledge and Innovation Communities (KICs) created under the leadership of the European Institute of Innovation and Technology (EIT). It is a commercial company with 27 shareholders that include top ranking industries, research centres and universities - all of them key players in the energy field. More than 150 additional partners contribute to the company´s activities, forming a first class network that is always open to new entrants, furthering KIC InnoEnergy´s pursuit of excellence. KIC InnoEnergy is profit oriented, but have a "not for dividend" financial strategy: it reinvests any profits generated in its activities.

KIC InnoEnergy is headquartered in the Netherlands, and manages its activities through offices across Europe in Belgium, France, Germany, the Netherlands, Poland, Portugal, Spain and Sweden.

Figure 12.1 **KIC InnoEnergy partners over Europe.**



KIC InnoEnergy is committed to reducing costs in the energy value chain, increasing security and reducing CO_2 and other greenhouse gas emissions. To achieve this, the company focuses its activities around eight technology areas:

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

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

KIC 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.

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, and • Any reservation payments to suppliers. EXCLUDES • Construction phase insurance, and • 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 steel work such as J-tubes and personnel access ladders and platforms) and the tower • Delivery to nearest port to supplier, and • Warranty. EXCLUDES • OMS costs, and • 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, and • 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 • Condition monitoring, and • 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 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 • Life time 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 (end-2013) prices
- Commodity prices fixed at the average for 2013
- Exchange rates fixed at the average for 2013 (that is, for example, £1 = €1.15)
- Energy prices fixed at the current rate, and
- Market expectation "mid view".

Wind farm assumptions

Site Types are defined as follows, in line with The Crown Estate's *Offshore Wind Cost Reduction Pathways: Technology Work Stream*.

Table A.2 **Summary of Site Types.**

Site	Type A	Type D
Average water depth (MSL) (m)	25	35
Distance to nearest construction and operation port (km)	40	125
Average wind speed at 100m above MSL (m/s)	9	10
Example UK wind farms	Walney 1 and 2, Westermost Rough	Creyke Beck (Dogger Bank), Heron (Hornsea)

General. The general assumptions are:

- A 500MW wind farm, as part of a multi-gigawatt UK Round 3 zone
- 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 20 years
- 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. Year 1 is defined as year of first full generation.
AEP and OPEX are assumed as 100% for years one through 20.

Table A.3 **CAPEX spend profile.**

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

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 P90 energy yield is 11% lower than P50 (in base case)
- 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 4MW 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 88 m/s tip speed. It has a rotor of 125m diameter, and a specific rating of around 325W/m² (which is representative of the products at this scale available for FID in 2014, namely the AREVA M5000-135, Siemens SWT-3.6-120 and 4.0-130 and Vestas V112-3.0MW turbines).
  - The 8MW turbine has a low-ratio gearbox mid speed, mid-voltage AC generator, 177m diameter rotor, and hence the same specific rating.

Support structure. The support structure assumptions are:

- A monopile with separate transition piece and tower is used for wind farms using 4MW-Size Turbines on both Site Types and 8MW-Size Turbines on Site Type A; and a four-legged piled jacket with a separate tower is used for 8MW-Size Turbines on Site Type D, and
- Ground conditions are "typical", that is, most relevant to UK Round 3 zones, 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 is ignored.

OMS. OMS assumptions are:

- Transmission charges are incurred as OPEX not CAPEX, and
- Access is by work boats 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 the results of 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.**

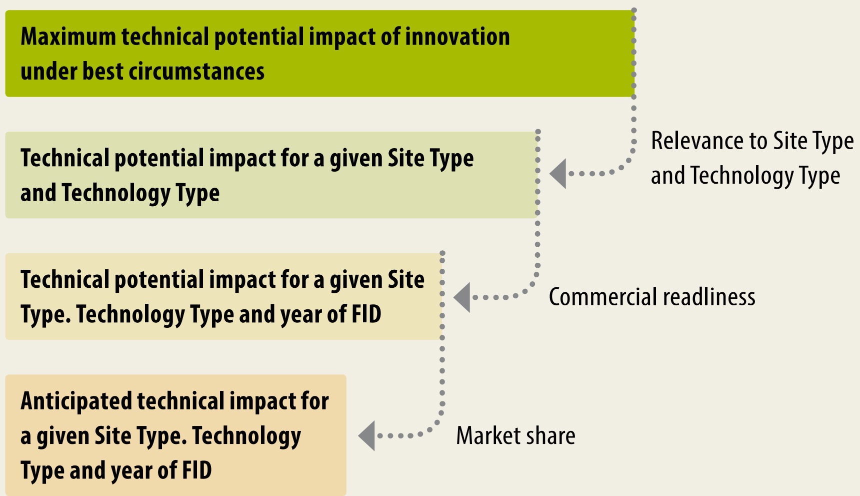
Tech-Site-FID	Transmission land rent	Insurance contingency	Pre-FID risk	Supply chain	Decommission-ing costs	WACC
4-A-14	19.8%	10.5%	2.9%	-0.5%	1.1%	9.1%
8-A-14	20.6%	12.8%	3.2%	-0.5%	0.8%	11.1%
4-D-14	30.4%	9.6%	2.1%	-0.5%	1.3%	9.5%
8-D-14	33.0%	11.7%	2.6%	-0.5%	0.9%	11.5%
4-A-20	19.2%	9.0%	3.1%	-5.4%	1.0%	7.9%
8-A-20	20.0%	11.0%	3.4%	-5.3%	0.7%	9.2%
4-D-20	28.7%	8.4%	2.3%	-5.4%	1.2%	8.2%
8-D-20	33.1%	10.3%	2.8%	-4.8%	0.8%	9.7%
4-A-25	19.3%	8.5%	3.2%	-7.9%	0.9%	7.0%
8-A-25	20.2%	10.3%	3.6%	-7.8%	0.6%	7.7%
4-D-25	28.3%	8.0%	2.4%	-7.9%	1.1%	7.2%
8-D-25	32.4%	9.6%	2.8%	-7.3%	0.7%	8.1%

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 8MW-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 0.1266, which is based on a discount rate of 10%.

Figure A.1 **Four stage process of moderation applied to the maximum potential technical impact of an innovation to derive the 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,* the combined potential effect of improvements in jacket design and design standards from the baseline year of FID in 2011 is a 6% reduction in support structure cost and a 1% reduction in installation cost. Taking into account the progress anticipated, in the three year period to the baseline year in this study and adjusting for actual progress, the input to this study is a potential 5.2% reduction in support structure cost and a 0.9% 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 4MW-Size Turbines or 8MW-Size Turbines on Site Type A are modelled as using monopiles, hence this innovation is not relevant. Projects using 8MW-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. Based on industry feedback, 92% of the potential of this innovation is modelled as available for wind farms reaching FID in 2025.

Market share

Based on industry feedback, the market share for this innovation for projects using 8MW-Size Turbines in 2025 is modelled as 81%.

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 (5.2%)
x Relevance to Site Type D and 8MW-Size Turbine (100%) = 5.2%
x Commercial readiness at FID in 2025 (92%) = 4.8%
x Market share for project using 8MW-Size Turbine with FID in 2025 (81%) = 3.9%

Impact for construction CAPEX = Maximum potential impact (0.9%)
x Relevance to Site Type D and 8MW-Size Turbine (100%) = 0.9%
x Commercial readiness at FID in 2025 (90%) = 0.8%
x Market share for project using 8MW-Size Turbine with FID in 2025 (81%) = 0.66%

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 (104.6 – 104.8) / 104.8 = -0.2%, or a 0.2% reduction in the LCOE.

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

Parameter	Baseline case 8-D-14	Target case 8-D-25
Support structure CAPEX (€k/MW)	722	722 x (1 – 0.039) = 694
Construction CAPEX (€k/MW)	496	496 x (1 – 0.0066) = 493
Other CAPEX (€k/MW)	1,684	1,684
Total CAPEX (€k/MW)	2,902	2,871
OPEX (€k/MW/yr)	84	84
Net AEP (MWh/yr/MW)	4,262	4,262
LCOE (€/MWh)	(2,902 x 0.1266 + 84) /4,262 = 104.8	(2,871 x 0.1266 + 84) / 4,262 = 104.6

Appendix B

Data supporting tables

Table B.1 **Data relating to Figure 3.1.**

Element	Units	4-A-14	8-A-14	4-D-14	8-D-14
Development	€k/MW	101	90	108	95
Turbine	€k/MW	1,279	1,498	1,279	1,498
Support structure	€k/MW	677	689	861	722
Array electrical	€k/MW	98	89	99	91
Construction	€k/MW	543	320	645	496

Table B.2 **Data relating to Figure 3.2.**

Element	Units	4-A-14	8-A-14	4-D-14	8-D-14
Operations and planned maintenance	€k/MW/yr	31	23	37	28
unplanned service and other OPEX	€k/MW/yr	65	48	78	57
Net capacity factor	%	41.4	42.8	47.4	48.7

Table B.3 **Data relating to Figure 3.3.**

Element	Units	4-A-14	4-D-14	8-A-14	8-D-14
LCOE including Other Effects	€/MWh	159	170	165	177
LCOE as % of 4-D-14	%	94.0	100.0	97.2	104.5
Net capacity factor	%	41.4	47.4	42.8	48.7

Table B.4 **Data relating to Figure 4.1.**

Impact of innovation on...	4-A	4-D	8-A	8-D
CAPEX	-1.8%	-2.3%	-1.5%	-1.9%
OPEX	-0.9%	-0.9%	-0.9%	-0.9%
Net AEP	0.5%	0.5%	0.5%	0.5%
LCOE	-2.2%	-2.4%	-1.9%	-2.1%

Table B.5 **Data relating to Figure 5.1.**

Impact of innovation on...	4-A	4-D	8-A	8-D
CAPEX	-0.7%	-0.6%	-0.8%	-0.8%
OPEX	-5.2%	-5.4%	-8.6%	-8.9%
Net AEP	0.7%	0.7%	1.2%	1.2%
LCOE	-2.3%	-2.4%	-3.3%	-3.5%

Table B.6 **Data relating to Figure 6.1.**

Impact of innovation on...	4-A	4-D	8-A	8-D
CAPEX	-1.3%	-1.3%	-2.5%	-2.3%
OPEX	-0.9%	-0.9%	-1.2%	-1.2%
Net AEP	1.2%	1.2%	2.7%	2.7%
LCOE	-2.4%	-2.4%	-4.9%	-4.7%

Table B.7 **Data relating to Figure 7.1.**

Impact of innovation on...	4-A	4-D	8-A	8-D
CAPEX	-3.9%	-4.2%	-3.7%	-3.7%
OPEX	-0.1%	-0.1%	-0.1%	-0.2%
Net AEP	0.1%	0.1%	0.1%	0.1%
LCOE	-3.1%	-3.3%	-3.1%	-3.1%

Table B.8 **Data relating to Figure 8.1.**

Impact of innovation on...	4-A	4-D	8-A	8-D
CAPEX	-2.2%	-2.9%	-1.5%	-3.4%
OPEX	0.0%	0.0%	0.0%	0.0%
Net AEP	0.0%	0.0%	0.0%	0.0%
LCOE	-1.7%	-2.2%	-1.3%	-2.8%

Table B.9 **Data relating to Figure 9.1.**

Impact of innovation on...	4-A	4-D	8-A	8-D
CAPEX	0.2%	0.3%	0.4%	0.4%
OPEX	-5.0%	-9.3%	-5.9%	-9.4%
Net AEP	1.1%	1.1%	1.2%	1.2%
LCOE	-2.0%	-3.0%	-1.8%	-2.6%

Table B.10 **Data relating to Figure 10.1**

Impact of innovation on...	4-A	4-D	8-A	8-D
CAPEX	-9.3%	-10.5%	-9.3%	-11.2%
OPEX	-11.5%	-15.6%	-15.6%	-19.0%
Net AEP	3.6%	3.6%	5.6%	5.6%
LCOE	-12.9%	-14.7%	-15.2%	-17.3%

Table B.11 **Data relating to Figure 10.2.**

Impact of innovation on...	4-D	8-A	8-D
CAPEX	-0.8%	-9.7%	-4.5%
OPEX	0.7%	-37.5%	-28.7%
Net AEP	18.6%	9.2%	24.1%
LCOE	-16.0%	-22.9%	-27.4%

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

Element	Units	4-A-14	4-A-20	4-A-25	8-A-14	8-A-20	8-A-25
Development	€k/MW	101	101	101	90	91	91
Turbine	€k/MW	1,279	1,254	1,240	1,498	1,450	1,427
Support structure	€k/MW	677	617	583	689	628	591
Array electrical	€k/MW	98	90	74	89	82	68
Construction	€k/MW	543	488	448	320	284	262
Operations and planned maintenance	€k/MW/yr	31	30	30	23	23	23
Unplanned service and other OPEX	€k/MW/yr	65	58	55	48	40	37
Net capacity factor	%	41.4	42.3	42.9	42.8	44.2	45.2

Element	Units	4-D-14	4-D-20	4-D-25	8-D-14	8-D-20	8-D-25
Development	€k/MW	108	108	108	95	96	96
Turbine	€k/MW	1,279	1,254	1,240	1,498	1,450	1,427
Support structure	€k/MW	861	785	741	722	662	614
Array electrical	€k/MW	99	90	74	91	83	68
Construction	€k/MW	645	569	515	496	415	371
Operations and planned maintenance	€k/MW/yr	37	36	35	28	27	26
Unplanned service and other OPEX	€k/MW/yr	78	68	62	57	47	42
Net capacity factor	%	47.4	48.4	49.1	48.7	50.2	51.4

Table B.13 **Data relating to Figure 10.5.**

	Units	4-A-14	4-A-20	4-A-25	8-A-14	8-A-20	8-A-25
Net capacity factor	%	41.4	42.3	42.9	42.8	44.2	45.2
LCOE including Other Effects	€/MWh	159	125	108	165	124	102

	Units	4-D-14	4-D-20	4-D-25	8-D-14	8-D-20	8-D-25
Net capacity factor	%	47.4	48.4	49.1	48.7	50.2	51.4
LCOE including Other Effects	€/MWh	170	133	113	177	134	108

Table B.14 **Data relating to Figure 10.6.**

Innovation	Relative impact of innovation on LCOE
LCOE for a wind farm with FID in 2014	100%
Increase in turbine power rating	10%
Improvements in jacket manufacturing	1.4%
Improvements in blade materials and manufacture	1.1%
Improvements in blade pitch control	1.0%
Improvements in range of working conditions and feeder arrangements for support structure installation	0.9%
Introduction of multi-variable optimisation of array layouts	0.8%
Improvements in jacket design and design standards	0.8%
Improvements in blade aerodynamics	0.7%
36 other innovations	10.7%
LCOE for a wind farm with FID in 2025	72.9%

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