Renewable Energies

Future renewable energy costs: onshore wind

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

BVG Associates

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

- 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

KIC InnoEnergy is a European company dedicated to promoting innovation, entrepreneurship and education in the sustainable energy field by bringing together academics, businesses 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) fostered by the European Institute of Innovation and Technology (EIT). It is a commercial company with 28 shareholders that include top ranking industries, research centres and universities, all of which are key players in the energy field. More than 150 additional partners contribute to the company´s activities to form a first class and dynamic network that is always open to new entrants and furthers KIC InnoEnergy's pursuit of excellence. Although KIC InnoEnergy is profit-oriented, it has a "not for dividend" financial strategy, reinvesting any profits it generates back into its activities.

KIC InnoEnergy is headquartered in the Netherlands, and develops its activities across a network of offices located in Belgium, France, Germany, the Netherlands, Spain, Portugal, Poland and Sweden.

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KIC InnoEnergy

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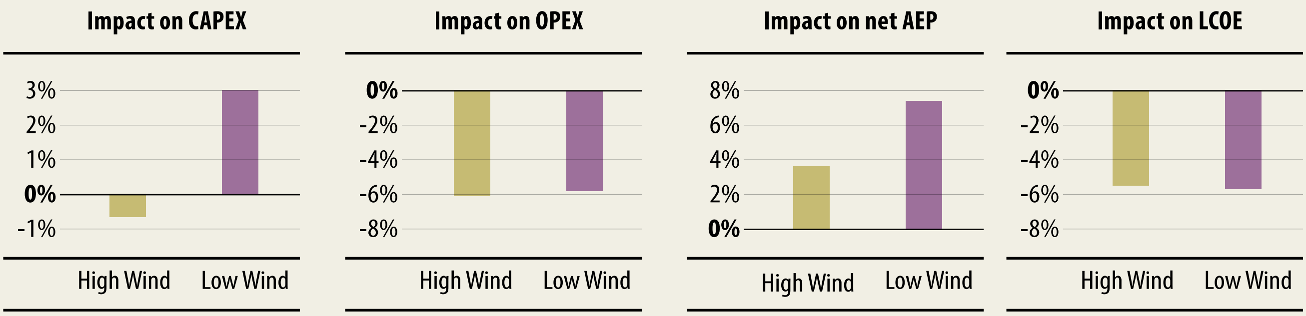
Executive summary

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, where relative changes due to individual innovations are most important, credibility comes with a realistic overall LCOE trajectory. This second report in the series examines how technology innovation is anticipated to reduce the cost of energy from European onshore wind farms over the next 12-15 years.

For this report, input data is based partly on *Future renewable energy costs: offshore wind*, published in June 2014, which in turn was 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 by modelling costs and defining and assessing the impact of many discrete innovations. For this report, the many offshore-specific innovations have been replaced by a series of onshore-specific innovations, and the impact of those relevant to both markets have been revised to ensure its applicability to the European onshore wind market. Fresh industry engagement supported this process.

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 two turbine classes (International Electrotechnical Commission (IEC) Class I and IEC Class III) and two sets of site conditions (a low wind, flat site and a high wind, hilly site) and three points in time at which the projects reach the final investment decision (FID) (2014 [the baseline], 2020 and 2025), following the definitions given in Appendix A.2. The fundamental links between Turbine Class Type and Site Type in the onshore market mean that, although four potential combinations exist, only two viable combinations are modelled: a High Wind Scenario and a Low Wind Scenario. The combined impact of anticipated technology innovations over the period under these two scenarios is presented in Figure 0.1.

Figure 0.1 **Anticipated impact of all innovations for both Low Wind and High Wind Scenarios, with FID 2025, compared with FID 2014.**[1]



Source: BVG Associates

The study concludes that LCOE savings of about 5.5% are anticipated in both low and high wind scenarios. In both scenarios, numerous innovations generate small improvements in LCOE through changes in capital expenditure (CAPEX), operational expenditure (OPEX) and annual energy production (AEP). In the Low Wind Scenario, two innovations also apply that have the potential to have a dominant effect, driving an overall increase in CAPEX and a further increase in AEP.

The first innovation is the optimisation of rotor size with advanced materials. Innovations in this area enable increases in blade length with less of an increase in mass, tip deflection and turbine loading than would be expected using simple scaling-up and with no change in materials.

Using taller towers is another significant innovation relevant to flatter, low wind sites, again enabled by innovations in tower design, rather than simply using taller conical tubular steel towers which generally become uneconomic at greater than standard heights.

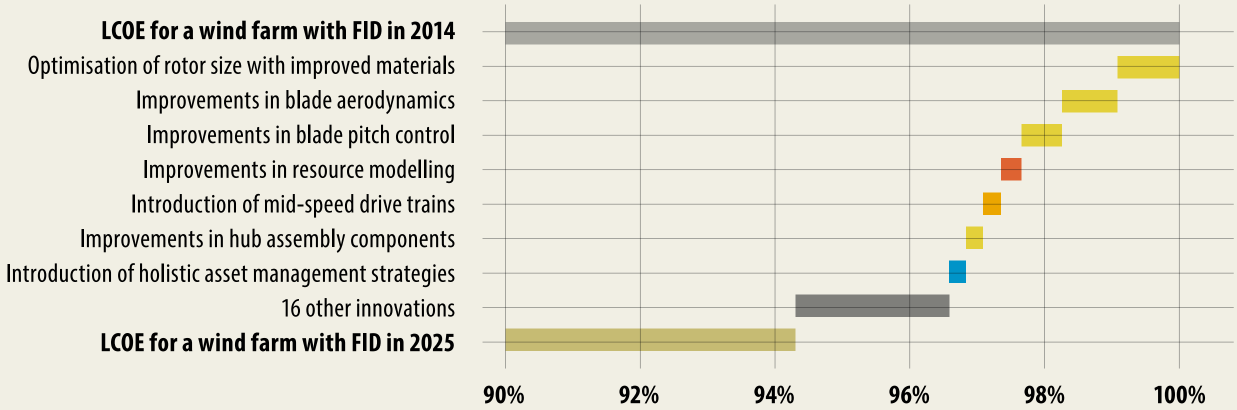
The market uptake of both of these innovations is dependent on tip height constraints imposed at the stage of obtaining planning consent, rather than solely on industry progress in verifying and implementing the innovations. Therefore, addressing this issue is important.

As an increasing proportion of viable high wind speed sites have already been developed, wind farm developers and hence turbine manufacturers are refocusing their efforts on maximising returns from lower wind speed sites, so we anticipate considerable focus and progress in this area.

Figure 0.2 shows that well over half of the LCOE savings anticipated in the Low Wind Scenario arise from innovations in the turbine, which is not surprising given that, excluding development and transportation costs, the turbine accounts for about 60% of equipment and installation CAPEX (70% with tower), and that these innovations also drive OPEX and AEP improvements.

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 CAPEX, OPEX and 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 all innovations by element for the Low Wind Scenario with FID in 2025, compared with FID in 2014.**



Almost 25 technology innovations were modelled 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 and so some of those described in this report may well be superseded by others. Overall, however, we anticipate that the level of cost of energy reduction shown will be achieved. In most cases, the anticipated impact of each innovation has been moderated downwards in order to give overall levels of cost of energy reduction consistent with past trends. 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.

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

Innovations in the turbine rotor extend beyond the optimisation of rotor diameter discussed above. Innovations in blade design and manufacture, aerodynamics and pitch control are anticipated together to reduce turbine loading and drive down CAPEX costs in the support structure while increasing gross AEP, with overall savings of between 2-3%. These savings make this area the largest contributor to the overall reduction in LCOE.

Innovations in the turbine nacelle are anticipated to reduce LCOE by between 1-1.5% in the period. Savings are due mainly to innovations in the drive train and the power take-off system. All of these innovations drive LCOE down through improved reliability and hence reduced OPEX and losses.

Innovations in operation, maintenance and service (OMS) offer strong potential to reduce LCOE. In this study a reduction of around 1% is expected on LCOE from innovations in OMS. Some of the innovations, for example, the introduction of condition based maintenance, require a change of strategy rather than just a change in technology. As such, the anticipated impact in the period modelled is lower than might initially be expected, considering the potential available. The challenge for the industry is to find optimal balance points between the technical risk and cost reductions offered by such innovations.

In wind farm development, through innovations in wind speed measurement and modelling to better optimise site layout, the AEP is anticipated to increase and hence LCOE decrease by 0.5-1% in the period.

Innovations in balance of plant are anticipated to be limited to the use of higher towers on flat sites where overcoming the current technical and planning limitations on tower height is anticipated to increase the gross AEP and hence to lower LCOE by around 0.4%, with little impact on CAPEX due to the use of innovative design solutions. This low value is primarily due to the fact that these technologies have been available to industry in some form for some years and have as yet failed to gain traction, partly due to planning restrictions.

Little, if any, LCOE saving is expected to arise from innovations in the construction of onshore wind farms. This is a well established process with little to suggest technology savings. The introduction of specialised vehicles and modular blades are incorporated into this study because, although savings on the typical sites modelled in this study are minimal or non-existent, these innovations have the potential to enable the use of sites currently not economically accessible. Some of these sites will have higher wind speeds than more accessible sites, so these innovations could in time reduce the average LCOE across the European Union (EU).

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, regarded as possibly suited to more remote sites. At a wind farm level, centralised grid control and moving complexity from each turbine to the substation offers the prospect of further savings on large wind farms, 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 long-distance transmission from large wind farms. 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 further cost reduction opportunities when looking to 2030 and beyond.

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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 the 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 if all turbines generating continuously at rated power.

CAPEX. Capital 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.

High Wind Scenario. A Scenario in which Class I Turbines are installed on the High Wind Site Type. See Appendix A for further details.

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

Low Wind Scenario. A Scenario in which Class III Turbines are installed on the Low Wind Site Type. See Appendix A for further details.

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 the application of various real-world factors. For details of the methodology, see Section 2.

RD&D. Research, development and demonstration.

Scenario. A specific combination of Turbine Type, Site Type, 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 Type. Term used in this report to describe a representative turbine (suited to a given wind regime) 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.

Foto: Domingo López

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 technological 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 onshore 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*[2], published in June 2012, refreshed to bring it up to date and to represent the situation in onshore wind. This earlier work involved significant industry engagement, as detailed in the above report.

2 The Crown Estate, (June 2012), available online at www.bvgassociates.co.uk/Publications/BVGAssociatespublications.aspx , last accessed July 2014.

This has been augmented by continued dialogue with players across industry, right up until publication of this report.

The study does not consider the market share of the different Turbine 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 with 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 two baseline wind farms for which results are presented. Assumptions relating to these wind farms are presented in Section 2.

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

- **Section 4. Innovations in wind farm development.** This section incorporates the wind farm design, consenting, contracting and developer's project management activities through to the works completion date (WCD).
- **Section 5. Innovations in wind turbine nacelle.** This section incorporates the drive train, power take-off and auxiliary systems, including those that may be located in the tower.
- **Section 6. Innovations in wind turbine rotor.** This section incorporates the blades, hub and any pitch or other aerodynamic control system.
- **Section 7. Innovations in balance of plant.** This section incorporates the support structure; the tower and foundation. It also considers cables connecting turbines to any substation only. Substations are not considered. These transmission costs are included in the other effects discussed in Section 2.4.
- **Section 8. Innovations in wind farm installation.** This section incorporates the transportation of components from the component supplier, plus all installation and commissioning activities for the support structure, turbine and array cables. It excludes installation of the substation and 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 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.

Foto: Maximo Panes

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 Types on given Site Types, impacted 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 The Crown Estate's *Offshore wind cost reduction pathways: Technology work stream* report.

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 for analysis of 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 Type.

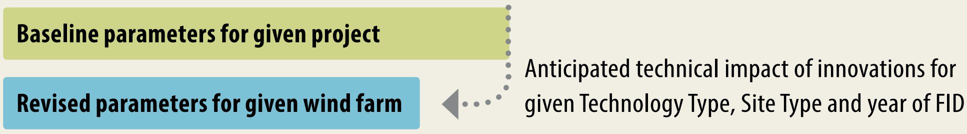
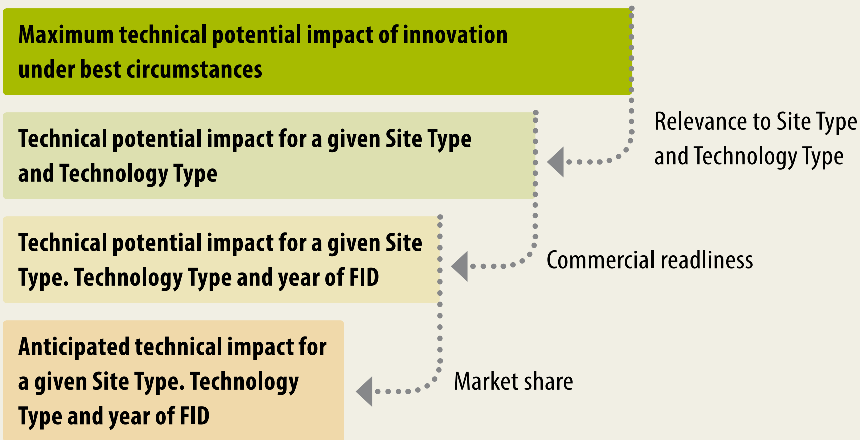


Figure 2.2 summarises this process of moderation.

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 Type.



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 Type 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.

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
- Wind farm development
- Wind turbine nacelle
- Wind turbine rotor
- Balance of plant
- Wind farm construction, and
- Wind farm operation, maintenance and service

Impact on
- Gross AEP, and
- Losses

2.3.2. Relevance to Site Types and Turbine Types

This maximum technical potential impact of an innovation compared with the baseline may not be realised on both Site Types with both Turbine Types. In some cases, an innovation may not be relevant to a given Site Type and Turbine Type combination at all. In particular, for onshore wind, the anticipated dominance of Class I Turbines on projects on the High Wind Site Type and Class III turbines on projects on the Low Wind Site Type makes the remaining two combinations irrelevant. In other cases, the maximum technical potential may only be realised on one Site Type, with a lower technical potential realised on the other. For example, using concrete hybrid towers is only applicable on projects on the Low Wind Site Type where taller towers have the greater benefit. In this way, relevance indicators for a given Turbine Type and Site Type may be between zero and 100%, with at least one Turbine Type and Site Type combination having 100% relevance.

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

2.3.3. Commercial readiness

In most cases, the technical potential of a given innovation will not be fully realised even on a project with 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 a design's ongoing evolution 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 with FID in that year. If the figure is 100%, this means that the full technical potential is realised by the given year of FID. For many of the innovations modelled, it is anticipated that further progress will be made after the last year of FID modelled (2025).

The factor relates to how much of technical potential is commercially ready for deployment in a commercial project of the scale defined in the baseline, taking into account not only the offering for sale of the innovation by the supplier but also the appetite for purchase by the customer. 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 concrete hybrid and space frame towers 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 Type and year of FID. This is a market share of a group of innovations for a given Turbine Type for projects with 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 and Site Types.

The resulting anticipated impact of a given innovation, as it takes into account the anticipated market share on a given Turbine Type 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 and 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 and 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 and 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 and Site Type and year of FID as follows:

- Scenario-specific WACC, taking into account risk beyond that covered by contingency
- Transmission and land cost, covering transmission capital and operating costs and charges related to the infrastructure from input to the transmission network
- Supply chain dynamics, simplifying the impact of the supply chain levers such as competition and collaboration
- Insurance and contingency costs, both relating to construction and operation insurance and typical spend of construction phase contingency, and
- The risk that some projects are terminated prior to FID, thereby inflating the equivalent cost of work carried out in this phase on a project that is constructed. For example, if only one in three projects reaches FID, then the effective contribution to the cost of energy of work carried out on projects prior to FID is modelled as three times the actual cost for the project that is successful.

A factor for each of these effects was derived for each specific Turbine and Site Type and FID year, as presented in Appendix A.

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 12.0% effect to account for transmission costs (the first factor in Table A.4) is applied as a factor of 1.120. 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 other health and safety

The health and safety of operational staff is of primary importance to the onshore 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. Many of the innovations that are considered to reduce the LCOE over time have an intrinsic benefit to health and safety performance, for example:

- The increased reliability of turbines and hence less time working in the turbine, and
- Condition monitoring / remote diagnostics, which provide a more effective and proactive service and hence result in fewer complex retrofits.

Foto: Begoña Espinosa

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 a review of current (within three years) cost models for onshore wind farms in combination with industry engagement, based on the technical parameters of the baseline wind farms (see Appendix A).

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. This is particularly true for onshore wind where local site topography and regional customs and practices in wind farm development and operation can vary significantly. As such, any baseline represents a wide spectrum of potential costs and it is accepted that there will be actual projects in operation with LCOEs significantly higher and lower than those associated with these baselines.

The baseline costs presented in Table 3.1 and Figure 3.1 and Figure 3.2 are nominal contract values, rather than outturn values, and are for projects with 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 LCOEs 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 120m scale rotors will be commercially available to the market for projects with FID in 2014, as demonstrated by the use of GE 2.75-120 or Acconia AW 125/3000 turbines on a number of European onshore wind farm projects. "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 commercial scale project. No assumptions are made in this report about the market share of high wind projects compared with low wind projects.

Table 3.1 **Baseline parameters.**

Type	Parameter	Units	High Wind	Low Wind
CAPEX	Development	€k/MW	78	78
	Turbine	€k/MW	714	827
	Support Structure	€k/MW	348	416
	Array Electrical	€k/MW	65	77
	Construction	€k/MW	74	59
OPEX	Operations and Planned Maintenance	€k/MW/yr	19	17
	Unplanned Service and Other OPEX	€k/MW/yr	23	19
AEP	Gross AEP	MWh/yr/MW	3,493	2,676
	Losses	%	9.2	10.5
	Net AEP	MWh/yr/MW	3,172	2,395
	Net Capacity Factor	%	36,2	27,3

Source: BVG Associates

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

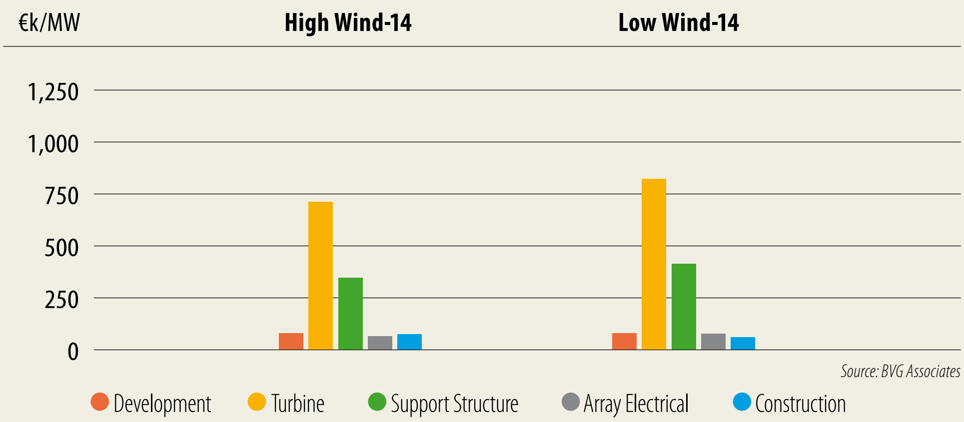
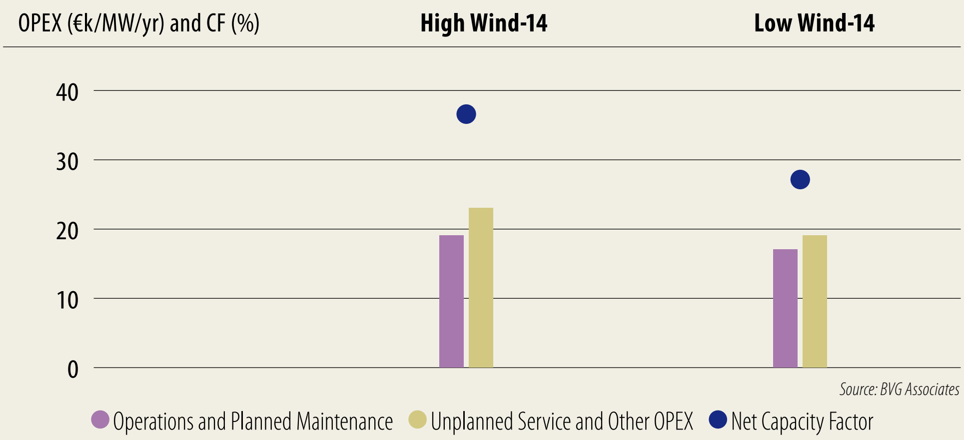


Figure 3.2 **Baseline OPEX and net capacity factor.**



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 two baseline Site Type and Turbine Type combinations. A comparison of the relative LCOE for each of the baseline wind farms is presented in Figure 3.3 with the high wind project used as the comparator.

The LCOE for projects on the Low Wind Site Type is about 50% higher than for projects on the High Wind Site Type. AEP is about 25% lower and the remainder relates to higher CAPEX due to the use of a larger rotor and taller tower. The baseline capacity factor for the Low Wind Site Type is at the upper end of reported ranges of capacity factors for EU onshore wind farms of this type; however, it must be considered that the Class III Turbine is modelled with a 123m rotor representing a state of the art turbine available to projects with FID in 2014 and as such should be expected to perform well in relation to older sites of this type. Likewise, the capacity factor for the baseline High Wind Site Type is higher than for existing wind farms, but the difference is justified.

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

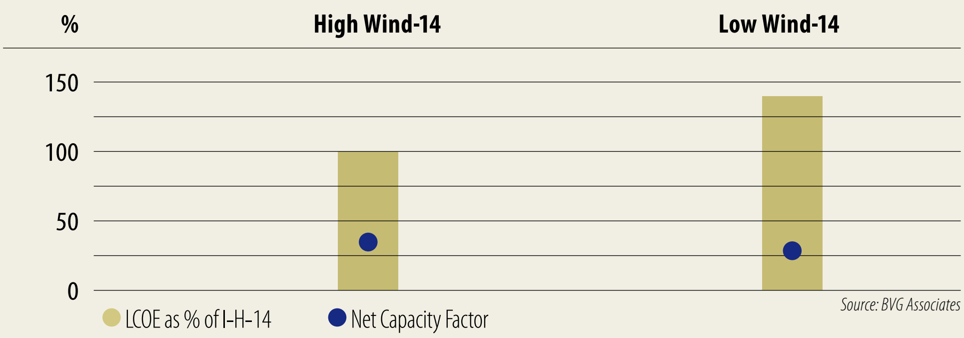


Foto: Courtesy of EDP Renewables

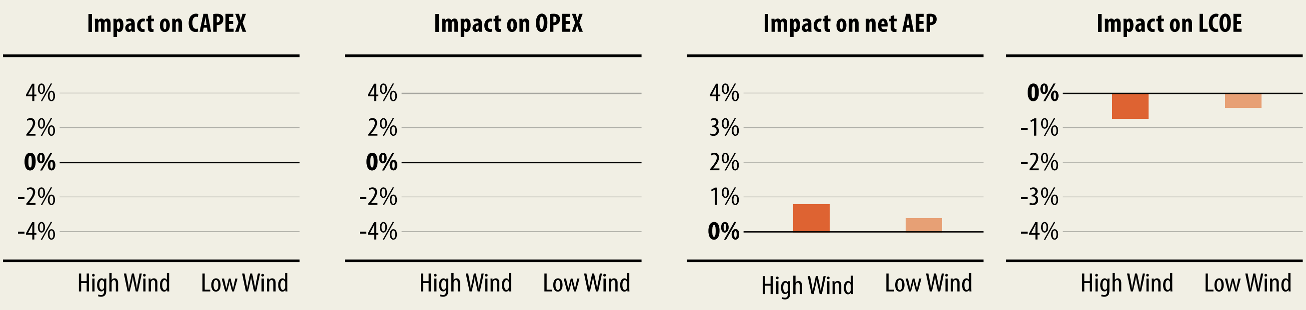
4. Innovations in wind farm development

4.1. Overview

Innovations in wind farm development are anticipated to reduce the LCOE by between 0.5 and 1% between FID 2014 and 2025. The savings are dominated by improvements in AEP associated with improved micrositing.

Figure 4.1 shows that the impact on LCOE is greatest for projects on the High Wind Site Type. This is due to the greater opportunities available to better model more complex terrain on such sites.

Figure 4.1 **Anticipated impact of wind farm development innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**



Source: BVG Associates

Table 4.1 and Figure 4.2 show that the individual innovation with the largest anticipated impact by FID 2025 is improvements in resource modelling, which will allow developers to optimise the layout of sites on the basis of improved understanding and modelling of the complex air flows over real terrain and in the wake of turbines. The anticipated benefit of this innovation is slightly greater for projects on the High Wind Site Type, associated in this analysis with more complex terrain.

Figure 4.2 **Anticipated and potential impact of wind farm development innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

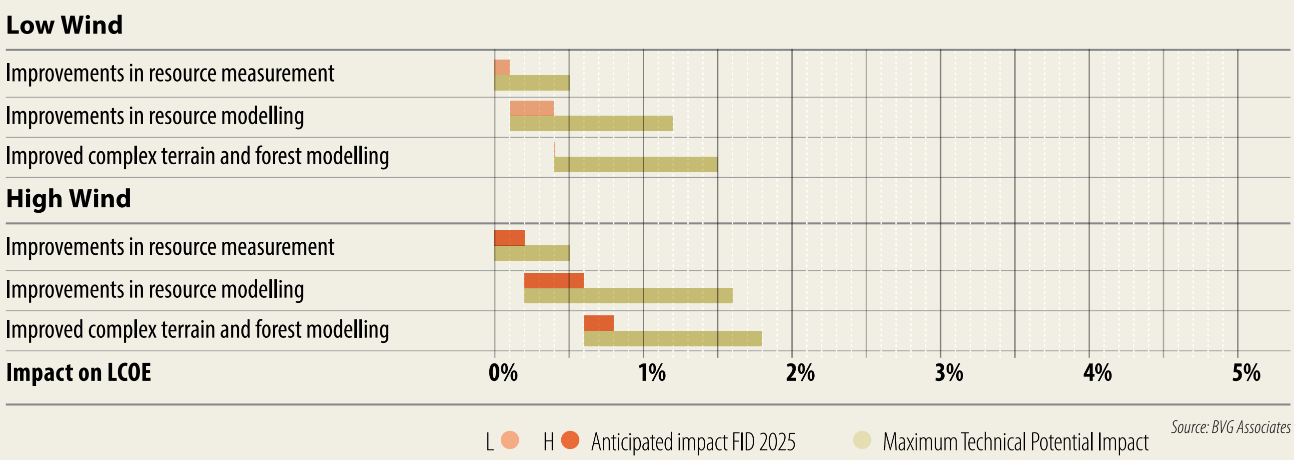


Table 4.1 **Anticipated and potential impact of wind farm development innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Low Wind								
Improvements in resource measurement	0.0%	0.0%	0.5%	0.5%	0.0%	0.0%	0.1%	0.1%
Improvements in resource modelling	0.0%	0.0%	1.1%	1.1%	0.0%	0.0%	0.3%	0.3%
Improved complex terrain and forest modelling	0.0%	0.0%	1.1%	1.1%	0.0%	0.0%	0.0%	0.0%
High Wind								
Improvements in resource measurement	0.0%	0.0%	0.5%	0.5%	0.0%	0.0%	0.2%	0.2%
Improvements in resource modelling	0.0%	0.0%	1.0%	1.0%	0.0%	0.0%	0.4%	0.4%
Improved complex terrain and forest modelling	0.0%	0.0%	1.0%	1.0%	0.0%	0.0%	0.2%	0.2%

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.

Improvements in resource measurement

Practice today: Characterisation of the wind flow on a 50MW site is likely to be achieved using one (for simple site topography) or two fixed met masts with a vertically oriented Light Detection And Ranging (LiDAR) or (SOnic Detection And Ranging, (SODAR) unit used for short campaigns to address specific issues such forestry or complex terrain.
Innovation: This innovation is the adoption of advanced wind flow measurement technologies such as scanning (3D) LiDAR to more accurately characterise the wind flow across a site. This approach is anticipated to slightly increase development CAPEX but to deliver an overall saving on LCOE by improvements to gross AEP as a result of improved micrositing.
Relevance: It is anticipated that around half the value of this innovation will be realised for a project on the Low Wind Site Type and all of the value will be realised for a project on the High Wind Site Type, as defined here with more complex topography.
Commercial readiness: About half of the total benefit of this innovation will be available for projects with FID in 2020 with about two thirds of the benefit available for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on a quarter of projects on the Low Wind Site Type and half of projects on the High Wind Site Type with FID in 2020. Both figures are anticipated to rise for projects with FID in 2025.

Improvements in resource modelling

Practice today: Wind resource models are widely used to optimise site layouts against multiple criteria. These models strike a balance between accuracy and speed of operation which is optimised for current computer performance. Some companies are already moving towards more powerful computing arrangements to drive more advanced models.
Innovation: This innovation relates to the ongoing advances in computer performance (both in terms of the general upward trend and willingness to invest in higher performance at a given time) and in understanding the behaviour of wind speeds and wakes within wind farms. Small increases in development CAPEX will drive improvements in site layout and reduced wake losses.
Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type, but most benefit is available to projects on the Low Wind Site Type.
Commercial readiness: Three quarters of the benefit of this innovation will be available for projects with FID in 2020 and about half of the remaining benefit will be available for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on a quarter of projects on the Low Wind Site Type and half of projects on the High Wind Site Type with FID in 2020. Both figures are anticipated to rise for projects with FID in 2025.

Improved complex terrain and forest modelling

Practice today: Sites including complex or forested terrain are typically modelled using standard tools with some additional rules of thumb and approximate adjustments made to roughness and zero plane heights. Integration of more advanced handling of forestry sites is a priority for tool developers.

Innovation: This innovation concerns the development and integration of specialised forestry and complex terrain modelling capabilities into existing and new tools to enable more accurate site design. At the cost of additional development CAPEX, such tools will enable losses to be reduced by enabling accurate forecasts of wakes and forestry/complex terrain effects and hence the design robust site layouts.

Relevance: This innovation is only applicable to projects on the High Wind Site Type.

Commercial readiness: More than half the benefit of this innovation will be commercially available for projects with FID in 2020 with three quarters of the benefit being available for projects with FID in 2025.

Market share: It is anticipated that this innovation will be used in the design of a quarter of projects on the High Wind Site Type with FID in 2020 and 2025. Use on projects on the Low Wind Site Type is not modelled.

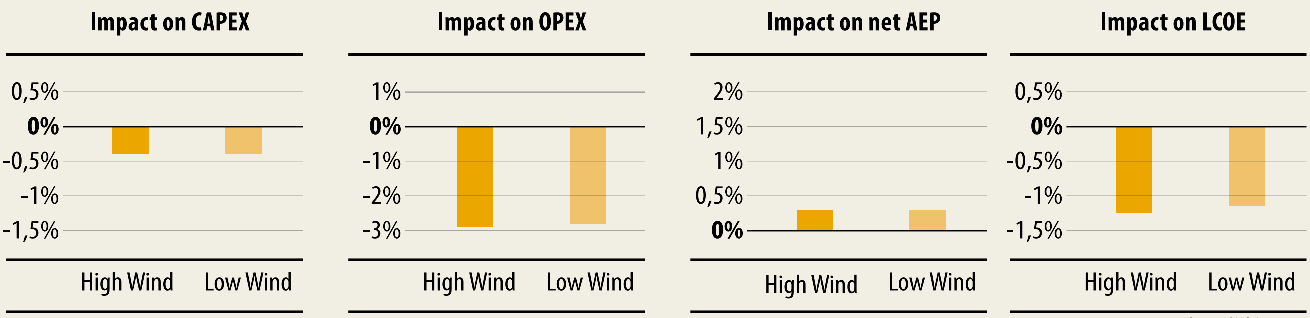
Foto: Juan Fabeiro

5. Innovations in the wind turbine nacelle

5.1. Overview

Innovations in the turbine nacelle are anticipated to reduce the LCOE by about 1 to 1.5% between FID in 2014 and 2025. The savings are dominated by improvements in OPEX, rather than CAPEX or AEP. Figure 5.1 shows that the impacts are about equal on both projects on the High Wind Site Type and Low Wind Site Type. This is because innovations in this area are generally equally applicable to both.

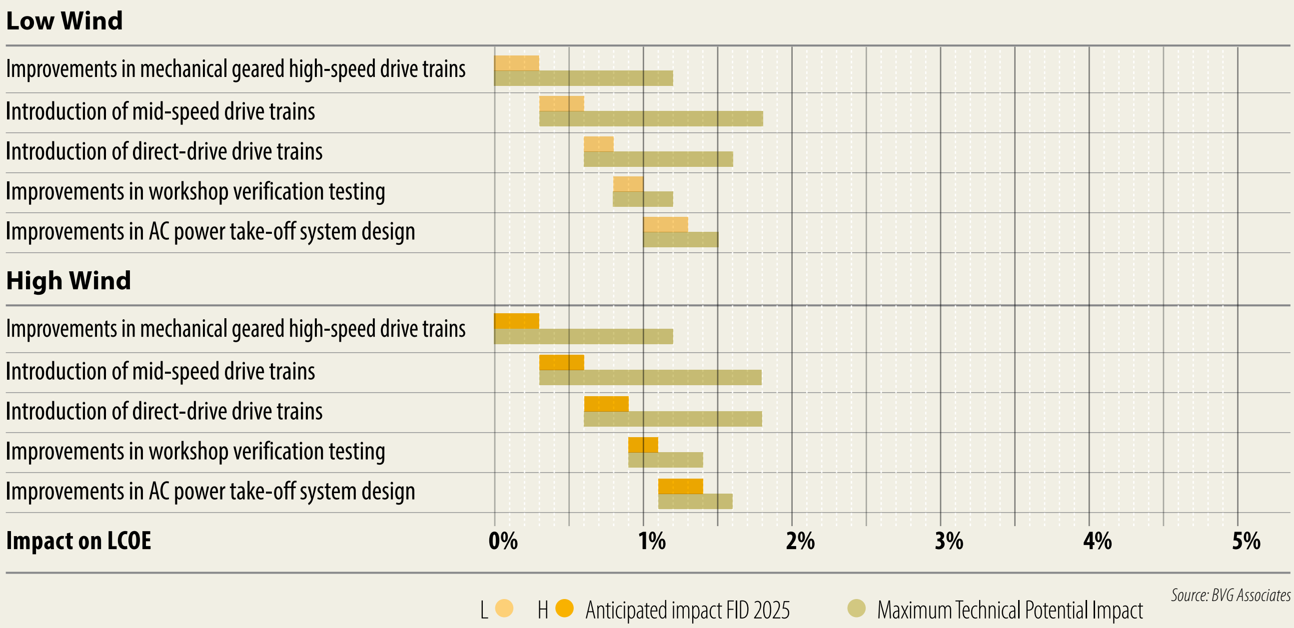
Figure 5.1 **Anticipated impact of turbine nacelle innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**



Source: BVG Associates

Figure 5.2 and Table 5.1 show that the innovation with the highest potential impact is the introduction of mid-speed drive trains. Mid-speed drive trains reduce the complexity of the gearbox, reduce turbine CAPEX and improve reliability leading to decreased losses and lower unplanned OPEX. Other competing drive train innovations are anticipated to have a similar impact, as is innovation in the AC power take-off system.

Figure 5.2 **Anticipated and potential impact of turbine nacelle innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**



Source: BVG Associates

Table 5.1 **Anticipated and potential impact of turbine nacelle innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Low Wind								
Improvements in mechanical geared high-speed drive trains	0.8%	2.0%	0.1%	1.2%	0.2%	0.4%	0.0%	0.3%
Introduction of mid-speed drive trains	0.8%	2.1%	0.4%	1.5%	0.2%	0.4%	0.1%	0.3%
Introduction of direct-drive drive trains	-0.5%	3.0%	0.8%	1%	-0.1%	0.7%	0.2%	0.2%
Improvements in workshop verification testing	0.0%	1.6%	0.1%	0.4%	0.0%	0.7%	0.0%	0.2%
Improvements in AC power take-off system design	0.3%	1.1%	0.0%	0.5%	0.2%	0.6%	0.0%	0.3%
High Wind								
Improvements in mechanical geared high-speed drive trains	0.8%	2.1%	0.1%	1.2%	0.2%	0.5%	0.0%	0.3%
Introduction of mid-speed drive trains	0.8%	2.2%	0.4%	1.5%	0.1%	0.4%	0.1%	0.3%
Introduction of direct-drive drive trains	-0.5%	3.2%	0.7%	1.2%	-0.1%	0.7%	0.2%	0.3%
Improvements in workshop verification testing	0.0%	1.7%	0.1%	0.5%	0.0%	0.7%	0.0%	0.2%
Improvements in AC power take-off system design	0.3%	1.1%	0.0%	0.5%	0.1%	0.6%	0.0%	0.3%

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 the 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 a 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, independently, 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: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
Commercial readiness: About two thirds of the benefit of this innovation will be available for projects with FID in 2020 rising to just under three quarters for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on half of projects with FID in 2020 dropping to under a third of projects with FID in 2025 as alternative drive train designs gain market share.

Introduction of mid-speed drive trains

Practice today: Mid speed gearboxes are available for onshore wind turbines, although uptake has been low to date. Three of the most significant six offshore wind turbine manufacturers/consortia have adopted this solution for their next generation products.
Innovation: Removal of the high speed stage in the gearbox reduces the gearbox size and mechanical losses. These benefits are somewhat offset by the increased size and inefficiencies associated with the move to a multipole, mid-speed 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: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
Commercial readiness: As first generation designs are already in production, it is anticipated that most of the benefit will be available for projects with FID in 2020 and almost all for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on a limited number of projects with FID in 2020 rising to just under a quarter of projects with FID in 2025.

Introduction of direct-drive drive trains

Practice today: A number of manufacturers have adopted permanent magnet direct drive technology in onshore wind turbines.

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 and electrical system. Increases in generator size and complexity are reduced by the use of permanent magnet generators. We anticipate that a slight increase in CAPEX will be more than offset by the expected reduction in unplanned service OPEX and losses.
Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
Commercial readiness: As first generation designs are already in production, it is anticipated that most of the benefit will be 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 this innovation will be implemented on around a sixth of projects with FID in 2020 rising to a quarter of projects with FID in 2025.

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 test rigs are being commissioned but standards are still absent and the focus is on testing drive trains for offshore wind turbines.
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: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
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 around a fifth of projects with FID in 2020 and just under half of projects with FID in 2025.

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: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
Commercial readiness: About two thirds of the benefits of this innovation are anticipated to be available to projects with FID in 2020 and most 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 half of projects with FID in 2020 and around two thirds of projects with FID in 2025.

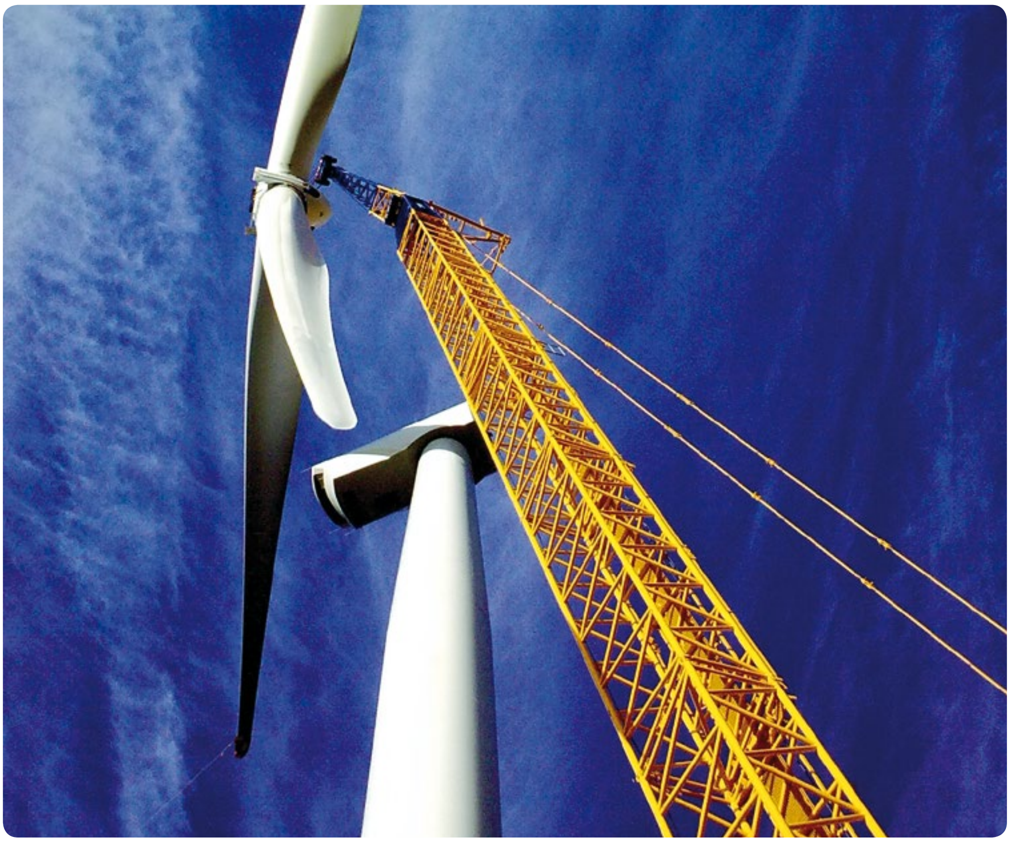


Foto: Jose Miguel Vazquez

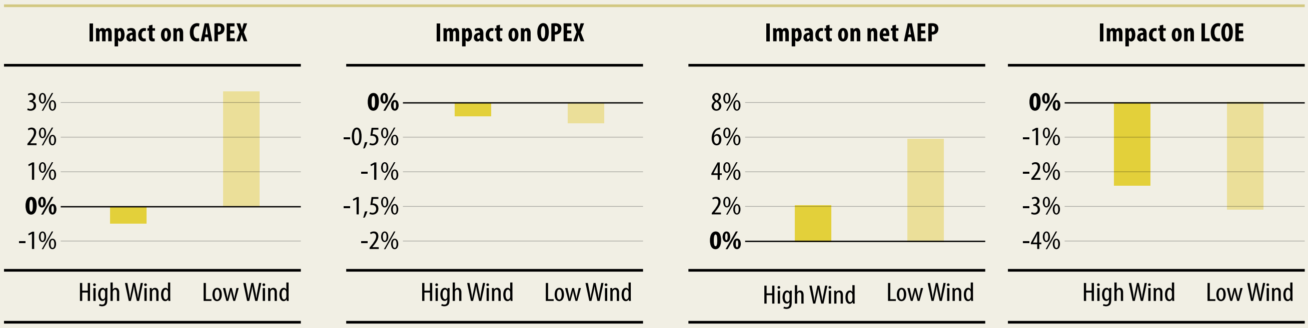
6. Innovations in the wind turbine rotor

6.1. Overview

Innovations in the turbine rotor are anticipated to reduce the LCOE by between 2.5 and 3%. The savings are dominated by improvements in AEP, offset for projects on the Low Wind Site Type by CAPEX increases due to the use of more optimised, larger rotors.

Figure 6.1 shows that the most significant impacts are anticipated on projects on the Low Wind Site Type, where greater changes in rotor size are anticipated.

Figure 6.1 **Anticipated impact of turbine rotor innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**



Source: BVG Associates

Figure 6.2 and Table 6.1 show that the innovation anticipated to have the greatest impact on LCOE by FID in 2025 is improvements to blade aerodynamics which deliver improved gross AEP.

On the Low Wind Site Type, optimisation of rotor size with advanced materials is also anticipated to have a significant impact on LCOE by FID in 2025. The larger rotor improves AEP while the use of advanced materials helps to minimise the increase in associated CAPEX.

Figure 6.2 **Anticipated and potential impact of turbine rotor innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

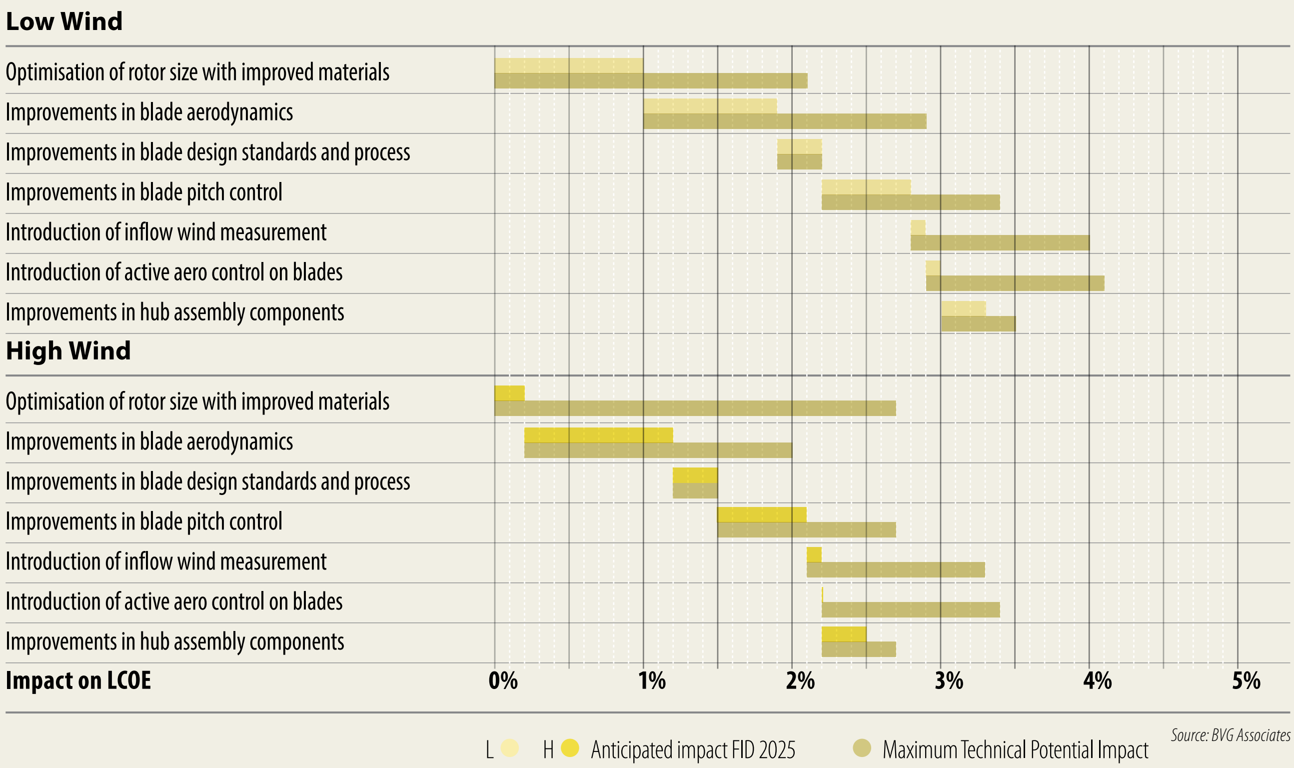


Table 6.1 **Anticipated and potential impact of turbine rotor innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Low Wind								
Optimisation of rotor size with improved materials	-9.7%	0.2%	10.0%	2.1%	-4.3%	0.1%	4.4%	1%
Improvements in blade aerodynamics	0.8%	-0.1%	1.3%	1.9%	0.4%	-0.1%	0.6%	0.9%
Improvements in blade design standards and process	0.2%	0.1%	0.2%	0.3%	0.2%	0.1%	0.1%	0.3%
Improvements in blade pitch control	0.6%	-0.2%	0.8%	1.2%	0.3%	-0.1%	0.4%	0.6%
Introduction of inflow wind measurement	-0.9%	-0.5%	2.0%	1.2%	-0.1%	-0.1%	0.2%	0.1%
Introduction of active aero control on blades	-1.1%	-1.6%	2.4%	1.2%	0.0%	-0.1%	0.1%	0.1%
Improvements in hub assembly components	0.4%	0.8%	0.0%	0.5%	0.2%	0.4%	0.0%	0.3%
High Wind								
Optimisation of rotor size with improved materials	-9.5%	0.2%	10.0%	2.7%	-0.5%	0.0%	0.6%	0.2%
Improvements in blade aerodynamics	0.7%	-0.1%	1.3%	1.8%	0.4%	-0.1%	0.8%	1.1%
Improvements in blade design standards and process	0.2%	0.1%	0.2%	0.3%	0.2%	0.1%	0.1%	0.3%
Improvements in blade pitch control	0.6%	-0.2%	0.8%	1.2%	0.3%	-0.1%	0.4%	0.6%
Introduction of inflow wind measurement	-0.8%	-0.6%	2.0%	1.2%	-0.1%	0.0%	0.2%	0.1%
Introduction of active aero control on blades	-1.1%	-1.7%	2.4%	1.2%	0.0%	0.0%	0.0%	0.0%
Improvements in hub assembly components	0.4%	0.8%	0.0%	0.5%	0.2%	0.4%	0.0%	0.3%

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.

Optimisation of rotor size with improved materials

Practice today: Rotors for onshore wind turbines are at near optimal sizes when balancing cost and AEP drivers, using materials available today.

Innovation: Many novel materials and manufacturing processes are in development to give a mix of stiffer, lighter, lower cost blades. In some cases aerospace innovations are now starting to be incorporated. This will allow larger rotors (a 10% increase is modelled) to be used with lower cost penalties than those associated with existing technologies, leading to an increase in optimum (lowest LCOE) rotor diameter for a given wind speed site. The increase in rotor size drives increases in both turbine and support structure CAPEX (although no increase in hub height is modelled), a modest increase in construction CAPEX and a significant boost to gross AEP. A small increase in planned OPEX results from increased inspection requirements and unplanned OPEX drops due to improved material properties.

Relevance: All of the benefit of this innovation will be realised on projects on the Low Wind Site Type but only half will be realised on projects on the High Wind Site Type.

Commercial readiness: Over a third of the benefit of this innovation is anticipated to be available to projects with FID in 2020, rising to just over half for projects with FID in 2025.

Market share: It is anticipated that this innovation will be implemented on about a sixth of projects on the High Wind Site Type with FID in 2020 and over two thirds of projects on the Low Wind Site Type. We recognise that the use of larger rotors is dependent also on tip height constraints imposed at the stage of obtaining planning consent, which is anticipated to delay their introduction somewhat. Further increases in implementation on both Site Types are anticipated for projects with FID in 2025.

Improvements in blade aerodynamics

Practice today: Most blade manufacturers are using some computational fluid dynamics (CFD) modelling and 2D 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 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 help reduce thrust fatigue loading.

Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.

Commercial readiness: Just under half of the benefit of this innovation is anticipated to be available to projects with FID in 2020, rising to almost three quarters for projects with FID in 2025.

Market share: It is anticipated that this innovation will be implemented on about two thirds of projects with FID in 2020 rising to over three quarters of projects with FID in 2025.

Improvements in blade design standards and process

Practice today: In recent years there has been a marked increase in the quality of testing of blades and blade materials and 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). A small increase is also anticipated in gross AEP.

Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.

Commercial readiness: Almost all of the benefit of this innovation is anticipated to be available to projects with FID in 2020 and all benefits are anticipated to be available to projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on about two thirds of projects with FID in 2020 rising to over three quarters of projects with FID in 2025.

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 up to a further 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: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
Commercial readiness: Half of the benefit of this innovation is anticipated to be available to projects with FID in 2020 and just under two thirds is anticipated to be available for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on most of projects with FID in 2020 and in 2025 with slightly higher uptake on projects on the Low Wind Site Type.

Introduction of inflow wind measurement

Practice today: Current turbine designs use anemometry mounted at the rear of the nacelle to infer inflow wind conditions. This information is used for supervisory (start/stop/mode-change) control rather than closed-loop pitch and power control algorithms. Forward looking wind measurement devices, typically LiDAR, are now being trialled as a potential alternative to traditional anemometry with additional benefits.
Innovation: Forward looking LiDAR has the ability to characterise the inflow wind field more completely and earlier than an anemometer measuring at a single point 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: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.

Commercial readiness: Just over a quarter of the benefit of this innovation is anticipated to be available to projects with FID in 2020 rising to just under two thirds for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on under a tenth of projects with FID in 2020 rising gradually for projects with 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, apart from whole blade pitching, although there has been an upturn in the use of passive aerodynamic enhancement devices and trials have started on some active 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 is anticipated, combined with an increase in turbine CAPEX and unplanned service cost to account for the increased failure rates of these advanced control solutions. This reduced reliability is also reflected in a modelled increase in losses.
Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
Commercial readiness: Just over a quarter of the benefit of this innovation is anticipated to be available to projects with FID in 2020, rising to just under two thirds for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on very few projects with FID in 2020. A small increase in uptake for projects with FID in 2025 is anticipated, likely mostly on projects on the Low Wind Site Type.

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: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
Commercial readiness: Over one third of the benefit of these innovations will be available for projects with FID in 2020, with a little under two thirds available for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on most of projects with FID in 2020, rising further for projects with FID in 2025, with slightly higher uptake on projects on the Low Wind Site Type.

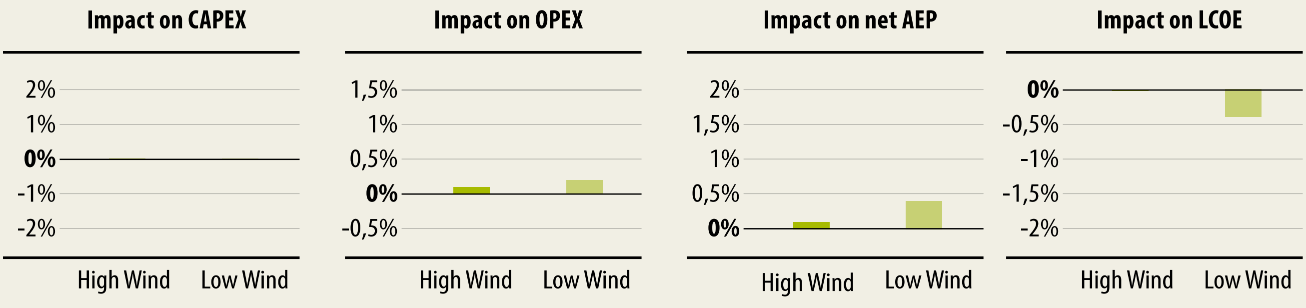
Foto: Juan Ramon Martín

7. Innovations in balance of plant

7.1. Overview

Innovations in balance of plant are anticipated to reduce LCOE on projects on the Low Wind Site Type by 0.4% between FID in 2014 and 2025. The savings are dominated by improvements in AEP relating to the use of taller towers. The anticipated impact on projects on the High Wind Site Type is significantly lower as the optimum tower height is within the feasible range of conventional rolled steel designs and as such does not benefit so much from these innovations.

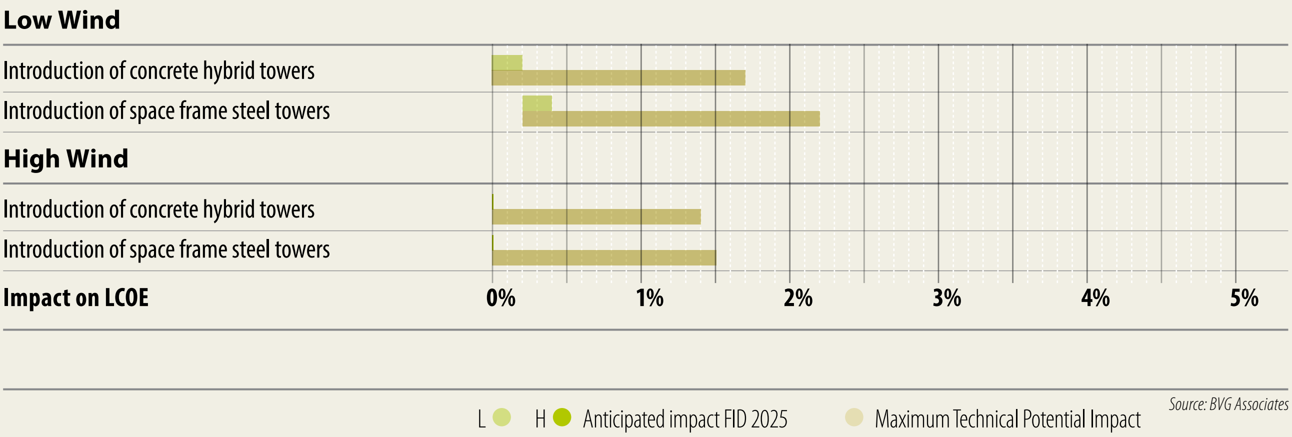
Figure 7.1 **Anticipated impact of balance of plant innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**



Source: BVG Associates

Figure 7.2 and Table 7.1 show that the individual innovation with the largest anticipated impact by FID in 2025 is the introduction of concrete hybrid towers, but that the introduction of space frame steel towers has a marginally higher potential impact in the same timeframe. A 10% increase in hub height has been modelled here. It is recognised that tip height limitations relating to planning constraints and visual intrusion limit the opportunity for implementing such innovations. Softening this barrier to development would have a positive impact on LCOE. The introduction of space frame steel towers also has benefits in terms of transport, especially to less accessible sites.

Figure 7.2 **Anticipated and potential impact of balance of plant innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**



Source: BVG Associates

Table 7.1 **Anticipated and potential impact balance of plant innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Low Wind								
Introduction of concrete hybrid towers	-0.4%	0.0%	2.0%	1.7%	0.0%	0.0%	0.3%	0.2%
Introduction of space frame steel towers	0.7%	-2.4%	2.0%	2%	0.1%	-0.2%	0.2%	0.2%
High Wind								
Introduction of concrete hybrid towers	-0.7%	0.0%	2.0%	1.4%	0.0%	0.0%	0.0%	0.0%
Introduction of space frame steel towers	0.2%	-2.3%	2.0%	1.5%	0.0%	-0.1%	0.1%	0.0%

7.2. Innovations

Innovations in balance of plant relate to improvements in the tower supporting the turbine. A subset of the more important of these has been modelled here. Innovations in foundations are generally quite site-specific and innovations in array cabling have relatively small impact. Energy storage solutions are not modelled as these increase LCOE in the terms of this study, while increasing also the value energy produced by reducing intermittency. Substations have been modelled separately in this study, see Section 2.4.

Introduction of concrete hybrid towers

Practice today: Turbines are supported on 100-120m conical welded steel towers. These heights represent the optimal balance between tower CAPEX and energy capture for the current technology, within the constraints imposed by planning conditions. Concrete hybrid towers are in use on a limited number of sites where taller towers are seen as more beneficial.

Innovation: This innovation is the adoption and ongoing improvement of hybrid concrete/steel towers. Pre-cast concrete sections form the base of the tower with a steel section forming the upper stage supporting the nacelle. This design allows for tower height to be increased (in this model by 10%) without incurring the CAPEX increases associated with the traditional conical welded steel design, especially when having to address natural frequency constraints. An increase in construction CAPEX is partly offset by a small saving in support structure CAPEX and yields an increase in gross AEP.

Relevance: This innovation is only relevant to projects on the Low Wind Site Type, as optimum tower height is typically lower (and not technology-limited) on projects on the High Wind Site Type.

Commercial readiness: About two thirds of the benefit of innovation in this area is anticipated to be available for projects with FID in 2020 with most of the benefit anticipated to become available for projects with FID in 2025.

Market share: It is anticipated that, where relevant, a tenth of projects with FID in 2020 will use this innovation and that this will increase to around a sixth for projects with FID in 2025.

Introduction of space frame towers

Practice today: Turbines are supported on 100-120m conical welded steel towers. These heights represent the optimal balance between tower CAPEX and energy capture for the current technology, within the constraints imposed by planning conditions. Space frame towers have not been used on commercial scale turbines although GE has recently introduced a new design.

Innovation: This innovation involves the adoption and ongoing improvement of steel space frame towers. The tower is formed entirely from a bolted steel space frame. This design allows for tower height to be increased (in this model by 10%) without incurring the CAPEX increases associated with the welded steel shell design, especially when having to address natural frequency constraints, and also offers improvements in transportation. A small increase in construction CAPEX and planned OPEX (associated with increased inspections of bolted joints) is partly offset by a saving in support structure CAPEX and yields an increase in gross AEP.

Relevance: The innovation is only relevant to projects on the Low Wind Site Type, as optimum tower height is typically lower (and not technology-limited) on the High Wind Site Type.

Commercial readiness: A quarter of the benefit of innovation in this area is anticipated to be available for projects with FID in 2020 increasing to a half for projects with FID in 2025.

Market share: It is anticipated that few projects with FID in 2020 will use this innovation and that this will increase to around a tenth of projects with FID in 2025. Designs of this type have been available in the past and failed to gain widespread acceptance. While newer designs are available and claim to address some perceived issues with lattice towers, it remains highly uncertain whether these designs will gain favour in the industry.

8. Innovations in wind farm construction and commissioning

8.1. Overview

Innovations in construction and commissioning are not anticipated to reduce the LCOE significantly between FID in 2014 and 2025.

Figure 8.1 shows that the impact of installation and commissioning is negligible on both Site Types, though with a slight benefit for projects on the High Wind Site Type. These innovations have been included because they have potential advantages outside of the scope of this study. In this study the two Site Types modelled have been chosen such that they can be constructed economically using methods available to the market today.

The innovations in this section are primarily concerned with increasing the number of sites that can be constructed economically by overcoming access issues for transportation of components relevant to many potential locations, but not particularly the two Site Types modelled. By widening the range of sites where projects may be constructed, developers will be able to develop projects with (on average) better wind resources and lower LCOE.

Figure 8.1 **Anticipated impact of construction innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

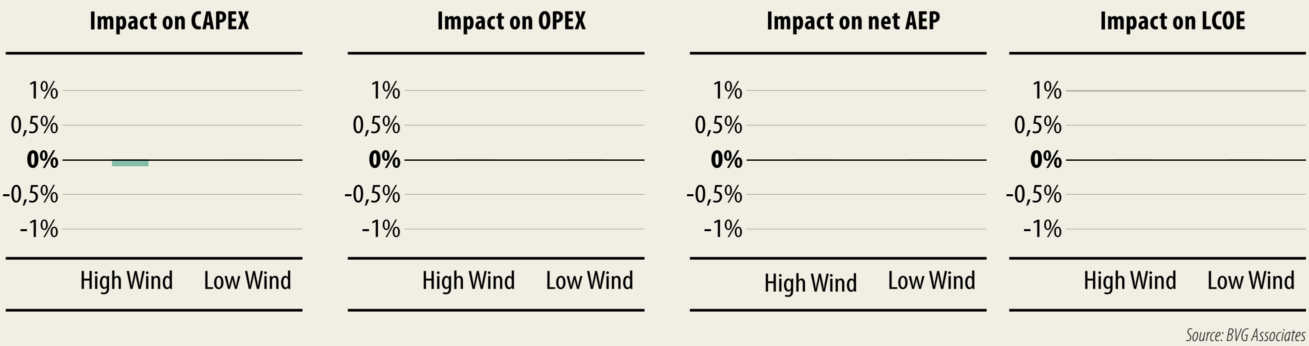


Figure 8.2 and Table 8.1 show that the improvement of transport vehicle designs for site access offers the greatest potential benefit but this is low for the project modelled on the High Wind Site Type here, as discussed above.

Figure 8.2 **Anticipated and potential impact of construction innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

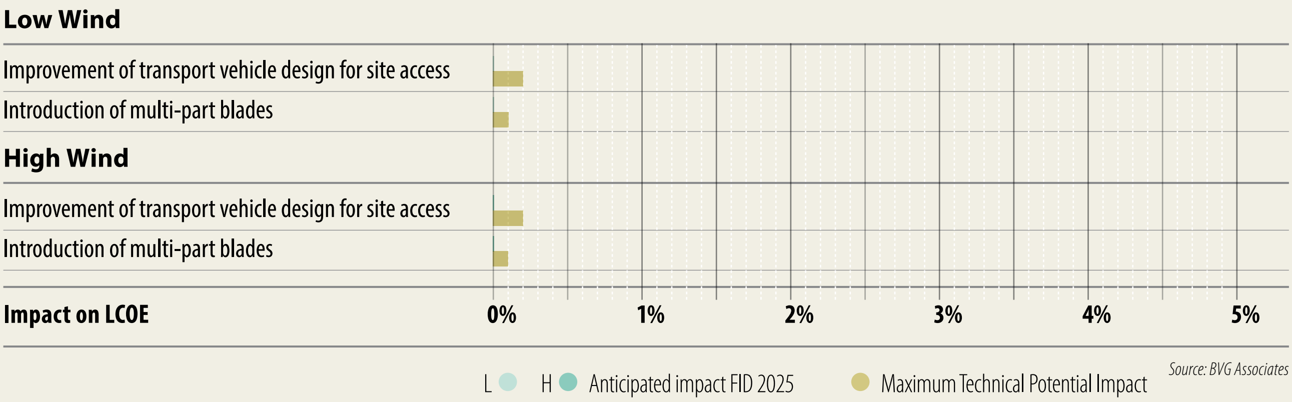


Table 8.1 **Anticipated and potential impact of construction innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Low Wind								
Improvement of transport vehicle design for site access	0.2%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
Introduction of multi-part blades	0.1%	-0.2%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
High Wind								
Improvement of transport vehicle design for site access	0.3%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
Introduction of multi-part blades	0.2%	-0.2%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%

8.2. Innovations

Innovations in wind farm construction and commissioning 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.

8.2. Innovations

Innovations in wind farm construction and commissioning 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.

Improvement of transport vehicle design for site access

Practice today: Large components are delivered using standard vehicle designs for abnormal loads. Access to sites is improved by the incorporation of independent steering and in some cases by lift-turn-replace processes on tight bends.

Innovation: This innovation is the development of vehicles specifically designed to transport large components on challenging routes, for example, trailers with inbuilt capacity to lift and reposition loads to achieve crane free access.

Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.

Commercial readiness: Just under half of the benefit of this innovation is anticipated to be available for sites with FID in 2020, rising for sites with FID in 2025.

Market share: This innovation is anticipated to be used on around a tenth of projects on the High Wind Site Type with FID in 2020 rising to a fifth for those with FID in 2025. For projects on the Low Wind Site Type the market penetration is anticipated to be half that of those on the High Wind Site Type.

Introduction of multi part blades

Practice today: Blades are delivered ex-works as a single unit ready for installation. They are transported to site and installed as a single piece.
Innovation: This innovation is the fabrication of blades in sections. The blade is delivered to the site in two or more sections then assembled on site. The increased construction cost is offset by the use of standard vehicles to deliver blade sections to the site resulting in an overall decrease in construction CAPEX, with a small OPEX penalty due to an on-site joint.
Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
Commercial readiness: Half of the benefit of this innovation will be available for projects with FID in 2020, with three quarters available for projects with FID in 2025.
Market share: This innovation is anticipated to be used on around a tenth of projects on the High Wind Site Type with FID in 2020 rising to a fifth for those with FID in 2025. No market penetration is anticipated for projects on the Low Wind Site Type.

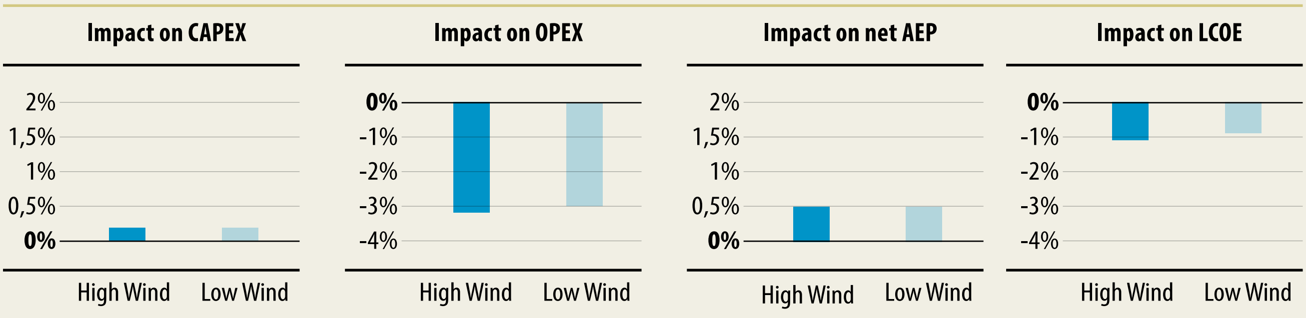
Foto: Iñaki Escubi

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 around 1% between FID in 2014 and 2025. The savings are dominated by improvements in OPEX and small improvements to wind farm availability (and hence net AEP) and are offset by a small increase in CAPEX. Figure 9.1 shows that the impact on OPEX is slightly higher for projects on the High Wind Site Type. The LCOE reduction is greater for projects on the High Wind Site Type because OPEX is a larger contribution to LCOE for these projects.

Figure 9.1 **Anticipated impact of OMS innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

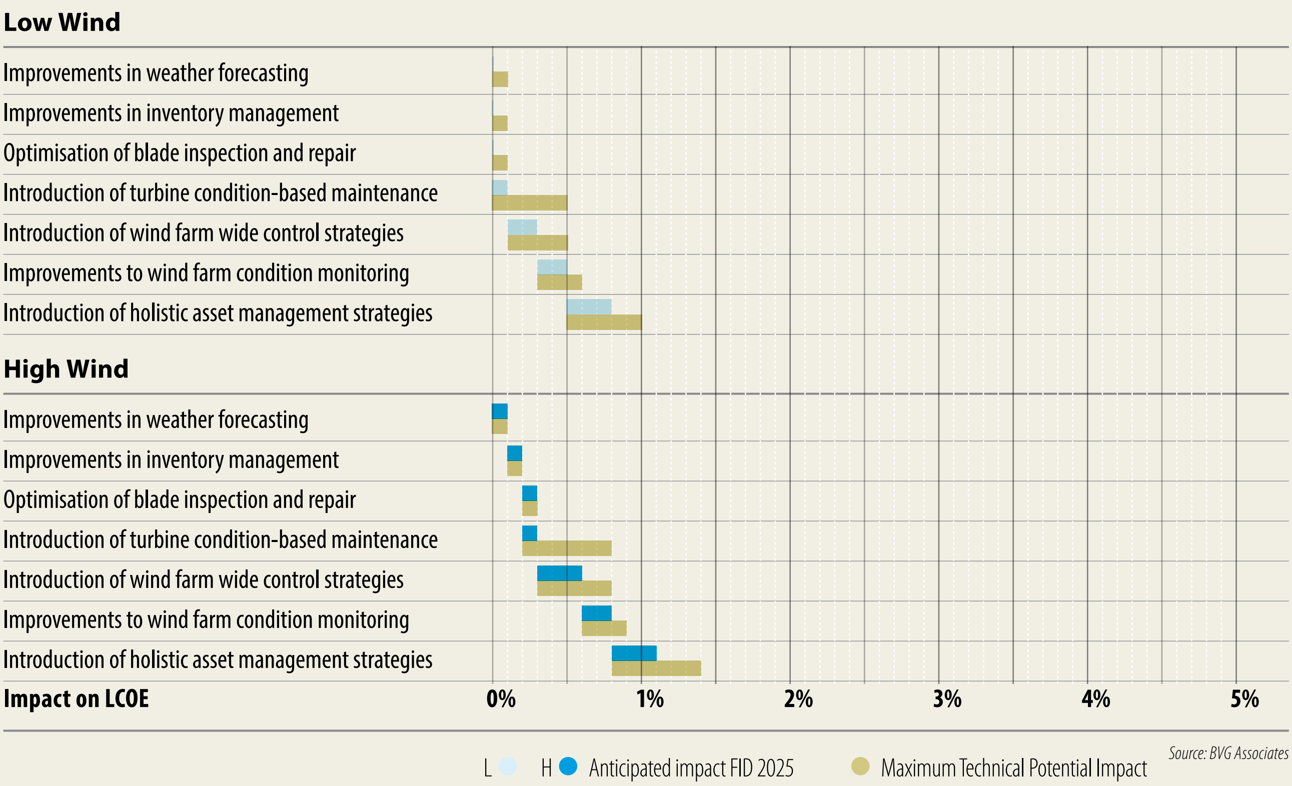


Source: BVG Associates

Figure 9.2 and Table 9.1 show that the individual innovation with the largest anticipated impact for both Site Types with FID 2025 stems from the introduction of holistic asset management. Formalising long term strategy and delivering this strategy through the consistent and structured development of systems and processes lead to improved technician productivity (through increased first time fix rates and reduced mean time to repair) and the greater support of the analysis and reduction of common faults improving overall reliability of the asset throughout its life.

We anticipate that most of the potential of innovations in this element will be achieved by FIDs in 2025. The notable exception to this is condition based maintenance, which depends on the industry being willing to take the long view and learn from other industries. This innovation requires a more significant mindset change than the others and as such a lower market share is anticipated in the timescales considered here. As modelled, only the innovations available to the asset owner at the point of FID are considered. In many cases, innovations can be applied during the project life, offering additional benefits for a fraction of the operational life of the wind farm.

Figure 9.2 **Anticipated and potential impact of OMS innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**



Source: BVG Associates

Table 9.1 **Anticipated and potential impact of OMS innovations for both Low and High Wind Scenarios with FID in 2025, compared with the same Scenario with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Low Wind								
Improvements in weather forecasting	0.0%	0.3%	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%
Improvements in inventory management	0.0%	0.3%	0.0%	0.1%	0.0%	0.2%	0.0%	0.0%
Optimisation of blade inspection and repair	0.0%	0.3%	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%
Introduction of turbine condition-based maintenance	-0.2%	2.1%	0.2%	0.5%	0.0%	0.5%	0.0%	0.1%
Introduction of wind farm wide control strategies	-0.3%	0.5%	0.5%	0.4%	-0.2%	0.3%	0.3%	0.2%
Improvements to wind farm condition monitoring	-0.1%	1.1%	0.1%	0.3%	0.0%	0.8%	0.1%	0.2%
Introduction of holistic asset management strategies	0.0%	1.8%	0.1%	0.5%	0.0%	1.0%	0.1%	0.3%
High Wind								
Improvements in weather forecasting	0.0%	0.3%	0.0%	0.1%	0.0%	0.2%	0.0%	0.1%
Improvements in inventory management	0.0%	0.3%	0.0%	0.1%	0.0%	0.2%	0.0%	0.1%
Optimisation of blade inspection and repair	0.0%	0.3%	0.0%	0.1%	0.0%	0.2%	0.0%	0.1%
Introduction of turbine condition-based maintenance	-0.2%	2.2%	0.2%	0.6%	0.0%	0.5%	0.0%	0.1%
Introduction of wind farm wide control strategies	-0.3%	0.6%	0.5%	0.4%	-0.2%	0.3%	0.3%	0.3%
Improvements to wind farm condition monitoring	-0.1%	1.1%	0.1%	0.3%	0.0%	0.8%	0.1%	0.2%
Introduction of holistic asset management strategies	0.0%	1.9%	0.1%	0.6%	0.0%	1.1%	0.1%	0.3%

9.2. Innovations

Innovations in wind farm OMS cover a range of practical and technical modifications to the current practice. 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 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. In order to make the most efficient use of resources, and especially heavy equipment such as cranes, reasonable accuracy will need to be extended. Forecasting can also be used to increase the value of energy sold, but this is not modelled in this study.

Relevance: Projects on the High Wind Site Type will realise the full benefit of this innovation, with projects on the Low Wind Site Type realising three quarters of the benefit.

Commercial readiness: Half of the benefit of this innovation is anticipated to be available for projects with FID in 2020, rising to over two thirds in 2025.

Market share: It is anticipated that this innovation will be implemented on three quarters of projects of the size considered in this study with FID in 2020 and almost all such 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 the 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 which will therefore reduce unavailability losses.

Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.

Commercial readiness: Most of the benefit of this innovation is anticipated to be available for projects with FID in 2020, as such systems are already prevalent in other sectors.

Market share: It is anticipated that this innovation will be implemented on half of projects with FID in 2020 and three quarters of projects with FID in 2025.

Optimisation of blade inspection and repair

Practice today: Blade inspection is conducted approximately every three years either via rope access or access platform. Results of these inspections are analysed and any repairs conducted in a similar manner to the inspections using wet lamination. Companies are beginning to experiment with non-access inspections and alternative repair techniques.

Innovation: Further development and refinement of imaging (for example, drones or ground based telephoto capture) and image processing techniques will enable low cost interim inspections. This will allow owners to capture a proportion of blade damage sooner and conduct repairs in a more cost effective and responsive manner. New repair techniques such as UV cured prepreg solutions will expand the weather windows in which repair work may be conducted and improve the quality of such repairs. Increased expenditure on additional interim inspections is more than offset by reductions in the time-on-turbine during full inspection and repair campaigns. Reduced significant blade damage and failures from early identification also provides an additional uplift in availability.

Relevance: Projects on the High Wind Site Type will realise the full benefit of this innovation,

with projects on the Low Wind Site Type realising three quarters of the benefit.
Commercial readiness: Around two thirds of the benefit of these innovations is anticipated to be available to projects with FID in 2020, rising to nearly all for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on half of projects with FID in 2020 and three quarters for projects with FID in 2025.

Introduction of turbine condition-based maintenance

Practice today: In order to maintain the manufacturer warranty, operators are required to adhere to time based planned maintenance strategies. There is evidence that, as turbines come out of the initial warranty periods, operators are taking ownership of some risk and implementing condition-based maintenance (CBM) strategies on projects, which improves AEP and reduces OPEX. Such approaches are sometimes referred to as risk-based or reliability-based maintenance strategies.
Innovation: With the successful deployment of CBM strategies in other industries, and some initial success stories from the wind industry, CBM is anticipated to develop in sophistication and become 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 will reduce OPEX costs and losses with a small increase in turbine CAPEX by targeting maintenance on key issues and will improve watching for changes in behaviour system, rather than carrying out a wide range of standard maintenance activities independent of the underlying need to carry out such work.
Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
Commercial readiness: Two thirds of the benefit of this innovation is anticipated to be available for projects with FID in 2020 with nearly all available for projects with FID in 2025.
Market share: It is anticipated that this innovation will be implemented on a limited number of projects with FID in 2020 and a quarter of projects with FID in 2025.

Introduction of wind farm wide control strategies

Practice today: Automatic, autonomous 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 (the reduction of maximum power) which may in some cases already be managed by simple wind farm level control algorithms, possibly at the automated request of grid operators.
Innovation: More holistic control strategies that use systems able to measure the residual useful life of components on individual turbines and hold an understanding of the income drivers (for example, market spot prices) have the potential to provide multi-objective optimal control of wind farms to minimise LCOE and/or maximise revenue. This innovation will slightly increase turbine CAPEX but is anticipated to reduce unplanned OPEX and losses and to increase AEP.
Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.
Commercial readiness: Around half of the benefit of this innovation 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 this innovation will be implemented on half of projects with FID in 2020 and three quarters of projects with FID in 2025.

Improvements to wind farm condition monitoring

Practice today: Vibration monitoring systems are commonly deployed offshore and on larger onshore turbines. Expert analysis of the output of these systems is provided by component or wind turbine suppliers (especially in warranty/extended warranty periods) or, less commonly, by in house or third party providers.

Innovation: This innovation relates to the expanded use of existing technology and the development of additional technologies such as online oil monitoring, advanced blade monitoring or electrical system monitoring, and the holistic use of multiple datasets to further improve decision making. These technologies increase turbine CAPEX but have a significant impact on unplanned OPEX and losses by increasing the leading indication of potential faults allowing for proactive resolution and resource planning.

Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.

Commercial readiness: Technologies within this innovation are at different stages of development. Around half of the benefit is anticipated to be available for projects with FID in 2020 with more than three quarters available for projects with FID in 2025.

Market share: It is anticipated that this innovation will be implemented on three quarters of projects with FID in 2020 and almost all projects with FID in 2025.

Introduction of holistic asset management strategies

Practice today: The increase in scale of many wind farm developments both onshore and offshore has lead to an evolution in how owners and, to an extent, service and warranty providers view the management of installed equipment onsite. Owners have moved away from a relatively hands-off approach to day-to-day operations and are now seeking to gather and structure knowledge of the performance of the asset and the O&M strategy with a view to optimising the through-life performance of their sites.

Innovation: This innovation relates to the expansion of formal asset management thinking as encoded in the ISO55000 standard. Consideration and optimisation of the processes and systems supporting wind farm O&M allow for more efficient capture of learning which in turn feeds back to increase first time fix rates and to identify and engineer out common or systematic failures.

Relevance: This innovation is relevant to projects on both the High Wind Site Type and Low Wind Site Type.

Commercial readiness: Around half of the benefit of this innovation 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 this innovation will be implemented on half of projects with FID in 2020 rising to three quarters for projects with FID in 2025.

Foto: Gotzon Aznar

10. Summary of innovations and results

10.1. Combined impact of innovations

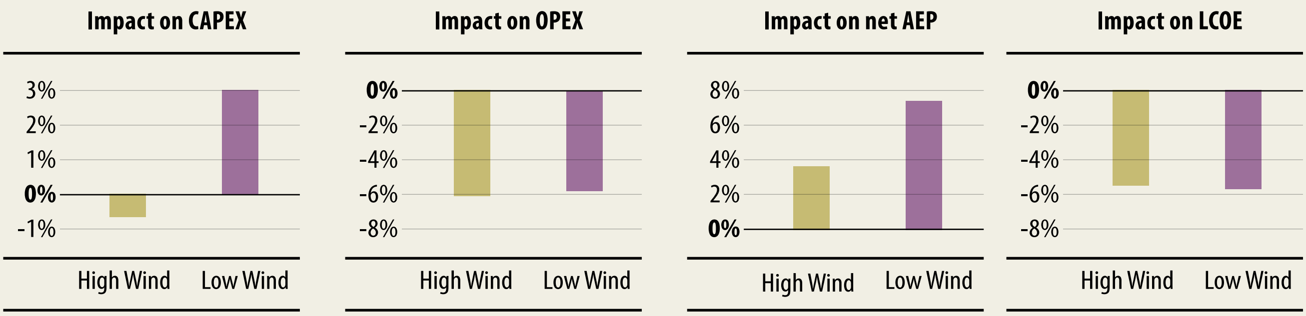
Innovations across all elements of the wind farm are anticipated to reduce the LCOE by around 5.5% between projects with FID in 2014 and 2025. Figure 10.1 shows that the savings are generated mainly through reductions in OPEX and increased AEP.

The figures show that there is limited scope from cost reduction in project CAPEX, representing a view that the onshore wind industry benefits from a relatively mature technology base that is now generally constrained by transport and planning limitations.

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 that are available are for projects using Class III Turbines on the Low Wind Site. This is due mainly to the opportunities available for further optimising rotor size and tower height on such projects by taking advantage of innovations in materials and design concepts.

Figure 10.1 **Anticipated impact of all innovations for both Low Wind and High Wind Scenarios, with FID 2025, compared with FID 2014.**

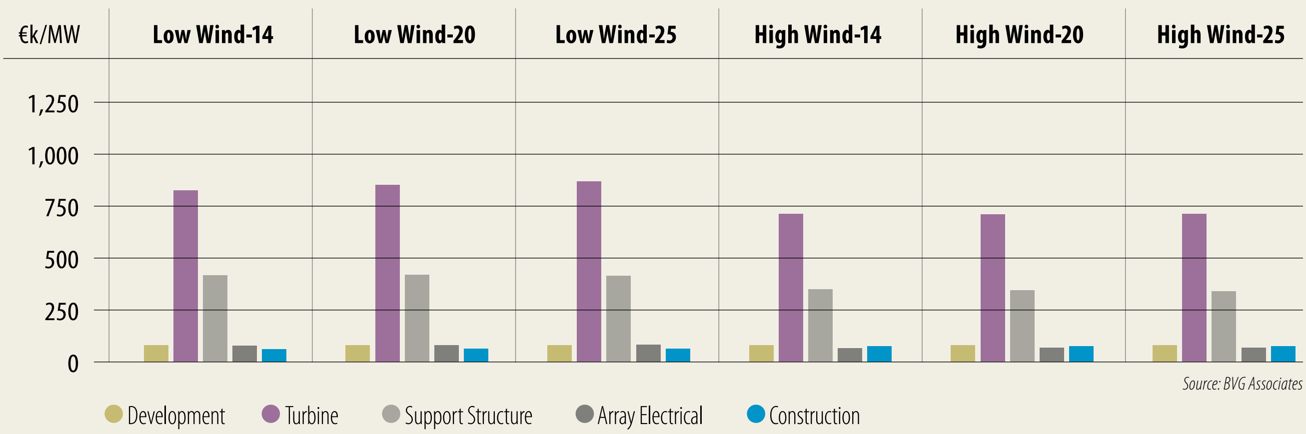


Source: BVG Associates

10.2. Relative impact of cost of each wind farm element

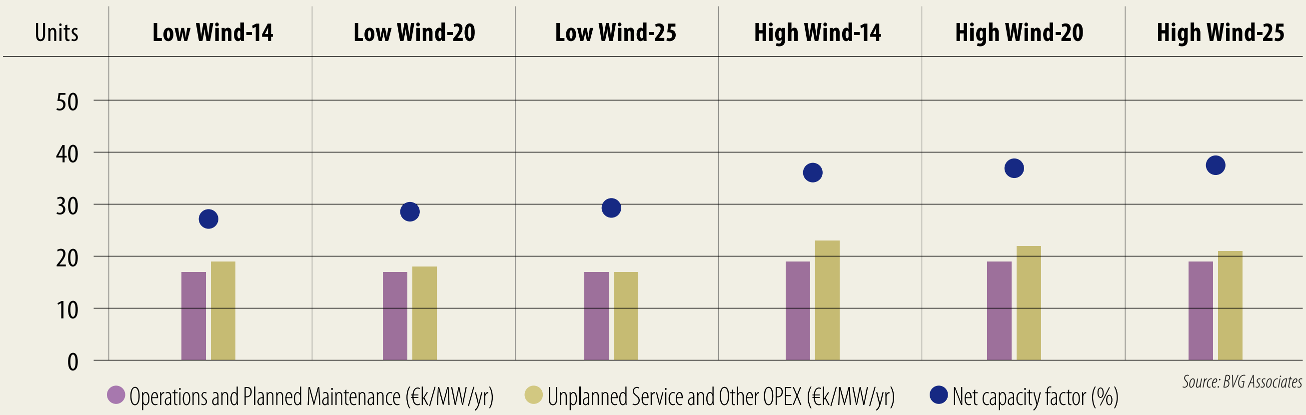
In order to explore the relative cost of each wind farm element, Figure 10.2 shows the cost of all CAPEX elements for all scenarios and Figure 10.3 shows the same for OPEX elements and the net capacity factor. These figures show the increase in turbine and support structure CAPEX for projects on the Low Wind Site Type due to increases in rotor size and tower height and the relative stability of the cost of CAPEX elements on the High Wind Site Type. The cost of planned maintenance is relatively stable but, in all cases, the cost of unplanned service and other OPEX decreases over time and the capacity factor increases.

Figure 10.2 **CAPEX for wind farms with FID 2014, 2020 and 2025.** (Low Wind: III-L, High Wind: I-H)



Source: BVG Associates

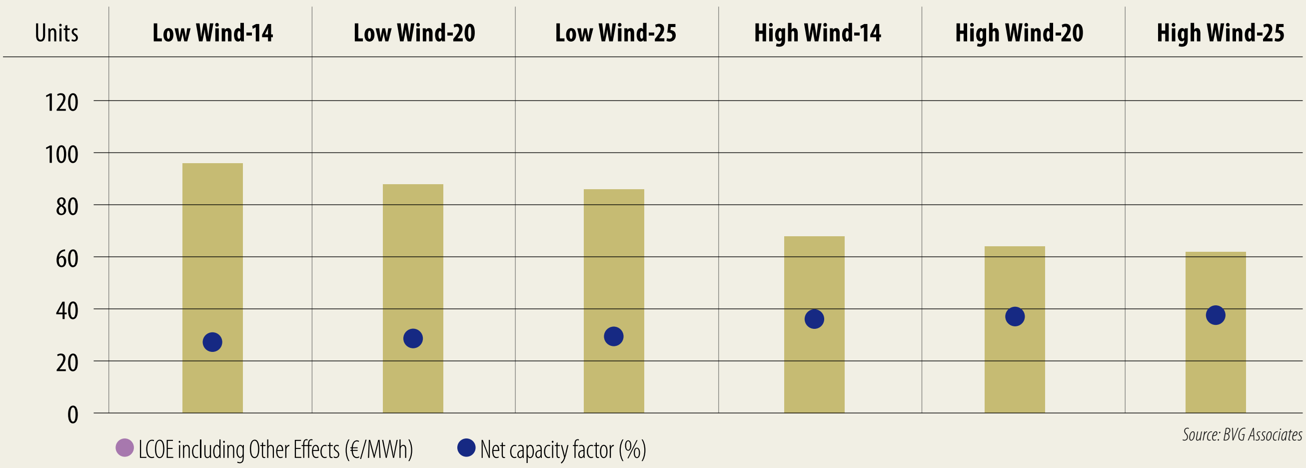
Figure 10.3 **OPEX and net capacity factor for wind farms with FID 2014, 2020 and 2025.**



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

In order to compare LCOE, Figure 10.4 also incorporates the other effects discussed in Section 2.4. It shows that, especially with the benefit of an increasing capacity factor over time and with the reduction in OPEX achieved through innovations, LCOE is reduced for both Turbine Types. Although projects on the Low Wind Site Type benefit from greater LCOE reductions in both relative and absolute terms, projects on the High Wind Site Type still offer significantly lower LCOE over the period shown due to the higher inherent value of the wind resource available.

Figure 10.4 **LCOE for wind farms with FID 2014, 2020 and 2025 with Other Effects incorporated.**



The contribution of innovations in each element to this LCOE reduction is presented in Figure 10.5. It shows that innovations in the turbine have the dominant effect on LCOE, but innovations in many other elements are also important. It also shows that the impact of one of the most significant innovations in the Low Wind Scenario, the optimisation of rotor size with improved materials, is not in the top seven innovations in the High Wind Scenario, but the overall difference in LCOE reduction between the two scenarios is less than 0.2%.

Figure 10.5 **Anticipated impact of technology innovations for a wind farm with FID in 2025, compared with a wind farm under the same scenario with FID in 2014**

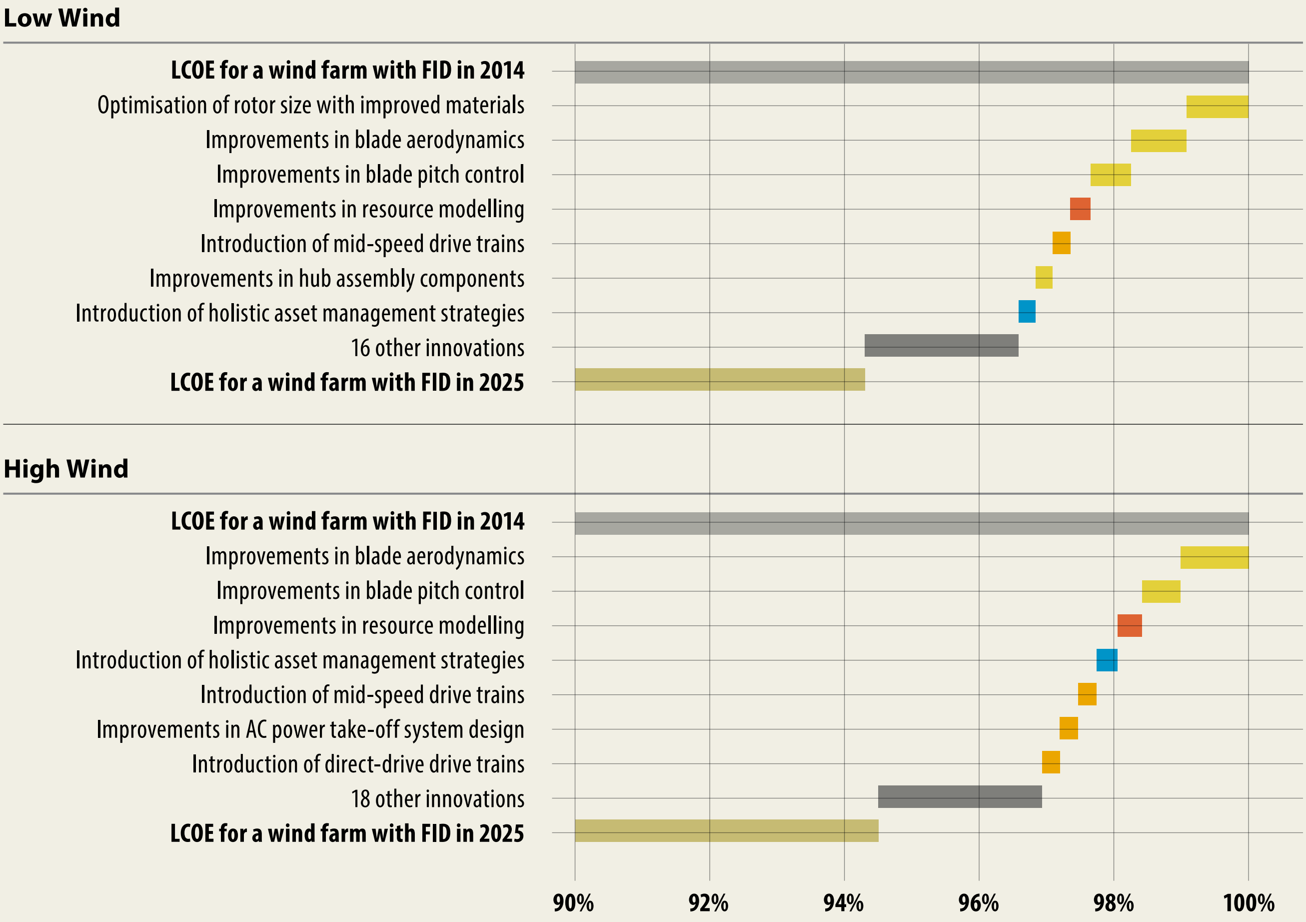


Foto: Iñigo Montoya

11. Conclusions

In Section 4.1 to Section 9.1, we considered a large number of innovations with the potential to reduce the LCOE by FID 2025. Within these, a number of distinct themes emerge, which will be the focus of the industry's efforts to reduce costs:

- Improving the design, manufacture and control of blades, including further optimisation of rotor diameter in the light of these innovations
- Introducing and improving site resource assessment and modelling tools
- Enhanced OMS methods incorporating both evolutionary and revolutionary shifts in thinking and practice, and
- Adopting and further developing novel wind turbine drive train and electrical designs.

Many of the individual innovations discussed in this report are anticipated to have small impacts on LCOE reflecting the maturity of the technology base for onshore wind. One notable exception to this pattern is the anticipated impact of the optimisation of rotor size on projects built on lower wind speed sites, including savings resulting from innovations in blade design, manufacture and control. These innovations enable blade length to be increased with less of an increase in mass, tip deflection and turbine loading than would be expected using simple scaling-up.

Another innovation most relevant to flatter, low wind sites is the use of taller towers, again enabled by innovations in tower design that avoid using taller conical tubular steel towers which generally become uneconomic at heights greater than standard.

The use of larger rotors and taller towers is dependent on tip height constraints imposed at the stage of obtaining planning consent, rather than solely on industry progress in verifying and implementing the innovations.

As an increasing proportion of viable high wind speed sites have already been developed, wind farm developers and hence turbine manufacturers are refocusing their efforts on maximising returns from lower wind speed sites, so we do anticipate considerable focus and progress in this area.

While rotor size and tower height optimisation are anticipated to deliver some of the largest LCOE reductions on the IEC Class III Turbine Type, there are a range of other innovations which will deliver LCOE savings across both Turbine Types. In particular, improvements to pitch control and aerodynamics offer the opportunity to decrease support structure loading and to increase the gross AEP of the turbine. The optimum balance of control complexity, rotor CAPEX, OPEX (associated with increases in duty cycles and the maintenance of rotor mounted equipment), and support structure CAPEX will emerge over the next two or three iterations of new products from each turbine manufacturer.

The industry has already recognised that improving existing OMS practices represents a strong lever to influence LCOE, not least because the barriers to achieving some of the changes are not solely technical, but also organisational. One of the largest of these is moving from time-based maintenance strategies to condition-based maintenance strategies on projects, focussed on addressing biggest risks while minimising unnecessary intervention. Much of this has a strong inertial element in OMS practice which needs a mindset change to overcome. At least part of this mindset change will require the testing and exploration of technical risk associated with changing practices.

The maturing onshore market has forced manufacturers to increase the focus on turbine reliability in delivering affordable energy. In particular, manufacturers have begun to adopt new designs of drive trains in the onshore market. The further development and increased adoption of such technologies and other innovations in the design of the turbine electrical system will drive ongoing LCOE reductions through to FID in 2025.

While many of the innovations modelled in this report are closely related to those which might be expected to impact LCOE in the offshore market, there are certain innovations specific to the onshore market, in particular those associated with the assessment and design of wind farm sites. The onshore environment represents a highly challenging technical proposition for both the assessment and modelling of wind resource and hence the optimisation of site layouts. This area has seen extensive innovation over the life of the industry and it is anticipated that this will continue for the foreseeable future. It is plausible that some such models may reach a point within the timeframe covered by this study where the margin returns of further investment are deemed insufficient to continue refinement; however, the overall field and particularly that dealing with complex terrain will remain a strong lever to reduce LCOE.

Approximately 25 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, we anticipate that the level of cost of energy reduction shown is achievable. In most cases, the anticipated impact of each innovation has been moderated downwards in order to give overall levels of cost of energy reduction consistent with past trends. 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.

NASA Earth Observatory image by Robert Simmon

12. About KIC InnoEnergy

KIC InnoEnergy is a European company dedicated to promoting innovation, entrepreneurship and education in the sustainable energy field by bringing together academics, businesses 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) fostered by the European Institute of Innovation and Technology (EIT). It is a commercial company with 28 shareholders that include top ranking industries, research centres and universities, all of which are key players in the energy field. More than 150 additional partners contribute to the company´s activities to form a first class and dynamic network that is always open to new entrants and furthers KIC InnoEnergy's pursuit of excellence. Although KIC InnoEnergy is profit-oriented, it has a "not for dividend" financial strategy, reinvesting any profits it generates back into its activities.

KIC InnoEnergy is headquartered in the Netherlands, and develops its activities across a network of offices located in Belgium, France, Germany, the Netherlands, Spain, Portugal, Poland and Sweden.

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

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

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**

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

Appendix A

Further details of methodology

Assumptions that are relevant to this study 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 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 • Ex-works supply • 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 and the tower • Ex-works supply for tower • Construction of foundation • Site civil works, and • 5 year warranty. EXCLUDES • OMS costs, and • RD&D costs. *Support structure and Array electrical elements are combined to assess innovations in balance of plant.*	€/MW

Array electrical	Cabling to wind farm transformer. INCLUDES • Ex-works supply, and • 5 year warranty. EXCLUDES • OMS costs, and • RD&D costs. *Support structure and Array electrical elements are combined to assess innovations in balance of plant.*	€/MW
Construction	INCLUDES • Transportation of all components from each supplier's facility • All installation work for support structures, turbines and array cables, and • Commissioning work for all but turbine (including snagging post WCD). EXCLUDES Installation of 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 • Planned preventative maintenance, health and safety inspections, and • Lease of land.	€/MW/yr
Unplanned service and other OPEX	Starts once first turbine is commissioned. INCLUDES reactive service in response to unplanned systems failure in the turbine or electrical systems. Other OPEX includes 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 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 metering point.	MWh/yr/MW

A.2 Assumptions

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

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

Average wind speed at hub height (m/s) (wind shear exponent)	Turbine IEC Class	Local terrain	Turbine spacing
L – Low Wind Site			
7.0 (0.14)	III	Open, flat area with few windbreaks.[3] Good accessibility via road for all vehicles required and without significant seasonal variation.	Nine rotor diameters (downwind) by six rotor diameters (across-wind) in a rectangle.
H – High Wind Site			
9.0 (0.10, and with additional speed-up at below hub height due to topography).	I	Open, hilly area with few windbreaks. Limitations to accessibility for certain vehicles and seasonal restrictions.	Similar intent to the Low Wind Site, but dictated by local topography.

Note that although sites are denoted as High Wind and Low Wind these descriptors relate only to the relative average wind speeds of the two Site Types in this report and should not be taken to imply any statement on the distribution of wind speeds across Europe or the position of these sites within that distribution.

Air density is assumed to be 1.225 kg/m^3.

General. The general assumptions are:

- A 50MW wind farm
- A wind farm design is used that is certificated for an operational life of 20 years
- The development and construction costs are funded entirely by the project developer, and
- A multi-contract approach is used to contracting for construction.

CAPEX spend profile

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

Year 1 is defined as year of first full generation.

AEP and OPEX are assumed as 100% for years 1 through 20.

3 Open agricultural area without fences and hedgerows and very scattered buildings.

Turbine. The baseline turbine assumptions are:

- The turbine is rated at 3MW and certificated to international wind turbine design standard IEC 61400-1:
  - The turbine used on the Low Wind Site is certificated to IEC Class III. It has a three-bladed upwind rotor, a three-stage gearbox, a partial-span power converter, a doubly-fed induction generator, 1500 rpm 690VAC output, and 75 m/s tip speed. It has a rotor of 123m diameter, and a specific rating of around 250W/m^2, which is representative of the products of this class available for FID in 2014, for example the Acciona AW125/3000 (available at 120m hub height), Gamesa G114 2MW (available at 93,120 and 140m hub height), GE GE2.75-120 (available at 85 and 110m hub height), Nordex N131 3MW (available at 99m hub height), Senvion 3.0MW112 (available at 139m hub height) and Vestas V112-3.3MW (available at 119 and 140m hub height).
  - The turbine used on the High Wind Site is certificated to IEC Class I. It is as above but has a rotor of 104m diameter, and a specific rating of around 350W/m^2,which is representative of the products of this class available for FID in 2014, for example the Acciona AW100/3000 (available at 100 and 120m hub height), Alstom ECO100-3MW (available at 75, 90 and 100m hub height), Nordex N100/3300 (available at 75 and 100m hub height), Senvion 3.2MW114 (available at 93 and 143m hub height), Siemens SWT3.0-101 (available at 80m hub height) and Vestas V112-3.3MW (available at 94m hub height).

Support structure. The support structure assumptions are:

- Hub height on the Low Wind Site is 120m, typical of IEC Class III Turbines and hub height on the High Wind Site is 100m, typical of IEC Class I Turbines.
- A concrete slab foundation with tower base embedment in good ground conditions (bearing pressure, chemical composition etc.).

Array electrical.

The array electrical assumption is that a three core 33kV AC cable is used.

Construction. The construction assumptions are:

- Transport is on a just-in-time basis, without significant holding area on site.
- Construction is carried out sequentially at each base, with tower, nacelle and rotor installed in a single visit.

OMS. OMS assumptions are:

- Local service team with 7-day working within 'office hours' and remote access via SCADA system.

A.3 Other effects

The table below corresponds to definitions made in Section 2.4. These figures are derived from work undertaken specifically for this report and advice received from industry contacts. They do not form an integral part of the study.

Table A.3 **Summary of impacts of Other Effects.**

Tech-Site-FID	Transmission	Insurance	Pre-FID risk	Supply chain	WACC
III-L-14	12.0%	6.6%	5.8%	0.0%	7.0%
I-H-14	12.5%	7.4%	6.1%	0.0%	7.0%
III-L-20	11.6%	6.4%	5.9%	-3.8%	7.0%
I-H-20	12.1%	7.3%	6.2%	-3.6%	7.0%
III-L-25	11.4%	6.3%	6.0%	-4.3%	7.0%
I-H-25	11.9%	7.2%	6.4%	-4.1%	7.0%

Decommissioning costs are excluded in this report for the following reasons:

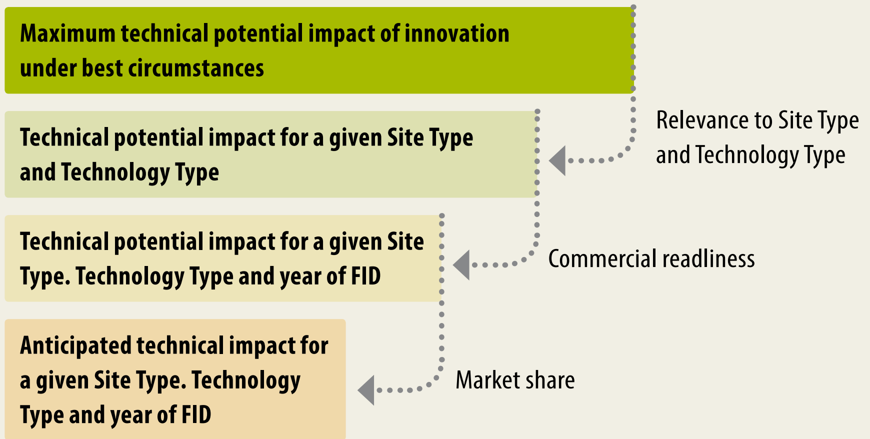
- Costs are incurred at the end of the life and as such are heavily discounted.
- The magnitude of the final cost is heavily dependent upon scrap recovery values, which are difficult to predict with any accuracy 20 years out, but is likely to be negative.

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 blade aerodynamics for projects characterised by the High Wind Scenario.

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 0.099, which is based on a discount rate of 7%.

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 Type.



Maximum technical potential impact

Based on work undertaken specifically for this report and accounting for advice received from industry contacts, we determine the maximum potential impact of improvements in blade aerodynamics on an onshore wind farm to be 1.8%.

Relevance to Site Types and Turbine Type

In the Low Wind Scenario this innovation is anticipated to be fully relevant as it enables maximum thrust loading on the larger rotor to be managed more effectively, thereby maximising savings on the tower specification. In the High Wind Scenario the relevance is modelled as 80% to reflect the more limited savings available on the shorter tower.

Commercial readiness

Just under half of the benefits are anticipated to be available for projects with FID in 2020, 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

Based on industry feedback, the market share for this innovation for projects using Class I Turbines in 2025 is modelled as 20%.

The anticipated LCOE impact is evaluated by comparing 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 Type, commercial readiness and market share. Target case impacts are calculated as follows:

Impact for turbine CAPEX = Maximum potential impact (-0.15%)
x Relevance to the High Wind Scenario (100%) = -0.15%
x Commercial readiness at FID in 2025 (74%) = -0.11%
x Market share for project using Class I Turbine with FID in 2025 (80%) = -0.09%

Impact for support structure CAPEX = Maximum potential impact (3.00%)
x Relevance to the High Wind Scenario (100%) = 3.00%
x Commercial readiness at FID in 2025 (74%) = 2.22%
x Market share for project using Class I Turbine with FID in 2025 (80%) = 1.78%

This process is repeated for savings on OPEX and impacts on gross AEP and losses.
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 (53.40 – 52.83) / 53.40 = -0.0106, or a 1.06% reduction in the LCOE.

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

Parameter	Units	Baseline case I-H-14	Target case I-H-25
Turbine CAPEX	€k/MW	714	714 x (1 + 0.009) = 715
Support Structure CAPEX	€k/MW	348	348 x (1 - 0.0178) = 342
Other CAPEX	€k/MW	255	255
Total CAPEX	€k/MW	1,289	1,284
Unplanned Service and Other OPEX	€k/MW/yr)	23	23 x (1 + 0.0014) = 23
Total OPEX	€k/MW/yr	42	42
Gross AEP	MWh/yr/MW	3,493	3,493 x (1 + 0.0077) = 3,520
Losses	%	9.2	9.2 x (1 + 0.00059) = 9.2
Net AEP	MWh/yr/MW	3172	3195
LCOE	€/MWh	53.40	52.83

Appendix B

Data supporting tables

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

Element	Units	High Wind Scenario	Low Wind Scenario
Development	€k/MW	78	78
Turbine	€k/MW	714	827
Support Structure	€k/MW	348	416
Array Electrical	€k/MW	65	77
Construction	€k/MW	74	59

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

Element	Units	Low Wind Scenario	High Wind Scenario
Operations and Planned Maintenance	€k/MW/yr	17	19
Unplanned Service and Other OPEX	€k/MW/yr	19	23
Net Capacity Factor	%	27.3	36.2

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

Element	Units	I-H-14	III-L-14
LCOE including Other Effects	€/MWh	69	108
LCOE as % of I-H-14	%	100,0	156,4
Net capacity factor	%	36,2	27,3

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

Impact of innovation on...	High Wind Scenario	Low Wind Scenario
CAPEX	0.0%	0.0%
OPEX	0.0%	0.0%
Net AEP	0.8%	0.4%
LCOE	-0.7%	-0.4%

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

Impact of innovation on...	High Wind Scenario	Low Wind Scenario
CAPEX	-0.3%	-0.4%
OPEX	-2.9%	-2.8%
Net AEP	0.3%	0.3%
LCOE	-1.3%	-1.1%

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

Impact of innovation on...	High Wind Scenario	Low Wind Scenario
CAPEX	-0.4%	3.4%
OPEX	-0.2%	-0.3%
Net AEP	2.1%	5.9%
LCOE	-2.4%	-3.0%

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

Impact of innovation on...	High Wind Scenario	Low Wind Scenario
CAPEX	0.0%	0.0%
OPEX	0.1%	0.2%
Net AEP	0.1%	0.4%
LCOE	0.0%	-0.4%

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

Impact of innovation on...	High Wind Scenario	Low Wind Scenario
CAPEX	-0.1%	0.0%
OPEX	0.0%	0.0%
Net AEP	0.0%	0.0%
LCOE	0.0%	0.0%

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

Impact of innovation on...	High Wind Scenario	Low Wind Scenario
CAPEX	0.2%	0.2%
OPEX	-3.2%	-3.0%
Net AEP	0.5%	0.5%
LCOE	-1.1%	-0.9%

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

Impact of innovation on...	High Wind Scenario	Low Wind Scenario
CAPEX	-0.6%	3.2%
OPEX	-6.1%	-5.8%
Net AEP	3.7%	7.5%
LCOE	-5.5%	-5.5%

Table B.11 **Data relating to Figure 10.2 and Figure 10.3**

Element	Units	III-L-14	III-L-20	III-L-25	I-H-14	I-H-20	I-H-25
Development	€k/MW	76	76	76	76	77	77
Turbine	€k/MW	968	995	1,017	696	693	696
Support Structure	€k/MW	488	489	487	339	335	331
Array Electrical	€k/MW	96	99	101	106	106	107
Construction	€k/MW	58	59	61	72	72	72
Operations and Planned Maintenance	€k/MW/yr	17	17	17	19	19	19
Unplanned Service and Other OPEX	€k/MW/yr	19	18	17	23	22	21
Net capacity factor	%	27.3	28.6	29.4	36.2	37.0	37.5

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

	Units	III-L-14	III-L-20	III-L-25	I-H-14	I-H-20	I-H-25
Net capacity factor	%	27.3	28.6	29.4	36.2	37.0	37.5
LCOE including Other Effects	€/MWh	108	100	97	69	64	62

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

Innovation	Value
Low Wind speed	
LCOE for a wind farm with FID in 2014	100,0%
Optimisation of rotor size with improved materials	0,9%
Improvements in blade aerodynamics	0,8%
Improvements in blade pitch control	0,6%
Improvements in resource modelling	0,3%
Introduction of mid-speed drive trains	0,3%
Improvements in hub assembly components	0,3%
Introduction of holistic asset management strategies	0,3%
16 other innovations	2,3%
LCOE for a wind farm with FID in 2025	94,3%
High Wind speed	
LCOE for a wind farm with FID in 2014	100,0%
Improvements in blade aerodynamics	1,0%
Improvements in blade pitch control	0,6%
Improvements in resource modelling	0,4%
Introduction of holistic asset management strategies	0,3%
Introduction of mid-speed drive trains	0,3%
Improvements in AC power take-off system design	0,3%
Introduction of direct-drive drive trains	0,3%
18 other innovations	2,4%
LCOE for a wind farm with FID in 2025	94,5%

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Future renewable energy costs: onshore wind
How technology innovation is anticipated to reduce the cost of energy from European onshore wind farms

The document is also available in an online format on the KIC InnoEnergy website: www.kic-innoenergy.com

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