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International Renewable Energy Agency

INNOVATION OUTLOOK

OFFSHORE WIND

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. ***www.irena.org***

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ABBREVIATIONS

AC	Alternating current
AEP	Annual energy production
CAPEX	Capital expenditure
CENER	Spain's National Renewable Energy Centre (Centro Nacional De Energías Renovables de España)
CfD	Computational for Difference
CFD	Computational fluid dynamics
DC	Direct current
DECC	UK Department of Energy and Climate Change
DECEX	Decommissioning expenditure
DFIG	Doubly fed induction generator
DTU	Technical University of Denmark (Danmarks Tekniske Universitet)
ECN	Energy Research Centre of the Netherlands (Energieonderzoek Centrum Nederland)
EPC	Engineer, procure and construct
EPCI	Engineer, procure, construct and install
FEED	Front-end engineering and design
FID	Final investment decision
GW	Gigawatt
HTS	High-temperature superconducting
HV	High voltage
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
IoT	Internet of Things
JIP	Joint industry project
km	Kilometre
LAT	Lowest astronomical tide
LCOE	Levelised cost of electricity
LiDAR	Light detection and ranging

LORC	Denmark's Lindoe Offshore Renewables Center
LTSA	Long-term service agreement
m	Metre
MSL	Mean sea level
MW	Megawatt
MWh	Megawatt-hour
OMS	Operation, maintenance and service
OPEX	Operational expenditure
OWA	Offshore Wind Accelerator (Carbon Trust)
PTV	Personnel transfer vessel
R&D	Research and development
RD&D	Research, development and demonstration
RTO	Research and technology organisation
SCADA	Supervisory Control and Data Acquisition
SCOE	Societal cost of energy
SME	Small and medium-sized enterprise
SOV	Service operations vessel
TRL	Technology readiness level
UK	United Kingdom of Great Britain and Northern Ireland
USA	United States of America
USD	US Dollar
WACC	Weighted average cost of capital
WCD	Works completion date

Driven by technological innovation and non-technological enabling factors, offshore wind will become a key part of the global energy mix. But the sector must keep cutting costs, integrate with onshore power grids and gain a foothold in key markets

SUMMARY FOR POLICY MAKERS

The case for offshore wind

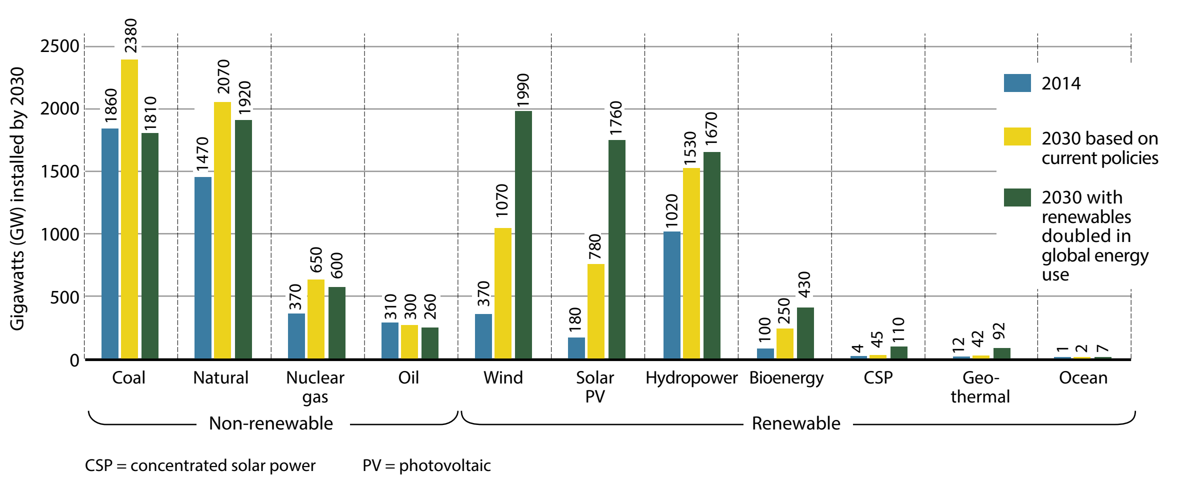
Offshore wind technology opens up sites with high wind resources. Offshore wind farms can be built quickly, at gigawatt-scale, close to densely populated coastal areas. This makes offshore wind an important addition to the portfolio of technologies to decarbonise the energy sector in a cost-effective manner.

Advances in wind power technologies continue to drive cost reduction and expansion into new markets. While onshore wind power is increasingly cost competitive against conventional power generation technologies, growing attention is being paid to technology development for offshore applications that open the door to sites with better wind resources. This combination of higher capacity factors and the availability of large-scale sites makes offshore wind an attractive alternative for utility-scale low-carbon electricity.

Wind development is essential to decarbonise the global economy. According to IRENA's analysis, wind power will have to become the leading power generation technology by 2030 to ensure a decarbonisation of the global economy. Offshore wind capacity can reach 100 gigawatts (GW) by 2030 as innovation continues as the industry takes shape. It could increase faster if policies were adopted to double renewables in the global energy mix. This ambitious decarbonisation pathway requires 1990 GW of total installed wind capacity by 2030, of which offshore wind would provide about 280 GW.

Innovation Outlook: Offshore Wind Technology aims to inform policy makers and other stakeholders about anticipated developments in the next three decades that will make offshore wind competitive on a large scale. The information in the report aims to help guide incentive programmes and policy actions supporting sustainable energy innovation.

Figure S1: Possible paths for global power generation



Much of the growth needed in renewable power generation has to come from wind development.

Based on REmap (IRENA, 2016), a roadmap to double the renewable share in global energy use by 2030

A sector driven by technological innovation

Offshore wind has grown from a few megawatts of installed capacity to more than 12 gigawatts in barely 15 years.

The technology's evolution started in 1991, when the first megawatt-scale offshore wind farm was commissioned in Denmark in shallow waters, close to shore, using turbines rated at only one-eighth of today's largest turbines. The first commercial-scale offshore wind plant was commissioned in 2002, also in Denmark, with an installed capacity of 160 megawatts (MW). By the end of 2015, the world's installed offshore wind capacity exceeded 12 GW, mainly off the coasts of Europe.

Offshore wind turbines are now the largest rotating machines on Earth. Developments in wind turbine technologies as well as in foundations, installation, access, operation and system integration have permitted moves into deeper waters, further from shore, to reach larger sites with better wind resources. Until 2007, offshore wind turbines were installed in water depths below 20 metres (m) and closer than 30 kilometres (km) from shore. Today, in contrast, turbines are being installed routinely in water depths up to 40 m and as far as 80 km from shore.

Figure S2: Global annual installed and operating capacity for offshore wind farms, 2001-2015

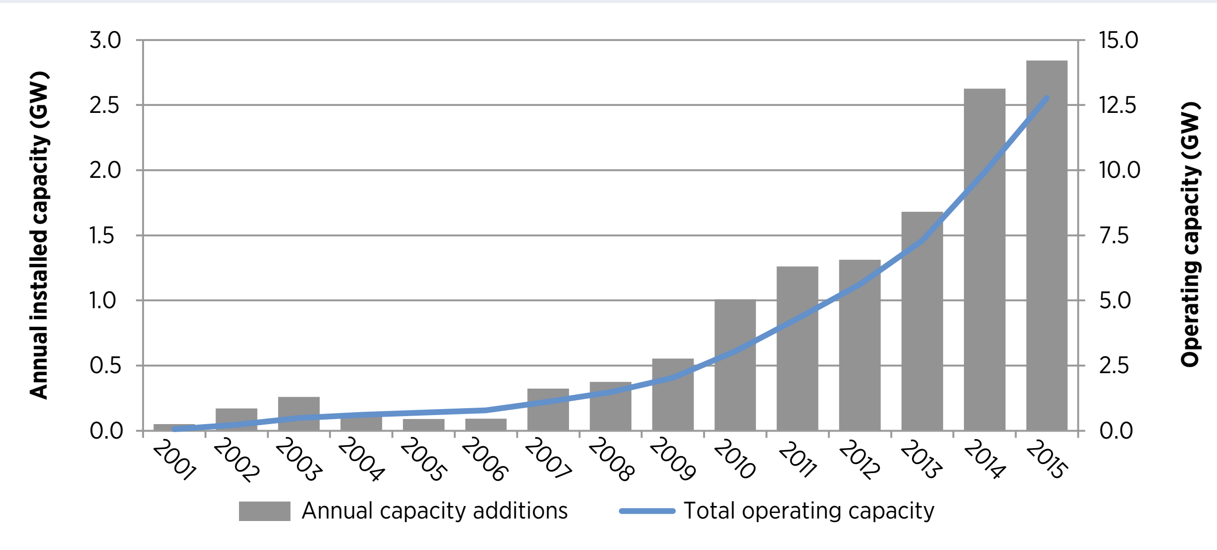


Figure S3: Distance to port for commercial-scale projects commissioned globally, 2001-2015

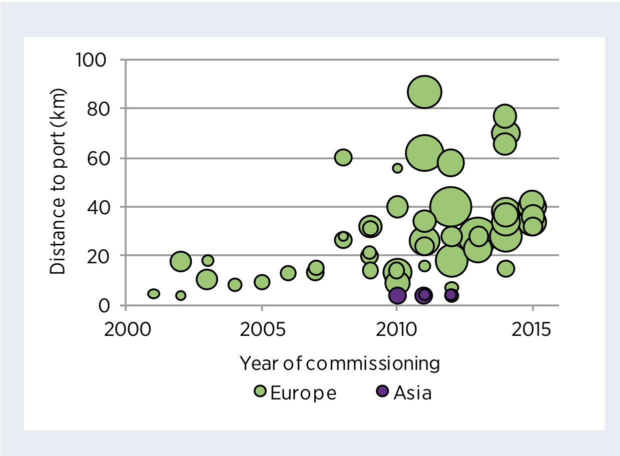
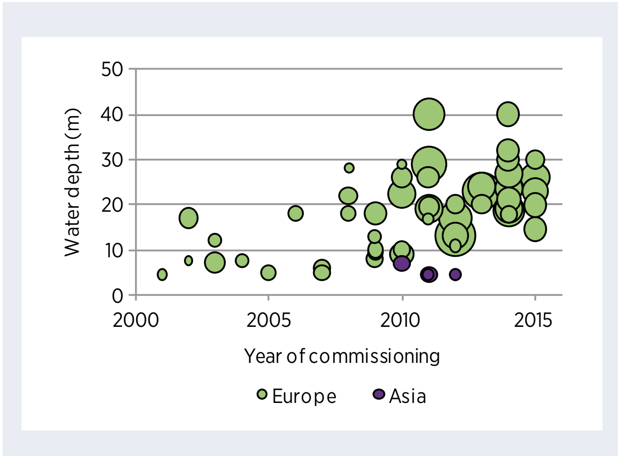


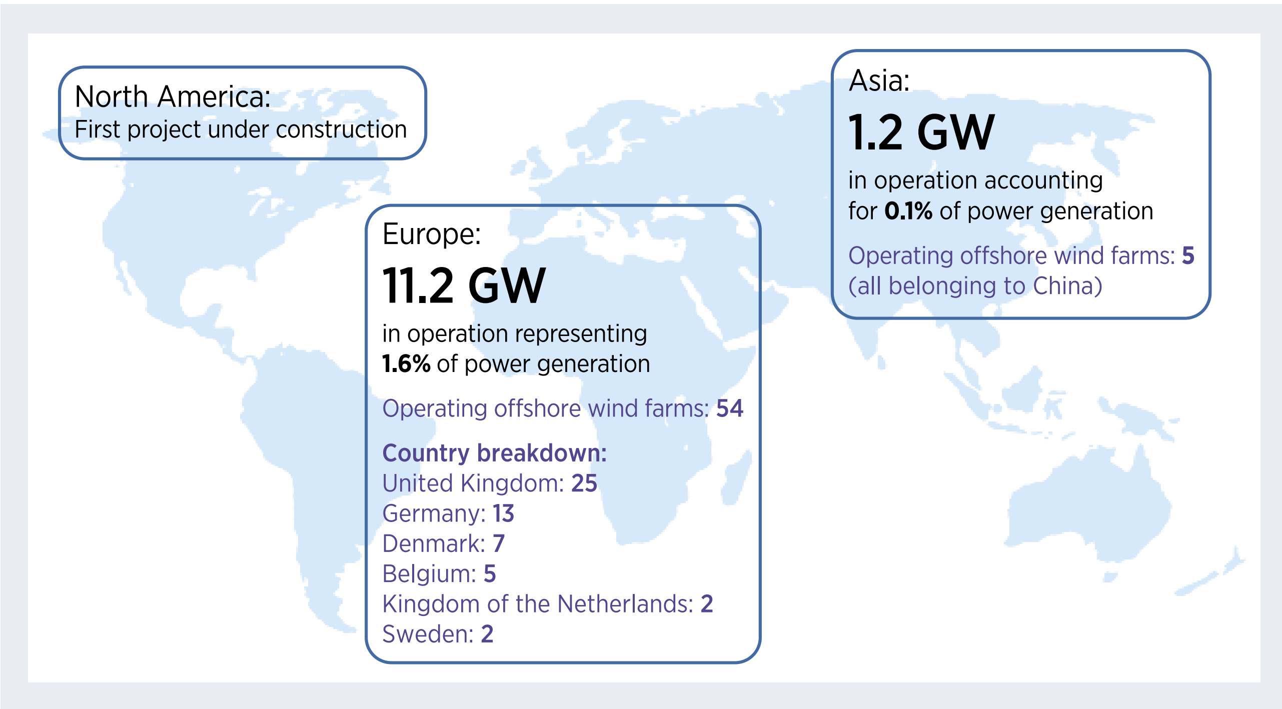
Figure S4: Water depth for commercial-scale projects commissioned globally, 2001-2015



Bubble area indicates each project's capacity in megawatts (MW).
"Port" refers to main operation, maintenance and service (OMS) port.

Most of the capacity installed or operating for offshore wind to date is located off northern Europe. Half of the capacity is in UK waters, one-third in German waters, and the rest almost entirely in other parts of the North Sea or in the Baltic Sea.

Figure S5: Offshore wind deployment at the end of 2015



Competitiveness of offshore wind

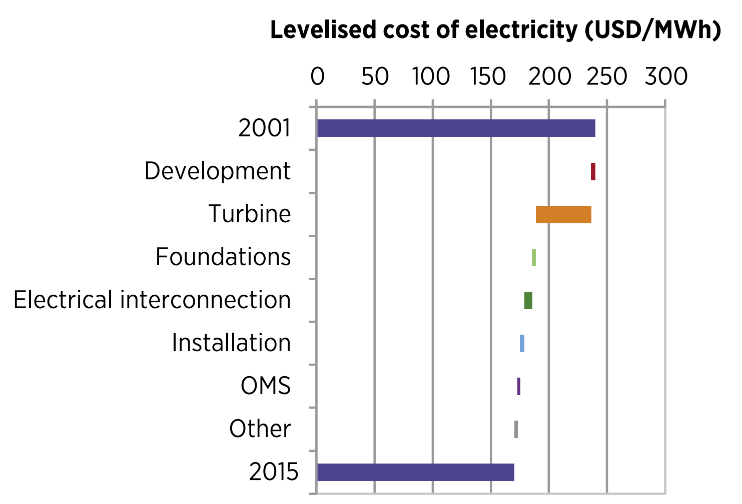
As innovation keeps driving down costs, offshore wind power could be highly competitive within a few years.

The main driver for growth in the offshore wind industry has been significant decreases in power-generation costs, driven by advances in the technology. Cost reductions have been aided by government financial support to address the security of electricity supply and decarbonisation of electricity production. Such efforts have, in turn, driven innovation in the sector, which has brought costs down as well as boosting performance.

Costs have fallen more than 30% in the 15 years since the first wind farm opened. The levelised cost of electricity (LCOE) from offshore wind, which averaged about USD 240 per megawatt-hour (MWh) in 2001, had fallen to approximately USD 170/MWh by the end of 2015.

Innovations that enabled this cost reduction include offshore-specific turbine designs, bespoke offshore wind installation vessels and advanced offshore electrical interconnection equipment. Between 2001 and the end of 2015, the rated capacity of commercially deployed offshore wind turbines grew from 2 MW to more than 6 MW. This progress not only improved the efficiency of the turbines but also resulted in cost economies across the rest of the wind farm, which is why, in Figure S6, innovation in turbines is shown as the largest contributor to reductions in the electricity cost. "Other" change shown came from changes in typical financing costs, site characteristics and other non-technological issues, including project life, competition and other supply chain levers, exchange rates and commodity prices.

Figure S6: Electricity cost reduction elements for projects commissioned in 2001-2015



OMS = operation, maintenance and service

Despite the progress made, the offshore wind sector must continue to reduce costs, ease its integration into onshore grid systems and expand the markets that it is able to address, while preserving its focus on the environment, health and safety. Technology innovation will remain a key ingredient, as well as reducing the cost of finance and savings through greater efficiency across the supply chain.

As an example, in 2015 and 2016, winning bids for auctions for pre-developed offshore wind farms in Europe, such as Horns Rev 3 and Borssele I, have indicated important further cost reductions for projects commissioned for 2020, due mainly to increased competition at the developer level for the same site and driving additional savings in a variety of areas.

Innovation prospects

Rapid strides with technology and other innovations will drive further reductions, helping expand the offshore wind market around the world.

The most significant innovations related to offshore wind technology are expected to include the introduction of next-generation turbines with larger rotors, as well as advances in electrical transmission. Other types of innovation — such as in policy-making, finance and business models — will also boost the sector over the next 30 years.

Ongoing developments in blade and drivetrain technology will allow even larger turbines with higher power ratings. Offshore wind turbines deployed at present typically have a rated capacity of about 6 MW, with rotor diameters around 150 m. Larger turbines might not have a much lower capital cost per MW of rated power than existing designs, but they deliver a lower LCOE due mainly to higher reliability and lower foundation and installation costs per MW. It is expected that the commercialisation of 10 MW turbines will take place in the 2020s, while 15 MW turbines could be commercialised in the 2030s.

Offshore installation will continue to be simplified. Several steps can be eliminated by assembling and pre-commissioning wind turbines in a harbour and installing the complete, integrated turbine (including rotor and tower) in a single operation offshore. A further innovation is to install the turbine and the foundation together, towing the turbine-foundation structure to the site via a bespoke vessel or tugboats. This innovation can be applied to bottom-fixed or floating systems. These innovations have potential to reduce installation cost and reduce exposure to health and safety risks.

Floating foundations are another area of innovation with high potential impact. They are expected to start to be commercially available by 2020. This type of foundation offers the offshore wind industry access to large areas with a strong wind resource and proximity to population centres in waters that are deeper than 50 m. In mid-depth conditions (30-50 m), floating foundations may offer a lower-cost alternative to fixed-bottom foundations due to the potential for standardisation of foundation designs, maximisation of onshore activity and the use of low-cost, readily available installation vessels.

Electrical interconnection of offshore wind farms presents multiple innovation opportunities. These include reducing the necessary amount of offshore high-voltage alternating current (HVAC) infrastructure. High-voltage direct-current (HVDC) transmission is used in preference to HVAC transmission from far-from-shore projects to reduce losses and cable costs. Reducing the cost of HVDC infrastructure could open up new markets and enable the connection of offshore HVDC substations to the first elements of international or interstate HVDC supergrids.

Many innovations in other areas are already reaching a commercial stage. For example, innovations in the development of the wind farm — such as optimisation of the site layout for better use of the wind resource, minimisation of aerodynamic wake effects and optimum use of varying seabed conditions — will enable much more informed and holistic layouts of offshore wind farms. Innovation opportunities also exist and are being harnessed rapidly in operation, maintenance and service (OMS), and this report discusses them all in detail.

Potential game changers

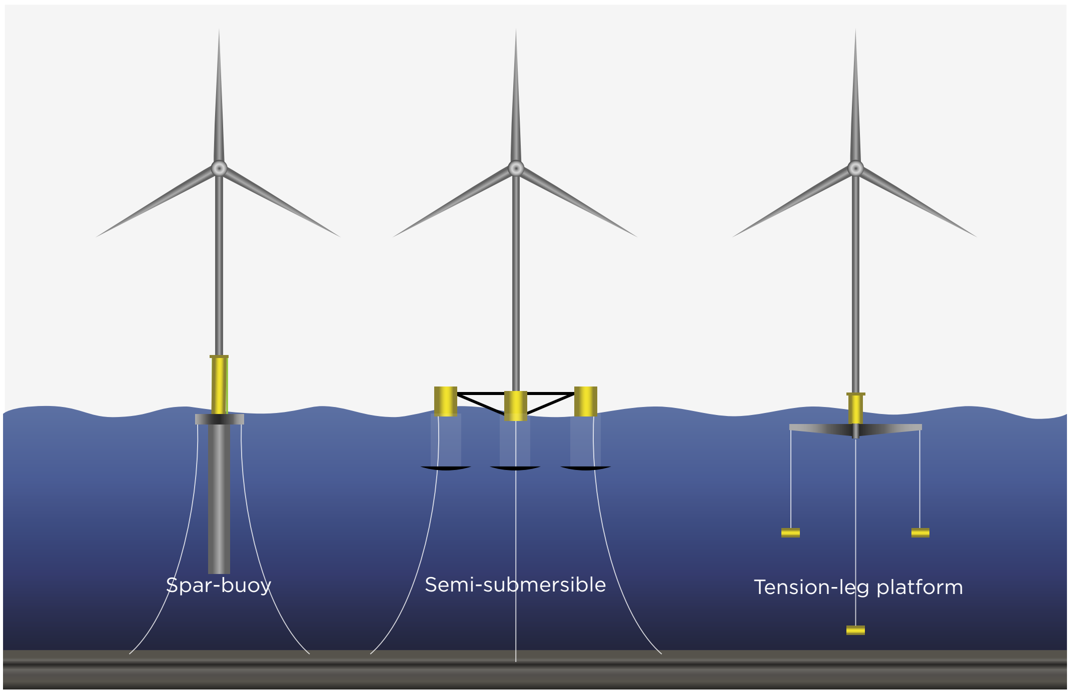
Specialised technologies such as floating foundations will reduce costs further and open up vast areas of currently inaccessible sites for turbines.

Currently, offshore wind farms have been installed in water depths below 50 m using turbine foundations that are fixed directly to the seabed. This limits access to sites with higher winds and potentially large markets. Japan and the United States, for instance, have few shallow-water sites, and existing foundation concepts would not be cost-effective. Floating foundations could be game changers in opening up significant new markets with deeper waters. Floating foundations make installation easier and cheaper by reducing the amount of offshore activity and avoiding the use of heavy-lift vessels. Floating foundations are buoyant structures maintained in position by mooring systems.

Three technologies (Figure S7) are in development at present:

- **Spar buoys**, such as the Hywind concept developed by Statoil,
- **Tension-leg platforms**, such as Glosten's PelaStar, and
- **Semi-submersibles**, such as that developed by Principle Power.

Figure S7: Different types of floating foundation for offshore wind turbines



Based on NREL

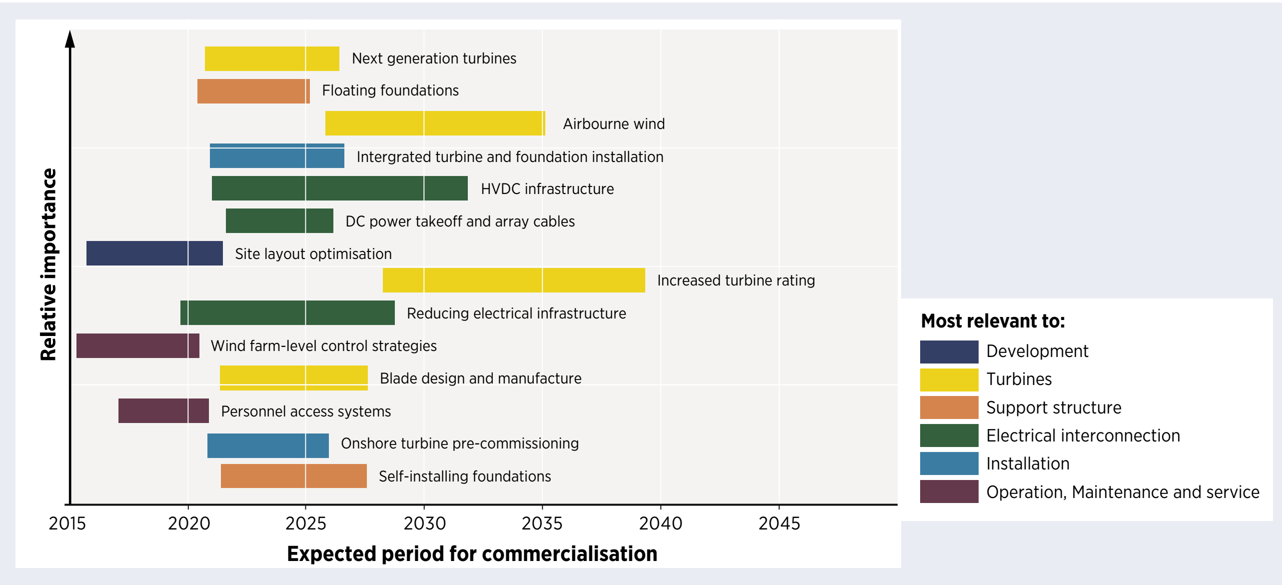
Several full-scale prototypes have been deployed, while demonstrations for new floating turbine concepts continue. The first full-scale prototype was a spar buoy in Norway in 2009, followed by a semi-submersible installation in Portugal in 2011 and three installations in Japan (spar and semi-submersible) between 2011 and 2015. No tension-leg platform has yet been deployed for a wind turbine, but variants of all concepts have been used in the oil and gas sector.

Other turbine concepts, including multi-rotor and vertical-axis wind turbines, could also prove to be game changers.

Airborne wind energy, using kites or fixed wings to reach winds higher up, has also started to receive more attention. Benefits include the increased scale and consistency of wind resources at higher altitude and lower mass and costs for materials.

Market-changing cost reductions could also be possible through extending the life of existing projects, including repowering them with the latest turbine technology.

Figure S8: Anticipated timing and importance of innovations in offshore wind technology, 2016-2045



The outlook

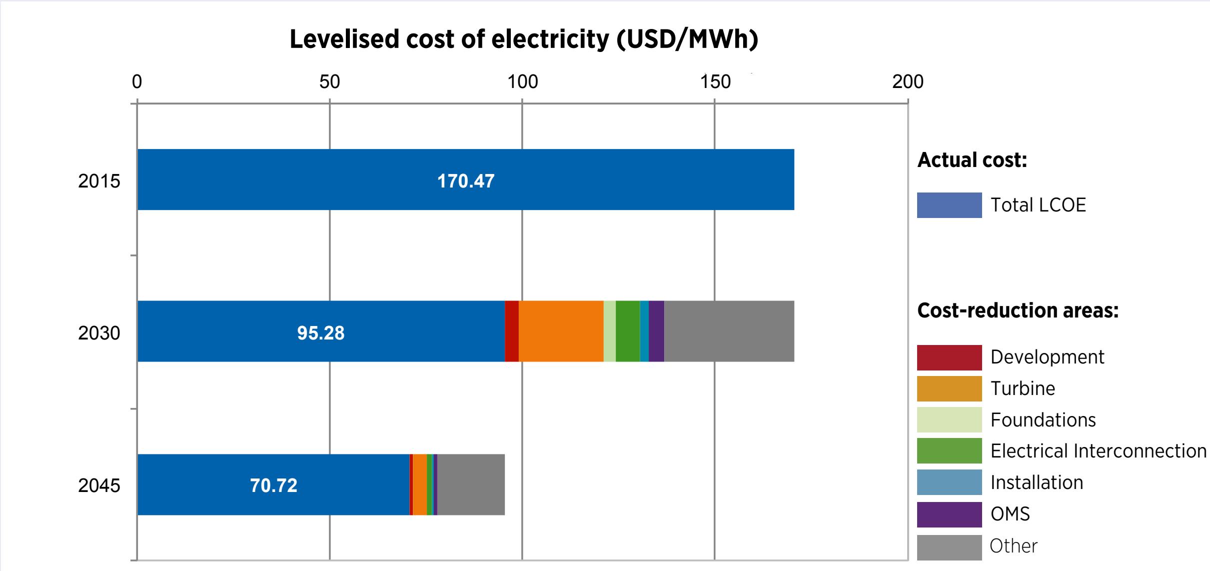
Technological advances and other types of innovation can take offshore wind power to waters deeper than 50 m, expand its geographic range and reduce costs by more than half over the next three decades.

Technological innovations, combined with various non-technology innovations, like different site choices, new market strategies and refined tools to reduce finance risks, should decrease the LCOE for offshore wind farms to USD 95/MWh by 2030 and USD 74/MWh by 2045. This excludes the potential impact of game-changing technologies. Such reductions should put offshore wind firmly in the portfolio of technologies needed to decarbonise the energy sector in a cost-effective manner.

Other significant effects relate to changes in risk and hence the cost of finance and levels of competition and industrialisation (Figure S9). This is already seen with the shift to project-specific competitive auctions in Europe. Global trends in commodity prices, especially for steel and, to some extent, copper and fuel, affect the analysis up to 2015, but the effects of commodity prices and macroeconomic conditions are assumed to remain constant over the period from 2015 to 2045.

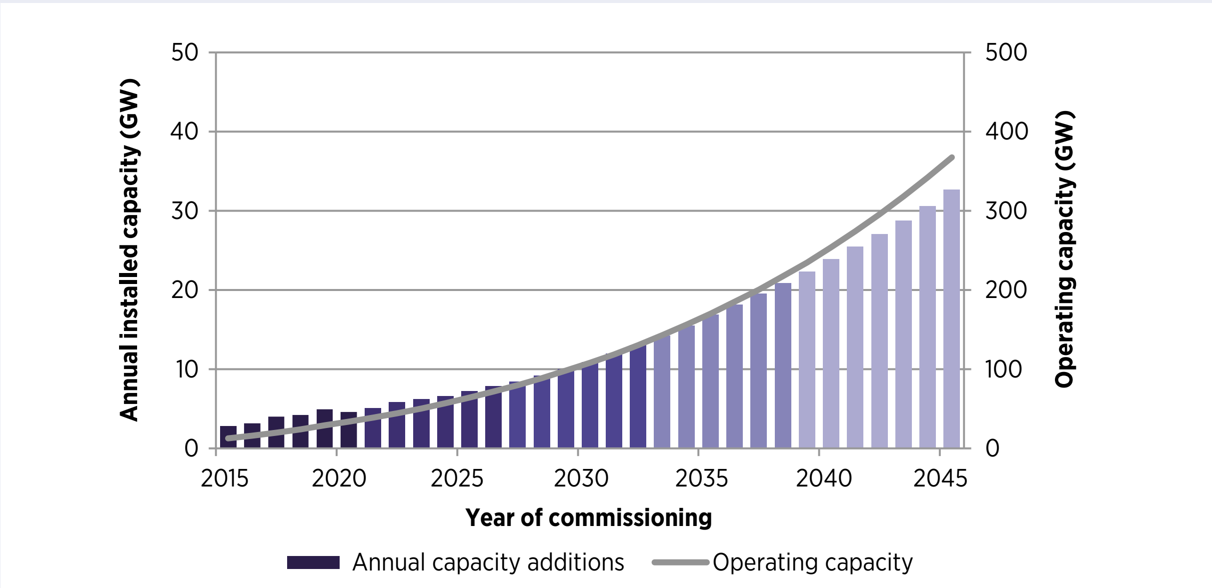
In the next three decades, offshore wind is anticipated to grow from a new commercial technology to an industrialised and important component of the global energy mix, driven by technology innovation as well as by non-technology enabling factors discussed in this report. The operating capacity is expected to grow from close to 13 GW in 2015 to roughly 400 GW by 2045.

Figure S9: Impact of innovation on energy cost elements for projects commissioned in 2015-2045



OMS = operation, maintenance and service

Figure S10: Forecasted global annual installed and operating capacity of offshore wind, 2016-2045



Policy recommendations

Concerted efforts from the public and private sectors will drive further cost reduction, making offshore wind a competitive and reliable option for clean power supply for decades to come.

Policy makers have an important role in creating a climate for investment in technology across the offshore wind industry. This involves:

- Providing as much clarity about the future market size and long-term policy direction as possible.
- Facilitating competitive environments in which reduction in the cost of energy is both rewarded through the right to deliver new projects and supported through the provision of targeted public research and development (R&D) funding.
- Establishing frameworks for the development of international and interstate transmission supergrids.
- Ensuring that public R&D funding is targeted at areas of greatest anticipated cost-of-energy impact and supplemented by incubation support.
- Supporting information sharing within the industry, including the establishment of common language and nomenclature with which to define cost elements.
- Putting in place frameworks and regulations for markets to be able to receive new technologies.
- Supporting skills and supply chain development in order to enable commercialisation of technology.

Experience so far shows the best modes of research, development and demonstration (RD&D) to advance high-impact innovations through engagement with a range of stakeholders.

Key approaches include steering R&D, maximising the impact of grant funding, and enabling demonstration of larger turbines and new concepts. Useful synergies can also be found beyond offshore wind or renewables and outside the energy sector as a whole.

Steering R&D

- Research and technology organisations should ensure that all areas of the industry progress to market in step; for example, there is little value in developing next-generation turbines if the required innovations to install them have not been developed.

- Research and technology organisations and R&D enablers should maintain technology and LCOE roadmaps and monitor progress, to steer R&D focus in an environment of evolving need.

Maximising grant impact

- Funders should focus on quantifying the cost-of-energy impact, the potential market share and the impact of innovations in relation to other industry goals.

- Funders should maximise the benefit of grant funding for small and medium-sized enterprises (SMEs) by including an incubation support element.

- Promotion of collaborative research and RD&D networks, along with public grant funding, will increase academic and SME involvement and help reduce electricity costs from offshore wind.

- R&D funding also needs to connect innovators with industry end-users in order to ensure the most direct route to market.

- RD&D funding should balance support for lower-impact, easier-to-implement innovations and game-changing technologies.

Enabling demonstration

- Relevant bodies should consider imposing conditions on developers of commercial-scale projects that they incorporate one or more locations where novel technology can be demonstrated.

- Other stakeholders also may have an important role in facilitating onshore and offshore prototype demonstration sites for larger turbines, whether relating to leases, planning approval or other potential constraints.

Collaboration in other sectors

Many kinds of technological development in sectors beyond offshore wind can also serve to strengthen offshore wind. Policy makers need to appreciate such links, so that the full value of RD&D for these technologies to be reflected in co-ordination between sectors and decisions about funding.

For example:

- Funding providers can facilitate useful cross-sector collaboration, so that offshore wind benefits from new technologies while the developers of those technologies gain access to a new market.

- Communications professionals engaged in promoting wind power need to stay well informed on technology and industry trends in order to raise awareness about new technologies in the most effective manner. IRENA's *Innovation Outlook* series, comprising reports like this one on a growing range of renewable energy technologies, may be helpful in this regard.

IRENA serves as a platform for international co-operation for its member countries, as well as for researchers, funders, investors and other stakeholders. This innovation outlook aims to inform policy makers and other stakeholders on technology and industry trends and promote the best practices as technologies continue to evolve.

GLOSSARY OF TERMS

Annual energy production (AEP)	The electrical energy production of a wind farm in megawatt-hours (MWh) per year. The gross AEP is the forecasted output of the turbines averaged over the wind farm life, excluding aerodynamic array losses, electrical array losses and other losses, but including any site air density adjustments from the standard turbine power curve. The net AEP is measured at the offshore metering point at the entry to the offshore substation (see below).
Array cable	Electrical cable that connects the turbines to each other and to the offshore substation (see below).
Balance of plant	The collective term for the turbine foundations and array cables.
Bathymetric data	Data derived from the depth measurements of oceans, seas or other bodies of water.
Benthic	Referring to organisms that live at the bottom of an ocean, sea or other body of water.
Cable carousel	A turntable used for the storage and installation of the array cable (see above) and the export cable (see below).
Capacity factor	Ratio of the net AEP (see above) to AEP if all turbines generated continuously at rated power. The gross capacity factor uses the gross AEP.
Capital expenditure (CAPEX)	Costs incurred in the development and installation of a wind farm up to the works completion date (see below). This includes the cost of obtaining planning approval and project management, the turbine, balance of plant (see above), electrical interconnection, installation and contingency.
Commercial-scale	Referring to an offshore wind farm using at least five state-of-the-art scale turbines, that is not installed primarily for test or demonstration purposes and that is more than 500 m from shore and is not accessible by road transport.
Concrete gravity base foundation	A type of foundation (see below) that is placed on the seabed with a mass that is sufficient to provide stability against the impact of the wave, current and turbine loading.
Condition monitoring system	A system added to wind turbines to provide additional health checking and failure prediction capability.
Cone penetration test	A testing method used at wind farm sites to determine the geotechnical properties of soils and to assess subsurface ground conditions.
Decommissioning expenditure (DECEX)	The net cost of removal or burial of all components at the end of the wind farm's operational life.
Development cost (DEVEX)	Costs incurred in the development of a wind farm, excluding installation, up to the works completion date (see below). Incorporated in this study in CAPEX (see above).
Direct-drive	A drivetrain (see below) that uses a multi-poled, low-speed generator without a gearbox.
Drivetrain	The collective term given to a range of components housed in the wind turbine nacelle (see below) that converts the rotational energy from the rotor (see below) into three-phase alternating current (AC) electrical energy. This includes the main shaft, gearbox and generator.
Engineer, procure and construct (EPC)	A contracting strategy that combines several work packages into a single contract. Developers typically use this approach to minimise interface risk. Normally this also includes installation (hence then EPCI).
Export cable	Electrical cable that connects the onshore and offshore substations (see below).

Final investment decision (FID)	The point in the project life cycle at which all the planning approvals, agreements and contracts required to commence project installation have been signed (or are near execution form) and there is a firm commitment by equity holders and debt funders to provide funding to cover the majority of installation costs. In many projects, this is a sharply defined point, when investors formally commit to provide the necessary capital, but in some balance sheet-financed projects, decision can be sequenced.
Foundation	The structure that interfaces between the seabed and any transition piece (see below) or the turbine tower.
Front-end engineering design (FEED)	An early-stage study to identify areas of technical uncertainty and to develop the concept design of the wind farm in advance of contracting.
High-voltage direct-current (HVDC) converter station	A type of offshore substation (see below) in which electricity is converted from alternating current (AC) to direct current (DC) via high-voltage electronic semiconductors.
Learning rate	In this context, the percentage reduction in the LCOE (see below) for each doubling of offshore wind capacity installed.
Levelised cost of electricity (LCOE)	The levelised cost of electricity (LCOE, or "cost of energy") is defined as the revenue required (from whatever source) to earn a rate of return on investment equal to the discount rate (also referred to as the weighted average cost of capital or WACC) over the life of the wind farm. Tax and inflation are not modelled. The technical definition is included in Appendix C and is consistent with IRENA's standard definition used also for other sectors.
Light detection and ranging (LiDAR)	Wind measurement technology that uses light sensors to measure the distance between the sensor and the target object.
Long-term service agreement	An agreement between the wind farm owner and the wind turbine manufacturer or a third-party supplier for the provision of operation, maintenance and service (OMS, see below) services.
Meteorological station	A weather station erected at a proposed wind farm site to monitor and measure meteorological and oceanographic conditions.
Monopile foundation	A type of foundation (see above) with a cylindrical tube (normally steel) that is typically driven tens of metres into the seabed, although it also can be inserted into pre-drilled holes when conditions preclude driving.
Nacelle	The structure that supports the wind turbine rotor (see below) and houses the drivetrain (see above) and other auxiliary components.
Non-monopile steel foundation	Collective term used to describe all steel foundations (see above) excluding monopoles (see above). Includes braced, welded, space-frame structures (collectively called jackets), tripods and tripiles.
Offshore electrical interconnection	Collective term used to describe export cables and offshore substations (see above and below).
Offshore substation	The structure that houses the electrical system that increases the voltage of electricity produced by wind turbines to reduce electrical losses when it is exported to shore. Some wind farms may have more than one offshore substation.
Operating capacity	The total capacity of wind farms installed minus capacity that has been decommissioned.
Operational expenditure (OPEX)	Costs incurred after the works completion date (see below), including OMS (see below) and transmission charges.
Operation, maintenance and service (OMS)	Collective term covering all activities that take place from the works completion date (see below) to the start of decommissioning (see above). "Operation" refers to the day-to-day control of the wind farm, "maintenance" is planned preventative activity and "service" is reactive activity in response to unplanned systems failure in the turbine or electrical systems.
Ornithology	The scientific study of birds.

Pelagic	Referring to organisms that live in the open oceans or seas.
Personnel transfer vessel (PTV)	A vessel that provides access for technicians to the turbines and offshore substation (see below) during installation and OMS (see above). Typically, PTVs are 20 m aluminium catamarans with a capacity for 12 technicians.
Planning approval	The process during wind farm development when a developer seeks approval from the relevant planning bodies to proceed with installation and operation. Also known as consenting or permitting.
Rotor	The collective term for the blades and the hub of the wind turbine. The rotor extracts kinetic energy from the air and converts this into rotational energy in the drivetrain (see above).
Service operation vessel (SOV)	A vessel that provides accommodation, workshops and equipment for the transfer of personnel to the turbine during OMS (see above). These vessels are typically up to 85 m long with accommodation capacity for 60 technicians.
State of the art	Used in this report to refer to technologies deployed in commercial offshore wind farms that are commissioned before the end of 2015.
Supervisory control and data acquisition (SCADA)	A computer system used to monitor and control the wind farm during OMS (see above).
Transition piece	An element of the foundation (see above) that provides the connection between the foundation and the wind turbine tower.
Turbine rating	The maximum power output from a wind turbine.
Unexploded ordnance (UXO)	Derelict explosives, usually from historical conflicts.
Weighted average cost of capital (WACC)	The weighted average lifetime cost of capital in real, pre-tax terms, taking into account the cost of debt and equity and the ratio between debt and equity.
Works completion date	The point when all installation activity on a wind farm is completed and control is passed to the operational team.

1. INTRODUCTION

Offshore wind is a renewable energy source with several advantages:

- It benefits from a higher, more consistent wind resource than onshore wind.
- It produces utility-scale low-carbon electricity using very low levels of water compared to electricity generation from fossil fuels, nuclear and biomass.
- It can provide electricity generation capacity close to densely populated coastal areas.
- It can be installed relatively quickly at gigawatt (GW) scale.
- It has fewer physical constraints than onshore wind generation in populated areas, such as turbine size, operating noise and visual amenity.
- It can use many of the technologies developed over decades by the onshore wind industry.

As a result, there has been significant early deployment in north-west Europe and China, and more recently in Japan, the Republic of Korea and the United States.

Despite the success in building an industry, the levelised cost of electricity (LCOE) of offshore wind is higher than that of established sources of renewable energy such as onshore wind and solar photovoltaics (PV), energy derived from coal power stations, and the principal benchmark of combined-cycle gas turbine power stations. Significant progress has been made in reducing the LCOE of offshore wind, principally through the introduction of a new generation of turbines, but offshore wind's medium- and long-term future is dependent on additional technological development and innovation to reduce the LCOE further.

Analyses of cost reduction in offshore wind to date mostly have addressed the relatively short-term perspectives of governments or utilities. Few publicly available analyses consider the LCOE for projects commissioned after 2025. To achieve its full potential, a longer-term view is needed to enable a concerted effort by policy makers, industry and academia to commercialise the new technologies and remove barriers. This report summarises the current market and technology status of offshore wind as well as anticipated progress to 2045, where offshore wind energy delivers about 110 GW of operating capacity to the global electricity mix by 2030, and about 370 GW by 2045 (see Section 5.9). The report also identifies the actions by policy makers that are needed to support continued innovation in offshore wind.

The report is divided into the following sections.

Section 2 describes the history and current status of the offshore wind market.

Section 3 summarizes technology innovation to date in offshore wind, on a component-by-component basis for the major elements of a wind farm. It also discusses the impacts of this evolution on a variety of goals, in particular reduction of the LCOE.

Section 4 presents these goals in increasing the global deployment of offshore wind over the next three decades and lists the related technology challenges.

Section 5 presents technology innovation prospects for meeting the challenges described in Section 4, considering the periods 2016-2030 and 2031-2045, looking both at conventional wind farm concepts and potential game changers. The section also presents regional market forecasts, accounting for uncertainties in technology commercialisation as well as market forces.

Section 6 focuses on research, development and demonstration (RD&D) support for offshore wind. The section presents lessons learned from successful and failed RD&D programmes in offshore wind and other sectors. High-potential-impact technologies, RD&D and commercialisation strategies are presented. The section then provides recommendations for policy makers and investors.

Five appendices provide further detail supporting the content of Sections 1 through 6:

- Appendix A lists the principal characteristics of operating offshore wind farms commissioned up to the end of 2015.

- Appendix B lists key organisations currently active in the offshore wind industry, along with brief descriptions of their role.
- Appendix C gives more detail about the LCOE calculations in the report.
- Appendix D summarises the patent and journal analysis that was undertaken to help identify technology prospects for the next three decades.
- Appendix E describes typical milestones and the timeline for developing an offshore wind farm.

Box 1: On calculating the cost of energy

The methodology used to derive LCOE reductions is based on a significant history of modelling technology and other impacts, as described in Appendix C.

Element costs, energy production and the cost of capital and hence LCOE for a typical project in 2001 and 2015 are based on industry experience and historical records and on the specific site conditions and project assumptions defined in Appendix C. These include the cost of transmission.

The future trajectory for technology, market and LCOE is based on evolutionary changes to well-established, commercially deployed technology in a market environment where offshore wind is one of a number of competing technologies.

Capital and operational costs for 2030 are based on a bottom-up analysis of specific anticipated innovations and their impact, taking into account their total potential impact, the fraction of this that will be commercially available for projects commissioned in 2030 and the likely market share of the innovation. Results have been grouped by wind farm element, as described in Appendix C. The effects of other factors, such as changes in typical site conditions, and market, financial, environmental and social factors, are also considered separately, in order to present real-world future LCOEs. The effect of commodity prices and macroeconomic conditions are assumed to remain constant over the period.

The changes in element costs in 2045 are based on a simplified extension of the analysis to 2030, recognising the elements that innovation is most likely to impact. It is not viable to model the anticipated impact of each specific innovation at this stage.

At each stage, bottom-up estimates are rationalised against top-down viewpoints from industry experts and literature.

All costs are in real (end-2015) prices, assuming a European cost base (as this is where by far the greatest experience is available) and assuming commodity and exchange rates at the average for 2015, except where explicitly discussed. Although the geographical distribution of offshore wind farms is anticipated to increase, as this report is focused on the impact of technology, the change in supply chain costs due to the geographical diversification is not modelled.

Table 4 and the other similar tables presented at the end of the discussion on each element are average anticipated impacts of innovations in this element in the central scenario (as discussed in Section 5). Clearly, not all wind farms will see the same impacts. Uncertainty is discussed also in Section 5.

The capital expenditure (CAPEX), operational expenditure (OPEX) and annual energy production (AEP) values in these tables are factored separately such that they combine multiplicatively with the other CAPEX,

(continued on next page) ➔

OPEX and AEP values for other wind farm elements to give the overall change anticipated in CAPEX, OPEX and AEP during the period. The LCOEs stated match the waterfall charts presented at the beginning of Sections 3 and 5. This means that in some cases, there is not a fully consistent relationship between the CAPEX, OPEX and AEP figures stated and the LCOE figure stated.

Above each of these tables is a summary stating which types of innovation in that element are anticipated to have the greatest impact on the LCOE. The impacts of potential "game-changing" technologies are discussed but are not incorporated into the future LCOE trajectory as the possible impact is too uncertain.

Charts showing the breakdown of the contribution of each wind farm element to LCOE are presented, from the development up to the decommissioning expenditure (DECEX), in line with the example provided in Figure A. These show a significant contribution from the cost of finance, which is calculated as the difference in the LCOE compared with having a weighted average cost of capital (WACC) of 0%.

In much previous work, the breakdown of the contribution to LCOE was presented in line with Figure B. Here, the cost of finance associated with each element is included in that element and therefore no separate cost of finance is shown. There is no impact on the OMS elements because expenditure is annual.

Figure A: Example: Contribution of each wind farm element to LCOE

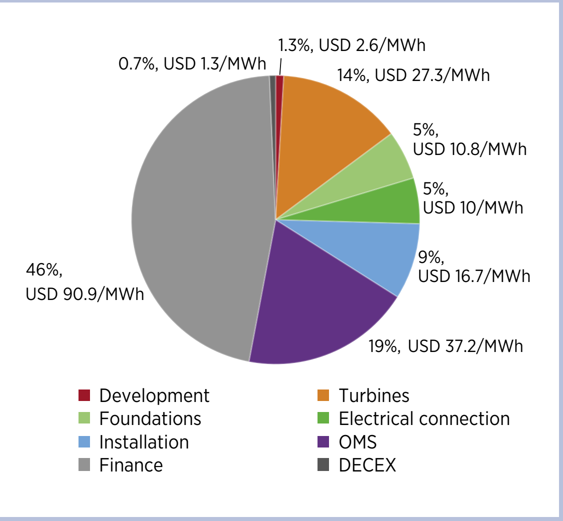
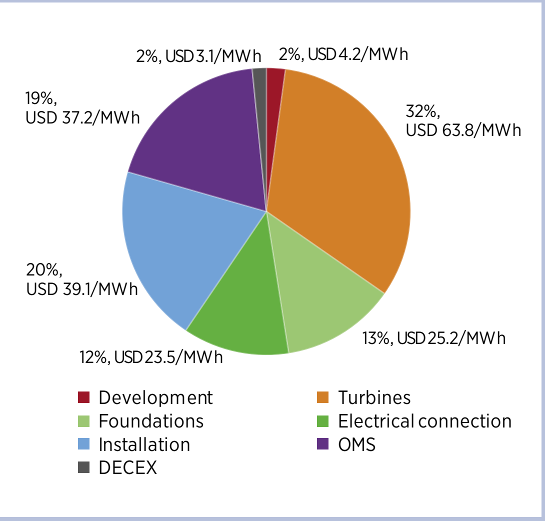


Figure B: Example: Contribution of each wind farm element to LCOE



(Cost of finance is applied to capital items.)

The benefit of presenting the data in line with Figure A is that the impact of cost of finance is visible. It makes clear how important reducing the cost of finance is, through measures such as reducing risk, increasing competition in the supply of finance and reducing the time between capital expenditure and the start of energy production. It is noted that there is an ultimate floor to WACC, and although the finance contribution to the LCOE can be reduced, it cannot be eliminated entirely.

The drawback of the approach presented in Figure A is that the contribution of each of the capital items is underplayed. This difference in presentation does not reflect any change in underlying modelling.

2. GLOBAL OFFSHORE WIND HISTORY AND CURRENT STATUS

This section presents trends in technologies and deployment site characteristics from 2001 through 2015. The current market status also is provided.

2.1 History of offshore wind market and technology

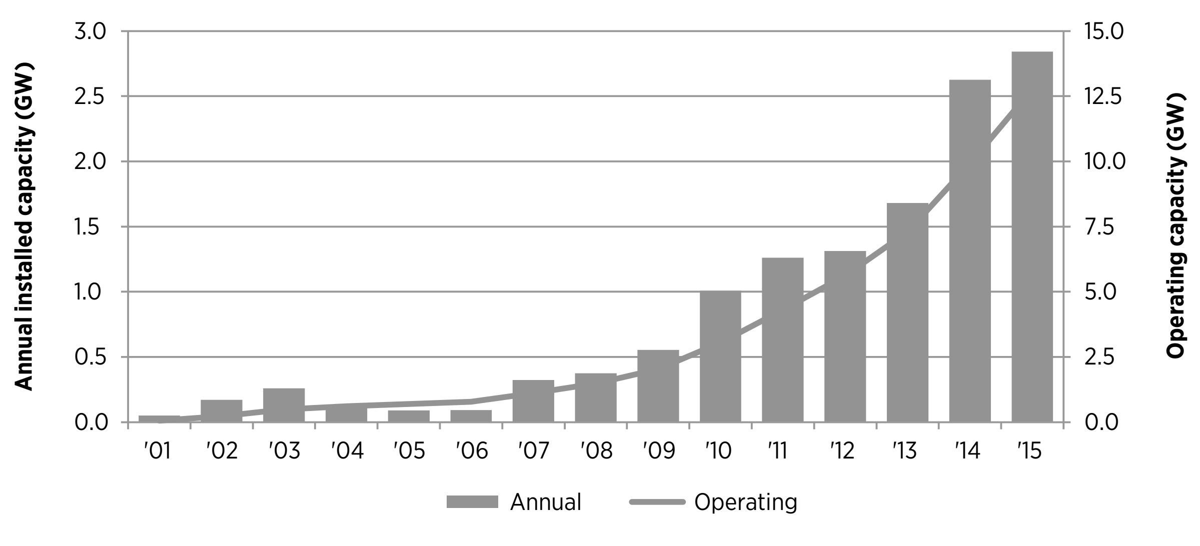
The first offshore wind farm was commissioned in Denmark in 1991. Known as the Vindeby Offshore Wind Farm, this 5 MW project, consisting of eleven 450 kW turbines, was built at a near-shore site in shallow waters. This and the projects that followed last century generally used concrete foundations and small turbines, similar to those installed onshore at the time.

In 2002 the first utility-scale offshore wind farm, with a capacity of 160 MW (80 turbines of 2 MW each), was grid-connected at Horns Rev off the coast of Denmark. From that point to the end of 2015, global operating capacity grew from 0.26 GW to 12.7 GW, of which 1.2 GW was in Asia. This growth was driven by enabling policies and attractive incentives to improve energy security of supply and build an industry. These were coupled with the desire of turbine manufacturers and others to create a new market.

An inventory of operating offshore wind farms is included in Appendix A. Figure 1 illustrates the growth of offshore wind installed capacity from 2001 through 2015. Early projects were funded primarily by large utility companies, supported by attractive public incentives in the form of fixed, regulated prices. Towards the end of this period, more projects were funded by third-party debt, with lower levels of public financial support.

From 2001 through 2015, on average, projects moved to sites farther from shore, in deeper waters and with higher wind speeds. The rated power of turbines increased and manufacturers developed new wind turbines specifically for the offshore market. The capacities of projects also grew. Installation methods and offshore installation vessels became more sophisticated and more efficient. Costly, specialised components gradually were replaced by more affordable standard components, produced in greater numbers. Deployment was enabled at a greater

Figure 1: Global annual installed capacity and operating capacity of offshore wind, 2001-2015



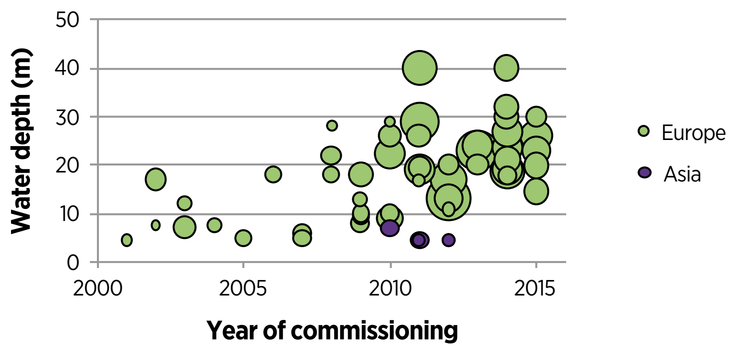
range of sites accessing better wind resources. Figure 2 to Figure 6 illustrate the trends in commercial-scale (see Glossary of Terms) project characteristics over the period.

Generally, water depths, distances to ports and project sizes increased as the industry moved from early commercial projects mainly in UK waters that were limited to 30 turbines to a wider geographical spread of projects. Installation in German waters accelerated these increases towards the end of the period. Associated with the move to these sites has been a general increase in wind resources. The significant use of Siemens' 3.6 MW family of turbines from 2011 is visible, as is the early use of Senvion's 5-6 MW turbines from 2008.

The trend in foundation type has been to use concrete foundations only on more benign, Baltic Sea sites. Monopiles have been used in shallower sites and with smaller turbines, and non-monopile steel structures (including jackets, tripods and tri-piles) have been used in deeper waters and with larger turbines. The envelope of water depths and turbines sizes where monopiles has been economic has increased over time, and now includes 6 MW turbines. Project-specific considerations mean that some exceptions to these trends are likely to remain.

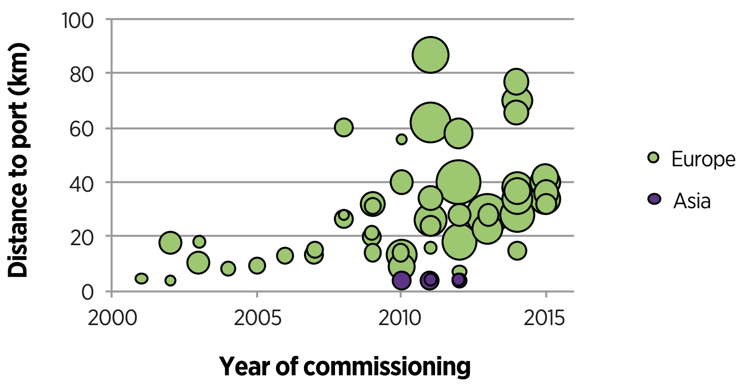
By the end of 2015, 6 MW turbines with 154 m rotor diameters were installed at sites in 40 m water depth and with average wind speeds of 10 metres per second (m/s). The first pre-commercial 7 MW and 8 MW turbines were deployed onshore, and the first pre-commercial floating wind turbines were commissioned in deep waters off the coast of Japan, Norway and Portugal.

Figure 2: Water depth for commercial-scale projects commissioned globally, 2001-2015



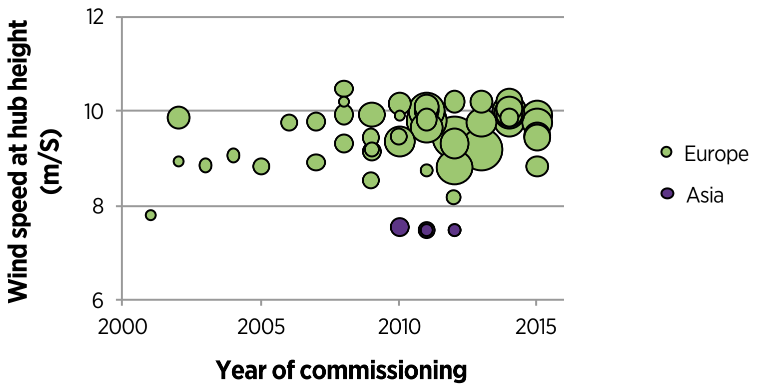
Bubble area indicates the capacity (MW) of the project.

Figure 3: Distance to main OMS port for commercial-scale projects commissioned globally, 2001-2015



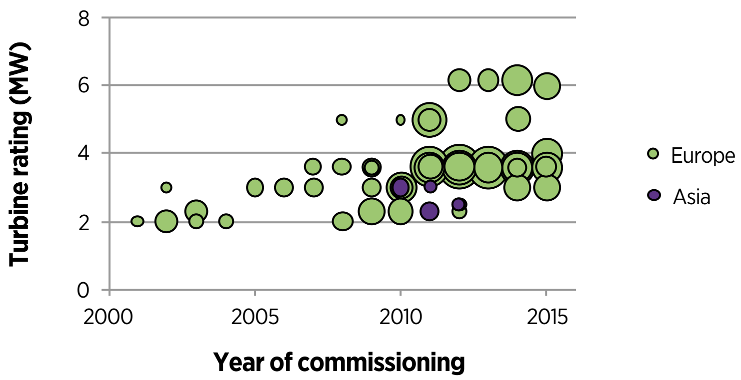
Bubble area indicates the capacity (MW) of the project.

Figure 4: Mean wind speed at 100 m above mean sea level (MSL) for commercial-scale projects commissioned globally, 2001-2015



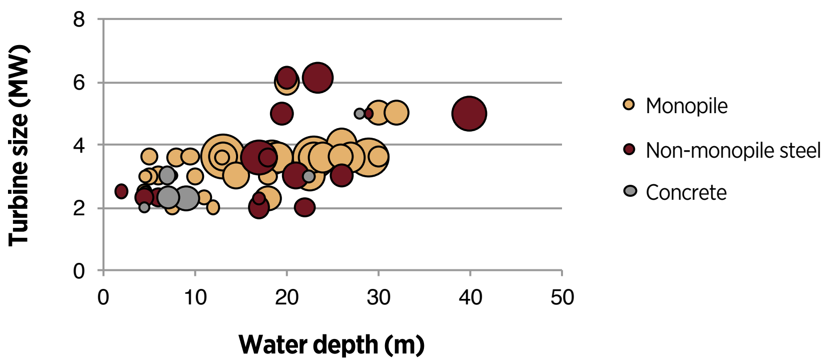
Bubble area indicates the capacity (MW) of the project.

Figure 5: Wind turbine power rating for commercial-scale projects commissioned globally, 2001-2015



Bubble area indicates the capacity (MW) of the project.

Figure 6: Wind turbine foundation types,water depths and turbine ratings for commercial-scale projects commissioned globally, 2001-2015



Bubble area indicates the capacity (MW) of the project.

2.2 Status of current activity

This section summarises current market activities in Europe, Asia and rest of the world. Detailed country-by-country assessments show how offshore wind is quickly having a noticeable impact on national renewable energy generation in early-mover markets.

Europe

Of the 11.2 GW of capacity operating in Europe at the end of 2015, about half was located in UK waters, about 30% was in German waters, and the remaining capacity was located almost entirely in other parts of the North Sea and the Baltic Sea.

In 2015, offshore wind energy contributed 1.6% of Europe's total electricity generation and 6.9% of Europe's renewable electricity generation. In addition to the countries with generating capacity, a number of other countries are putting in place frameworks for delivery in their national waters.

Asia

The 1.2 GW of capacity installed in Asia as of the end of 2015 was located mainly in China and Japan. This included several demonstration wind farms in the region, with the first 100 MW farm (Donghai Bridge, China) commissioned in 2010.

In Asia, offshore wind contributes less than 0.1% of electricity generation. The number of developers and supply chain companies involved also is smaller than in Europe. No significant independent operation and maintenance companies are active in the industry.

Rest of the world

In North America, there was one 30 MW project under construction at Block Island as of the end of 2015, which was due to be grid-connected in 2016. Additionally, several large projects have secured site control and have started conducting environmental surveys, which suggests that the next few years could see an expansion of offshore wind in North America. The US Department of the Interior maintains a database of offshore wind energy projects that are under development (BOEM, n.d.).

Elsewhere in the world, activity is minimal.

As a whole, the global offshore wind energy market is set to continue to grow. Section 4 describes the primary market goals that will drive strong growth in the global deployment of offshore wind.

A description of the leading organisations in the global industry is given in Appendix B.

Case study: Offshore wind sector in Poland

In order to meet the target of the EU Renewables Directive[1], Poland must source 15% of its final energy demand (19% of electricity) from renewable sources by 2020, up from 7.2% in 2005. Wind is the fastest growing renewable energy source in the country, and it is expected to contribute about half of the renewable electricity required to reach the 2020 target. Poland's National Renewable Energy Action Plan predicts that wind power will reach 6 550 MW by 2020, including 500 MW offshore and 550 MW in small installations.

Poland's 2015 Renewable Energy Sources Act (RES Act) establishes incentives for offshore wind farms. Any project being awarded a tender through an auction will benefit from a Contract for Difference (CfD) tariff with a fixed price for up to 15 years (but not beyond 31 December 2040). Other renewable energy investments can benefit from the support scheme up to only 31 December 2035. The aim of this prolonged period for the incentive is to support offshore plants that will be built in the years 2020-2025.

As of mid-2016, 37 location permits for offshore wind farms had been issued in Poland. The transmission system operator had defined connection conditions and signed connection agreements for three plants in the country. In addition, local industry was preparing to supply foundations, substations, transport vessels and OMS services.

[1] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

Table 1: Offshore wind operating capacity by end of 2015, by region

Region	Operating offshore wind capacity in 2015 (GW)
Europe	11.2
Asia	1.2
Rest of the world	0

Key findings

- Offshore wind has grown over a 15-year period from being a novel concept to being a multinational industry.
- Nearly all offshore wind development has occurred in Europe, with deployment starting in Asia in recent years.
- The rated power of offshore wind turbines used in commercial projects has tripled in capacity over a 15-year period, from 2 MW to 6 MW.
- Offshore wind is being deployed in increasingly deep water and farther from shore.
- The main driver for industry to implement offshore wind energy projects has been significant cost-of-energy decreases, aided by government financial support which different countries have put in place to address security of electricity supply, constraints in new onshore wind capacity, weaknesses in transmission infrastructure and decarbonisation of electricity production.
- Innovations in wind turbine technology, offshore installation methods and reduced cost of capital have been critical enablers of offshore wind development.

3. TECHNOLOGY INNOVATION TO DATE

This section reviews the evolution of offshore wind technology from 2001 through 2015. The current state of the art is described for each of six technology elements. Key technology developments during this 15-year period are identified, along with their collective impacts on the LCOE and other factors. Throughout this section, "state of the art" refers to technologies deployed in commercial offshore wind farms commissioned before the end of 2015. Much of the discussion relates to projects in Europe, as this has been the location of dominant activity to date. Early indications are that equipment costs are much lower in China, while installation costs are only marginally lower. Little evidence is available yet regarding operational expenditure (OPEX).

In future studies, it will become more important to take into account site characteristics, technologies and costs of wind farms deployed in different markets, including the shallow/intertidal market in China, for example. A typical offshore wind farm commissioned at the end of 2015 has quite different characteristics from one commissioned at the beginning of the period. The evolution of project characteristics and technology development are strongly inter-related. Table 2 compares the principal characteristics of a typical wind farm in 2001 and 2015. Other assumptions used in modelling the LCOE are provided in Appendix C.

The LCOE of a typical offshore wind farm commissioned in 2015 is about USD 170/MWh on average, down from an indicative figure of USD 240/MWh in 2001. Figure 7 shows the breakdown of LCOE reductions between 2001 and 2015 by technology element. Specifically, each bar in this waterfall chart represents the reductions in LCOE attributable to innovations in development, turbines, foundations, electrical interconnection, installation, OMS and other non-technology factors. Each of these elements is considered in turn in the following subsections.

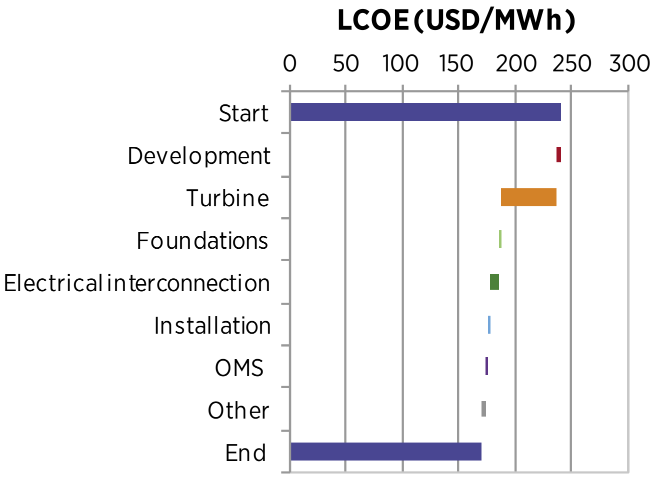
It is important to note that a bar does not indicate change in the cost of an element. Instead, it indicates the impact of innovations in a given element, which may drive changes in the cost of that and other elements. For example, the increase in turbine rated power between 2001 and 2015 did not reduce the cost of energy through lower-cost turbines (per MW), but rather through lower-cost foundations, installation and OMS and increased energy production.

Table 2: Comparison of wind farm characteristics from example projects commissioned in 2001 and 2015

	Typical offshore wind farm, 2001[1]	Typical offshore wind farm, 2015
Water depth at lowest astronomical tide (m)	10	25
Distance from OMS port (km)	20	40
Wind farm capacity (MW)	60	300
Wind speed at 100 m above mean sea level (m/s)	9.0	9.8
Number of turbines	30	75
Turbine rating (MW)	2	4
Turbine rotor diameter (m)	80	130
Foundation	Monopile	Monopile

1 It is recognised that due to the small sample size, no "typical" wind farm was commissioned in 2001. The characteristics for the 2001 wind farm are an average for the wind farms installed in the period 2001-03.

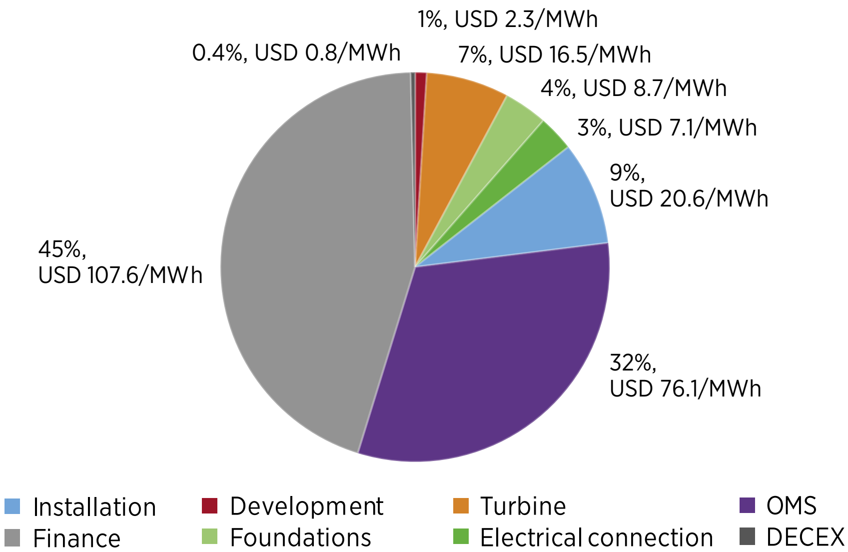
Figure 7: LCOE reduction by technology element for projects commissioned in 2001-2015



The most significant technology innovations were the introduction of a new generation of turbines with large rotors and a range of innovations in foundations. Further "other" changes in cost came from financing costs and other non-technological issues, including project life, competition and other supply chain levers, exchange rates and commodity prices. These factors are captured in the "other" element in Figure 7. Further details about innovations and their impact on LCOE reduction are presented in Appendix C.

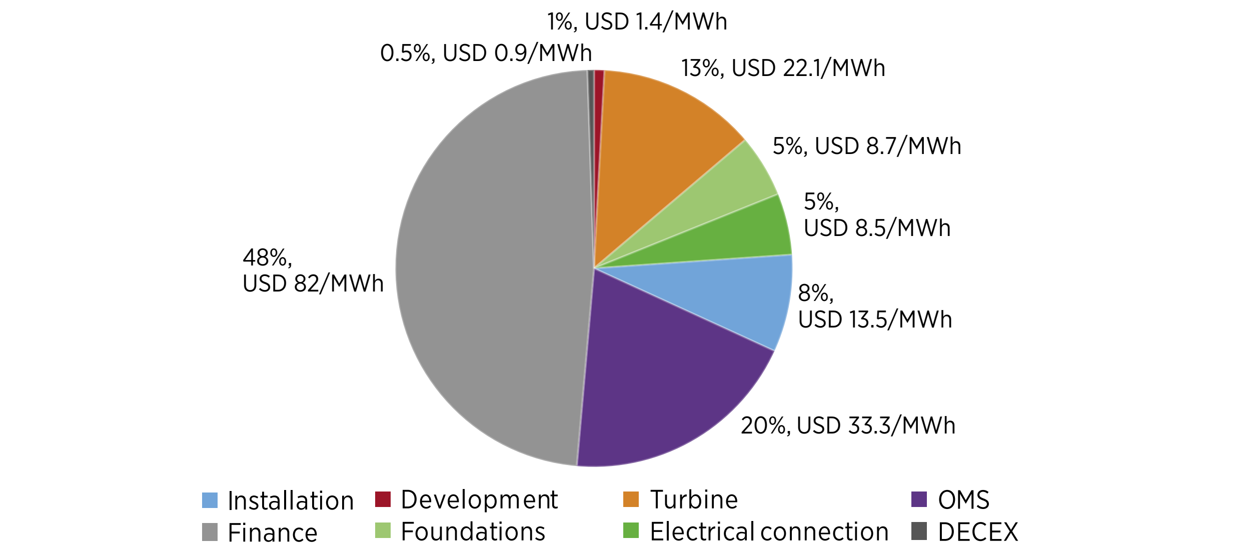
The LCOE of a typical offshore wind farm commissioned in 2001 is, on average, approximately USD 250/MWh. Figure 8 shows the breakdown of LCOE by technology

Figure 8: Contribution of each element to cost of energy for typical project commissioned, end-2001



Values shown are rounded.

Figure 9: Contribution of each element to cost of energy for typical project commissioned, end-2015



Values shown are rounded.

element, including decommissioning expenditure (DECEX). The cost-of-energy analysis shows that nearly half the cost of energy is attributable to financing costs; that is, the cost of interest charges on the debt and the rate of return required on the equity needed to fund construction of these projects. If the WACC was set to zero in real terms, then the contribution of financing cost to LCOE would be removed. Representative costs of finance were derived through discussion with a range of industry sources. It therefore is important to mitigate risk when introducing technology innovations, as risk is a driver for financing costs.

Table 3 summarises the CAPEX, OPEX, net capacity factor and LCOE for a typical offshore wind farm in 2001 and 2015.

The LCOE of a typical offshore wind farm commissioned in 2015 is approximately USD 170/MWh. Figure 9 shows the breakdown of LCOE by technology element.

3.1 Wind farm development

Wind farm development covers the process from the point of site identification, to the final investment decision (FID). This process is described in Appendix E. A range of technologies are required for developing the wind farm. Many of these technologies have been adapted from other industries to meet the needs of the offshore wind industry. The following subsections show the state of the art for the technology-driven activities of wind farm development.

Table 3: LCOE breakdown in 2001 and 2015

Year	CAPEX (USD/MW)	OPEX (USD/MW/yr)	Net capacity factor (%)	LCOE (USD/MWh)
2001	3 430 000	235 000	35%	240
2015	4 800 000	130 000	46%	170

For a wind farm commissioned in 2015, wind farm development typically started between 7 and 10 years before the year of first turbine installation. This section therefore considers the wind farm development activities that took place starting from between 2005 and 2008, rather than the latest technologies being used in 2015 on projects that may be commissioned only in the 2020s.

Wind farm design

Wind farm design proceeds in parallel with permitting activities. Utility developers typically complete concept design and layout optimisation activities in-house, and place contracts with specialist engineering firms for key component design.

Primary wind farm design activities include:

- Wind resource assessment,
- Wind farm layout optimisation (position of turbines and electrical interconnection),
- Turbine foundation design, and
- Installation and operation strategy development.

Commonly used wind resource assessment and wind farm layout design software includes WasP from the Technical University of Denmark (DTU), WindFarmer from DNV GL and Windpro from EMD. IRENA's Global Atlas for Renewable Energy is a useful tool for early-stage wind farm development and design. For wind farms being designed in 2015 for commissioning around 2020, advanced software, such as computational fluid dynamic (CFD) modelling, is sometimes being used (see Section 5.1).

Developers use iterative processes involving multiple engineering disciplines throughout the stages of front-end engineering design (FEED) and detailed design. For example, some analysis teams consider aerodynamic losses as a function of separation distances between turbines, while other analysis teams consider the cost and electrical losses of array cables as a function of turbine separation. The results of these and other analyses are combined to enable overall optimisation, but they often are based on manual positioning of turbines. For wind farms designed in 2015 for commissioning around 2020, more multi-disciplinary optimisation tools are starting to be used (see Section 5.1).

Figure 10: Example analysis of an offshore wind farm using DNV GL's WindFarmer software

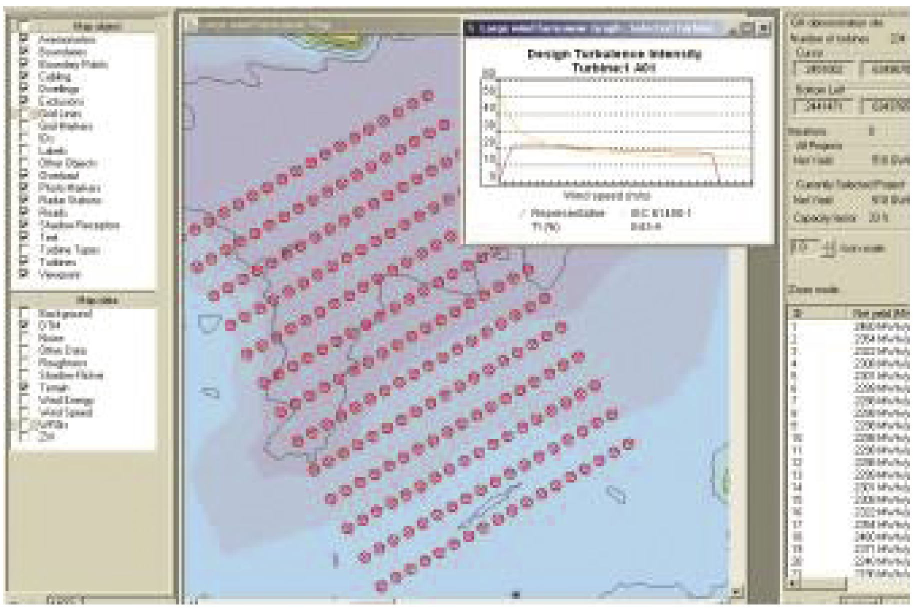
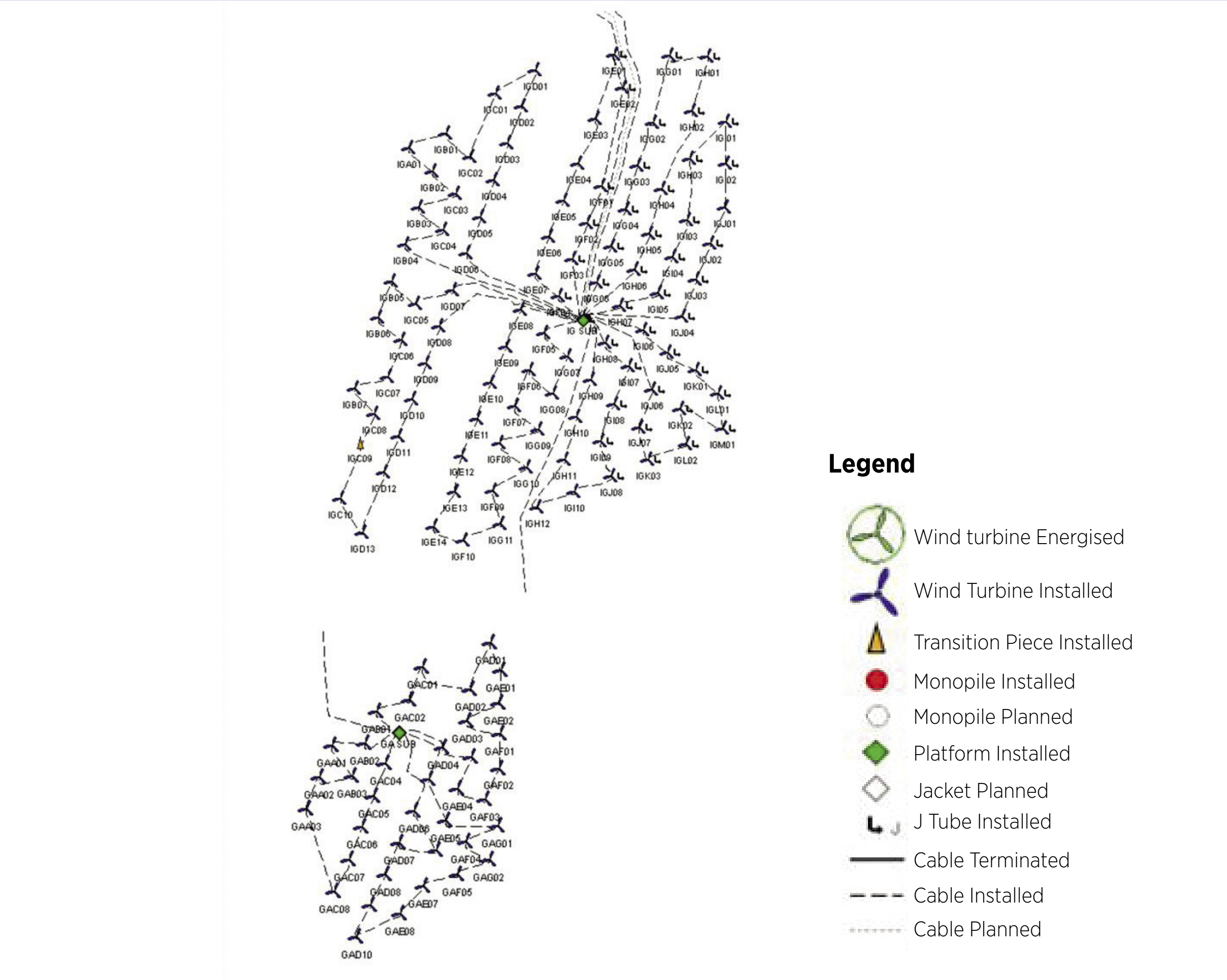


Image © DNV GL
Source: DNV GL, 2015

Figure 11: Turbine and array cable layout at Greater Gabbard offshore wind farm, UK



Source: LORC, n.d.

Surveys

For many projects, fixed meteorological stations are erected at the wind farm site at an early stage of development to monitor meteorological and oceanographic conditions. The masts typically have anemometers at three heights. A fixed meteorological mast is an expensive pre-FID item for the developer. For some projects, other, less accurate measurement and prediction processes have been used. Floating LiDAR has been commercialised but is used alongside other sources of wind resource data or measurement, as uncertainty currently is slightly higher.

Other surveys typically are contracted by the developer to specialist data acquisition companies. Time scales for data collection are determined from best practice guidelines issued by planning approval bodies; typically, they recommend at least two years of environmental data collection.

Geophysical surveys include bathymetric, cable route and unexploded ordnance (UXO) surveys. Geotechnical survey strategies are informed by geophysical surveys and by the anticipated foundation technology to be used. They include cone penetration tests, typically to depths of up to 3 m below the seabed. Geotechnical investigation generally is the most costly part of survey work, making it a significant at-risk investment for developers.

Wildlife surveys include benthic and pelagic, ornithological and marine mammal surveys. Surveys are undertaken mainly by survey vessels, with some ornithological surveys using aircraft.

Key changes in wind farm development technology, 2001-2015

Improved wind farm design. The increasing use of operational experience, more advanced cost models and integrated software have enabled developers to better optimise wind farm design and reduce uncertainty.

Improved wind resource characterisation. The combination of meteorological masts, modelling tools and results of specific studies on wind characteristics offshore have greatly improved confidence in resource estimation and the impact of wake effects on wind speeds and turbulence levels within wind farms. Understanding the available wind resource has improved wind farm design and reduced financial risk.

More effective use of surveys. Through the period, industry learned the benefit of using more-detailed ground surveys earlier during wind farm design in order to increase certainty and remove unnecessary design margins. Towards the end of the period, some environmental surveyors began to use light aircraft. Aircraft surveys cover larger areas in less time than other methods, but they usually are cost-effective only for survey areas greater than 150 km^2.

Generally, the improvements in wind farm development that have the most impact relate to increasing energy production and decreasing component and installation costs, rather than to reducing the cost of development itself.

Greatest impact on LCOE. The greatest savings from innovations in this element were from improved wind farm design and more effective use of surveys.

Table 4: Impact of wind farm development technologies, 2001-2015

CAPEX	OPEX	AEP	LCOE
-2.2%	**-1.0%**	**0.8%**	**-1.6%**

Note: The methodology is described in Box 1 and Appendix C.

3.2. Turbines

The turbine comprises the rotor, nacelle and tower.

Most turbines operational at the end of 2015 were in the 3 MW to 4 MW range with a rotor diameter of between 90 m and 120 m. The largest offshore wind turbine (in terms of rotor diameter) to be deployed at a commercial-scale (see Glossary of Terms) wind farm before the end of 2015 was the 6 MW Siemens SWT-6.0-154 turbine, which has a rotor diameter of 154 m. By the end of 2016, the MHI Vestas V164-8.0 MW turbine, with a rotor diameter of 164 m, was expected to have been similarly deployed.

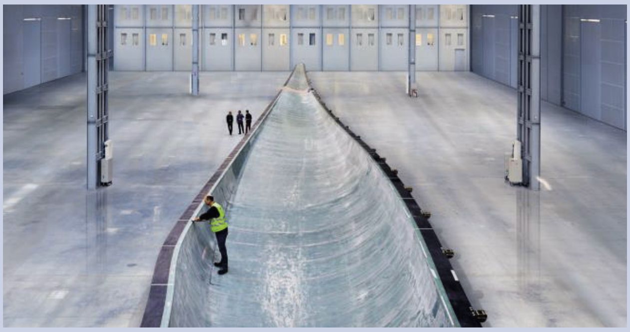
Rotor

The rotor comprises composite blades, a cast iron hub, rolling element blade bearings, a blade pitching system, auxiliary systems (including a back-up power supply) and a weatherproof hub cover. In 2015, commercial offshore turbines were all three-blade upwind configurations. By the end of 2015, the largest commercially deployed rotors had 75 m long blades. The hub height was approximately 100 m above sea level, the minimum level to meet marine safety limitations on clearance between the blade tip and the water for this rotor diameter.

As of 2015, blades were manufactured using full-length moulds and using glass fibre or a combination of glass and carbon fibre. Most blades used epoxy resin, although lower-cost, lower-strength polyester resin also was used.

The pitch angle of each blade is controlled using hydraulic actuators or geared electric pitch motors. Control systems use algorithms to adjust blade pitch angles over a range of about 90 degrees to optimise energy capture, minimise loads on the blades and the rest of the turbine, and to start and stop the turbine. Some turbines use individual control of each blade pitch

Figure 12: Large mould for an offshore blade



Credit: www.siemens.com/press
Source: Siemens, 2012a

Figure 13: Blade being attached to the hub of an offshore turbine

Credit: www.siemens.com/press
Source: Siemens, 2012b

Figure 14: Example of a hydraulic pitch drive arrangement

Source: MHI Vestas Offshore Wind, 2014 angle which can further increase energy capture and reduce loading. The rotor assembly is connected to the drivetrain, which is part of the nacelle.

Nacelle

The nacelle comprises the drivetrain, elements of the power take-off system, control and monitoring systems, and auxiliary items such as the cooling system and equipment to help with maintenance and service activities, all enclosed in a weatherproof cover. The nacelle also is the space in which much of the service activity takes place.

Three drivetrain concepts are in use in commercial offshore turbines of 5 MW scale and above:

- A three-stage gearbox with high-speed generator (operating at about 1 500 revolutions per minute),
- A lower-ratio gearbox and mid-speed generator (operating at about 400 revolutions per minute), and
- A low-speed, direct-drive permanent magnet generator (operating at about 12 revolutions per minute), which avoids the use of a gearbox.

The capital cost and mass of these concepts are similar, and it is uncertain which ultimately will offer the lowest cost of energy based on reliability and operational cost considerations.

Three-stage gearboxes are well understood, having been used in most onshore wind turbines for many years, but they also have been the source of significant unreliability. They allow use of smaller and lower-cost generators, however.

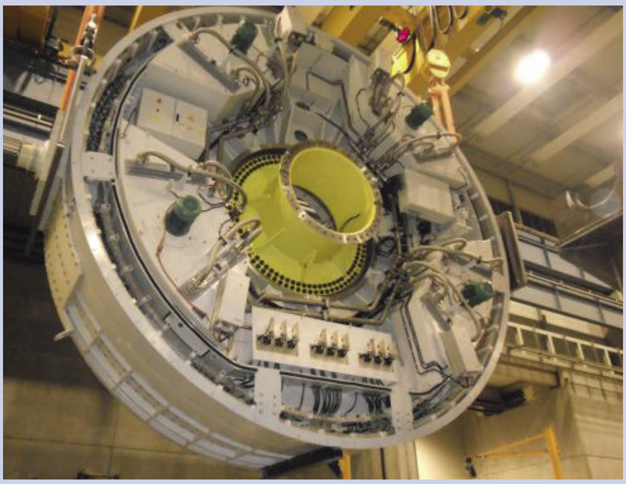
Direct-drive solutions reduce mechanical complexity, but they replace this to some extent with electrical complexity and generally are more expensive. Some also require the use of rare-earth magnetic material, with potential supply and environmental concerns.

Proponents of mid-speed drivetrains argue that this concept achieves a cost-effective balance between the two other concepts. It is anticipated that offshore designs will converge toward direct-drive or mid-speed solutions, as offering the lowest LCOE.

All offshore turbines are variable speed, enabling the rotor to turn at a speed optimised to the conditions and using full- or partial-span power electronics to convert generation frequency to grid frequency.

Substantial bed plates and bearing arrangements are used to support the drivetrain components and interface to the yaw system that turns the nacelle and rotor to face the wind.

Figure 15: Permanent magnet direct-drive generator



Source: GE Reports, 2015

Figure 16: Tower manufacture

Source: Scottish Energy News, n.d.

Tower

Towers are welded conical steel structures made in two or three sections and bolted together as part of the installation process. Towers are outfitted with internal ladders and a personnel lift. In some cases, the power electronics and step-up AC transformer for the turbine are housed at the base of the tower. In other cases, these are housed in the nacelle. The tower top mates with the yaw bearing within the nacelle, and the base has a flanged connection to the foundation. Designs and production processes are similar to those used in smaller onshore turbines, but with increased corrosion protection.

Key changes in turbine technology, 2001-2015

Increase in turbine rating. This high-impact progression has been enabled by innovations in rotor and drivetrain technology, and by advancements in design tools. Power has tripled with only small increases in turbine cost per MW. Larger turbines have enabled economies of scale in the balance of plant and in installation, as well as improvements in energy capture per MW.

Increase in rotor size. This has been enabled by better structural design tools, better manufacturing processes and (in some cases) the introduction of carbon fibre and other structural innovations in the blades. The growth in rotor size (swept area) has enabled greater energy capture without greatly increasing CAPEX per MW. Part of the increase has been driven by a more holistic understanding of the contribution of relatively larger rotors for the size of generator to reducing the LCOE, compared to early offshore turbines that used rotors that were relatively smaller than their onshore equivalents operating on sites with lower wind speed.

Improvements in aerodynamics and control. Improvements in blade and control design have reduced loading and increased energy capture. These improvements have been enabled by better CFD analysis tools, better co-optimisation of structure and aerodynamics, and access to better wind tunnel testing.

Improved component reliability. Drivetrains using direct-drive and mid-speed permanent magnet generators have been introduced. These designs, along with advancements in conventional drivetrain concepts and electrical systems offer the prospect of improved reliability and hence decreased OPEX and increased energy production. Improved dynamic full drivetrain testing also has started to increase confidence in the lifetime reliability of key train components.

More sophisticated design tools. The latest turbines have evolved to handle input torque levels which are over five times larger than early offshore turbines. This has been enabled by sophisticated design tools that link dynamic wind loads to drivetrain and other turbine loads and more information gathered from condition monitoring systems, in a more holistic overall approach.

Greatest impact on LCOE. The greatest savings from innovations in this element were from the increase in turbine rating and rotor diameter.

Table 5: Impact of wind turbine technologies, 2001-2015.

CAPEX	OPEX	AEP	LCOE
-6.1%	**-28%**	**18%**	**-20%**

Note: The methodology is described in Box 1 and Appendix C.

3.3 Foundations

Developers of offshore wind project have used a range of foundations to support turbines. These also are sometimes referred to as substructures. Many factors drive the foundation selection in each project. The main factors include water depth, seabed conditions, turbine loading, rotor and nacelle mass and rotor speed, corporate experience and supply chain capability (in both the manufacture and installation of foundations).

To date, foundations have been bottom-fixed (fixed to the seabed, through piles, suction or gravity) and can be categorised under three main groups:

- Monopiles, usually with an associated transition piece,
- Jackets and other steel space-frame structures secured using piles, and
- Gravity base foundations made mainly from concrete.

For all foundation types, there are secondary steel items such as personnel access structures and steel conduits for array cables. Ancillary equipment includes davit cranes, safety equipment, navigation aids and lighting.

The early focus in offshore wind has been on adapting a small number of concepts previously proven in oil and gas, but a wide range of concepts has been, and continues to be, explored, including more flexible designs.

Monopiles

Monopile foundations are cylindrical steel piles that normally are driven tens of metres into the seabed. Installation sometimes is assisted by internal drilling when the soil conditions preclude driving. They are the most commonly used foundation in the offshore wind industry in 2015.

Monopile designs have evolved to larger diameters and greater wall thicknesses to keep up with increasing turbine mass, dynamic loading and stiffness requirements. Today's state-of-the-art monopile production facilities have the capability to produce units with a diameter of up to 10 m, a length of up to 120 m, a wall thickness of up to 150 millimetres (mm) and a mass of up to 1 500 tonnes. Installed monopiles have yet to reach these dimensions.

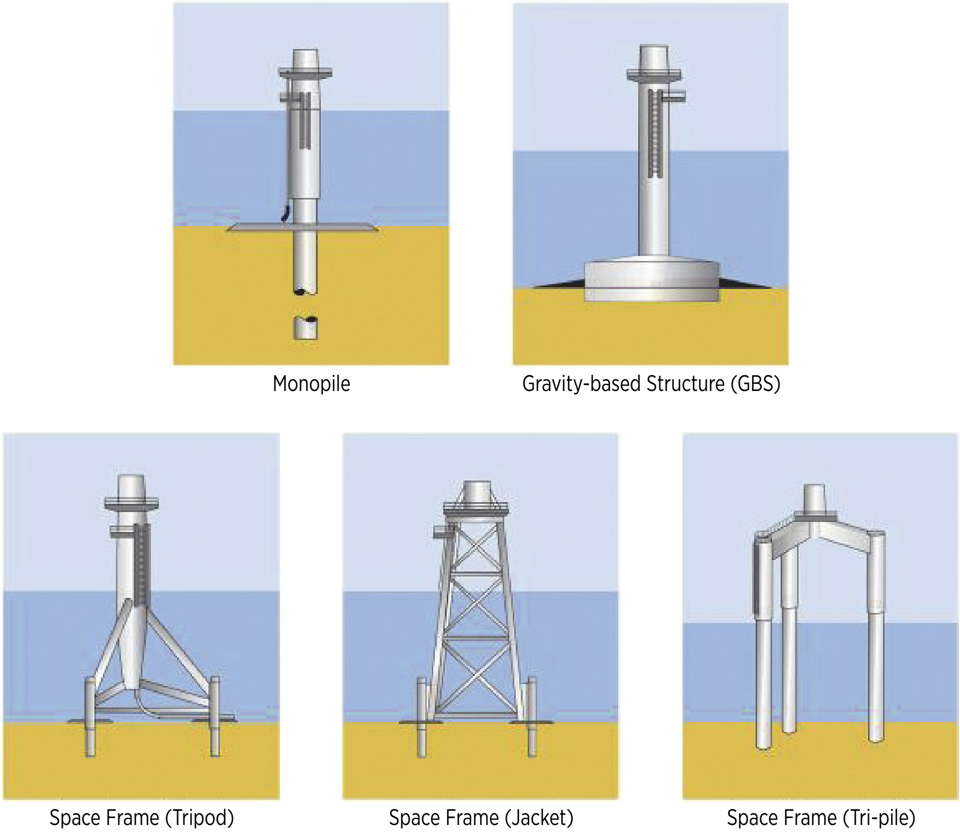
Monopiles typically interface to a separate transition piece, which is installed after the piling is complete. This design avoids damaging the turbine tower interface and secondary steel work during driving and allows for levelling of the interface with the turbine. Some monopile designs, including as used in China, now have integrated transition pieces with bolted-on secondary steel work.

The production processes for both monopiles and transition pieces are largely automated, with gantry cranes moving steel plates to rolling equipment and welding stations. Transition pieces also require metal spray and paint processes and assembly of auxiliary equipment.

Jackets and other non-steel foundations

Braced, welded, space-frame structures (collectively called jackets) provide the required stiffness in a more structurally efficient manner than monopiles and typically become more cost-effective than monopiles when supporting larger turbines in deeper water. Apart from a single three-legged demonstrator that used suction buckets for the seabed connection, all units deployed to date have been four-legged with a piled seabed connection.

Figure 17: Illustration of offshore wind foundation types



Source: WindEurope, 2013

The production process typically involves delivering pre-rolled and pre-cut tubular sections to the production facility, where they are assembled using manual welding, although in some cases pre-manufactured nodes have been used to connect tubular sections.

Other steel foundation options, such as tripods and tripiles, also have been used. Industry currently does not consider these options to be cost-effective due to their higher steel content and more challenging manufacturing processes. Tripiles also require a more complex installation process.

Gravity base foundations

Gravity base foundations are structures that are placed on the seabed with a mass that is sufficient to provide stability against the impact of the wave, current and turbine loading. They typically have been built using reinforced concrete and can have either a flat base or a conical design. Again, gravity base foundations generally provide stiffness more efficiently than monopiles and hence become relatively more cost effective when supporting larger turbines in deeper water.

They offer an alternative for sites either where piling would be impractical due to a rocky sea bed or where the piling noise would have an unacceptable impact on local wildlife. To date, installation costs have precluded their economic use in unsheltered conditions.

The production process typically involves fabricating a base plate at a port (potentially using pre-fabricated components) and then slip forming the main column.

Key changes in foundation technology, 2001-2015

More appropriate design standards. The design of foundations historically has been governed by standards developed for the offshore oil and gas industry. These are considered too conservative for offshore wind, so joint industry projects (JIPs) have been developed to make the standards more relevant to offshore wind, in terms of both material fatigue properties and soil-structure interaction. This has had the impact of reducing steel mass (and hence cost).

Improved design capability. An increasing amount of performance data is available from sensors placed on the fleet of installed foundations. Industry has used this information and a greater understanding of wind and wave interaction to refine designs and reduce steel mass.

Investment in manufacturing facilities. The first offshore wind jackets were produced in oil and gas fabrication yards and shipyards used to fabricating one-off designs. As the market has grown, some companies have invested in dedicated facilities that support serial production in parts of the process, thereby reducing cost, although there is more to do in this regard.

Improved jacket design. There is a track record of one-off jacket design in the oil and gas industry, but offshore wind players are evolving their designs to drive down cost for serial production of many tens of units. For example, early jacket designs were chosen to reduce steel mass, but this involved specifying non-standard pipe sizes. New jacket designs use standard pipes that are less expensive to procure and assemble, even if they have slightly higher masses.

Crane-free installation. Concrete gravity base foundations have been installed on a number of shallow-water sites in the Baltic Sea using heavy-lift crane vessels. This installation method has not proven cost effective in the North Sea. New designs can be floated to the site and lowered onto the seabed by flooding internal compartments without a crane.

Standardised secondary steel. Developers have sought to standardise the design of boat landings and platforms across different projects to allow the supply chain to find economies of scale and reduce costs, both in foundations and OMS equipment.

Greatest impact on LCOE. The greatest savings from improved design and investments in manufacturing facilities.

Table 6: Impact of foundation technologies, 2001-2015

CAPEX	OPEX	AEP	LCOE
-2.9%	-0.2%	0.0%	-1-3%

Note: The methodology is described in Box 1 and Appendix C.

3.4 Electrical interconnection

The electrical interconnection comprises onshore and offshore infrastructure and connects the wind farm to the existing electricity grid. Although most wind farm technology is independent of geography, in some cases national requirements for grid connection hardware have an impact. The differences in these requirements are not considered in this study. The onshore infrastructure does not differ significantly from that used outside of offshore wind, and therefore this section focuses on the offshore electrical interconnection, which comprises:

- Array cables that collect the power from strings of turbines and that connect, in most cases, to an offshore substation,
- Offshore substation(s) that contain the switchgear for the turbine strings, step up the voltage, manage reactive power compensation and, if needed, convert to DC, and
- Subsea export cables that connect the wind farm to the onshore grid.

The generator output from a turbine is typically three-phase and variable frequency. It is connected to a converter in the turbine that transforms the output to a fixed frequency suitable for the grid (generally, but not universally 50 Hertz (Hz) in Africa, Asia and Europe, and 60 Hz in the Americas). A transformer located in the nacelle or tower base then steps up the voltage to up to 33 kilovolts (kV) (currently, although this is anticipated to increase in future for larger turbines) for connection to the wind farm array cable network. A set of three protective switches, known commonly as a ring main unit, normally connects the turbine into the series-connected array cable string.

Array cables

Subsea array cables usually are insulated three-core copper, or occasionally aluminium, power conductors. They are designed to meet strength, flexibility and temperature requirements. They incorporate optical fibres for data communications. Cables may be "wet" or "dry" designs, for example using water-tight lead-sheathing. Array cables have power conductor core sizes ranging from up to 800 mm^2 close to the AC substation, to 150 mm^2 at the far end of the array cable strings.

Offshore substation

The array cable strings are terminated at the substation by a circuit breaker on a common electrical busbar, which is used to connect all the strings together. The substation busbar is connected via outgoing circuit breakers to two or three transformers that step up the voltage for export to shore, from 33 kV to about 220 kV AC or between 320 and 800 kV DC.

For AC export, the output from the transformers is connected via circuit breakers to subsea and onshore cables and then to an onshore substation for connection into the transmission network. For DC export, the transmission systems typically use AC "collector" platforms to step up array cable voltages and feed the offshore converter platform. For DC export, the output from these transformers is connected to an AC-to-DC offshore convertor station that transmits the power via subsea and onshore cables at high-voltage DC (HVDC) to an onshore DC-to-AC convertor station for connection into the transmission network.

A typical large offshore wind farm has two or more offshore AC substations, although some use a single substation structure with two or more transformers. The latter approach allows some level of redundancy in the electrical system to reduce the impact of a single point of failure.

Most substation platforms are installed on a monopile or jacket foundation using a floating crane vessel with a lifting capacity greater than 2 500 tonnes. Two types of vessel are used: a sheerleg crane, such as the Rambiz,

Figure 18: Installation of an offshore substation

Source: Eneco, n.d.

Figure 19: Greater Gabbard wind farm AC substation (Inner Gabbard)

Source: Siemens, n.d.

or a heavy-lift vessel such as the Oleg Strashnov. These vessels are used regularly in other sectors such as oil and gas. A sheerleg vessel cannot operate in high sea states, and hence several weeks may be scheduled for the installation.

For AC transmission, industry practice has not developed significantly since the first offshore substation at Horns Rev in 2002. A recent innovation has been the installation of a substation in modules at Humber Gateway wind farm in the North Sea. This enabled installation by a jack-up vessel with lower lifting capacity.

For DC transmission systems, the substation is too large for a heavy-lift vessel. The approach to date has been to use self-installing platforms. There are two options for self-installing platforms, both of which are towed to site: one has an integrated jacking system, and the second uses a gravity base that is ballasted at site.

AC substations are installed on a monopile or jacket foundation and typically weigh 1 000 to 2 000 tonnes. Substations have usually been custom-designed for each wind farm. By 2015, experienced developers such as Dong Energy are specifying substations with some modules being standardised, and so taking cost benefits from shared design costs and optimisation of manufacture.

Offshore HVDC convertor stations are more complex, contain a lot more equipment and have a mass greater than 10 000 tonnes. As a result of the mass, these stations are designed to be buoyant and hence self-installing.

The heaviest HVDC platform currently deployed is the DolWin 2 platform operated by the Dutch utility TenneT. This station, designed to connect three wind farms in the North Sea to the onshore grid, is rated at 900 MW and has a mass of about 20 000 tonnes.

Subsea export cables

The type of export cable used depends on the export voltage type (AC or DC) and the voltage level.

For AC export, three-core cables rated at up to 220 kV are used. The power conductor cores range from 600 mm^2 to 1 200 mm^2. Various types of armouring are specified to suit the seabed conditions, amount of vessel traffic and water depth.

DC export typically is used for grid connections greater than from about 80 km to about 150 km, depending on HVDC system lead time and system lifetime cost comparisons. Each circuit usually has two single-core HVDC cables rated at up to 400 kV. The reactance of subsea HVAC cables reduces the real power than can be transmitted. HVDC cables do not suffer from this problem, but the infrastructure to convert from AC to DC offshore and back again onshore is expensive.

Figure 20: Three-core AC export cable

Source: Think Defence, 2013

Figure 21: Single-core DC export cable

Courtesy of ABB.
Source: ABB, 2014

Onshore substation

The type of onshore substation depends on the export voltage type (AC or DC) and the voltage level. For AC export the substation includes circuit breakers and a range of static and active electrical components to compensate for the capacitance of the export cables. For DC export the substation DC-to-AC convertors are made using high-power semiconductors and inductive components.

Key changes in electrical interconnection technology, 2001-2015

Advances in power electronics. Developments in power semiconductor devices and the control and monitoring of these devices has resulted in more effective control of active and reactive power exported from the turbines and the active control of power factor compensation for long AC export cables. Another result has been improved reliability.

Increased export cable voltages. High-voltage export cables for early wind farms typically operated at 132 kV. Higher voltages offer lower losses and potential savings from reduced use of conductor material. Increasingly, 150 kV AC is the norm for wind farms in 2015, although some with export cable lengths of around 100 km have used 220 kV, and other wind farms have used up to 400 kV DC.

Table 7: Impact of electrical interconnection technologies, 2001-2015

CAPEX	OPEX	AEP	LCOE
-1.7%	**-4.7%**	**2.3%**	**-2.8%**

Note: The methodology is described in Box 1 and Appendix C.

3.5 Installation

By 2015, experienced developers have optimised installation schedules, and some projects have been delivered ahead of time. Most projects have been installed under separate installation contracts, but there is growing capability to undertake engineering, procure, construct and install (EPCI) contracts, and this has been preferred by developers using project (rather than balance sheet) finance.

Installation activities typically are based at a construction port. The following sections describe the state of the art for each major activity in the sequence in which they typically are undertaken.

Construction ports

Construction ports are used for final assembly and preparation of wind turbines before installation. A construction port needs:

- Good road access,
- 20 hectares (ha) of lay-down area, and
- Up to 200 m quayside with 10 tonnes/m^2 loading strength (BVG Associates, 2015b).

Figure 22: Offshore wind construction and staging port in Vlissigen, The Netherlands

Source: BOW, n.d.

Foundation installation

Foundation installation is undertaken either by the jack-up vessels that also are used later for turbine installation or by floating heavy-lift vessels with dynamic positioning systems.

Monopile installation usually is undertaken as a two-stage process with the monopile driven into the seabed with a transition piece then bolted or grouted in place. Usually the two stages are undertaken sequentially using the same vessel. Vessels installing monopiles typically now need a crane with a capacity of 900 tonnes or greater.

Space frames such as jackets are installed using the same vessel fleet as monopiles. These may be post-piled or pre-piled. With post-piling, a single vessel carries the piles and the main structure. The main structure is lowered into place, and the piles are driven through holes in its base. With pre-piling, the piles are driven into place using a re-usable template. The structure is lowered onto the piles and grouted in position by a second vessel. This may be weeks after the piles were driven.

Even the largest vessels have deck space for only three space-frame structures.

Gravity base foundations are currently of a non-buoyant design and are installed using a sheerleg crane vessel such as the Rambiz, lifting the foundations from a separate barge. Rock dumping follows to secure the foundation's position. Some gravity base foundations require significant seabed preparations covering an area of about 1 000 m^2, prompting concerns about their impacts on benthic (see Glossary of Terms) ecology.

All foundations, but particularly monopiles installed in sandy conditions, may suffer from scour. Rock dumping mitigates the risk, but new solutions are still being sought.

Electrical connection installation

The installation of offshore substations is described in Section 3.4.

Array cables may be laid and buried in a single process using a cable plough or in two stages in which a first vessel lays the cable and a second vessel buries the laid cable using a remotely operated vehicle. The cable may be carried as long lengths and cut to size at each location or pre-cut onshore. At each location the cable is laid before being pulled into the base of the turbine tower through the J-tube mounted on the foundation. Vessels with dynamic positioning are used for rapid installation, to minimise the risk of cable damage and to support the pull-in of the cable.

Each cable takes about 24 hours to be laid, buried and pulled in to the tower base. Vessels may be specialist cable ships or offshore installation vessels equipped with cable-handling equipment. Array cable installation has been a frequent factor in project delays and the need for rework, and several contractors have ceased trading as a result. As of 2015 the situation was much improved because the remaining contractors either were more experienced or had better financial backing.

Export cables are installed in a single length. The vessels usually are self-propelled with dynamic positioning. They have shallow drafts so they can operate in shallow water for the near-shore installation. Vessels use large cable carousels with capacities of up to 7 000 tonnes. Although the large cable manufacturers have their own vessels, these have not been used often, and the work typically is undertaken by specialist contractors. These companies also work in the oil and gas and telecommunications markets. Only a few are suitable for laying offshore wind export cables.

A key feature for export cable vessels is their ability to operate in shallow waters to support the pull-in to the beach landing. The vessel lays the offshore length of cable and then moors close to shore. Onshore equipment then pulls the cable from the vessel through a pre-cut trench.

Turbine installation

The state of the art is a five-lift strategy:

- Tower, fully assembled with internals,
- Nacelle and hub, and
- Each blade separately.

The vessels used are jack-ups designed specifically for offshore wind use, and there are about 20 available suitable for 6-8 MW turbines. They typically have an 800 tonne crane or greater, and some of these also will be used for foundation installation.

Turbine installation is very sensitive to high winds. The maximum wind speed that installation operations can continue in is currently about 13 m/s (for the nacelle).

Figure 23: Installation of a 6 MW wind turbine

Credit: A2SEA/Matthias Ibeler
Source: OffshoreWIND.biz, n.d.

Figure 24: Loading a turbine nacelle aboard an installation vessel

Credit: www.siemens.com/press
Source: Siemens, 2013

Key changes in installation technology, 2001-2015

Development of a two-vessel strategy for monopile installation. A two-vessel strategy has proved cost effective when an expensive vessel is used for piling. A second, cheaper vessel is used for transition piece installation. This approach was pioneered at the UK Greater Gabbard wind farm in 2011.

Introduction of flexible sea fastenings. Sea fastenings typically are fabricated for specific components on a project. By designing flexible fastenings, fabrication and steel costs are reduced and the mobilisation time of the vessels is significantly lower. This approach was first used at the UK Humber Gateway project in 2015.

Development of noise mitigation technologies. The impact of piling noise on sea mammals has been a significant issue for German projects. Innovations such as bubble curtains, sheaths and vibro piling are helping piling to remain within noise limits.

Introduction of pre-piling of jacket foundations. In a departure from oil and gas methods, pre-piling with a lower-cost vessel decouples the installation of the structure to make better use of favourable weather.

Introduction of jack-up vessels designed for 6-8 MW turbines. Significant investment in "second-generation" turbine installation vessels, which have larger decks, longer legs, more powerful cranes and higher transit speeds, are enabling faster installation of larger wind turbines.

Development of tools to support turbine component lifts offshore. Through the use of tag lines, lifting yokes and hook stabilisation tools, the limiting wind speed for installation has been raised from 8 m/s to 12 m/s.

Development of a two-vessel strategy for cable lay and burial. Using two vessels decouples the cable-laying process from the weather-sensitive cable termination process at the turbine.

Introduction of vessels designed for offshore wind cable-laying. The introduction of specialised vessels with dynamic positioning and large carousels such as Jan de Nul's Isaac Newton and Van Oord's Nexus represents a significant step forward for the sector, which reduces cable installation time and saves CAPEX.

Greatest impact on LCOE. The greatest savings from innovations in this element were from the use of more optimum vessels for each stage of installation.

Table 8: Impact of installation technologies, 2001-2015

CAPEX	OPEX	AEP	LCOE
-3.4%	0.0%	0.0%	-1.4%

Note: The methodology is described in Box 1 and Appendix C.

3.6 Operation, maintenance and service

OMS covers all activities from the completion of installation works to the start of decommissioning. Key activities include contract management, operations management, onshore facilities, wind turbine planned maintenance and unplanned service, balance-of-plant planned maintenance and unplanned service, and offshore logistics.

Contract management

Wind farm owners today adopt a range of approaches to OMS, spanning the following:

- Hands-off: They place a contract with the wind turbine manufacturer for a full package including all balance of plant, covering day-to-day operations management, planned maintenance and unplanned service.

- Light-touch: They place a contract with the wind turbine manufacturer for a maintenance and service package for the wind turbine only and with other specialist contracts for other services including electrical balance of plant, foundations, onshore operations base, vessels and helicopter support. The owner then provides some or all of the necessary operations management.
- Hands-on: They recruit and retain a team of OMS specialists, including wind turbine technicians. They work in partnership with specialist subcontractors, including wind turbine manufacturers, vessel operators and high-voltage electrical engineers. In this case the owner takes on more risk but has more opportunity to minimise OPEX and to maximise energy production.

In some cases, debt providers insist on a more hands-off approach, with significant liabilities residing with key suppliers in order to minimise the risk of default.

Operations management

Operations management includes day-to-day workflow management and the use of systems to store and analyse Supervisory Control and Data Acquisition (SCADA) and other condition monitoring and site data, both to respond efficiently to failures after they occur and, where possible, to identify potential failures before they occur.

Such prognostics allow for mobilisation of the necessary spares, tooling and technicians before the failure occurs, resulting in more efficient use of resources and reduced loss of energy production, or curtailed operation of the turbine to delay failure. Some owners pay specialist contractors to provide this prognostic service, while others have developed in-house tools.

Onshore facilities

For sites that are less than 50 km (about two hours' transit time) from a suitable port, the wind farm has an operations base on or close to the dockside. For a 500 MW wind farm, the base typically supports operations of three or more personnel transfer vessels (PTVs) and a team of about 45 offshore-trained technicians. There also is an onshore support team of about 15 including management. The base typically has a control room, stores, and health and welfare facilities.

Wind turbine maintenance and service

The most common arrangement is that the wind farm owner enters into a long-term service agreement (LTSA) with the turbine manufacturer. The LTSA typically covers the initial warranty period of 1 to 5 years and may extend up to 15 years. Generally, the contract allows the owner to take over turbine maintenance after this period, with the wind turbine manufacturer retained for specialist support on components such as the control system software.

Turbine planned maintenance involves a planned visit to the turbine every six months or once a year. During these visits, the technicians carry out a schedule of inspections and maintenance defined by the turbine manufacturer. Activities include checking oil and grease levels, changing filters, and checking instrument calibrations, bolt torques and electrical terminations.

Unplanned service involves technicians visiting the turbine in response to an alarm reported on the wind farm SCADA system. Such visits can be as trivial as for resetting a circuit breaker on a piece of auxiliary plant such as a cooling fan, or as serious as using a jack-up vessel to replace the main gearbox or generator following a failure that cannot be repaired *in situ*.

There is a move towards the use of SCADA and condition-monitoring data to predict equipment failure. For example, a generator bearing can be identified as needing attention early enough to be included in a planned maintenance visit, even if that means bringing forward the planned date of that visit. Such condition-based maintenance approaches have been used in other types of generating plants for many years, and they are likely to become business as usual for offshore wind farms by the early-to-mid 2020s.

E.ON, at its Scroby Sands wind farm, was the first offshore owner in the UK to bring wind turbine maintenance and service in-house, using its own technicians. However, this happened in 2014 after 10 years of wind farm operation. Statkraft, a joint owner of the Sheringham Shoal wind farm (UK), was one of the pathfinders in adopting the hands-on approach to turbine maintenance from the start of operation. Statkraft hired its own local team of turbine technicians who worked alongside the Siemens Wind Power technicians during commissioning and the first year of operation and took over all maintenance and service at the end of the first year, involving Siemens for expert advice where needed.

The hands-on approach to turbine maintenance is now becoming the state-of-the-art approach for many wind farms which have utilities as majority shareholders. For example, London Array Limited, which originally was owned 50% by Dong Energy and 30% by E.ON, has its own Siemens-trained wind farm technicians operating out of its OMS base in Ramsgate. It has a long-term service agreement with Siemens Wind Power regarding key turbine components including the control system hardware and software.

For some wind farms, the safer light-touch approach is still adopted. Galloper (UK) reached FID in October 2015 with four investors, three of which are institutional investors, each holding a 25% stake. For this site, Siemens will provide turbine maintenance and service for the first 15 years of operation as part of the turbine supply contract.

Balance-of-plant maintenance and service

Balance-of-plant wind farm equipment includes the turbine foundations and array cables. OMS of the offshore substation, export cables and onshore substation are included in this analysis in Section 3.6.

Figure 25: Typical service operations vessel

Source: Siemens, 2015

Foundations, and the seabed scouring around their bases, are regularly monitored. Some owners install sensors to provide remote monitoring, including of the scour protection on the turbines. Others contract specialist firms to carry out surveys and to effect repairs as needed. Increasingly such survey work is carried out using sonar, remotely piloted subsea vessels and aerial drones. Grouted interfaces between monopiles and transition pieces have in some cases required remedial action, and industry is paying particular attention to the complex welded joints between tubulars in jacket foundations.

Subsea cables may be disturbed by tides and currents, or damaged by anchors or jack-up vessel legs. The owner therefore contracts with specialist firms to survey the cable routes and to effect repairs or rebury cables as needed.

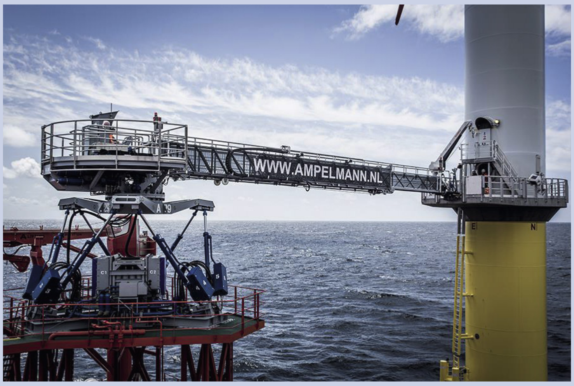
Offshore logistics

Transport for technicians and spares from the onshore operations base to the offshore wind farm typically is provided by PTVs. These vessels typically are custom-designed, twin-hull vessels which are 27 m long with a cruising speed of 25 knots. They carry up to 24 passengers and 20 tonnes of spares and equipment. The state-of the-art vessels feature an air-conditioned cabin and individual seats with air suspension for the technicians to ensure that travel fatigue and nausea do not significantly affect their ability to work efficiently once they have reached the turbines. Most vessels have aluminium hulls, which are expensive but resilient; however, there is a growing use of fibreglass vessels which are cheaper to build and use less fuel. The wind farm owner contracts with specialist firms for the supply and operation of these vessels.

Some far-offshore wind farms supplement PTVs with full-time helicopter support, for transporting technicians when the task in hand does not require heavy tools or spares.

Service operations vessels (SOVs) are larger and more capable than PTVs. Key features include a dynamic positioning system and a hydraulically stabilised bridge that provides service technicians safe walk-to-work access to the wind turbines in a wide range of sea conditions. This enables technicians to access turbines in waves of 2.5 m significant wave height. With the

Figure 26: "Walk-to-work" bridge



Source: Siemens, 2015

conventional landing methods of the smaller PTVs, involving nosing the vessel on to the foundation and the technician stepping onto a ladder, access is limited to significant wave heights of up to 1.5 m.

Other activities

Other OMS activities include environmental monitoring, community engagement and contributions to any community funds.

Key changes in OMS technology, 2001-2015

Improvements in condition monitoring and prognostics. Service strategies evolved from being mostly reactive to being increasingly proactive over this period, which resulted in lower OPEX and increased turbine availability (and therefore increased AEP).

Larger personnel transfer vessels. To minimise transit time and to extend the range of PTV-supported maintenance, there has been a trend towards larger PTVs. The latest are up to 26 m with speeds up to 30 knots. A migration from aluminium to fibreglass also is reducing both the build cost and the vessel OPEX.

Introduction of service operation vessels. Siemens has pioneered the use of SOVs rather than PTVs. These larger, more capable vessels improve the efficiency of technician time and widen the weather window for accessing turbines. This results in higher turbine availability for the same or lower cost, especially for sites farther from shore.

Development of turbine access systems. Innovations have increased the weather window for accessing turbines, which increases turbine availability. Innovations also have enhanced health and safety.

Use of helicopters in maintenance strategies. The introduction of helicopters for personnel transfer enables more efficient OMS operations at far-offshore wind farms, which helps to open up more markets. This innovation also enables turbine access at times when wave heights are too great for PTV personnel transfer.

Greatest impact on LCOE. The greatest savings from innovations in this element were from improvements in personnel transfer vessels and access systems.

Table 9: Impact of operations, maintenance and service technologies, 2001-2015

CAPEX	OPEX	AEP	LCOE
0.4%	-3.2%	0.6%	-1.0%

Note: The methodology is described in Box 1 and Appendix C.

3.7 Other factors

A number of additional, non-technical, site-related market, financial, environmental and social factors have impacted the industry as it has developed, and affected the LCOE in the process (BVG Associates, 2007, 2011).

Key changes in other factors, 2001-2015

Site-related factors. There has been a clear move to larger sites farther from ports and in deeper waters, generally with greater wind resource, as shown in Section 2.1. This has been driven mainly by the unavailability of lower LCOE sites for lease in the UK and by the growth of the German market, which generally is located in these more expensive conditions. Although there has been an increase in wind speeds on new sites, the cost-of-energy benefit of this change is offset by the other factors discussed above, leading to an overall increase in the LCOE due to site-related factors between 2001 and 2015.

Market factors. In Europe, offshore wind farm development, installation and operation have become relatively mature activities with specialist teams and equipment across multiple suppliers in all areas of the supply chain. The volume of work in the sector has reached several GW per year, for example with 2.3 GW of offshore capacity installed in European waters in the first half of 2015. Competition among suppliers has increased, and lessons have been learned about the biggest risks. Project teams have become more vertically integrated (that is, better communication and clearer interfaces between suppliers on a given wind farm), and horizontal collaboration among companies working on different projects has increased. More cost-effective ways to contract and deliver projects and manage risks have been identified, including at the site leasing stage. While other regions are at a much earlier stage, the European market experience provides a clear roadmap for their development. It is noted that a political framework in across Europe is still needed for continuous deployment.

Competition for, and availability of, resources, such as coastal fabrication facilities and vessels, from other sectors (most notably the oil and gas sector) has at different times positively and negatively impacted the costs for the offshore wind sector.

Global trends in commodity prices, especially for steel and to some extent, copper and fuel, also have impacted the LCOE.

Financial factors. As the industry has become significant, it has become a realistic investment opportunity for major equity and debt providers. Availability of finance from these sources has driven down the cost of capital. Finance models have moved towards project finance, with high levels of debt, which has been available at relatively low cost in recent years, further improving the LCOE.

The increasing use of debt finance also is reducing the cost of capital. Many projects to date have been built on the balance sheet of utilities. Some developers are now achieving lower costs of capital by using project finance with up to 80% debt ratios (albeit against a backdrop of low central interest rates).

Environmental and social factors. Environmental and social (visual amenity) factors have precluded the development of some sites, pushing up the LCOE. On other sites, environmental mitigation measures have added to installation costs. Although local content initiatives have helped to grow local employment, they have tended to increase the LCOE in some markets, by reducing competition.

Table 10: Impact of other factors, including WACC and design life, 2001-2015

CAPEX	OPEX	AEP	LCOE
50%	-7.0%	6.5%	-1.1%

Note: The methodology is described in Box 1 and Appendix C.

3.8 Research, development and demonstration activity, 2001-2015

This section describes RD&D trends and budgets, as well as patent activity, for the period 2001-2015, with a focus on activities that are predominantly complete, even if the commercial benefit has not yet been felt. Section 5 discusses RD&D activity that is "live" at the time of writing.

RD&D trends

Between 2001 and 2015 there were two main tranches of offshore wind RD&D. One was largely in Europe, which has been the world leader in offshore wind power during this period. The other was in Asia, where the RD&D agenda has focused on developing large turbines for offshore use and floating systems for deepwater sites. RD&D activities in North America have been more broad, covering common elements of the Europe and Asian initiatives. Little if any offshore wind RD&D took place outside of Europe, Asia and North America between 2001 and 2015.

In Europe, the European Wind Energy Technology Platform (now European Technology and Innovation Platform on Wind Energy) has published strategic research agendas which mapped the research priorities for the wind industry. These, in turn, drove priorities for public funding.

In 2005 the RD&D priorities were defined by the industry as wind resource estimation and mapping, improved reliability of turbines and the development of standards. In 2008 the focus areas broadened to include foundations, electrical interconnection, operations and maintenance, and external conditions such as seabed composition, ocean conditions, spatial planning and environmental factors. In 2014 additional focus on characterising soil and ocean conditions, spatial planning and environmental factors was added to these research agendas.

Alongside these pan-European agendas, privately funded RD&D focused on the development of offshore-specific turbine and foundation designs and installation methods.

In China, RD&D activities focused on the development of large turbines and practical solutions to foundation and installation in local conditions and with available vessels. In Japan, the focus was on floating foundations to address deepwater sites. The RD&D activities evolved from numerical studies and model testing to full-scale prototype deployment. The Fukushima nuclear disaster accelerated the pace of RD&D activities in Japan towards the end of the 2001-2015 period.

In the United States, RD&D initiatives focused on advanced technology demonstration projects and the removal of market barriers. Towards the end of the 2001-2015 period, the US Department of Energy's (US DOE) Advanced Technology Demonstration Projects focused on novel foundations, control systems and other innovations to reduce the costs of offshore wind energy in the country. The market barrier removal projects focused on environmental impacts, grid integration studies, and regional collaboration and stakeholder engagement.

RD&D activity by technology element

RD&D activities were undertaken across all the primary technology elements during the 2001-2015 period.

Wind farm development

Publicly funded RD&D initiatives focused on wind resource estimation and mapping, as well as survey techniques, light detection and ranging (LiDAR) and mitigating environmental impacts. Additional initiatives focused on market barrier removal, especially port and vessel infrastructure needs. Research was undertaken to understand and mitigate the effects of aerodynamic wakes (when the wake of one turbine impacts other turbines in a farm).

Example RD&D programmes include the US DOE's wind and water programme, and projects under the European Commission's framework programmes FP6 and FP7.

A patent and publication analysis (see Appendix D) shows around 500 publications relating directly to offshore wind farm development during the period 2001-2015. Traced patent activity, however, was minimal.

Turbines

RD&D initiatives focused on developing larger, more reliable turbines. The common goal across numerous private and public RD&D initiatives across Europe and North America was to drive down the cost of energy by increasing turbine size and improving energy output. Beyond the significant activity focused on onshore turbines that is also applicable offshore, specific focus areas included:

- Larger blades, to improve energy output,
- Direct-drive and mid-speed generators, to increase reliability,
- Condition monitoring, to give warning of component failures, and
- Test rigs for drivetrains and blades, to validate the dynamics and fatigue life of critical components of larger turbines.

Examples of RD&D programmes include the Energy Technologies Institute's very long blade project and offshore wind drivetrain test rig; the Carbon Trust Offshore Wind Accelerator (OWA); government grant-sponsored research in Europe, including the FP-6 offshore large turbine programme, North America and Asia; and internal RD&D programmes within turbine manufacturers like Adwen, Senvion, Siemens and Vestas.

A patent and journal review shows vigorous activity relating directly to offshore wind turbines. Approximately 700 patents were filed and around 1,200 journal and conference papers were published during the 2001-2015 period.

Foundations

RD&D initiatives focused on innovative foundations, some of which enable alternative installation methods. Floating foundations have been a major RD&D focus in Asia, North America and Europe. Four concepts were developed from ideation within a decade. Much of the floating foundation RD&D was based on adapting offshore oil and gas technologies to offshore wind energy applications.

There also has been significant RD&D on improved manufacturing methods, including high-power welding and automated non-destructive testing.

Much of this work has yet to be implemented due to the need for significant pipelines of work to justify the large investments required. Example RD&D programmes include Fukushima Forward (Japan), Advanced Technology Demonstration (USA), FloatGen (Europe) and the Carbon Trust OWA (UK). Patent and journal activity was moderate for foundations during the 2001-2015 period. Around 1,300 patents were filed and around 800 journal and conference papers were published.

Electrical interconnection

RD&D initiatives focused on high-voltage transmission systems, grid integration and standardisation of equipment. Towards the end of the 2001-2015 period, private RD&D initiatives focused on ways of reducing HVAC offshore substation infrastructure significantly and on extending the envelope of use of HVAC technology to farther from shore, as well as reducing the cost of HVDC technology.

Example RD&D programmes include the Carbon Trust OWA dynamic cable project, the Fukushima Forward floating substation and several private high-voltage RD&D projects by ABB, Alstom Grid, Siemens and others. Around 100 patents and 200 journal and conference papers were published during the 2001-2015 period.

Installation

RD&D initiatives focused on alternative installation concepts, ranging from onshore turbine assembly to integrated foundations and turbine installation. A subset of these RD&D initiatives focused on the installation of floating foundations.

Alternative cable installation concepts have been an RD&D focus area, especially the development of subsea quick-connect designs, which have the potential to simplify offshore operations and to enable alternative strategies for OMS of floating turbines.

Evolutionary developments in array cable installation also took place, considering vessel strategies and cable pull-in techniques. Cable installation also benefited from developments in the cable entry systems on foundations.

Example RD&D programmes include the European Commission's WetMate project and Energy Technology's development of a similar device. Around 600 patents were filed and 400 journal and conference papers were published during the 2001-2015 period.

Operations, maintenance and service

RD&D initiatives focused on improving access to offshore turbines, improving personnel transfer and larger vessel designs, developing alternative OMS strategies, and increasing the use of condition monitoring.

Example RD&D programmes include the Carbon Trust OWA Access project and private vessel and product development projects. Around 100 patents were filed and 700 journal and conference papers were published during the 2001-2015 period.

RD&D activity and budgets by region

The following sections highlight major offshore wind RD&D programmes and their approximate budgets in Europe, Asia and the rest of the world during the period 2001-2015.

Europe

In Europe, the estimated total public sector expenditure on offshore wind energy RD&D was USD 1-2 billion during the period 2001-2015. The private sector expenditure was two to three times that amount.

Large-scale publicly funded programmes include the European Wind Initiative and the European Commission's Framework Programmes (FP5, FP6 and FP7) through calls such as NER300 and Horizon 2020. The main areas of focus have been electrical interconnection, foundations and OMS. Publicly funded, longstanding test centres and institutions supporting offshore wind activities include Spain's National Renewable Energy Centre (CENER), Fraunhofer IWES, Lindoe Offshore Renewables Center (LORC) and Offshore Renewable Energy (ORE) Catapult. There also are a range of onshore and offshore sites for the operational testing and demonstration of new turbines and other wind farm components.

Private RD&D expenditure was dominated by the development of offshore-specific wind turbines. Companies such as Adwen (formerly Areva and Gamesa), GE (formerly Alstom), Siemens and Vestas made the largest investments.

Foundation RD&D also has been significant, with a tripod concept developed for the German Alpha Ventus demonstration project (with collaborative private and public funding) and by Dong Energy, with its suction bucket jacket technology demonstrated at a single location at Borkum Riffgrund 1 in Germany. Floating foundation RD&D has been taken forward by Statoil with its Norwegian Hywind demonstration project and by Principle Power with its Windfloat concept demonstrated in Portugal backed by public funds and private investment led by EDP.

Asia

In Asia, the total public sector expenditure on offshore wind energy RD&D was approximately USD 1 billion during the period 2001-2015. The private sector expenditure was approximately USD 1.5 billion.

The Japanese government invested around USD 700 million in offshore wind RD&D during the 2001-2015 period. Most of this investment was focused on fixed-bottom foundations, floating foundations and very large turbines suited to Japan-specific conditions, including typhoons. The private sector also invested alongside the Japanese government.

In China, wind turbine manufacturers produced 12 prototype offshore wind turbines of 4 MW and above, with four more in development. With prototypes expected to cost approximately USD 50 million each to design, produce and install, this represents an investment of USD 800 million. Further research at the component and subsystem level also has been carried out by turbine manufacturers, by supply chain companies, by universities and in national research institutes. In total, the spend on RD&D for offshore wind in China from 2001 to 2015 is estimated to be USD 1 billion.

Rest of the world

In the rest of the world, the total public sector expenditure on offshore wind energy RD&D was approximately USD 500 million during the period 2001-2015. The private sector expenditure was approximately USD 100 million. Nearly all of this expenditure was in the United States.

Case study: RD&D in China

China is expected to be the main driver of Asian market growth in offshore wind from now to 2045 (Carbon Trust, 2014). This is despite having installed less than 2 GW by the end of 2015, considerably below the target set in the 12th Five-Year Plan. The government has since established a new target for the 13th Five-Year Plan of 10 GW by 2020. Market growth in China beyond 2017 will require an increased feed-in tariff level so that projects are economically viable. Development of offshore wind is anticipated to speed up with the improvement of China's offshore wind power policy system, better co-ordination between government agencies, decreases in the cost of energy and progress in the reliability of offshore wind turbines.

RD&D to date has been driven primarily by technical companies such as China Renewable Energy Engineering Institute and has involved developers such as China Longyuan and turbine manufacturers such as Goldwind. Government has provided support through the Ministry of Science and Technology, the National Development and Reform Commission, the National Energy Administration and provincial governments, such as in Jiangsu. Funding to date has focused on areas ranging from component design, testing and certification to offshore wind farm design, foundation design, installation, OMS research and demonstration projects.

In some cases, RD&D in China has enabled suppliers to catch up with European activity, such as in the installation of larger monopiles and the implementation of higher-voltage transmission systems. In other cases, it has enabled the development of solutions which are focused on the Chinese market but are applicable also in Europe and other markets, for example in the development of monopiles with fins, monopile variants without separate transition pieces, installation methods suitable for intertidal conditions and turbines for environmental conditions seen in South East Asia but also some areas of the United States.

The US DOE Wind Program funds national laboratories, industry, universities and other federal agencies to conduct RD&D through directly funded and cost-shared projects. Among the national laboratories funded through the programme are the National Renewable Energy Laboratory (NREL), Sandia National Laboratory and Oak Ridge National Laboratory. Approximately USD 100 million of this programme was spent on offshore wind during the period 2001-2015.

Private sector expenditures focused on advanced control systems, next-generation turbines and floating foundations. Example private initiatives include GE-Alstom's establishment of an RD&D centre in the United States.

3.9 Offshore wind development, 2001-2015

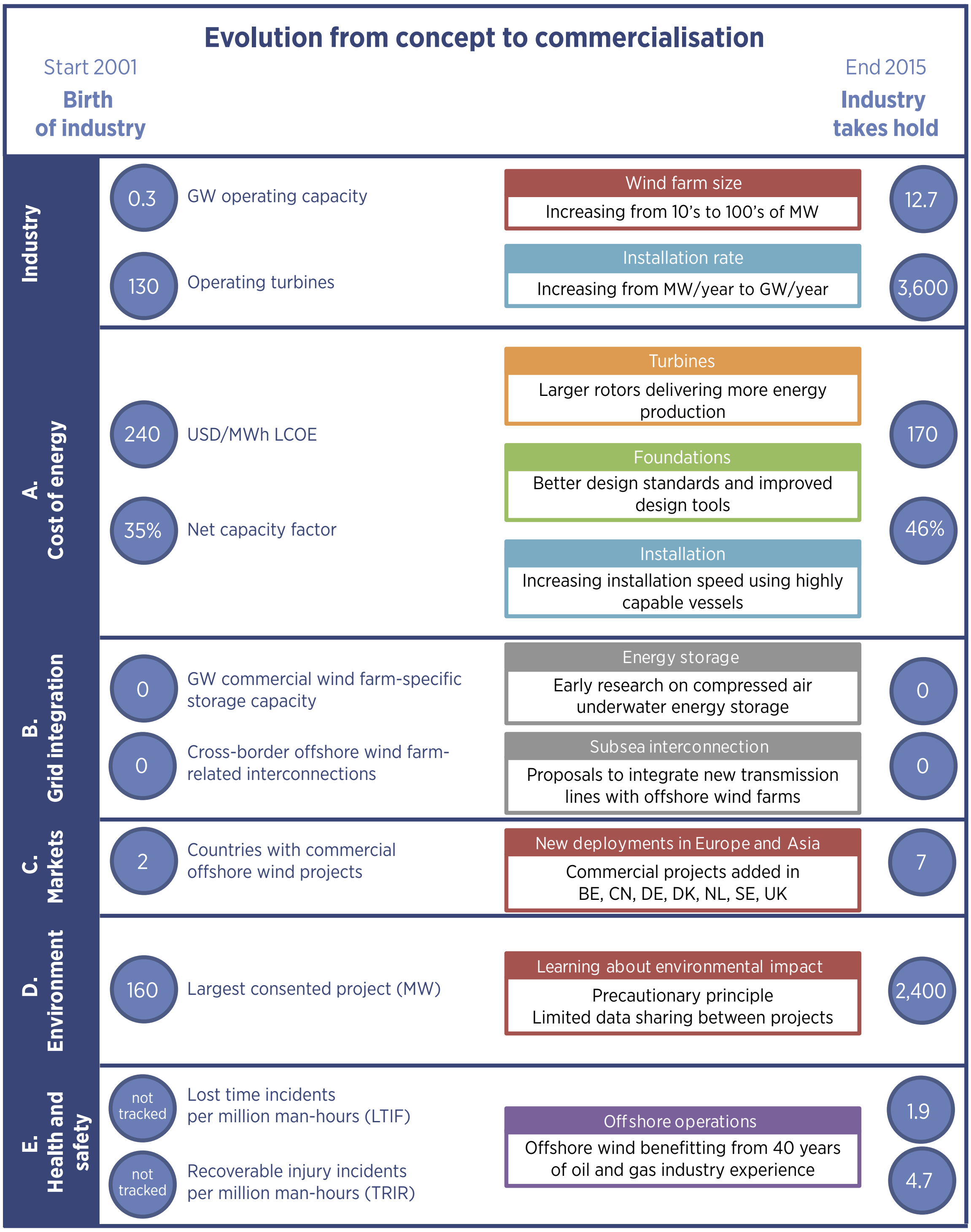
In just 15 years, from 2001 to 2015, the offshore wind industry has evolved from a novel concept to a multinational industry. This journey has seen turbine ratings triple, the cost of energy drop by a quarter, and power production and operating capacity grow exponentially. Advances have been made in all of the

Key findings

- The cost of energy from offshore wind dropped from about USD 240/MWh in 2001 to USD 170/MWh in 2015.
- Wind turbine ratings tripled from 2001 through 2015, while total wind farm CAPEX per MW increased by almost 40%, from about USD 3.43 million/MW to USD 4.8 million/MW. This increase is due to the other factors discussed in Section 3.7, which more than offset reductions due to technology innovations.
- Bespoke installation vessels and other technologies are enabling offshore wind to be located in increasingly deep waters and farther from shore.
- The reliability of offshore wind systems is increasing, hence decreasing OPEX from around USD 235 000/MW in 2001 to around USD 135 000/MW in 2015.
- Financing costs comprise nearly half the lifetime expenditure on offshore wind. Over the period 2001 to 2015, the weighted average real pre-tax cost of capital (WACC) reduced from 12% to 9%.

technology elements as well as in non-technology elements. Offshore wind is now poised for more growth and further cost reduction. Figure 27 summarises the offshore wind industry's journey from 2001 to 2015 using metrics relating to the industry as a whole as well as the five goals discussed in Section 4. It is recognised that due to lack of readily available data, the metric for goal D (decreasing environmental impact) is of only partial relevance.

Figure 27: Offshore wind development trajectory, 2001-2015



4. KEY TECHNOLOGY CHALLENGES AND OPPORTUNITIES

Offshore wind has come far in the last 15 years, but for the industry to have a significant impact on the global energy mix, some key goals must be achieved. The main goals for increasing the global deployment of offshore wind energy are summarised in Table 11 and discussed in the following sections.

4.1 Reducing the cost of energy

Figure 28 shows the separate impact of a 10% improvement in each of the four main parameters related to the cost of energy (LCOE). This is based on 2015 values derived in this study and shows that reducing CAPEX and increasing AEP have the greatest impact on the cost of energy. All changes are relative (*i.e.*, a 10% change in the WACC means change from (say) 10% to 9%).

Importance

Given strong competition from other electricity generation technologies and pressure from politicians to reduce public support to all forms of energy, it is essential that the offshore wind industry continue to reduce its cost of energy to well below USD 100/MWh by 2030. The industry also must be able to clearly explain how it will achieve this reduction, with a robust evidence base to support its arguments. This will give confidence to governments that they should invest in the development of long-term pipelines of projects.

Progress to date

Improvements in identifying opportunities for cost-of-energy reduction

The industry is becoming increasingly sophisticated in the way it models the economics of offshore wind. Although there has always been an understanding of the importance of LCOE, developers, suppliers and financiers now are focusing much more on a lifetime view when evaluating innovations (BVG Associates, 2012).

Initially, the focus was on the basic process of reducing the cost of individual components and processes.

Figure 28: Impact of improvement in key parameters on the cost of energy, based on the cost-of-energy breakdown for 2015 in this study

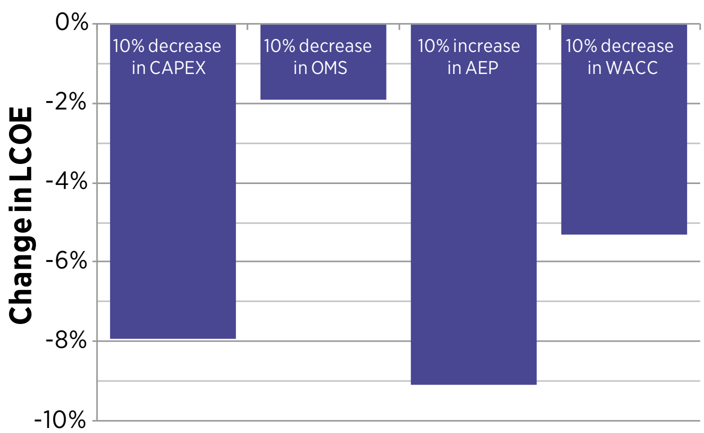


Table 11: Main goals facing the offshore wind industry

Goal	Description	Main technology opportunities
A. Reducing the cost of energy	For offshore wind to progress, the industry needs to continue to drive down the cost of energy significantly so as to better compete with other forms of energy generation.	Wind farm development (wind farm design and surveys), turbines (larger turbines, improved energy capture, greater reliability), foundations (novel solutions and improved manufacturing), electrical interconnection (solutions for far-offshore sites), installation (less sensitivity to weather), OMS (less sensitivity to weather, far-offshore strategies, condition-based maintenance), financing cost (by reducing risk and time from investment to generation)
B. Increasing grid integration	As a variable source of energy located away from existing electricity systems, offshore wind needs to deliver on the challenge and cost of integrating large volumes of energy generation into evolving and broadening energy systems with varying demand.	Turbines (DC output), electrical interconnection (infrastructure for HVAC and HVDC farther from shore)
C. Opening up new markets	Early projects generally have focused on sites in shallow waters, close to shore and with high winds. There will continue to be significant opportunities in existing and new markets in similar conditions where an evolution of existing technology will be sufficient. There are also new markets close to centres of demand where alternative technical solutions are essential to address different site conditions, especially deeper water and different wind regimes.	Wind farm development (wind farm design), turbines (designs for storm conditions), foundations (floating and other deepwater technologies), electrical interconnection (HVDC infrastructure), installation (integrated installation), OMS (far-offshore strategies)
D. Decreasing the environ-mental impact	Although the carbon impact of offshore wind is lower than for many other technologies, offshore wind still has a local environmental impact, for example relating to seabed disturbance and visual amenity. Further decreasing its local environmental impact will enable the industry to better continue to develop in sensitive markets.	Wind farm development (wind farm design), foundations, installation (less weather sensitivity), OMS (less weather sensitivity)
E. Improving health and safety	The industry has a reasonable record, but as in any industry, as it matures it is of critical importance to reduce accidents and improve working conditions further.	Wind farm development (wind farm design), turbines (greater reliability), foundations (greater reliability), electrical interconnection, installation (fewer, safer offshore lifts), OMS (access solutions)

Since then, the industry has been investigating the following options:

- Balances within CAPEX elements: for example, a new component design may be more expensive to produce, but it reduces installation costs to give a net CAPEX saving.
- Balances between CAPEX and OPEX elements: for example, using a more expensive turbine component that improves reliability will reduce unscheduled maintenance to give net lifetime saving.
- Balance between CAPEX, OPEX and AEP: for example, a larger rotor is more expensive but will increase energy production (and hence revenue) to reduce the cost of energy.

Developers now are using more sophisticated system-engineering models to optimise a range of site-specific parameters to further reduce the cost of energy.

There also are increasing levels of analysis on the impact of technology choice on risk and the cost of capital.

Reduction in the cost of energy

The main technology drivers for reducing the LCOE for offshore wind so far are discussed in Section 3 and summarised in Figure 27: In addition, the industry is achieving reductions through supply chain competition, economies of scale, collaboration within the supply chain and increased standardisation.

There also are improvements in LCOE due to declining costs of capital. Trends include increasing levels of post-construction re-financing and more-educated equity investors (supported by public and international institutions such as the European Investment Bank (EIB), Germany's KfW, Denmark's EKF and the UK's Green Investment Bank).

Some developers now are achieving lower costs of capital by using project finance with up to 80% debt ratios (albeit against a backdrop of low central interest rates). These changes in finance have contributed most of the cost reductions illustrated by the "other" bar in Figure 8.

Understanding the "societal cost of energy"

LCOE is an important measure of the competitiveness of a technology, but the calculation does not take into account a wide range of important factors that are external to the project. These factors include the cost of carbon, the cost of intermittency (including balancing plant and transmission network reinforcement), security of supply and the economic benefit of job creation and supply chain development.

Analysis by Siemens using a broader "societal cost of energy" (SCOE) approach suggests that offshore and onshore wind are more cost-effective options in Europe compared with fossil fuel and nuclear generation (Siemens, 2014). It is in the interest of governments to understand this more holistic SCOE approach when comparing the costs of electricity generation using different technologies. Such calculations must be bespoke to specific geographical markets and based on specific scenarios of future electricity supply and demand.

Synergies with other goals

Reducing the cost of energy plays a vital role in opening up new markets. Reducing the cost of energy through improving reliability also has the potential to have a significant effect in improving health and safety during the operational phase of projects, due to many fewer visits to wind farms for unplanned service interventions. Increasing grid integration, although generally not having a big impact on the LCOE, can play a significant role in reducing the SCOE.

Opportunities for innovation

There are opportunities for technology innovation to achieve the goal of reducing the cost of energy across all elements of offshore wind activity. Turbine innovations relating to increased rated capacity and improved reliability will have the greatest impact on reducing the LCOE. Examples of current RD&D that are anticipated to impact goal A (reducing the cost of energy; see Table 11) are included in Section 5.

4.2 Increasing grid integration

Definition and context

The electrical output from offshore wind farms typically is more consistent than that from onshore wind, due to the higher mean wind speeds required for sites to be viable, and it is relatively predictable a day or two ahead. As with onshore wind, an offshore wind farm's output can easily be reduced (curtailed) in response to lower demand without damaging the turbines, but output cannot be increased above the level available from the wind at any given time.

There is not a firm barrier to increasing levels of variable generation. For example, onshore and offshore wind already meet 42% of Denmark's electricity demand, although the country also has very strong grid interconnections with neighbouring countries. There is a cost associated with integrating variable generation within transmission networks that is not included within the calculations for LCOE. There are, however, also costs for integrating large generating assets, such as multi-GW fossil fuel or nuclear plants, which can shut down temporarily at any time.

As such, there is an increasing focus on understanding the total system cost of generation. This issue is common to all forms of generation, but there are specific opportunities associated with offshore wind, for example the direct integration of wind farms into international interconnectors, thereby reducing transmission costs, and the use of storage solutions in deeper water, as discussed in Section 5.4.

Importance

In the large national and cross-border markets, research to date suggests that integration costs are unlikely to be a major barrier to offshore wind deployment before 2030 (Committee on Climate Change, 2015). Integration costs are likely to increase in the longer term, however, with increasing levels of penetration of variable generation. These may be offset in an environment where low-carbon transport is delivered via electric cars and battery storage, with associated demand-management opportunities.

This issue is likely to be a more immediate challenge for smaller and island nations such as Chinese Taipei or Isle of Man that have a good offshore wind resource but limited transmission flexibility. Both have activity under way to develop offshore wind.

Progress to date

Strategic planning

Due to the anticipated increase in variable generation, system operators already are becoming much better at strategically planning how to adapt their transmission systems. This includes greater levels of demand response (such as paying energy users to switch off for short periods during peak demand) and ensuring the availability of a responsive balancing plant. Transmission network operators also are taking a more strategic approach to planning investment in infrastructure, based on an understanding of where future capacity will be built.

Interconnection

There are long-term plans in Europe to further integrate national energy markets. These include concepts of a so-called supergrid across the North Sea and north-western Europe. This would provide interconnection between the countries bordering the North Sea, which would improve competition in the European power market while allowing offshore wind farms to connect to and supply different markets much more easily. A similar scheme, the Atlantic Wind Connection, has been proposed for the US east coast.

This would require general improvements in HVDC transmission technology to provide increased system responsiveness and lower investment costs. Such work is under way and is funded privately by market leaders such as ABB, General Electric and Siemens. Such large transmission infrastructure projects also require long-term market visibility and strong investor confidence that assets will not end up "stranded" due to future policy shifts.

Electricity storage

There is an increasing focus on the issue of energy storage as a technology option to allow transmission networks to accommodate increasing levels of variable generation and demand. Most solutions are of generic relevance, although some offshore wind-specific solutions exist. As an example, some concepts use excess energy to store compressed air under water. At times of low wind resource, a project owner can use these compressed air energy storage systems to drive generators to provide consistent electricity supply (potentially in combination with natural gas or on its own).

More accurate forecasting

Advances in long-term and day-ahead weather forecasting, in combination with aggregation of capacity, is making it much easier for system operators to predict levels of offshore wind generation.

Synergies with other goals

The development of offshore supergrids will reduce the capital cost for offshore wind projects. It also will encourage the development of far-offshore projects where there is a higher, more consistent wind resource that will increase AEP to reduce the LCOE. In addition, better long-term weather forecasting will help de-risk the installation and operation of offshore wind projects, and hence the LCOE. Underwater energy storage, when commercially realised, is currently best suited to water depths of 200 m or more and therefore fits better with floating foundation technology.

Opportunities for innovation

The opportunities for technology innovation to achieve the goal of grid integration are mainly in the turbine and electrical interconnection elements, or they fall outside the conventional scope of wind farm supply. Examples of current RD&D that is anticipated to impact goal B (increasing grid integration; see Table 11) are included in Section 5.

4.3 Opening up new markets

Definition and context

To date, the offshore wind industry has focused heavily on the European market, particularly in the North Sea, Irish Sea and western Baltic Sea. Activity is typically close to areas of significant onshore wind deployment and where land space is at a premium. Sites in these regions are characterised by shallow water depths (10 m to 30 m), high mean winds (9 m/s to 10 m/s) and proximity to shore (15 km to 40 km).

To enable continued growth, companies are looking to the global market to identify other regions with similar resource characteristics where existing offshore wind technology can be transferred immediately. Companies also are developing new technology to enable projects to be located in sites with a much wider range of characteristics, as discussed below.

Importance

The development of a diverse, global market is important for ensuring that the industry can maintain strong, long-term growth. This will encourage ongoing investment and commitment by the supply chain and financial community.

Progress to date

Projects in deeper waters

Existing seabed-fixed foundation designs are unlikely to be commercially viable in sites with water depths of 45 m or more. This is due to both the cost of serial manufacturing of such large structures and the availability of vessels capable of carrying and installing the units.

So far, this has not been a problem for the existing European markets as there have been enough suitable sites to absorb current levels of demand. After 2040, however, European demand may exceed the availability of shallow-water sites. This pushes the industry's focus to other coastal areas that have water depths of more than 45 m and that have a high wind resource and good access to transmission networks. A number of other markets, particularly Japan and the US west coast, have only limited areas of shallow water sites.

A range of floating foundation concepts have been developed to address this market gap, although they all remain at a pre-commercial stage and are not yet cost competitive with seabed-fixed technology. Demonstration projects currently in operation include Statoil's spar buoy Hywind (2.3 MW), Principle Power's semi-submersible WindFloat (2 MW) and the Marubeni-led consortium's semi-submersible Fukushima Shimpuu (7 MW).

It is unlikely that a full-scale commercial project will be operational before 2020, but many analysts expect that floating wind projects will reach cost parity with seabed-fixed projects by 2030.

Projects farther from shore

With many of the potential near-shore sites in northern Europe now exploited, developers are progressing projects that are located farther from shore. Benefits of this evolution include reduced visual impact for local communities and better wind resources. Challenges include the higher cost of transmission infrastructure, higher cost of installation and operation activities, and greater electrical transmission losses.

For projects located more than between 80 km and 150 km from their grid connection point, HVDC transmission systems start to become more cost-effective than HVAC systems. This is because the higher revenue from reduced lifetime transmission losses outweighs the additional infrastructure costs to give a net lifetime cost benefit.

Similarly, basic maintenance and service logistics strategies using PTVs are not practical for projects located more than 60 km from their base ports. In this case, larger SOVs with onboard accommodation and workshops offer a more cost-effective solution as they have better seakeeping abilities, have better technician access systems and can remain at site for weeks at a time. With more wind farms located far from shore, there will be additional opportunities for shared facilities and for the development of portfolio service strategies across a range of wind farms in the same area.

The German market is leading progress in far-offshore wind farm developments with a number of projects already using HVDC transmission technology and SOVs. In the 2020s, the UK market also likely will see more far-offshore projects, which will encourage more investment in technology innovation and the development of best practice.

Beyond 2030, it is likely that far-offshore projects will become common practice in all markets, although near-shore projects will continue to be developed and may remain more cost effective.

Projects in different wind climates

With the industry focused on the northern European market, offshore wind turbines currently are for designed for:

- Annual mean wind speeds (at hub height) of at least 8.5 m/s,
- Operation in short-term mean wind speeds of 25 m/s to 30 m/s, and
- Storms with short-term gusts of up to 70 m/s.

This means that sites that have lower mean wind speeds or that are in hurricane-prone regions are unlikely to be commercially viable with existing technology, and innovation is needed to make products that can unlock these sites. For low wind speed sites, offshore wind likely will follow the trend in onshore wind and develop larger turbine rotors for the same turbine power rating that can gather more energy in lower winds. In hurricane-prone regions, turbine suppliers will need to further develop components that are more robust and to adapt turbine control and site operation strategies.

Projects supporting small-island states

There also are opportunities for offshore wind, in combination with storage and energy management solutions, to provide electricity to small-island states, thereby reducing their reliance on (often expensive) imported fuel.

Synergies with other goals

Opening up new markets provides increased deployment over which to depreciate new investments, which supports continued reduction in the cost of energy. Opening new markets also will allow developers to access areas with high wind resources to provide higher AEP and a lower LCOE. Floating foundations offer the potential for greater standardisation in production, due to much decreased interface with the seabed, which will reduce CAPEX and the LCOE.

Opening up new markets also has the potential to decrease environmental impact and improve health and safety by enabling the development of projects on sites with lower environmental and health and safety risks. If new markets were not available, there would be pressure for the industry to develop projects in increasingly unsuitable sites in constrained areas.

The use of SOVs will improve health and safety by providing safer methods of technician turbine access.

Growth into new markets is made easier though improvements in the cost of energy that have been proven on conventional sites but that also are relevant to new markets, such as due to larger turbines.

Far-offshore projects also will benefit from increasing grid integration and the development of so-called supergrids.

Opportunities for innovation

The opportunities for technology innovation to achieve this goal cross most areas but are mainly in the turbine and foundation elements. In particular, the development of floating foundations and associated O&M strategies will have the greatest impact on opening new markets. Reduction in the LCOE for bottom-fixed projects in waters of 30-45 m deep also will be significant for countries with little available seabed with water more shallow than this. Examples of current RD&D that is anticipated to impact goal C (opening up new markets; see Table 11) are included in Section 5.

4.4. Decreasing environmental impact

Definition and context

The carbon impact of offshore wind is lower than that for most other technologies, but the development of projects still has local environmental and social impacts (Thomson and Harrison, 2015). These impacts increase as projects get larger and as multiple wind farms are located within a region.

As part of obtaining planning approval in Europe, developers must consider the impact on local wildlife populations (including marine mammals, birds, fish and benthic life) as well as on local communities (particularly regarding the visual impact and onshore infrastructure) and on other stakeholders (such as tourism and fishing industries). In some other markets, requirements for commercial projects are much less well developed.

To enable continued growth, the industry must continue to improve its understanding of its environmental and social impact and put in place appropriate measures to make sure the long-term effects are minimised.

Importance

Offshore wind farms are large-scale infrastructure projects which may be located in or close to areas with sensitive ecosystems. They also can be located near coastal communities. Stakeholders, such as conservation groups, public advisory bodies and local communities, can have strong views about the regional and cumulative impact of projects, and this can influence planning approval decisions.

The focus of this report relates to technology measures to decrease environmental (including social) impact. It is recognised that offshore wind already has started to have a significant beneficial impact on local economies, and it is important for the industry to continue to communicate about such positive impacts. Although a typical project involves well over USD 1 billion in capital investment, there still is an important opportunity to establish wider community financial ownership in offshore wind. The World Wind Energy Association, among others, is active in promoting community ownership models that have been successful in establishing local support for wind energy in Northern Europe.

Progress to date

Impact on wildlife

The European market has more than two decades of experience in seeking planning approval for offshore wind projects, with a particularly strong pipeline of activity over the last 10 years. Over this time, developers and government planning authorities have greatly improved their understanding of the impact of offshore wind farms. This also includes greater knowledge about the ways developers can predict impacts during planning and mitigate them during installation and operation.

The level of investment in site assessments also means that there is now an unprecedented amount of data about marine life and seabed conditions. For developers, this experience in site assessment has been important for establishing best practice and standardised approaches, as well as for building strong in-house capability for obtaining planning approval. For planning authorities, the experience of existing wind farms means that they now are able to be more informed in their scrutiny but also impose more proportional planning approval conditions. This makes it more likely that a developer can proceed to FID after receiving approval.

The planning approval process has been accelerated by collaboration between government agencies in different countries and between project developers. It has also been helped by the development of more sophisticated technology and methodologies for impact assessment. This includes more accurate and cost-effective ways of measuring and monitoring local wildlife, such as aerial surveys, and new technology to minimise the impacts on marine mammals and fish of foundation piling noise during installation.

This track record of delivery also means that there is an increasingly mature supply chain for obtaining planning approval in Europe, with detailed, specialist knowledge. And the European experience is spilling over to other markets. For example, industry considers that the US Bureau of Ocean Energy Management has successfully incorporated European experience in the development of its wind energy areas. This positive trend is likely to continue as established European developers and suppliers enter the US market and bring their knowledge and resources.

Impact on local communities and stakeholders

Projects can face opposition from local communities and stakeholders who are concerned about the visual impact or detrimental effect on tourism or fishing industries. In response, and building on the experience of the onshore wind industry, offshore wind developers have been improving the ways they engage with the public by ensuring earlier participation in the process, giving the public more meaningful opportunities to shape details of a project and providing greater levels of education. This process has been supported by strong collaboration and sharing of best practice between project developers.

In the future, the trend for projects to be located farther offshore should reduce the level of opposition that projects face from local communities as the visual impact is reduced or removed entirely.

The development of onshore cabling and substations for offshore projects also has been contentious at times. Onshore works typically involve the construction of a relatively large industrial complex (often in a rural setting), and the installation of the onshore cable can affect properties and roads along its route.

In addition to improved community engagement and direct ownership, developers have sought to reduce opposition to onshore activity by using more sympathetic architectural designs to reduce the visual impact on the local landscape.

Synergies with other goals

Planning authorities have rejected a number of projects at the permitting stage, and many others have had restrictions imposed on the timing of installation and the methods that developers can use. These interventions have reduced the market for offshore wind and pushed up the LCOE. This is due to the effort put into rejected projects and the increased cost of activity in cases where authorities have imposed restrictions. Developing assessment and mitigation processes to help avoid such situations will have an impact on both the LCOE and market growth.

Developers and planning authorities in Europe have built up strong experience of obtaining planning approval for offshore wind farms. Applying the lessons learned from this experience will help open up new markets. Opening new markets also has the potential to decrease environmental impact and improve health and safety by enabling the development of projects on sites with lower environmental and health and safety risks. If new markets were not available, there would be pressure for the industry to develop projects in increasingly unsuitable sites in constrained areas.

Opportunities for innovation

The opportunities for technology innovation to achieve this goal cross most areas but are mainly in the wind farm development element. In particular, improved survey and analysis technology will help decrease environmental impacts. Examples of current RD&D that is anticipated to impact goal D (decreasing environmental impact; see Table 11) are included in Section 5.

4.5. Improving health and safety

Definition and context

The construction and operation of offshore wind farms entails a wide range of risks to human health and well-being. Activities with increased risk profiles include:

- Working offshore
- Working at height
- Diving
- Lifting operations
- Transfers to turbines from vessels or helicopters.

Importance

It is a top priority of any responsible industry to protect its workers through appropriate and effective policies, processes and safeguarding measures. In most cases, these measures will have an associated cost. This may be a direct cost, such as investment in specialist equipment, or an indirect cost, such as a longer installation process due to limits on operating conditions. As the offshore wind industry grows, with developers installing larger projects in more challenging environments, the industry is taking an increasingly professional approach to improving health and safety.

Progress to date

Development of guidelines and best practices

Early offshore wind projects benefited from existing guidelines and best practice developed in parallel sectors, particularly offshore oil and gas and onshore wind. As the offshore wind industry has matured, however, there has been a need for bespoke guidance that better addresses the specific issues of the industry.

This activity typically has been industry-led, with advice and input from relevant governmental bodies. For example, the G9 Offshore Wind Health and Safety Association (G9) was formed in 2010 by nine of the leading European offshore wind developers. Since then, G9 has implemented an annual reporting process that collates data on incidents at all European offshore wind farms. Findings from this process have led to the development of guidelines for two of the activities with the most reported incidents: working at height and managing small service vessels (including PTVs, guard vessels, stand-by vessels, survey vessels, tugs and supply vessels, and construction support vessels). Work also is under way on further guidelines covering diving operations and helicopter operations.

Similarly, the Global Wind Organisation, a non-profit organisation of wind turbine owners and manufacturers, has been responsible for developing standards for basic safety training and is the main accrediting agency for offshore wind health and safety training providers. The Global Wind Organisation's work is supplemented by national industry bodies that ensure that training standards meet local requirements.

Public commitments to health and safety

In addition to being the largest offshore wind market, the UK offshore wind industry has led in promoting the approach to health and safety. The Offshore Wind and Marine Energy Health & Safety Accord, launched in 2011, has been signed by 87 companies. Although the accord was organised by RenewableUK and UK stakeholders such as the Health and Safety Executive, signatories include companies active across the European market. Companies signing the accord commit to:

- Clear and visible leadership on health and safety,
- Showing an industry fully engaged in self-regulation, by confronting the key health and safety challenges, and
- Taking a proactive stance on health and safety to prevent and minimise risks.

Support for innovation

Some innovations either reduce or avoid health and safety issues. Other innovations, focused on other goals, incorporate measures to maintain or improve levels of health and safety. Innovations include:

- Walk-to-work access systems: automatically controlled, motion-compensating walkway systems that allow technicians to transfer between a turbine and vessel more safely and in more severe wave conditions than conventional systems.
- Reduced offshore activity: innovations that reduce the frequency and duration of offshore activities. This may involve a simple reduction in activity or may mean that more activity takes place onshore at the installation port or in a sheltered offshore site.
- Improved sea-keeping performance: for example, new PTV designs that reduce the vessel wave motion and make journeys more comfortable and reduce lost time due to seasickness and work-related illnesses.
- Crane-less cargo and personnel transfer systems: overhead wire-and-gondola systems that eliminate the need for a rigid connection between the vessel and the turbine.

Other innovations include improved work planning, more ergonomic design of turbine nacelles, and better communication and monitoring systems.

Synergies with other goals

Improving health and safety indirectly helps with reducing the cost of energy by avoiding accidents. Many innovations that are focused on reducing the cost of energy or opening up new markets also have the effect of improving health and safety. For example, floating foundations, as discussed in Section 4.3, typically involve much higher levels of pre-assembly and commissioning than seabed-fixed designs.

Opportunities for innovation

The opportunities for technology innovation to achieve this goal cross most areas but are mainly in the wind farm OMS element. In particular, activities that reduce the amount of offshore-based activity will have the greatest impact on improving health and safety. Examples of current RD&D that are anticipated to impact goal E (improving health and safety; see Table 11) are included in Section 5.

Key findings

There are five important goals that the industry must address to ensure a sustainable and competitive long-term market:

- Goal (A) – Reducing the cost of energy: The industry needs to continue to drive down the cost of energy to well under USD 100/MWh by 2030 in order to compete with other forms of energy generation.
- Goal (B) – Increasing grid integration: As a variable source of energy, offshore wind and associated technology needs to be adapted to integrate large volumes of energy generation into evolving and broadening energy systems.
- Goal (C) – Opening up new markets: Activity to date has focused on sites in Europe and China, generally in shallow waters, close to shore and with high winds. Technology innovations are needed to open up new markets with different site conditions, especially with deeper water and lower wind speeds.
- Goal (D) – Decreasing environmental impact: The industry needs to further decrease its local impact, especially with regard to the impact of installation activity, to continue to develop in sensitive markets.
- Goal (E) – Improving health and safety: The industry must continue to improve health and safety best practices and to ensure their widespread adoption, in line with any maturing industry.

Case study: Health and safety

The offshore wind industry in 2045 will have a co-ordinated and holistic approach to health and safety, with consistent data sets and a focus on risk management and ownership, according to RenewableUK, the UK's wind and marine energy industry body.

RenewableUK is actively involved in a range of initiatives intended to improve offshore wind health and safety. It believes that further improved risk management will run through government policy and all commercial financial and operational decisions. This will mean that health and safety implications are ever more consistently considered at an early stage and that best practice is further shared and implemented.

The industry also will have built on the strong experience and expertise of key European markets, particularly those with links with North Sea oil and gas, so that there will be a culture of more appropriate and responsible risk allocation between developers and their supply chain, with an emphasis on collaborative and long-term approaches.

Finally, in addition to developing a clear and consistent global data set of health and safety statistics, the industry will ensure that it looks beyond the numbers to learn lessons and to update best practice in response to new challenges.

5. TECHNOLOGY INNOVATION PROSPECTS

This section identifies technology innovations still to be commercialised as well as supply chain opportunities in offshore wind. It explains their potential impact on the five market goals identified in Section 4 over the next three decades. The innovations outlined are only a sample of the numerous R&D efforts in progress at different organisations, and were identified through patent analysis, industry experience, review of scientific papers and interviews with experts.

The innovations are discussed, wind farm element-by-element, in Sections 5.1 to 5.6. In each of these sections, innovations are reviewed, and their impacts on the market goals presented in Section 4 are discussed. Section 5.8 considers potentially game-changing technologies, and Section 5.9 presents a market forecast for the next three decades, taking into account that although the innovations and potential game changers discussed could contribute to the deployment of offshore wind, not all research presented in this section will result in commercialised products, and other innovations also may contribute.

The time frame for commercialising an innovation in the offshore wind industry typically is 3 to 6 years, with the more complex innovations such as larger turbines having a development period to full-scale commercialisation of up to around 12 years, consisting of design, prototyping, demonstrating and deployment (BVG Associates, 2012). In this section, the expected commercialisation date for each innovation is estimated based on the current development status of the innovation, the stages still to go and expectations for the timing of these based on the historical timeline for commercialising similar innovations and the increased pace of activity as the industry matures. The stages for commercialising an offshore wind technology generally include some or all of concept design; detailed design; prototype testing and certification; demonstration; early commercial deployment; full commercial implementation; upgrades during product lifetime; and introduction of variants.

The development and impact of new standards that are directly applicable to activities in offshore wind are incorporated in several sections. In some cases, such as in foundation design, "old" standards from other sectors enabled early progress in the industry but are now seen to drive excessive conservatism, but it is taking a long time to update these standards. In other cases, such as relating to data communication, establishing a standard enables a range of innovators to offer new products to market without having to struggle also to get others to use their protocols. Standards also have been seen to have the effect of enabling investment and movement into new geographic markets, as it offers decreased project risk through some level of assurance of good practice.

The cost of energy from offshore wind is coming down, and this trend is likely to continue. Figure 29 shows the anticipated LCOE range for typical sites at the time of development, from 2001 to 2045, incorporating the typical costs of energy already presented for projects commissioned in 2001 and 2015. The future trajectory is based on evolutionary changes to well-established, commercially deployed technology in a market environment where offshore wind is one of a number of competing technologies, with a deployment rate in line with Section 5.9.

The central scenario is based on best estimates of technology development, as discussed in Sections 5.1 to 5.6, and of the impact of changes in site type and other factors discussed in Section 5.7. The associated central market scenario is presented in Section 5.9. The short-term trajectory is lower than the UK's long-running, but now largely superseded, aspiration for an LCOE of GBP 100/MWh for projects with FID in 2020. Long term, it reflects a European cost base, as discussed in Appendix C. It is recognised that individual supply teams, projects and markets may have a higher or lower cost of energy than the central trend. It also is recognised that, over time, as the geographic spread of offshore wind increases to incorporate markets with lower supply chain costs, this should further decrease the LCOE.

The dark grey band shows a +/- 10% range, corresponding to a -20%/+27% change in market volume, as discussed in Section 5.9. The light grey band shows an indicative range due to uncertainty in the rate and scale of impact of technology innovation. The dashed grey lines are indicative of the range of variation in the LCOE due to variations in the other factors discussed in Section 5.7.

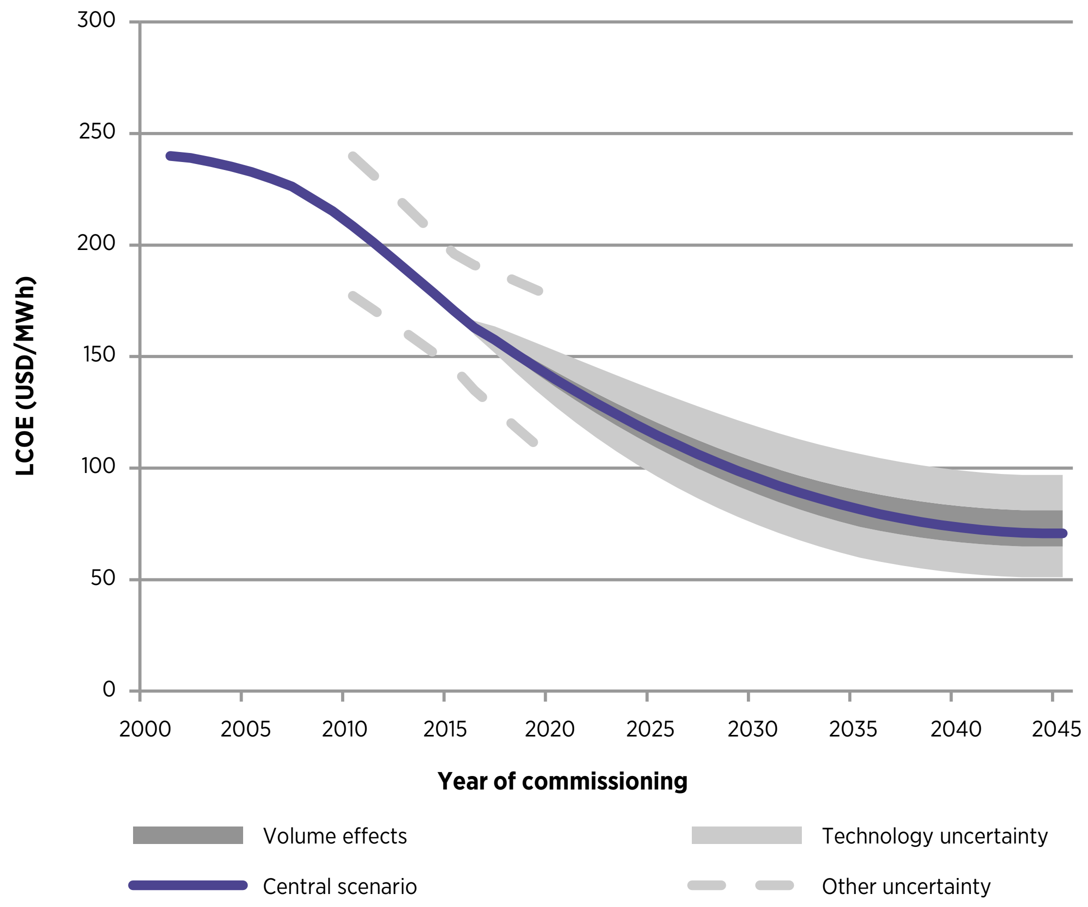
All forecasts assume constant commodity prices and macroeconomic conditions and a market environment where offshore wind is one of a number of competing technologies. The impacts of potential "game-changing" technologies, discussed in Section 5.8, are not included in Figure 29 as the possible (downward) impact is so uncertain.

There is a risk that offshore wind has an LCOE which is too high in comparison to other sources of energy for too long. This could mean that offshore wind cannot sustain the investment it needs to reduce costs, which would mean that it never reduces costs enough to be competitive.

Further details about assumptions and methodology for LCOE calculations are included in Appendix C.

As discussed in Section 2.1, the largest reductions in the LCOE from 2001 to 2015 came from innovations in turbines and installation, and from reductions in financing costs.

Figure 29: Cost of energy for projects commissioned in 2001-2045



See the text describing the figure for explanation of the lines and bands.

Figure 30: Impact of innovation in each element on the cost of energy for projects commissioned in 2015-2045

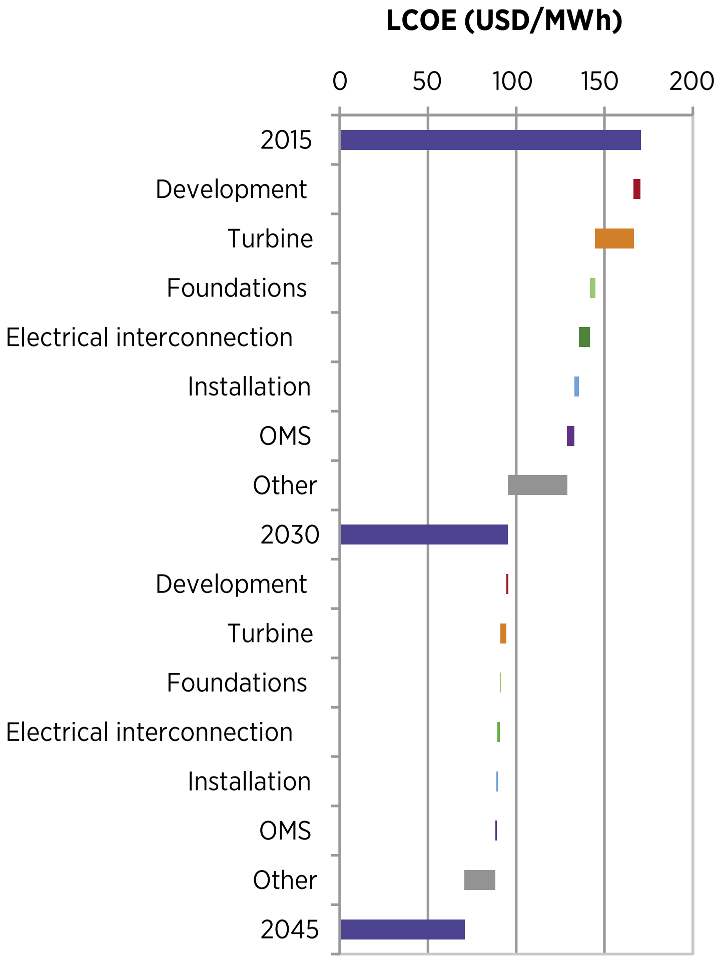


Figure 30 shows the anticipated cost-of-energy reductions due to innovation in each technology element for the period 2016-2045.

A similar trend is anticipated from 2016 to 2030. The largest single reduction is anticipated to come from lower financing costs due to a reduction in perceived risk (part of "other" in Figure 30), in an environment of unchanged macroeconomic conditions, an underlying assumption as stated in Appendix C. The second greatest reduction is likely to be due to wind turbine innovations that will enable greater power output and higher reliability without increasing the cost per MW of capacity, as discussed in Section 5.2.

Also of great importance (and included as part of "other" in Figure 30) is the impact of changing competition and growing pipelines of projects). These are discussed in Section 5.7.

From 2031 to 2045, reductions in OPEX are expected to have the greatest impact on cost-of-energy reduction, due to further innovations in turbines, especially improvements in wind turbine reliability.

Capacity factors continue to increase over the period. It is recognised that on many higher-wind sites, higher net capacity factors will be seen.

Figure 31 and Figure 32 show the anticipated breakdown of the LCOE by element for a typical offshore wind farm commissioned in 2030 and 2045, respectively. Similar breakdowns for 2001 and 2015 are presented in Section 3.

Figure 31: Breakdown of LCOE by element in 2030

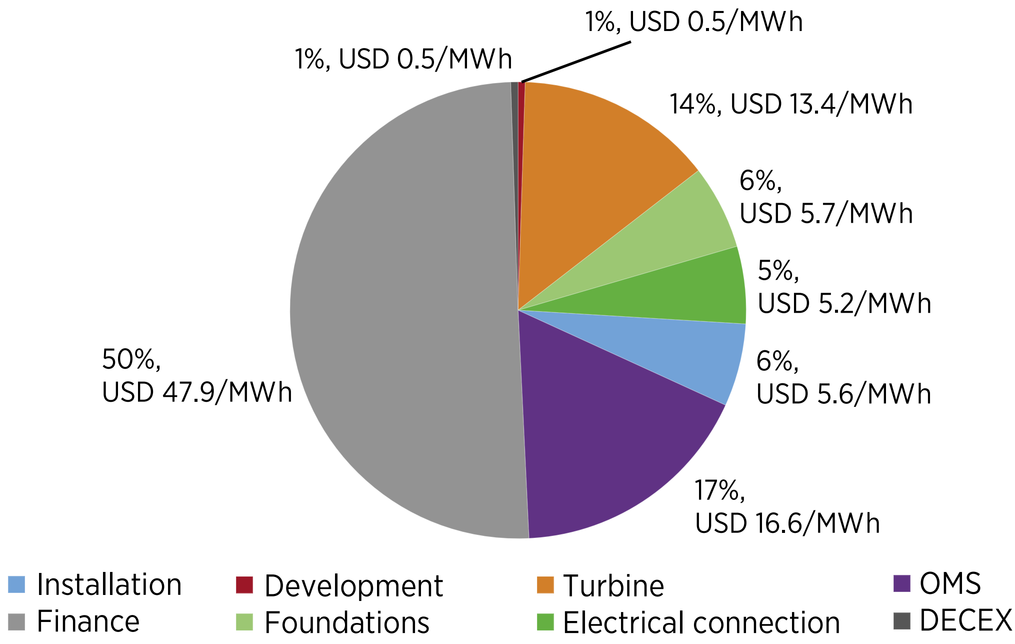


Figure 32: Breakdown of LCOE by element in 2045

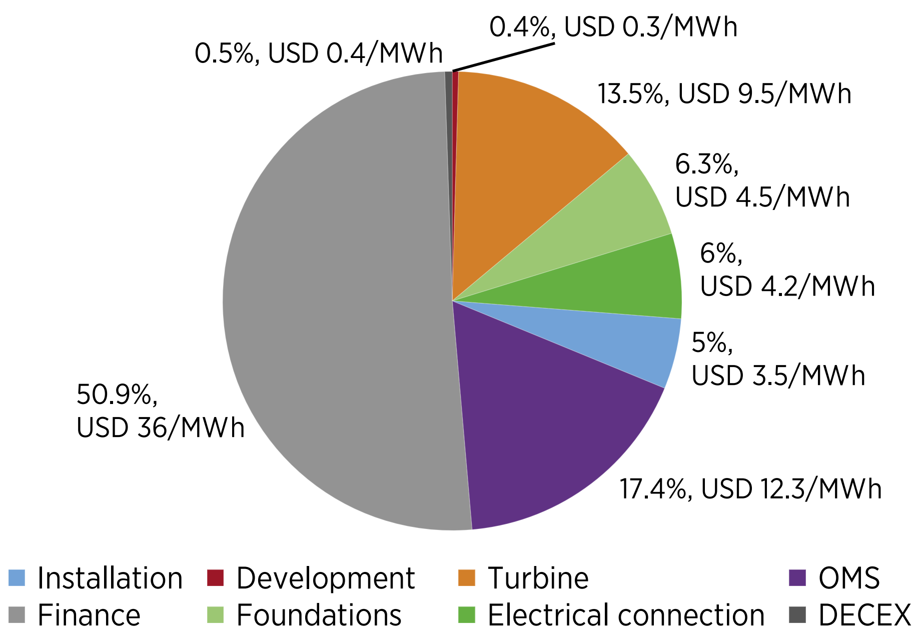


Table 12: LCOE breakdown in 2030 and 2045

Year	CAPEX (USD/MW)	OPEX (USD/MW/yr)	Net capacity factor (%)	LCOE (USD/MWh)
2015	4 800 000	135 000	46%	170
2030	3 750 000	75 000	50%	95
2045	3 400 000	55 000	52%	74

5.1 Wind farm development

This section describes future innovations in technology related to offshore wind farm development.

Innovations

Improved wind resource characterisation

LiDAR technology uses lasers to measure wind speeds at points remote from the sensor. With motion compensation hardware and/or software, LiDAR systems can be mounted offshore on buoys. Floating LiDAR stations are far cheaper and faster to install than conventional seabed-mounted meteorological (met) stations with masts and can be moved to different sites in the wind farm to give a fuller assessment of the wind resource. The industry is increasingly confident that LiDAR system accuracy will match or exceed the accuracy of a fixed met station.

Private sector in-house RD&D has been carried out on LiDAR devices by the main players, including Axys (Canada), Fugro Oceanor (UK/Norway), Leosphere (France), Sgurr Energy (UK) and ZephIR (UK). Other companies have focused on total system design, including buoy stability. There also have been collaborative research partnerships, for example through the Carbon Trust's OWA, to verify floating LiDAR performance and develop methodologies for its verification. More work remains to achieve "deploy and forget" devices, combining LiDAR units, power suppliers and communications systems with long-term reliability.

In parallel, there is work to develop hybrid wind resource forecasts using satellites, other remote sensing and other historical measured data sets to supplement site-specific measurements. Hindcast model data at high resolution and verified with measurements at locations away from the prospective wind farm site allow for more reliable production estimates at an early phase. Model data are being made increasingly available by commercial actors using high-performance computing. One such project is being undertaken by DNV-GL and is funded in part by Innovate UK. DTU also is active in this area.

Such innovations reduce wind farm development and finance costs, open up the market for deepwater projects, decrease environmental impacts by avoiding piling, and reduce health and safety risks by avoiding offshore heavy lifts (goals A, C, D and E). The first project to proceed based predominantly on wind data from floating LiDAR will be Dong Energy's UK Burbo Bank Extension project, due to be commissioned in 2016.

Improvements in seabed characterisation

Installation contractors report that there are significant uncertainties in the structure of the seabed at the procurement and construction stages. As a result, the approach and equipment used are at times not well suited to the conditions. This has particular implications in ensuring that the specified burial depth of cables is achieved and that the areas around the turbine locations are safe for jacking up.

The necessary geotechnical analysis is costly. Since wind farm development expenditure by developers is at risk, there are tight budgets.

Greater investment in seabed surveys lowers the construction risk and therefore the costs (goal A). Better understanding of the seabed also can lower health and safety risks from jacking up in dangerous conditions (goal E). This improvement can be incorporated in any new project and therefore can be used in projects commissioned before 2020. Improvements are coming from developers' growing experience rather than from a focused RD&D project.

Improvements in wind farm design software

Innovations in wind farm design software allow developers to optimise wind farm layout and technology choice based on multi-variable analysis, improving both the CAPEX and AEP from the wind farm and the efficiency of farm development. Diverse players such as universities (*e.g.*, DTU) and research and technology organisations (*e.g.*, NREL) are developing such systems for use by others, while large project developers such as E.ON have in-house solutions of varying levels of sophistication. This innovation also opens up new markets through more accurate cost-of-energy modelling (goals A and C). Progress is incremental, and early versions of software already have been used on projects with FID in 2015, although there is potential for further progress.

Wind farm development in 2030

For projects commissioned in 2030, spatial cost analysis and wind farm design tools will enable rapid and low-cost FEED and assessments of project economics before developers undertake significant site investigations. Detailed design iterations based on measurements likewise will be more effective in optimising the design of hardware and installation processes. Both construction contingencies and financing costs will decline as a result. There also will be increased focus on the design of energy system management and storage solutions that may drive solutions such as installing turbines with higher aggregate rating than that of the transmission system.

Greatest impact on LCOE

The greatest savings from innovations in this element in the period are anticipated to be from continued optimisation of wind farm layout design.

Wind farm development in 2045

The development of new wind farms commissioned in 2045 likely will be broadly similar to those commissioned in 2030, but with further optimisation. Based on deployment rates in the 2020s, it is anticipated that about 20% of wind farm development will be focused on the repowering of existing sites and will be undertaken in less than three years because developers will have a detailed understanding of site conditions and environmental impacts. In 2015, however, the assessment by developers of repowering, lifetime extension and other opportunities arising at the end of the nominal wind farm design life was only just beginning. Repowering is considered further in Section 5.8.

Supply chain opportunities and job creation

Innovations and market pressures are likely to lead to more experienced and better resourced development teams that can rapidly assess the economic viability of a site and its optimal design. Specialist companies likely will emerge to provide these services, and some developers will no longer need to sustain experienced teams in-house. In some cases, these companies will take on full EPC or EPCI contracts.

Table 13: Impact of wind farm development technologies, 2016-2030

CAPEX	OPEX	AEP	LCOE
-1.9%	-1.2%	1.1%	-2.3%

Note: The methodology is described in Box 1 and Appendix C.

Table 14: Impact of wind farm development technologies, 2031-2045

CAPEX	OPEX	AEP	LCOE
-1.0%	-0.9%	0.6%	-0.9%

Note: The methodology is described in Box 1 and Appendix C.

5.2 Turbines

This section describes innovations in offshore wind turbine technology. All of the innovations go through a demonstration phase, which for complete new turbines may be at a commercial development such as Gunfleet Sands 3 or a publicly supported demonstration site such as the onshore facilities at Hunterston in the UK operated by SSE, or at Østerild in Denmark operated by DTU.

Innovations

Introduction of innovative drivetrains

Several significant innovations were under development in 2015:

- Introduction of direct drive and mid-speed drivetrains,
- Introduction of continuously variable drivetrains, and
- Introduction of superconducting generators.

Direct-drive and mid-speed drivetrains have the potential to increase reliability by reducing the number of critical components. Examples are from the in-house private sector RD&D on mid-speed configurations by MHI Vestas and Adwen, and the direct-drive configurations developed by Siemens and General Electric (previously Alstom). Such innovation decreases the LCOE by increasing AEP (goal A). By reducing the number of turbine maintenance activities, the innovations increase health and safety (goal E). Early solutions were first incorporated in commercial-scale wind farms commissioned in 2015.

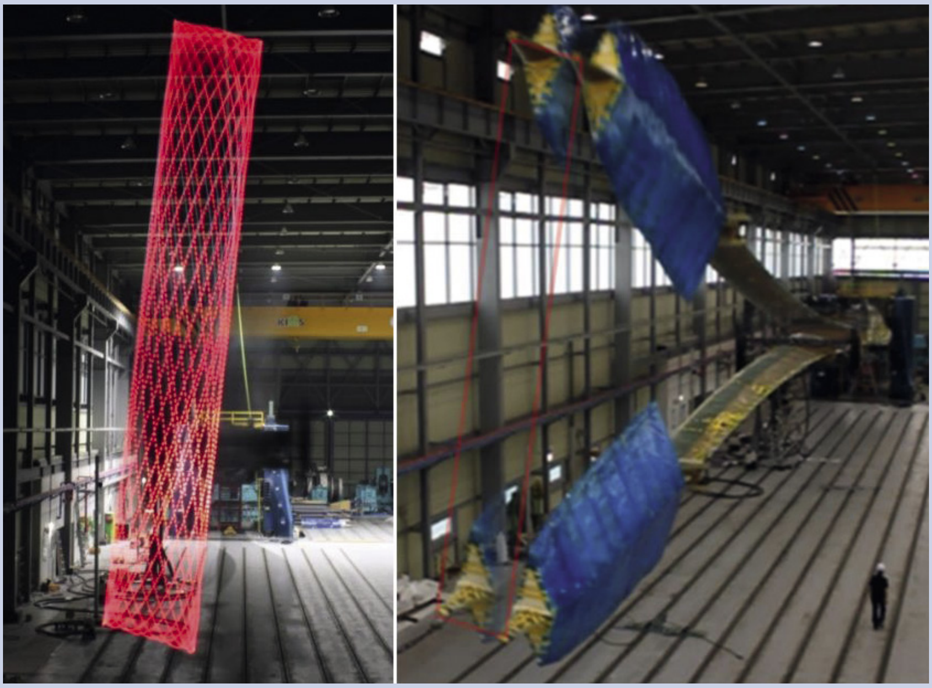
A continuously variable transmission involves a hydraulic or mechanical device that provides a variable ratio of input to output speed between the rotor and a synchronous generator. An example of this technology is the hydraulic system developed through in-house private sector research by MHI-owned Artemis Intelligent Power, which received UK government funding. This innovation removes the need for a power converter, as compliance and generator speed control is provided by the variable transmission device. This innovation reduces the cost of energy by reducing CAPEX and increasing AEP (goal A). Nacelle CAPEX is decreased by allowing the use of less expensive generators and avoiding the need for power convertors. AEP is increased through improved reliability. This innovation has the potential to be used in some of the next generation of offshore turbines that will be commercialised in the early 2020s.

A superconducting generator replaced traditional copper windings with wires with zero electrical resistance when cooled below a critical temperature. Technical advances in recent years have increased the critical temperature of wires to more than 77 degrees Kelvin, so that cooling can be achieved with liquid nitrogen. Further innovations are anticipated in the efficiency of the cooling system and its insulation. This innovation has been under development for some time by a number of companies – including AML, American Superconductor and General Electric – as part of in-house private-sector RD&D. This innovation reduces the cost of energy by reducing CAPEX and increasing AEP (goal A). Nacelle CAPEX is decreased through lower material use and by avoiding the high costs of rare-earth metals in permanent magnet generators. It increases AEP through greater efficiency in the generator. This innovation also enables the development of higher-rated generators than conventional gearbox or permanent magnet systems can achieve with the same size and weight. Superconducting windings can be used in a range of different generator concepts. This has the potential to be used in some of the next generation of offshore turbines that will be commercialised in the early 2020s.

Improvements in blade tip speed

As new wind turbine designs have been developed over the last 25 years, the speed of blade tips has remained relatively consistent, at between 70 m/s and 80 m/s, in order to control aerodynamic noise and erosion of the leading edge of blades. This has been achieved by slowing the rotor in proportion to the increase in rotor diameter. Offshore, there is less need to control aerodynamic noise, and there are cost-of-energy advantages in allowing an increase in tip speed to 90-100 m/s. This has the potential to increase AEP and reduce turbine CAPEX through reduced drivetrain torque loading, although some of this benefit is anticipated to be offset by increases in the support structure CAPEX (goal A). Increases in yield provide an opportunity to develop new markets with lower wind speeds (goal C).

Figure 33: Biaxial fatigue testing of a 56 m blade



Photograph courtesy of the Korean Institute for Material Science, n.d.

In 2015 increased erosion of the leading edge of blades offshore compared to onshore has been a major issue, even without significant increases in tip speed. Work is under way to develop new-build and repair solutions to address this, for example through private sector RD&D by 3M, Blade Dynamics (owned by GE), LM Wind Power and a range of newcomers to wind. A collaborative research partnership in this area is being led by the UK's Offshore Renewable Energy (ORE) Catapult. Designs with increases in tip speed have already been implemented, but further progression is likely to be incorporated into wind farms commissioned before 2025.

Improvements in hub assembly components

This innovation includes improved bearing concepts and lubrication, improved hydraulic and electric systems, improved back-up energy sources for emergency response and grid fault ride-through, and improved hub design methods and material properties. Much of this work is being carried out as in-house private sector research by the leading offshore wind turbine manufacturers and their key suppliers. Better design is anticipated to drive savings in turbine CAPEX and improved reliability, reducing unplanned OPEX and losses (goal A). This innovation can be incorporated into wind farms commissioned before 2025.

Introduction of new power take-off systems

This includes:

- Improvements in AC take-off systems, and
- Introduction in DC take-off systems

New AC take-off systems incorporate 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. Such strategies have been pioneered through private sector RD&D both by component suppliers, including GE, and by wind turbine manufacturers, including Gamesa. This trend is anticipated to continue and to deliver reductions in turbine CAPEX, unplanned service OPEX and losses (goal A). These benefits can be incorporated in wind farms commissioned in the early 2020s.

A DC take-off system eliminates the second half of the conventional turbine power conversion system that converts back to grid-frequency AC, saving capital costs and increasing reliability. Moving to DC collection also reduces the number of array cable cores from three to two and the material needed by 20-30%, which results in savings on array cable CAPEX.

General Electric has been researching this area in-house. Increased reliability drives a reduction of unplanned service OPEX and losses (goal A). The first commercialisation is likely to be in wind farms commissioned by 2025.

Improvements in blade design and manufacture

These improvements include:

- The enhancement of existing designs, including new aerofoil concepts and passive aerodynamic enhancements,
- Advanced tools and modelling techniques that improve aerodynamic performance, and
- Novel materials and manufacturing processes that give stiffer, lighter, lower-cost and higher-quality blades.

Early-stage private sector research, in many cases in collaboration with academic or research and technology organisation partners, has been carried out at most wind turbine blade suppliers and within their material supply chains for a long period, and a range of solutions already has been implemented, with more in development.

These innovations lower the cost of energy through better energy capture and lower CAPEX (goal A). By enabling larger rotors, they can stimulate new markets with lower offshore wind resource (goal C). These innovations have the potential for use in some of the next generation of offshore turbines that will be commercialised in the early 2020s.

Improvements in blade control

These improvements include:

- Improvements in physical methods of blade pitch control,
- The use of LiDAR to measure the wind flow approaching the turbine so that pitch and yaw angles can be adjusted to optimise energy capture and minimise loads, and
- The introduction of active aero control on blades, such as flaps, activated surfaces, plasma fields and air jet boundary level control to locally modify the aerodynamic performance of sections of the blade.

The opportunities to improve pitch control, including the use of LiDAR, were demonstrated by the UpWind project to establish the design limits and solutions for very large wind turbines (WindEurope, 2011). Theoretical modelling and practical trials also are underway. Generally, most collaborative projects (whether funded or not) involve a wind turbine manufacturer.

These innovations lower the cost of energy through better energy capture and better management of loads (goal A). These innovations have the potential to be used in some of the next generation of offshore turbines that will be commercialised in the early 2020s.

Increases in turbine rating

Developments in blade and drivetrain technology, as discussed above, will enable the development of larger turbines with higher capacity ratings. One area where there has been increased research as blades have become much larger is in modular blade technology, where different materials can be incorporated into blade components that eventually are assembled together, possibly closer to the wind farm site than was conventionally the case. Blade Dynamics (UK/USA, owned by General Electric), Modular Wind (no longer trading) and other larger players have taken in-house private sector research on modular blades to the practical demonstration stage, including with public RD&D support and facilitated by RD&D-enabling organisations such as the UK's Energy Technologies Institute.

These larger turbines are likely to have a higher CAPEX per MW of rated capacity than existing designs, but they will give a lower cost of energy through higher yields because of greater efficiency and reliability (goal A). The commercialisation of 10 MW turbines is likely to take place in the 2020s, and turbines with rated capacities of about 15 MW could be commercialised in the 2030s.

Underpinning research to improve turbine performance

Research undertaken in metallurgy (science of metals), tribology (the science of moving surfaces) and material science has the potential to improve component reliability. This includes academic research such as INSA de Lyon (France) and the universities of Southampton, Sheffield (UK) and Delaware (USA). It also includes research in research and technology organisations such as TWI (a private organisation formerly known as The Welding Institute) in the UK, and in-house research, for example by Nippon Steel (Japan), DSM (Netherlands) (materials), and Shell Global Solutions and Timken (USA) (tribology). This research can lower the LCOE through greater reliability leading to increases in AEP (goal A).

Research on wind turbulence can improve energy capture through developments in blade technology and control systems. This is particularly relevant for larger turbines for which the swept area interacts with the boundary layer. Research is being undertaken by research institutes such as the Energy Research Centre of the Netherlands (ECN) and the Lawrence Livermore National Laboratory and the NASA Jet Propulsion Laboratory (both USA). This research could lead to a lower LCOE through greater reliability and more efficient energy capture leading to increases in AEP (goal A).

Development of strategies to mitigate storm damage

Ten years ago Mitsubishi developed yaw system control strategies and back-up power supplies for onshore wind turbines to reduce the chance that, even with the loss of grid power, rotors do not remain in orientations where they could experience excessive loads. Other turbine manufacturers, such as Vergnet (France), have developed solutions where the tower, rotor and nacelle are tilted to the ground to avoid the worst storms. Such systems have been commercialised to date only at a smaller scale and in onshore applications. Such types of innovations will be needed to enable offshore wind developments in new countries that experience regular storms (goal C). An example is the Sandia National Laboratory-led Segmented Ultralight Morphing Rotor project in the United States.

Relevant also to all offshore wind farms that have times of operation around conventional high-wind cut-out wind speed for wind turbines are control strategies to increase the operating envelope and smooth the transition between operation and standby. Such measures increase energy production and improve grid stability.

New turbine configurations

This innovation includes the development of downwind and/or two-bladed turbines.

Downwind turbines do not require as stiff blades as upwind designs, due to decreased issues with tower clearance, which lowers the cost of larger rotors (goal A). Downwind turbines also may be better suited for regions with typhoons, where conventional turbines are more likely to see high winds from more damaging orientations. Hitachi (Japan) has developed such a turbine as part of in-house private sector research for the Japanese market (goal B).

Two-bladed rotors offer a lower cost of energy by reducing the material cost without a proportionate energy capture penalty (goal A). Obstacles to their use onshore has been the increased noise from faster tip speeds and greater visual intrusion, but these issues are less relevant offshore. 2-B Energy (Netherlands) has developed a two-bladed, downwind turbine for the offshore market and installed an onshore prototype in 2015. Other two-bladed turbines in development are Ming Yang's (China) 6.5 MW platform (downwind) and Envison's (China) 3.6 MW platform (upwind),

These new turbine configurations have the potential to be commercialised in the early 2020s.

Wind turbines in 2030

Offshore wind turbines in 2030 probably will have diverged further from their onshore counterparts, and offshore products will have been developed for different markets, including downwind and two-bladed models. Power take-off systems are likely to have been developed to meet the demands of HVDC-integrated international grids.

Greatest impact on LCOE

The greatest savings from innovations in this element in the period 2016-2030 are anticipated to be from the

Table 15: Impact of wind turbine technologies, 2016-2030

CAPEX	OPEX	AEP	LCOE
-4.5%	-27%	7.7%	-13%

Note: The methodology is described in Box 1 and Appendix C.

Table 16: Impact of wind turbine technologies, 2031-2045

CAPEX	OPEX	AEP	LCOE
-1.9%	-16%	2.0%	-3.5%

Note: The methodology is described in Box 1 and Appendix C.

use of larger and more reliable turbines, with improved aerodynamic performance.

Wind turbines in 2045

Offshore wind turbines in 2045 likely will include further evolutions of current configurations. Increases in rated capacity will continue towards 20 MW. Turbine design lifetimes will extend to about 30 years.

Supply chain opportunities and job creation

Supply chain opportunities will be for technology companies offering solutions that enable the commercialisation of novel drivetrains, power electronics and control systems.

Although offshore wind combines cost-effective electricity production with a higher level of job creation than in many related sectors, there will be a reduction in the number of jobs per MW constructed as economies of scale are reaped and because larger turbines will reduce the number of units per MW. Longer design lives will reduce the number of jobs in manufacturing but will sustain the number of jobs in OMS.

5.3 Foundations

This section describes innovations in bottom-fixed foundation technology. Floating foundations and their impact are discussed in Section 5.8.

Innovations

Improvements in design and design standards

Industry analysis at the start of the decade predicted that monopiles would be uncompetitive compared to jacket structures in water depths of more than 25 m with turbines with a rated capacity of 5 MW or more. Since then, however, there has been strong innovation in design, manufacturing processes and installation tooling so that monopiles are now expected to remain cost-competitive with larger turbines in water depths of even over 35 m. Monopile design now is considered to be largely optimised, but evolutionary improvements through in-house, private sector RD&D by developers and design consultancies are still anticipated for the transition-piece connection and the cable entry and termination.

As jacket designs become more commonly used for projects in deeper water, larger turbines and early price reduction, there is greater scope for more radical improvements in designs. For example, there is likely to be a trend towards the use of three-legged, rather than four-legged, designs.

For both monopiles and jackets, developers are anticipated to take a more holistic approach to the combined foundation/tower structure, rather than having different designers working independently. For example, some developers already are planning to take the tower out of the turbine supply contract to facilitate a more holistic approach (as well as to eliminate the turbine manufacturer's margin on the tower).

There also is room for further improvement in the modelling of pile-soil interaction (especially for monopiles) and in modelling the lifetime fatigue and extreme loads due to the combination of wind and wave loading. For example, the Pile Soil Analysis (PISA) joint industry project, led by Dong Energy (Denmark) and run through the Carbon Trust OWA (UK), is developing improved design methods for laterally loaded monopiles, using numerical finite element modelling that is validated through large-scale field tests. Modelling in this area already has led to the development of a shorter length pile in China, with lateral fins to increase stiffness in some ground conditions.

It is anticipated that design standards established for other sectors will be evolved further to be more applicable for offshore wind structures.

These improvements will lead to CAPEX reductions through savings in steel content and in reducing installation time through streamlined cable pull-in and termination (goals A and E). For jackets, improved designs also will reduce installation costs by enabling more units to be carried on installation vessels at a time. These impacts are anticipated to benefit wind farms commissioned in the early 2020s, as part of ongoing progress in foundation design.

Jacket foundation manufacturing

New fabrication facilities are being developed that are designed for the serial fabrication of jacket foundations. This includes more advanced handling and welding equipment and the capability to pre-fabricate nodes. For example, Polish Bilfinger Mars Offshore (Poland) and steel company Salzgitter (Germany) are developing an automated welding robot that, once it becomes operational in 2016, will be able to produce up to three nodes per shift.

More activity also may take place away from the main fabrication facility, with the modular assembly of sections by sub-suppliers or the pre-painting of tubulars.

These developments are anticipated to reduce support structure CAPEX through higher factory volumes and to reduce OPEX by increasing reliability (goal A). They also have the potential to open up markets for deepwater projects up to 50-60 m that were not economically viable in 2015 (goal C). These impacts are anticipated to benefit wind farms commissioned in the early 2020s.

Introduction of suction bucket technology

A number of foundation concepts involve the piled seabed connection being replaced by a suction bucket that is drawn into the seabed by a combination of the foundation's own weight and applied hydrostatic pressure. The structure can be vertically aligned during installation. The concept can be used with both monopod and jacket-type structures, but only with certain seabed conditions. For example, suction bucket technology cannot be deployed at sites that have rocky seabeds or a high probability of subsurface boulders.

The development costs typically are higher than for a piled foundation because of the need for more detailed site investigations. Fabrication costs are higher than for a conventional piled foundation because of the welding needed in the suction bucket. These costs are offset by faster installation using a lower-cost vessel (goal A). The installation process also is quieter than pile driving, which reduces environmental impact (goal D). Commercial deployment of suction bucket foundations is anticipated for projects commissioned in the early 2020s.

The Danish company Universal Foundation has deployed three suction bucket monopods with meteorological stations in UK and Danish waters and has undertaken extensive soil measurement campaigns within two UK Round 3 zones in anticipation of commercial deployment. The developer DONG Energy also has installed a demonstrator jacket foundation with suction buckets, as well as a 3.6 MW turbine in one of its German projects, and is undertaking a comprehensive monitoring process to assess the potential to deploy on a commercial scale.

Introduction of self-installing gravity base foundations

Self-installing gravity base foundations are either concrete structures or concrete-steel hybrids. Their introduction reduces the cost of installation because they can be towed to site using standard tugs and then positioned and installed without the use of costly heavy-lift installation vessels. Decommissioning is less expensive as it involves only the reversal of the installation process.

There have been significant levels of in-house self-funded research on computer modelling the performance of these designs, focusing particularly on the transit to site and installation. There also has been extensive tank testing with research facilities such as DHI Ballast Water Centre (Denmark) and Deltares (Netherlands). The first offshore wind self-installing gravity base foundation was deployed with a meteorological station in 2015 off the French coast in the English Channel.

These foundations deliver savings on support structure and installation CAPEX (goal A). The technology has health and safety benefits from reducing the need for offshore lifts (goal E). Commercial deployment of buoyant foundations is anticipated to occur for projects commissioned in the early 2020s.

The commercial development of these foundation designs also will support progress in integrated foundation and turbine installation, as discussed in Section 5.5.

Foundations in 2030

In 2030, monopiles are likely to retain a significant share of the market, although this will decline from a share of about 90% in 2016 as innovations enable their use in deeper water and with higher capacity turbines. By this point, the industry will have settled on a limited number of standardised jacket designs that are optimised for serial manufacture and installation. Alongside these piled designs, suction bucket and gravity-based foundations likely will be used more widely as these technologies are deployed at a commercial scale and as investors become more comfortable with the new designs.

Greatest impact on LCOE

The greatest savings from innovations in this element in the period 2016-2030 are anticipated to be due to improvements in holistic design of existing concepts, with the possibility of self-installing (crane-less) solutions.

Foundations in 2045

In 2045, it is likely that monopiles will remain the most cost-effective option for shallow-water sites (particularly when repowering early projects). For deeper-water sites, it is likely that developers still will be using a mix of piled jackets, suction bucket designs and gravity base foundations. It also is possible, however, that there is greater progress in one particular design type. In this case, the supply chain will consolidate and there will be greater opportunities for economies of scale.

Supply chain opportunities and job creation

There will be supply chain opportunities for companies that can develop more efficient manufacturing processes that increase production rates and reduce the need for costly manual welding. The production of concrete gravity base foundations typically supports higher levels of employment than steel designs and requires less highly skilled labour.

Table 17: Impact of foundation technologies, 2016-2030

CAPEX	OPEX	AEP	LCOE
-2.5%	-0.3%	0.0%	-1.7%

Note: The methodology is described in Box 1 and Appendix C.

Table 18: Impact of foundation technologies, 2031-2045

CAPEX	OPEX	AEP	LCOE
-0.6%	-0.1%	0.0%	-0.4%

Note: The methodology is described in Box 1 and Appendix C.

Case study: German RD&D funding

RD&D funding in Europe has been important for offshore wind, but the majority of expenditure has been by the industry itself, in particular by turbine manufacturers, driven by the size of the market. Major initiatives have included the Alpha Ventus demonstration project in Germany, which attracted about 15% grant funding from the German government. Linked to this was the Research Alpha Ventus (RAVe) programme co-ordinated by Fraunhofer IWES, which received EUR 50 million over seven years. Other public funding in Germany has been aimed mainly at the academic sector. The view in Germany, as in most other countries, is that RD&D funding can be important as a catalyst for activity, but it cannot replace the RD&D activities of the industry itself, nor can it take the place of a strong market for offshore wind.

5.4 Electrical interconnection

This section describes innovations in electrical interconnection, relating to both array cables (excluding installation) and transmission to shore (including installation).

Innovations

Improvements in array cable standards and client specification

There is an opportunity to reduce cable costs by choosing the most suitable cable core size, insulation thicknesses and mechanical protection for the site conditions. There are two issues:

- That developers ask for a cable specification higher than industry standard, and
- That aspects of the standards themselves are unnecessarily onerous.

Small increases in development cost are anticipated to be offset by larger savings in array cable CAPEX and savings on installation CAPEX (goal A). There already is progress towards incorporating this into new projects, and this has been achieved with a more collaborative relationship between developer and supplier.

Introduction of AC array cables with higher operating voltages

The introduction of array cables with higher operating voltages means that capacity can be increased and electrical losses can be reduced. Studies have proved the feasibility of increasing the operating voltage of wet cable designs to close to 66 kV. In 2015 a practical study in the UK led by JDR Cables, funded by the UK Department of Energy and Climate Change (DECC) and the Carbon Trust OWA, showed a significant benefit for 66 kV. The OWA subsequently funded JDR Cables (UK), Prysmian (Italy HQ) and Nexans (France HQ) to help commercialise their designs.

As the industry moves towards turbines with higher power ratings, the need for higher-capacity array cables becomes more critical to minimise the total array cable length and the number of substations required. For example, it is feasible to accommodate only 40 MW (or five 8 MW turbines) on a 33 kV string of 630 mm^2 copper cable, while it is possible to increase this to 80 MW (ten 8 MW turbines) on a 66 kV string using the same conductor size.

The innovation leads to a lower cost of energy from reduced array cable cost (goal A). This innovation is likely to be available for projects commissioned by 2020.

Development of AC transmission over longer distances

For projects commissioned before 2018, grid connections greater than between about 80 km and 150 km require an HVDC system to avoid high losses due to reactive resistance in export cables. The higher cost of HVDC transmission and concerns about the reliability of the convertor stations and lead times for delivery have driven the development of HVAC alternatives, such as the following:

- Intermediate reactor stations that restore current and voltage phases, such as the solution developed through private sector RD&D by Dong for the UK Hornsea 1 project

- Low-frequency transmission, which has been the subject of academic research (for example at DTU in Denmark) and has the benefit of reducing the capacitive effects of the export cable for a given power rating, and
- Higher voltage cables, which have lower losses for a given power rating. Manufacturers such as Nexans and Prysmian had designs at higher voltages in 2015, but the adoption of these in offshore wind farms is likely to be incremental. Development to 400 kV will result from manufacturing advances in cleanliness, pellet production and extrusion; improvements in cable design; and better material selection. This will lead to weight reduction and easier installation. RD&D is undertaken in-house by the principal manufacturers such as Prysmian at its High Voltage and Research Laboratory located in Eastleigh, UK. RD&D enabling by CIGRE (the Council on Large Electric Systems) will be significant in sharing best practice and standards. Export at 400 kV also offers a reduction in onshore electrical infrastructure.

These innovations lead to lower cost transmission (goal A) and can open up new markets where sites with high wind resource are located far from shore (goal C).

The first of these innovations are anticipated to be commercialised in projects commissioned in the early 2020s.

Developments in substation installation

HVAC substations typically are lifted onto their foundations using a heavy-lift vessel that is either costly or highly weather sensitive. Also, few vessels are available, which may have an impact on project schedules. Options to overcome these challenges are:

- Modular structures so that the individual lifts can be undertaken by a vessel with a lower crane capacity, and
- Float-over, gravity base or floating designs that eliminate the need for an offshore heavy lift.

These innovations can reduce the LCOE through lower installation CAPEX (goal A). Modular substations already have been installed. Other innovations in substation installation can be commercialised by 2020.

Reduced need for independent substation platforms

For projects exceeding 100 MW and commissioned before 2018, both HVAC and HVDC systems have used an independent offshore substation platform. Innovations are under development that enable the use of selected turbine transition pieces to house electrical hardware, thereby reducing the need for separate platforms. For example, in-house RD&D by Siemens proposes two smaller wind farm level substations rated at about 250 MW (rather than one at 500 MW), which can be mounted on a turbine jacket (Siemens, 2011). This arrangement also reduces the complexity of the switchgear and auxiliary systems. Siemens states that the concept can reduce overall weight by one-third and cost by 40%.

For HVDC systems, this eliminates the need for separate HVAC collector stations. This lowers not only the fabrication costs but also the installation costs because the lift can be undertaken by a lower-cost and/or less weather-sensitive vessel (goal A). For HVDC systems, the innovation increases opportunities for grid integration (goal B) and opens up new markets where sites with high wind resources are located far from shore (goal C).

Modular HVAC systems are anticipated to be commercialised in projects commissioned before 2020. Modular HVDC systems are anticipated to be commercialised in projects commissioned in the early 2020s.

For export cable installation, the main problem has been the inshore section and beach landing. A shallow draft vessel lays the cable as far as it can towards the landing point, and the remaining length is pulled ashore from the beach landing into a ploughed trench. Difficulties have been encountered because of the range of soil types in coastal areas. Improvements to this trenching process are under way, for example using IHC's Hi-Traq cable tractor. These can be incorporated into projects reaching FID before 2020.

Improvements in grid integration

Examples of RD&D activity that can support the development of grid integration (goal B) include:

Figure 34: Small-scale demonstrator of underwater compressed-air energy storage system

Source: EMEC, 2011

- Electrical components. This includes research into improved chemical batteries and capacitors with reduced charging and discharging times, and performance loss after repeated cycles. Much of this is undertaken though in-house research and in collaboration with academic researchers. Key companies in the utility-scale application market are NGK Insulators (Japan), NEC Energy (USA) and LG Chem (Republic of Korea). Commercial use of these components is anticipated to take place in the early 2020s. In addition to supporting grid integration, they can reduce the LCOE through lower CAPEX and higher AEP as a result of lower losses (goal A).
- Semiconducting and superconducting materials. Incorporation of these materials in electrical interconnections will eventually reduce the costs and losses in electrical transmission systems. This RD&D undertaken, for example in-house by companies such as AMSC and through collaborative research also involving academic research and research and technology organisations, such as the EU-funded SUPRAPOWER and INNWIND.EU projects. Commercialisation can take place in the late 2020s. In addition to supporting grid integration, they can reduce the LCOE through higher AEP as a result of lower losses (goal A).
- Energy storage. Research into marine energy-specific energy storage solutions is under way, such as the academic work being developed by the University of Nottingham (UK) and by Canadian start-up Hydrostor. Commercialisation is unlikely before 2030. Such storage systems may not decrease the LCOE directly but could lower system cost by reducing the cost of grid balancing. Energy storage and energy system management solutions not designed specifically for offshore wind are developing rapidly.

Electrical interconnection in 2030

In 2030, AC systems all will probably be designed without a separate substation platform. Export voltages will have increased to at least 275 kV. In 2030, HVDC circuit breaker technology is expected to be available and cost-effective for the industry. The first HVDC nodes will therefore be in operation connecting offshore HVDC substations to the first elements of international or interstate HVDC supergrids. It also is likely that some small-scale offshore energy storage facilities are connected to wind farms. Non-offshore wind-specific energy system management and energy storage systems will be relatively commonplace.

Greatest impact on LCOE

The greatest savings from innovations in this element in the period 2016-2030 are anticipated to be from the avoidance of independent substation platforms.

Table 19: Impact of electrical interconnection technologies, 2016-2030

CAPEX	OPEX	AEP	LCOE
-2.1%	-7.2%	1.3%	-3.6%

Note: The methodology is described in Box 1 and Appendix C.

Electrical interconnection in 2045

New wind farms may operate with DC throughout, with subsea DC hubs and subsea transmission networks linking different wind farms and national onshore grids. Fully integrated supergrids will be operational, and repowered wind farms will be built with HVDC nodes connecting clusters of wind farms exporting at HVAC or HVDC. Superconducting materials may be used in some high-power export cables, requiring also the use of cryocoolers and associated pumping technology. Offshore energy storage is expected to be commercially deployed at large scale on some projects in 2045 as a means of enabling higher renewables grid penetration, although offshore-specific solutions are likely to lag behind generic solutions applicable to other energy generation technologies.

Supply chain opportunities and job creation

Innovations that reduce the LCOE typically will be developed in-house by established tier 1 suppliers and are likely to create only limited opportunities for new suppliers. Innovations in grid integration will be commercialised through collaborative partnerships between manufacturers and the grid operators of different countries.

Much of the opportunity for cost reduction comes from lowering the amount of infrastructure needed to support offshore electrical interconnection. This is likely to reduce the demand for large fabrications which are relatively labour intensive. The natural consequence of reducing the LCOE, however, is also an increase in market opportunity, thereby increasing total employment opportunities.

5.5 Installation

This section describes innovations in offshore wind installation technology. All of the innovations described below achieve savings through more rapid installation. As well as reducing CAPEX, they have the potential to reduce the cost of finance through earlier commencement of generation.

Innovations

Introduction of high-wind-speed blade installation

Offshore turbine lifts are highly sensitive to wind speed, which limits the weather window for offshore installation. Innovations use either a yoke or a crane hook to stabilise the blades during installation. One example is the Boom Lock being developed by High Wind (Netherlands), a commercial collaboration between several engineering and offshore contractors, which has been deployed on a small project. In-house private sector RD&D also has been undertaken by Liftra (Denmark) and Siemens. These technologies aim to increase maximum blade lifting wind speeds from about 11 m/s to about 16 m/s. Improvements much above 16 m/s are unlikely because deck working conditions could become hazardous.

Table 20: Impact of electrical interconnection technologies, 2031-2045

CAPEX	OPEX	AEP	LCOE
-1.0%	-4.6%	0.6%	-1.3%

Note: The methodology is described in Box 1 and Appendix C.

These innovations reduce installation cost and reduce health and safety risk (goals A and E). Commercialisation is starting to take place now.

Introduction of optimised installation vessels

Most vessels used for installing space frame foundations are jack-ups, which usually only have enough deck space to carry two structures. Innovative vessel designs introduce larger decks with optimal layouts for space frame stowage and handling. Additional innovations in vessel design eliminate the need for jack-up systems for foundation installation. A2SEA (Denmark) and Jumbo Offshore (Netherlands) have developed innovative vessel designs as part of in-house RD&D, although none has been built.

These innovative vessel designs reduce installation cost and reduce health and safety risk (goals A and E). Commercialisation is anticipated to occur before 2025.

Introduction of quiet-piling technology

Subsea pile driving generates underwater noise that can adversely affect wildlife, especially marine mammals. Innovative solutions are being developed that either:

- Mitigate the impact of conventional piling by using a “bubble curtain” or “sleeve”, or
- Produce less piling noise, typically through the use of vibration piling technologies.

The bubble curtain concept has been tested at the Alpha Ventus demonstration project as part of a collaboration between the ForWind programme at Leibnitz University (Germany) and Fraunhofer IWES (Germany). A sleeve is being developed through in-house private RD&D by W3G Marine (UK).

A prototype vibro-piling tool has been developed and deployed as part of in-house private sector RD&D by Cape Holland (Netherlands). The Carbon Trust OWA collaboration supported the testing of a vibro-piling tool developed through in-house private sector RD&D by Piling & Vibro Equipment in the Netherlands.

These innovations reduce impact on marine wildlife, which in turn enables an extended installation season and reduces installation cost (goals D and A). These innovations also enable installation on more sites (goal C). Vibro piling also reduces the forces on the pile and therefore can result in lower fabrication costs (goal A). Commercialisation of some innovations is starting to take place, and most will be available before 2020.

Introduction of quick-connect array cable installation

The process of connecting array cables to the turbines and the offshore substation is time-consuming and expensive because each core in the cable must be connected on-site and out of the water. Quick-connect cable terminations are being developed to complete cable connections in a simplified manner, including in the water. The Energy Technologies Institute (UK) provided funding to MacArtney (Denmark) to develop a prototype 11 kV quick-connect cable termination as part of its collaborative RD&D programme. Development of this so-called WetMate connector has been targeted mainly at wave and tidal arrays, but serial production could make them a viable technology for offshore wind.

Less radical solutions to speed up existing activities have been developed through in-house private RD&D. Dong Energy has developed a concept involving the pre-termination of cable lengths.

Such innovations reduce the cost of cable installation and reduce health and safety risks by reducing the number of offshore operations (goals A and E). Commercialisation is anticipated by 2025.

Development of integrated turbine installation

Several offshore installation operations can be eliminated by assembling and pre-commissioning wind turbines in a harbour and installing the complete, integrated turbine (including rotor and tower) in a single operation offshore. In this case, the foundation is pre-installed. Huisman (Netherlands), W3G Marine (UK) with IHC Merwede (Netherlands), and others are developing integrated turbine installation solutions. An obstacle to development has been concerns that during transit the nacelle would exceed acceleration limits, particularly for pitch and roll from the installation vessel. Some work has been done, but further collaborative RD&D leading to demonstration involving a developer, a naval architect, vessel operator and a turbine manufacturer would be valuable.

These innovations reduce installation cost and reduce exposure to health and safety risks (goals A and E). Commercialisation is anticipated before 2025.

Integrated foundation and turbine installation

A further innovation to integrated turbine installation is to install the turbine and the foundation together. In this innovation, the combined turbine-foundation structure is towed to site by a bespoke vessel or tugboats. This innovation can be applied to bottom-fixed or floating systems. Principle Power (USA) has demonstrated this innovation for a floating foundation prototype. TYPSA (Spain) has demonstrated this innovation for a bottom-fixed meteorological mast. Concepts were developed by Ramboll (UK), BMT Nigel Gee (UK) and Freyssinet (France) (with a concrete gravity base) and by SPT Offshore (Netherlands) (with a suction bucket jacket) as part of a Carbon Trust OWA collaboration. The Austrian company Strabag and the UK company Ocean Resource also have developed integrated gravity base concepts. None of these three concepts had progressed to prototype by the end of 2015. Commercialisation is likely to need collaborative RD&D involving a turbine manufacturer and public funding for demonstration.

These innovations reduce installation costs, enable installation in regions with limited marine infrastructure, reduce environmental impacts during installation and reduce exposure to health and safety risks (goals A, C, D and E). Commercialisation is anticipated before 2025.

Greater onshore turbine pre-commissioning

Turbine manufacturers such as MHI Vestas and Siemens have developed their designs for next-generation turbines so that more of the turbine commissioning process can be undertaken onshore before the turbine is installed offshore. Access to the installed turbines offshore is sensitive to the weather, and time is lost in vessel transit. This innovation reduces the LCOE through lower commissioning costs and by enabling earlier generation (goal A). It also reduces offshore work and therefore reduces exposure to health and safety risks (goal E).

Installation in 2030

In 2030, offshore wind farm installation is likely to be completed using a quarter of the offshore person-hours currently required. Entire systems, from blade tip to seabed, are likely to be assembled and pre-commissioned in protected harbours using a land-based workforce. Savings in person-hours will result from eliminating transit time and weather downtime, as well as from the relative ease of completing operations in an onshore environment. Offshore crews are likely to work during expanded weather windows with less health and safety risk.

Greatest impact on LCOE

The greatest savings from innovations in this element in the period are anticipated to be due to optimisation of vessels, especially in increasing the operating envelope and more onshore pre-commissioning, with the possibility of integrated crane-less foundation and turbine installation.

Installation in 2045

In 2045, installation operations are likely to benefit from maritime cross-over technologies such as autonomous ships. In combination with integrated foundation and turbine installation methods, autonomous installation vessels can greatly reduce the need for people to work offshore. Most offshore lifting activities are likely to be crane-less, and port logistics bases will look more like a larger version of today's sophisticated consumer product distribution centres.

Supply chain opportunities and job creation

Incremental developments in existing installation methods are likely to be led by the current major

Table 21: Impact of installation technologies, 2016-2030

CAPEX	OPEX	AEP	LCOE
-2.2%	0.0%	0.0%	-1.5%

Note: The methodology is described in Box 1 and Appendix C.

Table 22: Impact of installation technologies, 2031-2045

CAPEX	OPEX	AEP	LCOE
-1.4%	0.0%	0.0%	-0.6%

Note: The methodology is described in Box 1 and Appendix C.

installation and EPCI contractors, often in partnership with offshore engineering companies. Radical new installation methods are most likely to be developed by new suppliers and are most likely to succeed if undertaken in partnership with component suppliers.

LCOE reductions through efficiency savings are likely to be achieved with fewer jobs per MW, potentially having a negative effect on employment. The natural consequence of reducing the LCOE, however, is also an increase in market opportunity, thereby increasing total employment opportunities. Reductions in LCOE also can be achieved through earlier generation, .This reduces the cost of finance by reducing the time between expenditure and income. In this way, in some cases LCOE savings can be achieved even with increases in CAPEX and jobs/MW. This is because the cost of finance benefit of a shorter installation programme can outweigh increases in costs.

5.6 Operation, maintenance and service

This section describes innovations in operation, maintenance and service (OMS) technology.

Innovations

Improvements in weather forecasting and analysis

Improvements in weather forecasting increase the efficient use of staff and vessels and reduce lost energy production by maximising activity during weather windows. This requires advances in the accuracy and the granularity of forecasts. Currently, accuracy drops significantly for forecasts beyond five days ahead for an area of approximately 100 km^2. To make the most efficient use of resources and especially of heavy equipment such as jack-up vessels, reasonable accuracy needs to be extended to 21 days. Significant efforts are being made globally through research and technology organisations such as the UK Meteorological Office to improve long-range forecasting.

Related RD&D is in interpreting weather forecasts in a more sophisticated way. Wind speed and significant wave height are not precise indicators of offshore workability. In-house private RD&D, for example by the marine consultancy ABPMer (UK), is under way to build models that accurately forecast weather windows.

Improvements in weather forecasting and analysis can reduce the cost of energy by enabling better planning of maintenance schedules, leading to less downtime and therefore greater energy production, and more efficient use of vessels and personnel (goal A). By scheduling work during better weather there is also a potential health and safety benefit (goal E).

Continuing improvements in forecasting technology have been benefiting projects for decades, and further RD&D will have a big impact in future.

Introduction of turbine condition-based maintenance strategies

In the past, maintenance has relied on a time-based schedule of planned activities. In contrast, condition-based maintenance targets activities to reflect the risk of failure based on operating experience. This is likely to become increasingly sophisticated. New and improved prognostic and diagnostic systems and processes allow operators to maximise turbine energy production and to minimise unnecessary maintenance interventions. These tools are being developed in-house by turbine manufacturers such as Vestas and by third-party service providers such as Romax (UK). Operators such as E.ON (UK/Germany), Scottish Power (UK) and Vattenfall (Sweden) have developed in-house models using SCADA and other condition-monitoring data to pick up trends in turbine performance to prioritise maintenance schedules.

Innovations are expected to reduce OPEX, and increases in yield are likely to more than offset a small increase in turbine CAPEX by targeting maintenance on key issues and better watching for changes in system behaviour, leading to a lower cost of energy (goal A). By scheduling work during better weather there is a potential added health and safety benefit (goal E). In some cases, condition-based maintenance may increase the amount of planned (preventative) maintenance in order to reduce the amount of unplanned service and reduce overall OPEX. In other cases, reducing the amount of planned maintenance can be carried out without increasing risk, for example by increasing times between hydraulic oil or hose changes should these items be shown still to be in good condition.

Significant benefit from innovations in this area is anticipated for projects commissioned in the early 2020s, although incremental progress will be ongoing.

Improvements in OMS strategy for far-offshore wind farms

In 2015, OMS strategies for wind farms more than 50 km from shore are still evolving. A small number of SOVs with accommodation for about 50 technicians, office space, workshops and welfare facilities have entered the market, with Siemens pioneering their use. Dock facilities, stores and loading, and walk-to-work personnel access systems can allow these vessels to support a number of daughter vessels. This has been a significant strand of work for the Carbon Trust OWA. Fixed offshore bases may become cost effective for some projects. Fred Olsen (Norway) announced in 2015 the Windbase concept which combines accommodation facilities linked to a helideck and a substation.

Further optimisation of SOV use is anticipated, with their application at some sites currently using an onshore maintenance base.

Reductions in the cost of energy are anticipated to come from significant OPEX savings (goal A). Improvements to health and safety systems may enable working at all times. New strategies can open up new markets by improving the economic viability of sites with high wind resources far from shore (goal C).

Innovations can benefit wind farms commissioned by 2020, and further improvements are anticipated by 2030.

Improvements in personnel transfer and access

Improved PTVs can deliver crews in larger numbers and greater comfort, maximising technician productivity on arrival. These vessels also can have greater payload capacities, transporting a greater stock of material and tooling. Significant RD&D has taken place in-house and through collaborative programmes such as the Carbon Trust OWA and Dutch consortium TKI Wind op Zee. Industry anticipates improved staff and knowledge retention as working conditions improve.

The use of larger, more capable SOVs and PTVs fitted with systems such as heave compensated walkways or lifting pods will allow safe transfer of technicians to turbines in wave conditions of up to 2.5 m significant wave height. On a typical North Sea site, this innovation can increase accessibility from about 70% to 95%. The Carbon Trust OWA and the Netherlands' TKI Wind Op See are examples of collaborative programmes that involve companies such as Fjellstrand (Norway), GustoMSC (Netherlands) and Umoe Mandal (Norway).

It is anticipated that these innovations will lower the cost of energy by lowering the cost of both planned and unplanned OPEX and reducing availability losses (goal A). They have the potential also to improve health and safety (goal E).

Alternatives to rigid vessel-turbine connection are overhead wire-and-gondola systems that eliminate the need for a rigid connection between the vessel and the turbine. These have been developed by collaborative research programmes such as by the US DOE, the US Navy and Lockheed Martin (USA).

Projects commissioned before 2020 can benefit from RD&D in this area, and benefits are anticipated to be almost fully available for projects commissioned before 2025.

Introduction of remote and automated maintenance

Most wind farm maintenance in 2015 was undertaken onsite by technicians. Automated and remote

Table 23: Impact of OMS technologies, 2016-2030

CAPEX	OPEX	AEP	LCOE
0.3%	-6.3%	2%	-2.5%

Note: The methodology is described in Box 1 and Appendix C.

maintenance systems are developing rapidly in other sectors and are being adapted to use in offshore wind. A significant area of development is aerial inspection of blades using drones. This is being undertaken in-house by companies that specialise in developing or operating aerial inspections for other industries, such as Cyberhawk (UK). RD&D enabling, for example by the ORE Catapult (UK), is also seeking to encourage work in this area.

Innovations can reduce the cost of energy through lower personnel costs and potentially through lower downtime if the technologies' operating window is greater than the current approaches (goal A). They are likely to have a significant impact on health and safety if technologies reduce the number of wind farm visits by technicians and eliminate the need to work at heights for blade inspections and repair in particular (goal E).

Introduction of wind farm-wide control strategies

The development of more holistic control strategies using systems able to measure residual useful life and understanding of the income drivers can provide multi-objective optimal control of (and decision making for) wind farms to minimise the LCOE. Effective RD&D will take place collaboratively with turbine manufactures and operators, and potentially with consultancies or research and technology organisations such as ECN that are developing control algorithms. This innovation will slightly increase wind farm CAPEX but is anticipated to reduce unplanned OPEX and losses and to increase AEP (goal A). This can be incorporated into wind farms commissioned in 2020, but further LCOE reductions will happen well into the future.

OMS in 2030

As the number of wind farms within a region increases, they can better share equipment and infrastructure. This is likely to include SOVs, fixed platforms or turbine maintenance jack-up vessels. The number of technicians per installed MW is likely to decrease significantly with the development of still larger and more reliable turbines and enhanced remote monitoring, prognostics, logistics and online documentation, enabling a higher fraction of failure to be fixed on first visit and before there are any impacts on other components.

Wind farm control strategies are anticipated to both improve reliability and increase energy production.

Owners are anticipated to give significant attention to life extension of turbines and generating asset balance of plant, as a way of reducing the LCOE.

Greatest impact on LCOE

The greatest savings from innovations in this element in the period are anticipated to be from the implementation of condition-based maintenance, linked to wind farm-wide control strategies and the further development of personnel systems, including via the use of SOVs.

OMS in 2045

For wind farms commissioned in 2045, most OMS work will be planned, condition-based maintenance, rather than unplanned service. Most service work on larger components will be proactive repairs, rather than reacting to failures after they have occurred.

As floating wind farms farther from shore become more widespread, onshore OMS strategies are anticipated to be replaced in some areas by fixed or floating service hubs to which turbines can be towed for major repairs.

Supply chain opportunities and job creation

OMS strategies are still evolving and the supply chain is immature. There is considerable scope for

Table 24: Impact of OMS technologies, 2031-2045

CAPEX	OPEX	AEP	LCOE
0.1%	-3.1%	0.9%	-0.8%

Note: The methodology is described in Box 1 and Appendix C.

new companies to enter the sector if they can offer cost-of-energy reductions, including via risk-reducing measures. Turbine manufacturers are likely to continue to drive innovations in condition monitoring, but there is scope for companies to offer solutions developed in other sectors, and there is likely to be an increase in third-party services provision.

Improvements in offshore transit and turbine access will reduce the number of personnel by enabling more efficient use of assets and resources. Technologies that can increase energy production and/or improve reliability can create new jobs.

5.7 Other factors

A number of additional, non-technical, site-related, market, financial, environmental and social factors also will continue to impact the industry as it develops.

In looking to 2030, typical sites are anticipated to be located in deeper water, farther from shore, with extended design life but in similar wind speeds. The change in water depth (coupled with the progression to larger turbines) will likely drive a move away from monopiles. The change in distance to shore will likely drive a change from land-based OMS to offshore-based OMS, but will not in itself drive a significant shift to HVDC technology. This combination of factors is anticipated to have no overall effect on the LCOE over the period. Looking to 2045, the trend in site conditions and design life extension is anticipated to slow, but continue.

The number of turbines within farms is expected to increase between 2015 and 2030. Without any mitigating innovations, the AEP would decrease due to increases in wake losses.

It is anticipated that market and financial factors including competition and the cost of finance are likely to help reduce the LCOE over both periods. The effect of commodity prices and macroeconomic conditions are assumed to remain constant over the whole period.

In 2015 and 2016, winning bids for auctions for pre-developed offshore wind farms in Europe have indicated important further cost reductions for projects commissioned from 2020. The winning bid for the Danish wind farm Horns Rev was EUR 103/MWh (USD 114/MWh), and the winning bid for the first two phases of Borssele offshore wind farm in the Netherlands was EUR 73/MWh (USD 80/MWh). Neither of these bid prices include grid connection, and both are for a period less than the operational life of the wind farm. In addition, the site characteristics for these projects generally offer the prospect of a lower LCOE than the typical conditions used in this study. The prices, however, point to important further cost reductions. It is anticipated that the cost reductions are due mainly to:

- Increased competition at the developer level for the same site (there were over 30 separate bids for Borssele).
- Increased benefit from anticipated savings due to having a pipeline of projects over a number of years, enabling savings in the supply chain

Table 25: Impact of other factors, including WACC and design life, 2016-2030

CAPEX	OPEX	AEP	LCOE
-11%	-13%	-2.4%	-20%

Note: The methodology is described in Box 1 and Appendix C.

Table 26: Impact of other factors, including WACC and design life, 2031-2045

CAPEX	OPEX	AEP	LCOE
-3.7%	-1.1%	-1.3%	-15%

Note: The methodology is described in Box 1 and Appendix C.

due to the expectation of higher utilisation of vessels and facilities, depreciation of investment over more activity, increased learning through repetition and the facilitation of new investment. This approach can be taken only by developers such as Dong Energy, with a market-leading pipeline of projects in a range of countries, or if a pipeline of projects is awarded in a single competition.

- Increased benefit from likely future savings in OMS that are not available at FID.

Environmental and social factors are likely only to increase the LCOE somewhat over both periods.

5.8 Game-changing solutions

The analysis in Sections 5.1 to 5.7 relates to an evolution of today's wind farm concept. Although some of the innovations involve a significant change in the design of a given component or process, they fit into the existing wind farm concept using conventional horizontal-axis turbines, each on a bottom-fixed foundation.

The potentially game-changing innovations discussed below incorporate a change in the wind farm concept or cannot be applied to the types of sites considered in Sections 5.1 to 5.7, or they change key assumptions used in calculating the LCOE for such sites. All, however, can be combined to a greater or lesser degree with some of the innovations described in Sections 5.1 to 5.7. Each has the potential to have a significant impact on one or more of the industry goals discussed in Section 4 in a way that single innovations discussed earlier in Section 5 do not.

Floating foundations

Floating foundations can open up significant new markets where deeper water is combined with a strong wind resource or in areas of high demand for electricity in which the existing supply is high. Floating foundations are buoyant structures maintained in position by mooring systems. Three main technologies are in development:

- The spar buoy such as the Hywind concept developed by Statoil (Norway),
- The tension-leg platform such as Glosten's PelaStar (USA), and
- The semi-submersible such as that developed by Principle Power (USA).

Many of these have been developed in-house by developers or marine consultancies, often with grant support. For example, PelaStar was supported through the Carbon Trust OWA. Demonstration is an important stage for floating concepts, and these have been supported by differential incentives to stimulate investment.

Several full-scale prototype floating wind turbines have been deployed. The first was a Hywind spar buoy in Norway in 2009, followed by a semi-submersible WindFloat (Principle Power) installation in Portugal in 2011 and three installations in Fukushima, Japan (spar and semi-submersible) between 2011 and 2015. The French Environment and Energy Management Agency (ADEME) announced the construction of two pilot floating wind farms, of 24 MW each, to be commissioned in 2020. The pilot wind farms will be located in the areas of Gruissan in the Mediterranean Sea and Groix in Brittany. No tension-leg platform has been deployed for a wind application; the first is anticipated in Germany in 2016. European demonstration projects were funded by a combination of government-issued grants and private capital. The Japanese projects were government-funded. More than 10 concept developers are trying to enter the market by progressing to the stage of full-scale demonstration.

A number of designs of floating foundations reduce CAPEX through lower installation costs by avoiding

Case study: Floating foundations in Japan

Japan is likely to be a key future market for floating foundations due to a strong wind resource and deep water close to shore. The fundamentals for adopting this technology are in place. Electricity prices can support early commercial projects, and energy policy decisions are in place.

Catalysed by the Fukushima nuclear disaster in 2011, Japanese industry and government have accelerated the pace of RD&D for floating foundations, having developed four demonstration projects (three floating turbines, including a 7 MW turbine, and a floating substation). The total RD&D expenditure is estimated in the hundreds of millions of dollars. Japan can be expected to continue on this path of technology acceleration and emerge as the leader in a wave of floating wind deployment around the Pacific Rim.

One challenge, which is of higher relevance and cultural importance in Japan than in many other markets, is the need for policy makers to facilitate agreement about offshore wind with the fishing industry, one of the nation's most important economic drivers and cultural icons.

the use of heavy-lift vessels. Greater standardisation in manufacturing is possible since water depth and soil type have no impact on foundation design, and this can lead to cost savings (goal A). In 2015, all floating foundations were more expensive to manufacture than fixed foundations on most sites under development. Commercially viable sites before 2030 are anticipated to be in locations with high wind speeds and close to shore and grid connection. Floating foundations are anticipated to play a major role in opening up new markets, particularly in Japan and the United States (goal C). The mooring systems used by floating foundations are anticipated to cause less disturbance of the seabed and less piling noise (goal D). The reduction in offshore lifts is anticipated to lower health and safety risks (goal E). Commercial deployment of floating foundations is anticipated in the mid 2020s.

See also the excerpt on *Floating foundations: a game changer for offshore wind?* for further discussion of floating foundations, available at the IRENA's Publications web page.

Multi-rotor systems

Multi-rotor systems could be game changers through reducing the LCOE. In a multi-rotor system, two or more rotors share the same support structure and some electrical components. Vestas announced the trial of a four-rotor system with a total rating of 8 900 kW in 2016. A range of concepts are in development:

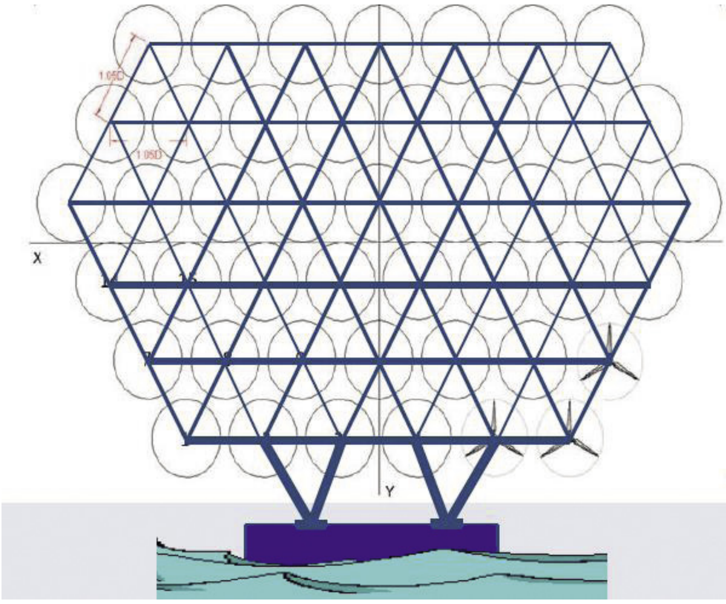
- Multiple rotors supported by a novel single tower arrangement, such as shown in Figure 35, which researchers at the University of Strathclyde argue offers a 30% lower LCOE for a 20 MW unit than the next generation of conventional 10 MW turbines.
- Multiple turbines supported by multiple, more-conventional towers on a single foundation, such as the one developed by Hexicon (Sweden) (shown in Figure 36) and Floating Power Plant (Denmark) (also combining wave energy generation; supported by a European Horizon 2020 grant).

In some concepts, turbine rotors are much closer together (at 1-2 diameters) than in conventional wind farms (at 6-10 diameters) which will increase aerodynamic wake losses, depending on the direction of the system to the wind.

Such concepts have several potential benefits compared to conventional offshore wind farms:

- Shared structures and increased floating stability components leads to lower CAPEX (goal A).
- Lower turbine and foundation installation cost with a smaller number of units towed to site (goals A and E).
- In increasing turbine size further, they avoid the technical challenges of increasing the swept area without disproportionate increases in drivetrain torque, tower head mass and resonant frequency problems (goal A).
- Lower cable and cable installation costs, as less cable and fewer cable terminations are needed (goals A and E).

Figure 35: Multi-rotor system



Acknowledgement: University of Strathclyde/Jamieson
Source: University of Strathclyde, 2015

Figure 36: Multi-turbine foundation

Source: Hexicon, n.d.

- Opportunities to streamline OMS with a lower frequency of offshore transfers per MW (goals A and E).

If it happens, commercialisation is likely to take place after 2030, following a route that will include a full-scale demonstrator. The impact on the LCOE is expected to be up to 20% compared with conventional technology at the time. Most of the development, turbine and electrical connection innovations discussed earlier in Section 5 can be applied in combination with these innovations.

Vertical-axis turbines

Vertical-axis turbines could be game changers by reducing the LCOE for very large-scale turbines. Vertical-axis turbines, as the name suggests, have a vertical shaft around which the rotor turns. The concept is not new, and a small number of commercial-scale wind farms using vertical-axis turbines were installed onshore in the 1990s. Since then, a number of players have sought to introduce vertical-axis turbines for utility-scale onshore projects, but with no commercial success, due to a range of issues including the rating-to-blade loading, cost and aerodynamic performance not meeting early expectations.

Over this period, the commonly used justifications for the lower cost of energy relate to simpler blade manufacturing, avoidance of the yaw system (to turn the turbine to face the wind) and more technology located at the ground level, resulting in cheaper maintenance and service. The verdict from wind farm developers, however, has been that any advantage is insufficient to support a move to the use of vertical-axis turbines onshore, although some vertical-axis turbine developers claim that turbine costs will be half those of conventional turbines in 2020.

In the offshore sector, there are some differences that offer the opportunity for vertical-axis turbines to change the game:

- Offshore turbine technology is now at a much larger physical scale than onshore technology. As conventional horizontal-axis turbines get larger, the design cost of the reversing gravity loads at the blade root increases. There are no changing gravity loads in a vertical-axis turbine, so vertical-axis turbines do not suffer from this effect. To balance this, technology developments in horizontal-axis turbines are reducing aerodynamic load variations on many turbine components. A number of these load variations are inherently larger with vertical-axis turbines, with a consequential cost penalty. It may be, however, that due to the arguments above, very large vertical-axis turbines could offer a cost advantage over very large horizontal-axis turbines.
- The cost of floating foundations generally is driven more by the location of the centre of mass of the turbine than other designs of offshore and onshore foundations, thereby increasing the attractiveness of vertical-axis turbines.
- Offshore, the cost of major component removal is much higher relative to onshore. Vertical-axis turbines, with components located closer to the water, offer the chance to avoid the use of cranes with high hook heights, thereby reducing installation, maintenance and service costs and avoiding working at height.

The furthest developed concept is that by the French company Nenuphar, which has built a 2 MW onshore prototype and will supply an offshore product to the Vertiwind project, as shown in Figure 37:

Vertical-axis turbines are well suited to floating foundations because the bending moment at the water level typically is lower than for a horizontal turbine.

If it happens, commercialisation is unlikely to take place before 2030, following part-scale and full-scale demonstrator turbines (onshore and offshore) and a pilot project. At this point, there will need to be about a 20% improvement in the cost of energy for the industry to embrace the technology. Key hurdles to be overcome include developers only seeking planning approval for sites with conventional horizontal-axis turbines, and the likely lack of competition for supply of vertical-axis turbines

If commercialisation is reached, then, due to the relative immaturity of the technology at that point, it can be expected that LCOE will fall faster than for conventional horizontal-axis turbines for some time.

Apart from the potential benefit in terms of LCOE (goal A), vertical-axis turbines, coupled with floating technology, offer the potential to open up new markets (goal C) and reduce working at height, hence improving health and safety (goal E).

Airborne wind solutions

Airborne wind solutions could be game changers by reducing the LCOE on bottom-fixed or floating wind farm sites. Airborne wind solutions are where the primary interaction with the wind happens at a point that is not rigidly connected to the foundation. Such systems can be classified by:

Figure 37: Floating vertical-axis wind turbines

Source: Nenuphar, n.d.

- Altitude: boundary layer (0–3 000 m) or troposphere (3 000 – 19 000 m).
- Type of airfoil: lighter or heavier than air; rigid or flexible; drag-, lift- or rotorcraft-based.
- Generator location and type: ground or airborne; geared or direct drive.

Devices typically either are static, using the speed of the wind flowing past them, or active, increasing the flow speed by moving themselves. Devices with generators on the ground typically use a system where the tether line connecting to the device is gradually let out, turning a drum connected to a generator. When the tether is at full extension, the device is put into low drag mode and pulled back to the ground station using the same arrangement, this time consuming energy.

Challenges for the airborne wind energy solutions relate to cable loading (for airborne generators); the impact of lightning, due to the higher risk of strikes; aircraft and radar interference, due to moving higher in the atmosphere; safety in the event of fault or failure; and the impact of storms.

Benefits include the increased scale and consistency of wind resources higher up and the decreased overall materials mass and cost. Examples of airborne wind solutions are provided in Figure 38 and Figure 39:

Commercialisation is unlikely to take place before 2025, following further part-scale and full-scale demonstrator devices (onshore and offshore) and a pilot project. Leading players, such as Kite Power Solutions (UK),

Figure 38: Example of an airborne wind solution using a rigid airfoil and airborne generators

Source: Makani, n.d.

Figure 39: Example of an airborne wind solution using a flexible airfoil and ground-based generators

Source: Kite Power Solutions, n.d.

are suggesting a potential 50% reduction in the LCOE compared to conventional horizontal-axis turbine technology in five-years' time, but it is likely that the ultimate benefit will be less. From the point of commercialisation, there are likely to be reasonable further reductions in the technology cost due to the lack of past experience with the aerodynamic and control elements of the technology and the wide range of optimisation opportunities available.

Airborne wind has a potential benefit in terms of LCOE (goal A). Independent studies and supplier claims have suggested that savings of 50% are possible, but the scale of demonstration devices is such that there remains significant uncertainty in such figures.

Due to lower overturning moments and lower foundation-mounted mass, airborne solutions are well suited to floating foundations, thereby offering the potential to open up new markets (goal C). With lower material use, lower structural loading (hence less impact during installation) and reduced avian impact, airborne wind also offers decreased environmental impact (goal D).

With more technology located closer to the water level for maintenance and service, airborne wind also offers the opportunity to improve health and safety (goal E).

Extending the life of wind farm assets

Although not necessarily involving significant technical innovation, the impact of the change in lifetime of wind farm assets could have a significant impact on the cost of energy. It is included as a game changer as it drives significant changes in the life-cycle of offshore wind farms, even if it does not involve significant changes in technology. There are a number of ways forward in this regard:

- Extending the life of existing generating assets. This is just starting to become a focus for the onshore wind industry, where there are many more assets that are nearing the end of their design life of 20 years. This may involve some component of replacement or refurbishment, increased condition monitoring and inspections. Standards and processes will be established by which safe, ongoing operation of assets beyond their design lives will become an option for asset owners. In time, this will be extended to offshore wind farms, with project lives being extended to beyond 30 years. Although OPEX may be somewhat higher and energy production somewhat decreased compared to earlier years, the CAPEX will have been fully depreciated and hence the cost of energy during this period will be much reduced. Likewise, the LCOE over the whole wind farm site life also will be reduced.

- Repowering offshore wind farms. As an alternative to continued operation in the same configuration, generating assets (turbines, including their foundations and array cables) may be replaced by larger units spaced further apart (hence keeping the same overall rated power), while continuing to use the same transmission assets after some refurbishment. As the transmission asset CAPEX will have been fully depreciated, this greatly reduces the costs that the repowered wind farm has to bear, hence reducing the cost of energy during this period and the LCOE over the entire wind farm site life. Although there are technical and commercial challenges in this approach, a number of organisations are starting to address these. (BVG Associates, 2015c)

- Neither of the above solutions require decisions to be made about increased CAPEX at the beginning of the wind farm life. As confidence in technology and the long-term market for energy from offshore wind increase, and the rate of LCOE reduction through the introduction of new technology slows, there will be increased focus on longer design life of new offshore wind farms, mirroring trends seen in fossil fuel generation. This will drive RD&D in longer life in various areas, such as array cables, OMS strategies relating to refurbishment and surface protection.

Extending the life of assets has an impact on the LCOE (goal A). Extended use of assets reduces the site needed per unit of energy generated, thereby reducing environmental impact (goal D) and improving health and safety (goal E).

Other potential game changers

Other potential game changers that have been explored at a prototype or small commercial scale in onshore wind include shrouded turbines (where air is accelerated through the active rotor disk) and turbines with co-axial or contra-rotating rotors. There are no significant reasons why these technologies, yet to make an impact onshore, should be more successful offshore.

Other potential game changers include piezoelectric solutions using structures deflected by the wind and solutions based on extracting the energy from vortex shedding, using tall structures that engineers conventionally have to protect from vortex shedding by the use of strakes. Again, none of these concepts is likely to progress offshore.

5.9 Market development to 2045

In 2015, offshore wind made only a small contribution to global renewable electricity generation, and almost 90% of that capacity was in Europe. Over the next 30 years, it is anticipated that offshore wind will expand significantly in other markets.

Three scenarios

It is recognised that the greatest driver of investment in RD&D is confidence in a future, competitive market of a size that justifies the investment. Likewise, currently the greatest driver of such a market is significant reduction in the cost of energy, the largest contributor to which is likely, for some time, to remain technology innovation.

A central scenario for market development is used in deriving the LCOE reduction trajectory presented at the start of Section 5. In this scenario, it is assumed that offshore wind is an important player in a renewable energy mix by 2045, through reasonable levels of policy support and private and public sector investment in RD&D and also through investment in manufacturing and installation hardware. In the scenario, it is assumed that offshore wind continues to feel pressure to reduce the cost of energy to compete with other energy technologies, meaning that neither it nor any other technology wins the race outright and dominates supply.

In this scenario the global learning rate for the LCOE is 17% from 2016 to 2030, and 12% from 2031 to 2045. This is a high learning rate in comparison to other industries, particularly in the 2031-45 period. Learning rates at the comparable stage of onshore wind development were similar, which gives confidence that they can be achieved in offshore wind. In onshore wind, this trend slowed as logistic and social considerations limited turbine growth and because non-turbine costs contribute relatively little to the LCOE. Offshore, there remains much innovation both relating to the turbine but also beyond, giving long-term opportunity for LCOE reduction.

High and low progress scenarios are then based on changing the cost of energy of offshore wind in 2045 in the central scenario by 10%, but continuing to assume that offshore wind remains an important part of the energy mix, without having a cost so low that the market accelerates massively or so high that it gets sidelined. In reality, either of these outcomes are possible. Learning rates are a function of the rate of cost reduction for a given market growth. A reduction in the LCOE due to learning therefore can come either from an increase in the rate of learning, or from an increase in the market size in which learning takes place. In this analysis, half of the change in the cost of energy is assumed to come from a changed learning rate (related to a change in appetite for investment in new technology), and the other half is assumed to come from changed market size (hence change in the number of doublings of capacity installed during the period).

This gives a global learning rate in the high-progress scenario of 16% over the whole period 2016-2045 and a resulting global operating capacity of 475 GW in 2045 (increased by 29% over the central scenario). In the low-progress scenario, the global learning rate is 14% and the operating capacity is reduced by 22% to 287 GW in 2045.

As a comparison to the offshore case, onshore wind had a global capacity of 13 GW in 1999 and will take until 2016 to grow to 475 GW, according to figures from the Global Wind Energy Council (GWEC, 2015).

Central scenario

In Europe and North America, offshore wind displaces significant amounts of fossil fuel and nuclear electricity generation. In the Asian market and the rest-of-world market, offshore wind is adding capacity to the grid.

This scenario aligns with the IEA 2030 figures for offshore wind capacity commissioned globally (IEA, 2015). The figures for the different global regions are based on projections and targets at continental- and country-level up to 2030. Market volumes are broadly in line with national plans stated by various countries, including China, although few data from such plans are available past the next five years. In some cases, early growth is reduced in order to fit with longer-term expectations. For the scenario for the period 2030-2045, the projections continue with the assumption of continuing increase in the rate of growth. This leads to a global figure that is around 50% higher than the IEA 2045 projection, which is based on linear growth.

Europe

In Europe, there is steady growth of the offshore wind sector to 2045, including re-powering of offshore wind farms as they reach the end of their economic life.

Asia

In Asia, the pipeline of announced projects shows a steady increase from 2016 to 2030. China, Chinese Taipei, India, the Republic of Korea and Japan all have offshore wind programmes. As in Europe, expansion of the market goes ahead despite policy uncertainty in single countries. In this scenario, by 2045, Asia has 34% of global offshore wind capacity.

Rest of the world

The rest of the world starts a long way behind Asia and Europe, but by 2030 the North American market grows to around 40% that of Asia, or around the same capacity as Europe in 2015. Beyond Europe, Asia and North America, an increase in installed capacity to 1 GW per year (5% that of the other regions) is anticipated by 2045.

Figure 43 shows the global sum for these three regions.

High and low scenarios

In the high scenario in Asia, growth is higher than in Europe because single large economies in Asia (China, in particular) have the potential to grow at a faster rate, where offshore wind is more established.

The rest-of-the-world market faces high uncertainty, and therefore the high and low scenario variations are larger than in Europe.

Case study: Market for floating turbines in 2030 and 2045

Two leading developers of floating foundation technology indicate expectations for a healthy deepwater offshore wind market by 2030. One developer expects Japan to be the first large commercial market, whereas the other developer expects the UK, especially Scotland, to be the first large-scale market for floating foundations. The first markets will require additional support mechanisms compared to bottom-fixed systems, but the return on that early investment is the potential for a larger floating offshore wind supply chain in the long term.

Both technology developers agree that in 2030 the global market for floating foundations will be split approximately evenly between Japan, the US west coast and the rest of the world. From 2030, they expect new markets to emerge in Australia, Chinese Taipei, New Zealand, the Republic of Korea and South America. Looking to 2045, the floating foundations developers expect the Pacific Rim offshore wind markets to be dominated by floating systems due to physical site conditions (deep water) and the inherent resilience of these systems to withstand earthquakes.

Figure 40: Annual installed and operating capacity of offshore wind in Europe, 2016-2045

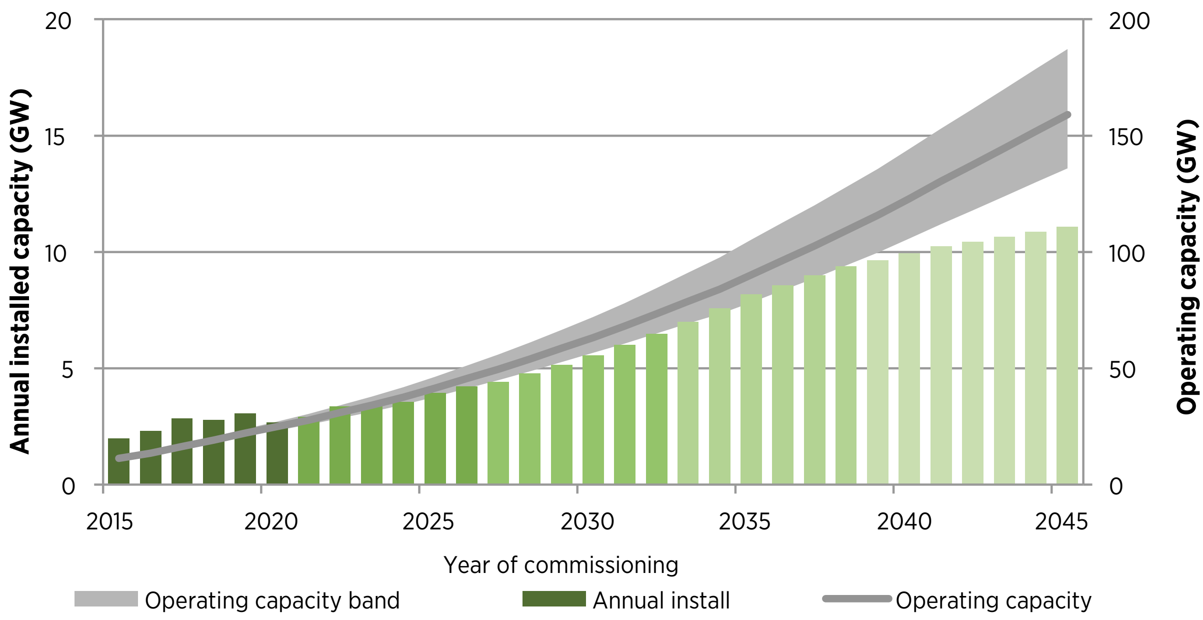


Figure 41: Annual installed and operating capacity of offshore wind in Asia, 2016-2045

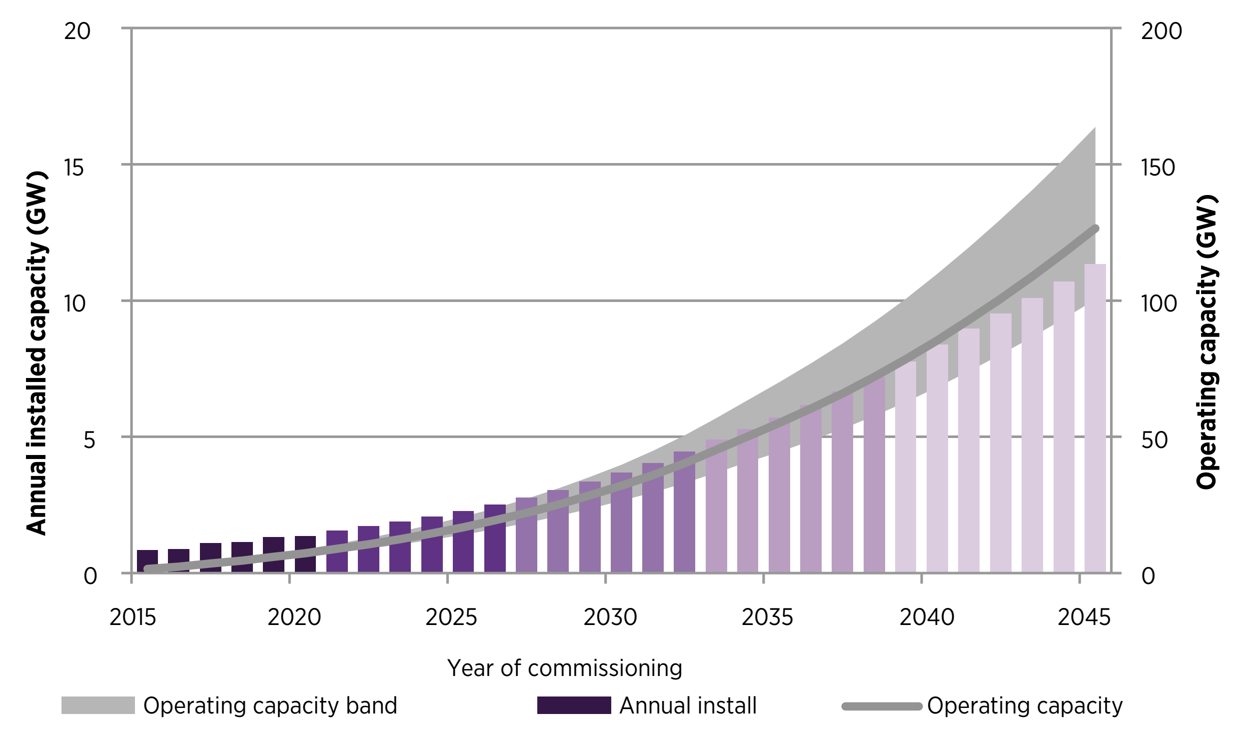


Figure 42: Annual installed and operating capacity of offshore wind in rest of world, 2016-2045

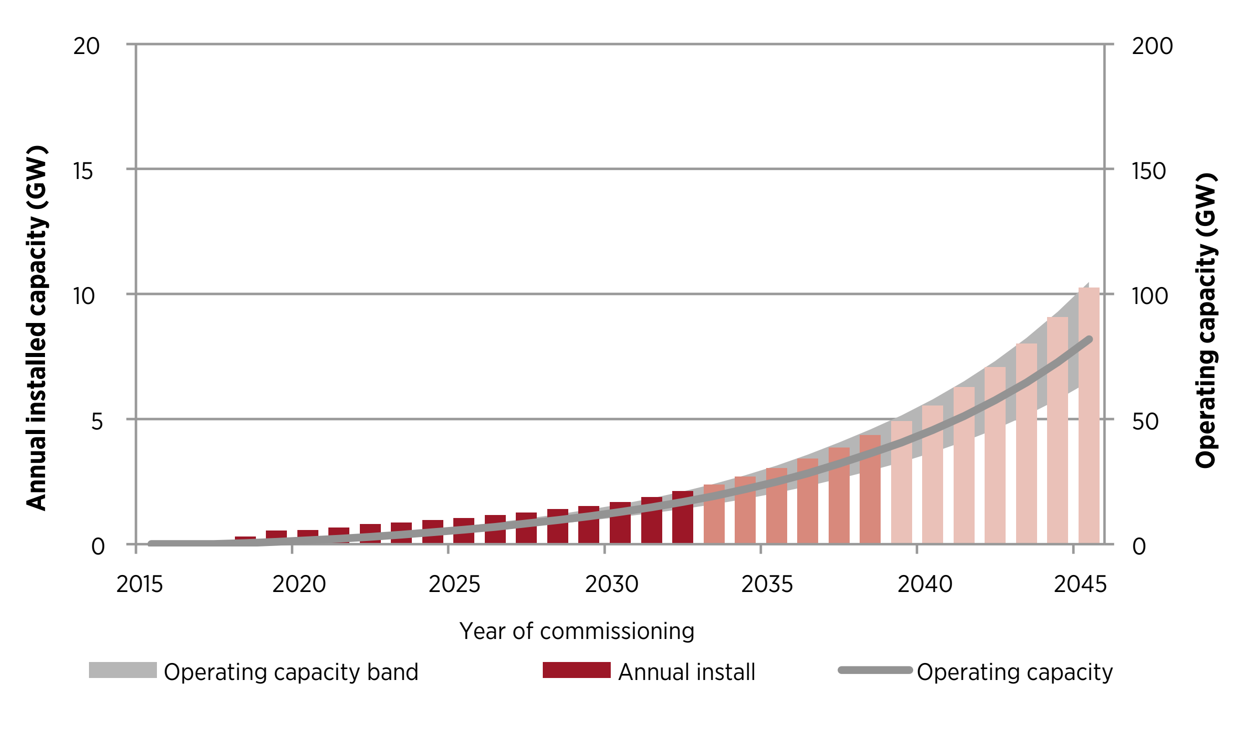
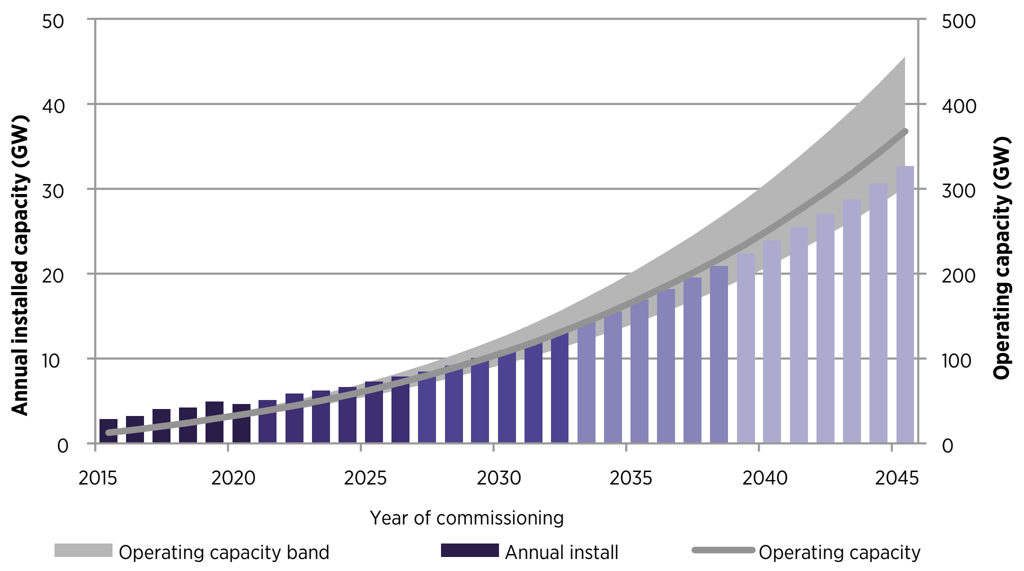


Figure 43: Annual installed and operating capacity of offshore wind globally, 2016-2045



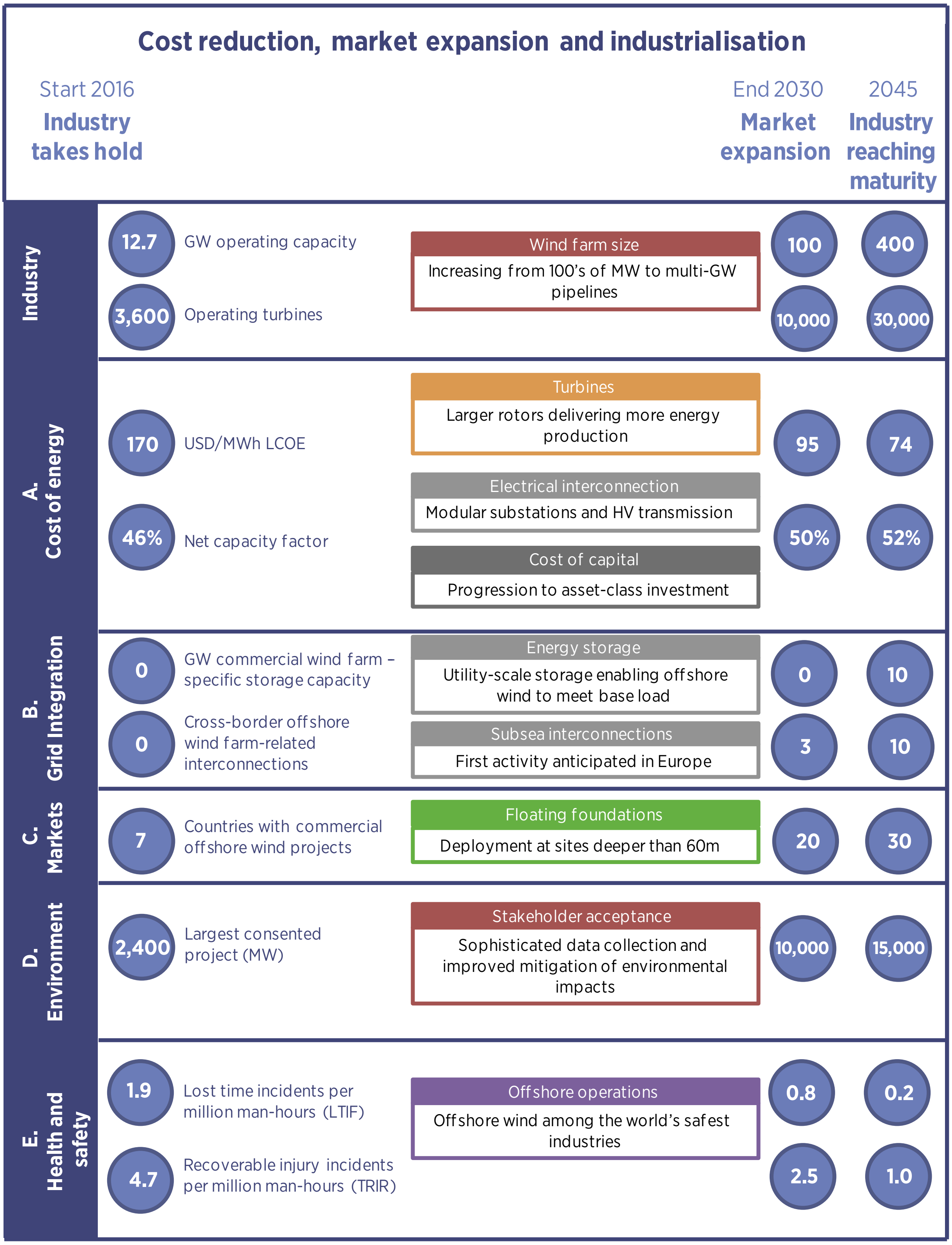
5.10 Offshore wind development prospects, 2016-2045

Over the next three decades, offshore wind is anticipated to grow from a new commercial technology to an industrialised and important component of the global energy mix. The operating capacity is expected to grow from around 13 GW to around 370 GW. Turbines are expected to increase in rating from today's 6 MW machines to 10 MW by 2030 and 15 GW by 2045. Floating foundation and other technology advances are anticipated to expand the number of countries deploying offshore wind. Figure 44 summarises the offshore wind industry's journey from 2016 to 2045. The figures are anticipated projected values.

Key findings

- Nearly half of the lifetime expenditure for an offshore wind project commissioned in 2015 will be financing costs.
- Of all the technology elements, turbines represent the greatest opportunity for reducing the cost of energy.
- Of all technology developments, floating foundations will have the most significant impact on opening up new markets for offshore wind.
- By 2030, new interconnectors will have started helping with grid integration of offshore wind. Small-scale energy storage is expected to be commercially deployed as part of some offshore wind projects.
- Market and financial factors, including competition, commodity prices and the cost of finance, are likely to help reduce the cost of energy (assuming an unchanged macroeconomic environment, in line with the assumption in Appendix C).
- After an increase in CAPEX per MW between projects commissioned in 2001 and 2015, the trend is reversed looking to 2030 and beyond, as technology innovation and supply chain effects outweigh any additional costs due to the use of sites in deeper water and farther from shore.
- Airborne wind is a potential game changer, with potential to reduce the cost of energy by up to half while at the same time opening up new markets.

Figure 44: Offshore wind's expected development, 2016-2045



6. RESEARCH, DEVELOPMENT AND DEMONSTRATION

The innovations described in Section 5 require significant RD&D if they are to have a significant impact on the LCOE of commercial projects. This section reviews the RD&D landscape in both the public and private sectors. It discusses how these have been used to support offshore wind innovation and to what extent they have been successful.

The section further considers the experience from other sectors in RD&D and offers ways to transfer lessons to offshore wind. Finally, recommendations are made to guide the strategies of policy makers, investors and researchers.

The section focuses on the types (modes) of RD&D undertaken, but it is important to recognise that any successful innovation needs be developed alongside skills and supply chain development. It also is vital that innovation strategies reflect specific national circumstances, for example the maturity of the supply chain and the institutional capabilities of the RD&D organisations that are already in place in a given country or region (IRENA, 2015).

6.1 The RD&D landscape

Public and private sector research activity comes in a range of modes, using standard IRENA terminology (IRENA, 2015):

1. Basic science and R&D

1a. Academic research. This includes collaborative research and is primarily publicly funded and takes place mainly in universities or broadly based research institutions. Examples are the University of Strathclyde and DTU (typically, technology readiness levels (TRLs) 1-3).

1b. Thematic RD&D in research and technology organisations. The work is primarily publicly funded and takes place in establishments such as Germany's Fraunhofer IWES and the US National Renewable Energy Laboratory (NREL) (TRLs 2-3).

2. Applied R&D

2a. RD&D enabling. This facilitates networks and collaborative programmes without providing direct RD&D funding. Examples are the UK's Knowledge Transfer Networks and DNV-GL's joint industry project on subsea power cables in shallow water renewable energy applications (TRLs 3-9).

2b. Collaborative research partnerships and industry projects. These bring together companies to address technology needs, generally in a number of areas and over a period of a few years. They are at least part-funded by the participants or wind users. The UK Carbon Trust OWA and TKI Wind op Zee are two significant examples (TRLs 6-8).

2c. In-house private sector RD&D. This is supported by market growth and is driven by competition as well as by public grant funding, loans and equity investment (TRLs 3-9).

2d. Experimentation and testing. This takes place in both public and private facilities. The initial investment may be public, but access is paid for by the user. Examples are the US Energy Innovation Center at Clemson University and the UK ORE Catapult's Fujin facility (TRLs 4-6).

3. Demonstration

Complete products and product combinations are tested in field conditions, both onshore and offshore. A significant proportion may be paid by the public sector. Examples are the onshore National Test Centre for Large Wind Turbines at Østerild in Denmark and the two-turbine offshore Beatrice Demonstrator in the UK (TRLs 6-9).

4. Market development

After single or multi-unit demonstrations, activities before full commercial use may include small-scale semi-commercial projects and manufacturing process and supply chain development.

5. Commercial diffusion

Even when most technology development work is complete, often significant resource, expenditure and risk capital is required in order to establish full commercial use in a range of markets, ensuring that quality, volume, supply chain and lifetime care challenges are properly addressed.

6.2 Lessons learned

The sections below consider how effectively each of the RD&D modes has been used in offshore wind. It also includes the most relevant examples from analogous sectors that involve large-scale heavy manufacturing and systems integration, such as automotive, defence, maritime, aerospace and nuclear power.

1. Basic science and R&D

1a. Academic research

In countries with an established wind industry, there are established academic research teams that are well aligned with industry needs and that undertake collaborative research programmes. A notable example is DTU, which has active relationships with Danish industry players Dong, Siemens, Vestas and others.

In other countries, offshore wind-specific academic research has been less responsive. For example in the UK, wind energy has been regarded by some as a mature technology for which there were few pure research questions remaining. To a large extent, this view developed because there was little indigenous wind industry technical expertise to challenge it. Industrial guidance and peer review of research is therefore important even if it does not lead to direct collaboration. The most successful, relevant academic research, driven by strong industrial links with wind industry players, has been in the fields of high-voltage electrical systems and electromechanical machines, where offshore wind is just one of a number of sectors benefiting, but where the main industrial lead has had offshore wind as a priority application.

Some countries have sought to form university consortia as a means of stimulating research to meet public policy goals. An example of this is the UK's SUPERGEN programme which has a wind energy strand.

Academic research is important in developing core technical competencies but is unlikely to have a measurable impact on innovations close to market. Many of the innovations described in this report draw on academic research, but clear links are hard to identify.

Applied academic research is primarily publicly funded. Some research funders, such as the UK research councils, are not permitted to fund research by companies. In these cases, the private sector element of collaborative research may be funded from other public funds (for example, from Innovate UK). This is inevitably more bureaucratic but ensures that the role of research funders is clearly demarcated.

An attractive model can be the virtual research institute formed through a partnership of public and private members. This has the advantage of low overheads, low barriers to initial investment and flexible involvement by members, and it can incorporate elements of existing RD&D facilities. An example is the UK Energy Research Centre, which has several university partners.

There is also significant non wind-specific academic research under way that continues to feed in to the

Academic research in the automotive sector

Most large engineering corporations maintain a network of academic collaborators. For example, in the automotive sector, academic research is carried out in universities across the world, in particular in China, Europe, Japan, the Republic of Korea and the United States.

Academic automotive research collaborations may go beyond providing well-defined research outputs. Indeed the most successful collaborations involve working together at a deeper level in a way that ensures that the private partner maintains access to the latest knowledge in a sector and that the academic institution gains an understanding of the broader research challenges facing the industry. From these examples, the ingredients of successful collaborations are a common interest in core subject matter, and independently exploitable outcomes that are relevant to each party. For example, a company would benefit from a tool or method that gives competitive advantage, and a university would benefit from a laboratory facility that can be used for other fundamental research.

development of control, communications, materials, electronics and other key technologies used in offshore wind farms.

1b. Thematic RD&D in research and technology organisations

Several well-established research and technology organisations are working in offshore wind. The best examples in Europe are the German Fraunhofer IWES and ECN. In the United States, NREL also has been active. In some cases, these organisations, notably ECN, have successfully commercialised analysis tools used by wind farm developers and asset managers across the industry.

The reputation and targeted research activity of some research and technology organisations have enabled the development of highly experienced teams of individuals with technical and commercial experience from the private sector. This is best achieved in countries that have a significant wind industry technology presence that enables the flow of researchers between the public and private sectors.

Some countries have sought to develop these synergies by funding test and demonstration facilities.

Government laboratories also fall into this category. These are maintained to provide a technical resource for governments with a significant delivery function. Defence research and technology organisations are common worldwide. DARPA (Defence Advanced Research Projects Agency) in the United States has one of the largest RD&D programmes in the world. DARPA is a leading supporter of computational fluid dynamics, used to optimise wind turbine aerodynamics. QinetiQ in the UK led much early work on LiDAR, which led to the commercialisation of one of the market leading solutions, ZephIR.

Some research and technology organisations have been formed as part of a broader RD&D strategy. For example, there are about 80 Fraunhofer institutes covering a wide range of sectors. In these cases, best practice can be widely shared. For example, when Fraunhofer IWES was formed in 2009, its strategy had been informed by the management of Fraunhofer's other institutes.

Research and technology organisations can be more attractive partners for companies than universities as they tend to work closer to market, often involving staff with first-hand industry experience. Commercial research and technology organisations may be either profit making or non-profit making.

2. Applied R&D

2a. RD&D enabling

These activities do not involve undertaking or funding RD&D but provide a focal point for companies and support networks, increasing communication and collaboration, and sharing of information and facilities.

In the private sector, this work may be undertaken by trade organisations, certification bodies or private sector RD&D organisations and seeks to bring companies together to develop technical solutions faced by the industry. An example is the Council on Large Electric Systems (CIGRE), an international non-profit association for promoting collaboration with experts in electric

Thematic automotive RD&D in research technology organisations

In the automotive sector, private, profit-making institutes include AVL (Austria), FEV (Germany), IDIADA (Spain) and Ricardo (UK). In Europe, the institutes collaborate to some extent via an industry forum, the European Automotive Research Partners Association, founded in 2002 and supported by the European Commission. Non-profit industry research and technology organisations include MIRA (UK) and the Southwest Research Institute (USA). The engineering consultancy Ricardo has transferred its experience to the offshore wind industry, helping to develop next-generation turbine drivetrains.

In Europe, the wind industry has learned from automotive and other sectors in establishing the European Energy Research Alliance's Joint Programme Wind Energy as a forum for communication and collaboration among wind-related research and technology organisations.

power systems. A strand of its work has been subsea power cables for offshore wind.

Some public sector enablers are required to generate revenue, which may place them in competition with private companies. For example, work may include technology road mapping, a service also offered by technical consultancies. RD&D enabling may be taken on by trade or governmental organisations: for example, the trade association WindEurope now manages what used to be the European Wind Energy Technology Platform, and the IEA co-ordinates a range of collaborative RD&D "tasks" without providing funding to the industry players involved.

The impact of these activities is hard to demonstrate, as there may be no direct link with successful RD&D, and even where there is, the level of contribution they make is uncertain. One strength is that they help public and private funders understand where innovation priorities lie, enabling better use of public funding. Companies also are supported to form consortia, which can have long-term benefits.

Support of RD&D enabling activity may be popular with public funders, as it does not involve significant long-term budgetary commitments. It can be supplemented with funding of specific RD&D activities through funding competitions.

2b. Collaborative research partnerships and industry projects

These partnerships may be seeded or supported in the long term by public money but will have a large element of private funding and are driven by commercial partners. Effective examples have been the Carbon Trust OWA and the Energy Technologies Institute in the UK, and TKI Wind op Zee in the Netherlands.

One of the strengths of this type of partnership is the opportunity for lower-tier suppliers to access higher-tier clients and end-users, and to work directly with them to understand their needs. Such partnerships also provide an independent forum in which to address cross-industry challenges.

One collaborative model is the RD&D "club" in which partners provide investment with defined objectives and make collective decisions on which projects to pursue. Examples are the UK's Energy Technologies Institute and the pan-European KIC InnoEnergy, both of which invest a combination of public and private money, enabling significant flexibility in their approach. Both also work across a range of energy sectors, enabling cross-fertilisation.

A risk faced by such collaborations is that the investing partners may not all have the same immediate application for a given funded project and may have quite different RD&D priorities. In other cases, the

RD&D enabling in the automotive sector

Automotive RD&D is driven largely by the highly competitive nature of a large and mature market. Legislation also plays a part – for example, emissions standards continually have been made tougher – but in a way that gives industry sufficient certainty and time to innovate to reach the levels required.

Some governments have offered vehicle purchasers tax incentives to adopt low-emission vehicles early, further pulling forward RD&D. As an example, incentives for electric vehicles have driven market growth and hence RD&D in many European countries, as well as in China, Japan, California and the rest of the United States.

Private initiatives, such as the testing and publishing of vehicle crash-test results through the Euro NCAP programme, have also driven significant, targeted RD&D.

Best practice can be readily transferred to offshore wind if contributors are sufficiently flexible to recognise the differences with their own sector. A crucial difference is the relative immaturity of the offshore wind sector, and that RD&D enabling needs to engage beyond the companies (and RD&D enablers) that currently recognise themselves as part of the offshore wind industry.

investment decisions can be disconnected from the offshore wind delivery functions of the organisations.

These partnerships work well if they are customer-led and are focused on meeting shared challenges faced in delivering a defined project pipeline. The Carbon Trust OWA has successfully supported new turbine-access systems, foundation concepts and LiDAR verification trials, and has been demonstrating vibro-piling tools with significant shared interest of members.

Collaborative RD&D partnerships in other sectors also have provided successful forums for the stimulation of collaboration between supply chain elements. These are used extensively within the aerospace sector. Good examples of thriving partnerships with physical assets that are impacting the UK supply chain include the National Composites Centre (NCC) and the Advance Manufacturing Research Centre (AMRC), which together now form part of the High Value Manufacturing Catapult.

2c. *In-house private sector RD&D*

This is conventional, commercial RD&D. Wind energy is a research-intensive industry, and RD&D has been highly effective for turbine manufacturers and their component suppliers in bringing to market next-generation offshore wind turbines that have substantially reduced the LCOE.

At one stage, more than 20 companies had RD&D teams working on next-generation offshore wind turbines. This number has fallen through natural wastage and

Collaborative research partnerships and industry projects in the offshore oil and gas and maritime sectors

The oil and gas sector frequently forms joint industry projects (JIPs), where oil majors typically identify a common problem and collectively fund one or more suppliers to develop a solution. The paying members get preferential access to the resulting products and/or industry project. The benefit of this collaboration is that the outcome is aligned with the needs of a range of participants, and parallel work is not repeated by a number of players.

The maritime sector does this as well, with research institutions generally being the ones who do the work. Maritime Research Institute Netherlands has formed effective JIPs using this model. Participants come from a wide range of company types and often from a number of countries.

These models have the potential to be used more in offshore wind, where collaborators often have been put off by the difficulty of agreeing on commercial terms. As the offshore wind industry matures, this should become less of a barrier.

Case study: Energy Technologies Institute investment in Blade Dynamics technology

The UK's Energy Technologies Institute is a private-public partnership between global energy and engineering companies and the UK government. It seeks to accelerate the development of new energy technologies. Due to the combination of public and private funds, it is able to 100% fund activities to develop and demonstrate technologies and disseminate their findings to help advance industry thinking.

This enabled ETI to invest over USD 15 million to support further R&D and then full-scale demonstration of innovative blade technology by the UK/US company Blade Dynamics. The company's modular blade technology had the potential to decrease the cost of energy significantly by enabling longer, lighter blades, increased manufacturing consistency and reduced tooling cost. The challenge for Blade Dynamics (often seen with other small companies with significant innovations) was that the cost, risk and time to market and the need for end-user involvement meant that no combination of venture capital and partial grant funding was likely to enable progress.

Patient investment and a holistic, hands-on approach involving end-users enabled rapid progress. Effort put into capability building, independent evaluation of the benefits of the technology and marketing eventually led to acquisition of the company by a major wind turbine manufacturer.

as a result of diminishing expectations of the future market size. Despite this, 6-8 MW scale products by Siemens and MHI Vestas have impacted the market earlier than many in the industry expected. This activity in companies rarely takes place in isolation, and turbine manufacturers have collaborations with academic institutions and research and technology organisations. A close relationship with the RD&D activities of key suppliers also has proved valuable, as change in the product scale often drives a need for innovation deep into the supply chain.

Private sector RD&D also has been successful among vessel designers and operators, where new, bespoke vessels have been designed and brought to the market by most of the main contractors, including A2SEA, GeoSea, MPI Offshore and Seajacks. These new designs have been evolutionary, and there has been little progress in bringing more radical concepts to market.

Significant technical developments in foundation design, manufacturing and installation have been undertaken, but there has been less successful commercialisation, due often to the large costs involved with establishing series production and installation processes, beyond that needed for one-off prototyping. The variation in site conditions also leads to a more fragmented market, which weakens the business case for investment in one concept.

Much of this mode of RD&D is driven by sufficient confidence in future sales to pay back investment, sometimes in multiple sectors but often only in offshore wind. In addition, public funders have supported in-house RD&D through capital grants, tax credits and the development of test sites. For example, the UK government awarded a grant to Vestas to develop its rotor technology, including new physical prototype manufacture and test facilities.

Although turbine manufacturers are protective of intellectual property, the circulation of RD&D personnel in the industry is significant, and collective knowledge in the industry grows as a result.

A downside to in-house RD&D is that rarely do the companies start from first principles in developing new products. As a result, radical concepts, such as vertical-axis turbines, two-bladed turbines and integrated installation methods, have been slow to market. There is therefore a clear rationale for public RD&D investment, recognising that it has greater additionality when focused on newer or smaller players. The presence of public RD&D funding rarely influences larger, existing players to deviate far from existing technology plans.

Recent learning includes the value of providing business incubation support, focusing on market development and eventual commercial diffusion, in parallel with conventional grant support which is traditionally focused narrowly on technical RD&D.

For public grants for private RD&D, options are to fund directly from government or through an arm's length body. In the UK, the former Department of Trade and Industry (now the Department of Business, Innovation

In-house private sector RD&D in the automotive sector

In-house activity by automobile manufacturers is the biggest segment of RD&D. They typically organise RD&D into three areas: research, advanced engineering and product development. The last of these is the biggest and is focused on developing the next commercial product, for sale in four years or less. Advanced engineering activities focus on developing, refining and validating technologies for the next-but-one commercial product. Research activities are the smallest, and are not firmly linked to product cycles. Advanced engineering teams often can become involved in collaborative projects, while research teams usually are the ones interacting with universities.

Automotive engineering companies in the UK, such as Ricardo and Romax, have made successful use of RD&D funding from the DECC, the European Regional Development Fund (ERDF), EU framework programmes, Innovate UK and the Regional Growth Fund. This has been used to develop and transition their technologies to new sectors (including offshore wind) and to build relationships with target customers in collaborative projects. In particular, Romax has used RD&D funding to develop its entry to the wind drivetrain engineering market, while Ricardo has developed hybrid and electric vehicle technologies in this way. Both companies have enjoyed significant growth in both sales and expertise through their in-house RD&D activities.

In-house private sector RD&D in the offshore oil and gas and maritime sectors

Oil majors have major in-house RD&D efforts to develop everything from support structures to subsea electro-mechanical equipment.

Top-tier oil and gas suppliers have large RD&D divisions, for example, Keppel Group (Singapore), Nippon Steel (Japan), Samson Ropes (US), Worley Parsons (US) and Vicinay Chain (Spain).

Large shipbuilders have significant in-house RD&D programmes focusing primarily on fabrication processes. The clear global leaders are Daewoo, Samsung and Hyundai (all from the Republic of Korea). RD&D is also widespread in naval architects which look to license innovative designs.

and Skills) set up Innovate UK as a funding body that could be more outward-facing and responsive to industry, and could develop more efficient funding and grant-management processes. In funding offshore wind RD&D, however, the UK government has chosen to fund most activity directly from the DECC, which enabled funding to be directed to meet very specific government objectives.

2d. Experimentation and testing

Experimental and test facilities may operate within public sector research and technology organisations or private companies, or as stand-alone facilities. These facilities generally are used to test specific components or systems and include wave tanks, drivetrain test rigs, blade test rigs, wind tunnels and lightning protection test facilities.

Examples of facilities are LORC, which was developed through a partnership between major players in the Danish offshore renewables sector, the Fraunhofer IWES drivetrain and the blade test facilities and Deutsche WindGuard wind tunnel in Germany, the KIM- WTRC blade test rig in the Republic of Korea and CENER's drivetrain and blade test facilities in Spain.

Public money has been used to support the investment in facilities, often on the basis that the owners adopt a sustainable business model for ongoing operation of the test assets.

Leading turbine manufacturers such as Siemens and Vestas and independent blade manufacturers such as LM Wind Power often develop in-house test facilities where possible to enable their own engineers to have more direct involvement in tests and to avoid leakage of intellectual property and the development of testing know-how that could benefit a competitor.

The case for public investment in facilities is stronger if they can be used for other sectors, as the offshore wind market alone is unlikely to be able to support dedicated open-access facilities without subsidy. A challenge for the large drivetrain facilities now established is that there probably are too few companies with a demand for open-access facilities to test new offshore wind turbines over the next decade, and the facilities are expensive and not ideally suited for use with smaller, onshore turbines. A further lesson is that the success of test facilities also depends on the technical capability and industry networks of key staff, vital in establishing and sustaining commercial relationships.

Experimentation and testing in the automotive and maritime sectors

Automotive manufacturers all have significant in-house test and development facilities; however, many independent facilities also are used. A similar structure has developed in the wind industry, for both onshore and offshore sectors, where less-sensitive tests are contracted externally by larger players only if in-house facilities are fully utilised.

In the maritime sector, third-party test facilities are common, for example the Maritime Research Institute Netherlands, Force Technology (Norway) and Qinetiq (UK). A number of universities have test basins that can test at up to 1:50 scale and that generally are commercially available. In many cases, these have proved to be a valuable resource for the offshore wind sector to test foundation concepts and to model seabed scour.

3. Demonstration

Demonstration facilities are used mainly in the various energy sectors, recognising that the investment risk for commercial facilities can be mitigated only via small projects using full-scale operational plants.

Several demonstrator projects for offshore turbines have been built, notably Alpha Ventus in Germany, Gunfleet Sands and Hunterston in the UK, and Fukushima in Japan. With the exception of Alpha Ventus, which had significant commitments from several German organisations, most have been one-to-three turbine projects. Larger demonstration projects such as the European Offshore Wind Deployment Centre and the Blyth Offshore Demonstration Wind Farm (both UK) have been slow in delivery.

A difficulty is that these projects are expensive, and private investors can only commit with some confidence in a financial return from the project itself. This is because a developer's pipeline of commercial projects that would benefit from demonstration of specific technology is often highly uncertain, and any value from learning from demonstration projects has a limited lifetime. RD&D funding therefore is needed to stimulate investment. In Scotland, the POWERS and SIFT funds, for turbine and foundation support, respectively, met this need. The lack of suitable demonstration sites, end-users wishing to participate and suitable technology to demonstrate has meant that these funds have limited take-up

The small demonstration projects are highly effective in the commercialisation of new turbines and foundations but do not typically incorporate other innovations in installation and operational methods. New installation methods therefore have been developed and demonstrated during commercial wind farm development and installation activities, which imposes significant constraints. A difficulty in demonstrating installation and operational methods is that a major challenge is proving the ability to implement the method at scale and over large areas.

A notable example of a demonstration facility in another energy sector is the International Thermonuclear Experimental Reactor (ITER), which is a major facility for the demonstration of nuclear fusion. This technology remains a fair distance from commercial application, however.

4. Market development

The paths to market development are quite different for small and larger organisations. Many small organisations have suffered from less focus and/or capability applied to developing the market than to developing the technology. Some RD&D funders have recognised this and are providing (or imposing) incubation support in these areas to increase the likelihood of players crossing the commercialisation "valley of death".

A range of end-users, especially major energy players that own significant wind farm assets, also have venturing teams that invest to transition small companies over this stage, with a view both to using successful technology themselves and benefiting from equity returns as others use it.

In some cases, RD&D funding has been available to support activities, especially when relating to manufacturing process development, if there is novel content.

Larger companies often are able to use greater in-house resource, synergies with other sectors and investment of their own funds in order to support market development.

There also have been many examples of acquisitions of small technology players by established industry players, providing the most efficient market development and commercial diffusion. In the automotive industry, major manufacturers such as General Motors are using their venturing arms to accelerate the commercialisation of advanced batteries, biofuels and other technologies.

5. Commercial diffusion

Commercial diffusion via partnerships, technology sale, licensing and direct sales initially in selected geographies or relating to selected turbine models have all been successfully applied by small and large players in bringing new offshore wind technology to market.

In some cases, after successful demonstration, commercialisation has failed due to evolution of the market since decisions were made to initiate technology development in a given direction. There are other examples of a lack of whole-company commitment to (or understanding of) the risks involved during commercialisation, leading either to decisions to suspend activity or to unsustainable commercial losses. A classic example of demonstrated technology that failed to diffuse is the EV-1 electric car.

6.3 High-potential-impact technology solutions

Eight areas of technology innovation have been identified as part of this study as having the highest overall potential impact on the different goals. These are shown in priority order in Table 27: The RD&D content and suggested strategies for delivering the necessary RD&D are discussed in Section 6.4. The high-medium-low impact scale is objective for goal A but subjective for the other goals. In each case, they are set to ensure that the range of innovations presented covers the full range of impact on each goal, from low to high. For specific countries or site conditions and in different time periods, the relative importance of innovations may change.

Future generation turbines

Developments in blade, drivetrain and control technologies, in particular, will enable the development of larger, more reliable turbines with higher capacity ratings.

These turbines are likely to have a higher CAPEX per MW of rated capacity than existing turbines, but they will give a significantly lower cost of energy through higher energy production and lower CAPEX per MW for the foundations and installation. Further improved reliability and maintainability will both decrease OPEX and further increase energy production, further reducing the cost of energy.

With fewer turbines for a wind farm of a given rated capacity, there will be fewer maintenance visits required, improving health and safety, and fewer foundations, reducing cost and environmental impact.

Table 27: High-potential-impact technologies in approximate order of priority

Technology	Beneficial impact on:				
	A. Reducing the cost of energy	B. Increasing grid integration	C. Opening up new markets	D. Decreasing environmental impact	E. Improving health and safety
Future generation turbines	H	L	M	L	H
Floating foundations	L	L	H	H	M
Airborne wind	H	L	H	M	H
Repowering of sites	H	L	L	M	L
Integrated turbine and foundation installation	H	L	M	M	H
HVDC infrastructure	L	H	M	L	L
DC power take-off and array cables	M	M	M	L	L
Site layout optimisation	M	L	L	M	L

Blade tip heights will be higher with these turbines, making them more visually intrusive if sited near to shore.

The commercialisation of 10 MW turbines is likely to take place in the 2020s. Turbines with rated capacities of about 15 MW could be commercialised in the 2030s.

Floating foundations

Floating foundation developments will cover spar buoy, tension-leg platform, semi-submersible and various other hybrid designs.

Floating foundations are anticipated to play a major role in opening up new markets, particularly in Japan and the United States.

The mooring systems used by floating foundations are anticipated to cause less environmental impact than fixed foundations. The reduction in offshore lifts is anticipated to lower health and safety risks.

Commercial deployment of floating foundations is anticipated to occur for projects commissioned in the early 2020s, but technology developments to reduce costs will continue into the 2040s.

Airborne wind

Development of airborne wind solutions will (in the early stages at least) cover a variety of concepts including kites, rigid wings and airborne rotors.

Airborne wind offers a significant potential LCOE benefit through lower material use and lower CAPEX, and higher energy production than conventional turbines.

Due to lower overturning moments and lower foundation-mounted mass, airborne solutions are well suited to floating foundations, thereby offering the potential to open up new markets.

Airborne wind also offers decreased environmental impact due to lower material use, lower structural loading (hence less impact during installation) and reduced avian impact.

With more technology located closer to the water level for installation, maintenance and service, airborne wind also offers the opportunity to improve health and safety.

Commercialisation at scale is likely to start in the late 2020s, but it could have a significant impact when it does reach the market.

Repowering of sites

Repowering offshore wind farms is an alternative to continued operation in the same configuration. It involves replacement of the generating assets (turbines and their foundations and array cables), most likely with larger units spaced farther apart.

Repowered sites may retain transmission assets after some refurbishment. As the transmission asset CAPEX will have been fully depreciated, this greatly reduces the costs of the repowered wind farm, reducing the cost of energy during the repowered period and the LCOE over the lifetime of the entire wind farm site.

Commercialisation will take place when the first generation of offshore wind farms reach the end of their design lives in the mid-2020s.

Integrated turbine and foundation installation

Most offshore installation operations can be eliminated through the development of technologies and processes that enable assembling and pre-commissioning of wind turbines in a harbour followed by the installation of the complete, integrated turbine (including rotor, tower and foundation) in a single operation offshore.

In this innovation, the combined turbine-foundation structure is towed to the site by a bespoke vessel or tugboats. This innovation can be readily used with floating systems. For fixed foundations, the most promising technology uses the gravity base foundation that can be floated out and sunk on the site.

These innovations reduce installation cost and reduce exposure to health and safety risks. Commercialisation is anticipated around 2025, but technology developments will need to continue to meet the needs of larger turbines.

HVDC infrastructure

HVDC transmission is used in preference to HVAC transmission from far-offshore projects to overcome the reactive resistance (capacitance) caused by the export cables in a long grid connection (offshore and onshore).

HVDC infrastructure costs will come down through learning and innovations in offshore arrangements and component technologies. It is likely to remain more expensive (in terms of LCOE) than HVAC infrastructure, however, for wind farms closer to shore. The length of grid connection at which HVDC becomes cost effective is currently between about 80 km and 150 km.

The benefits of HVDC are that it enables wind farms farther from shore with higher wind resources, leading to higher AEP, and fewer planning constraints. It therefore can open up new markets where near-shore developments are not possible.

Today, HVDC infrastructure is used to connect two points, but it cannot be used to create a multi-nodal network. Once such DC nodes are developed, then HVDC infrastructure for wind farms can become integrated within broader offshore "supergrids" that link national onshore infrastructure, providing balancing of supply and demand across borders.

Commercialisation of HVDC infrastructure for wind farms is under way, with point-to-point grid connections used on a few projects in European waters. The use of HVDC in subsea interconnectors is well established because all conversion equipment is onshore.

DC power take-off and array cables

A DC take-off system eliminates the second half of the conventional turbine power conversion system that converts back to grid frequency AC, saving capital cost and increasing reliability.

Moving to DC collection also reduces the number of array cable cores from three to two and material by 20-30%, which results in savings on array cable CAPEX.

The first commercialisation is likely to be in wind farms commissioned by 2025, although the pace of progress in this area has slowed somewhat in the last two years, as industry still has not adopted higher-voltage AC array cables.

Site layout optimisation

Improvements in the characterisation of wind resources, aerodynamic wake effects, metocean climate and seabed conditions, combined with more parameterised foundation and installation process design methods, is enabling much more informed and holistic layouts of offshore wind farms.

Progress is incremental, and early versions of software tools already were used on projects with FID in 2015, although there is potential for further progress.

6.4 Strategies for research, development and deployment of high-potential-impact technologies

This section considers which of the RD&D modes discussed in Section 6.1 are best suited to support the commercialisation of the high-potential-impact technology solutions discussed in Section 6.3.

1. Basic science and R&D

1a. Academic research

The high-potential-impact technologies are mostly well developed at concept stage, but there will continue to need to be further research in materials (most impacting turbine and airborne wind components, especially conventional blades and airborne wind capture surfaces), power electronics (most impacting turbine and electrical interconnect components) and aerodynamic modelling (most impacting conventional turbine and airborne wind design and site layout optimisation). Most of the high-potential-impact technologies will benefit from such research, although this does not significantly impact repowering of sites or integrated turbine and foundation installation.

Academic research also has an important role in sustaining the skills base in the industry, where new concepts are incorporated into engineering degrees.

1b. *Thematic RD&D in research technology organisations*

Research and technology organisations have a significant role in bringing forward high-potential-impact technologies. This is particularly the case for game-changing technologies that are unlikely to be developed by the incumbent wind industry suppliers. Research and technology organisations typically have good industry knowledge, and this makes them well placed to support the development of innovations developed only at concept level and involving cross-disciplinary activities relating to a number of wind farm elements. This includes integrated turbine and foundation installation methods, and site layout optimisation.

2. Applied R&D

2a. *RD&D enabling*

Enablers can be valuable in identifying synergies with other sectors, helping to articulate these synergies and supporting the development of partnerships. This is particularly true for aerospace, where the wind synergies have not been explored in detail, and in areas such as big data analytics, where current progress is rapid. Funders also can stimulate new partnerships and highlight key technology challenges defined by the industry. Of the high-potential-impact technologies discussed above, such support is most relevant to repowering of sites, integrated turbine and foundation installation, and site layout optimisation.

2b. *Collaborative research partnerships and industry projects*

Collaborative projects have a major role where supply chains do not significantly interact at RD&D and product development levels. The most significant area is in integrated installation, where the substantial savings can best be realised if radical installation strategies and vessel designs are incorporated into turbine design at an early stage of the product development life-cycle.

2c. In-house private sector RD&D

In-house RD&D will remain the most important type of RD&D activity and is fundamental to the progression of each of the high-potential-impact technologies. RD&D is needed especially in blades, drivetrains and control for future generation turbines. Other needs are in the dynamics of floating foundations and during integrated turbine and foundation installation. Significant in-house RD&D also is needed in concepts and control in airborne wind and in key turbine and substation components for DC electrical system development. Likewise, in-house RD&D is needed in the development and validation of site layout optimisation software.

Less detailed work is required with regard to repowering of sites, where practical experience will in time play an important role. Even for areas in which other modes of RD&D are important, it is likely that the challenges will be defined by in-house operational and RD&D teams. For RD&D undertaken by turbine manufacturers and developers in particular, the commercial pressure to reduce the LCOE is the key driver, as long as there is confidence in a sufficient market.

2d. *Experimentation and testing*

This is particularly useful in testing new materials and substructures, such as in blades, and in exploring floating foundations and integrated installation methods in test tanks. It also is likely that DC technology will need test infrastructure, both to verify efficiency and reliability in normal operation and to demonstrate acceptable response to internal and external fault conditions.

3. Demonstration

For high-potential-impact technology innovations involving the turbine or foundation, full-scale demonstration will be needed before commercial use on commercial projects, which can cost multiple billions of dollars. For those innovations relating to the turbine alone, manufacturers have a strong incentive to identify and develop onshore demonstration sites with high wind speeds. Self-standing offshore demonstration sites have been difficult to finance, and a priority is for RD&D enablers to work with developers of commercial projects to identify and facilitate demonstration, especially of technology that cannot be demonstrated onshore.

4. Market development

All technologies need market development. It is the fundamental requirement for reaping economies of scale. Support in market development is likely to be required especially in airborne wind (where there are a range of different regulatory and planning issues that could be addressed collectively by a range of players). To a lesser degree, changes in market processes also will be needed to develop the market for floating foundations, repowering of sites and HVDC infrastructure.

De-risking activities by export credit agencies, governments and others are likely to be critical in accelerating market development for technologies such as future generations of turbines, floating foundations, and integrated turbine and foundation installation.

5. Commercial diffusion

All technologies need commercial diffusion. At this stage, public support is less applicable due to the risks of impacting competition.

Table 28 summarises the important modes of RD&D as they relate to each high-potential-impact technology.

Table 28: Approaches to RD&D for high-potential-impact innovations

Technology	Suggested most-appropriate modes of RD&D
Future generation turbines	• The existing model of RD&D is driven by leading turbine manufacturers and is proven, although it does require confidence in a sufficient future market. [modes 2c, 3, 4, 5] • Significant sources of innovation are academic research, in-house private RD&D and collaborative activities in underpinning technologies not specific to offshore wind; for example computational fluid dynamics, new materials, bearings and power electronics. [modes 1a, 1b] • Facilities for experimentation, component-level testing and full-scale demonstration are important in lowering the risk of novel technologies and new products with increased scale. [modes 2d, 3] • Future benefits can come from industrial collaborative research with partners in parallel sectors, particularly in the manufacture of composite structures, electrical and mechanical systems, and big-data analysis. [modes 2a, 2b] • De-risking of early post-demonstration commercial projects can be critical in some cases. [mode 4]
Floating foundations	• Academic research, research and technology organisation studies, and experimentation and testing are important in understanding the long-term dynamic loads on structures, especially due to the interaction between wind and wave loading. [modes 1a, 1b, 2d] • Collaborative research and industry communication are valuable in ensuring that the designs meet industry needs and best incorporate lessons from the past. [modes 2a, 2b] • Collaborative research and industry communication will provide a market pull for innovations in cable connectors and installation strategies and ensure that these developments are in step. [modes 2a, 2b] • An important step is the full-scale implementation of technologies currently in development through in-house private RD&D. [modes 2c, 3] • Market development support will be needed due to changed environmental considerations, as well as in de-risking early post-demonstration commercial projects. [mode 4]

Technology	Suggested most-appropriate modes of RD&D
Airborne wind	• This technology is unlikely to be taken to market by existing turbine manufacturers; initially it will be taken forward by in-house RD&D by SMEs with external support, before eventual involvement of larger players. There will be a need for all modes of RD&D. [modes 1-5] • An important stage is the construction of scale prototype devices to stimulate interest by major investors. [mode 3] • Repowering may provide a low-risk means of demonstrating new technologies, including airborne wind. [mode 3] • Technical challenges can be addressed through collaborative research programmes, and these will benefit from involvement of organisations from outside the wind sector. [modes 2a, 2b]
Repowering of sites	• Market forces will drive necessary in-house innovation. [mode 2c] • In some cases, there will be a need for additional academic research and accelerated life testing. [modes 1a , 2d] • There will be a benefit from learning lessons from other, more mature sectors and between offshore wind players. [modes 2a, 2b] • Market development support will be needed in order to evolve market mechanisms to enable and justify repowering. [mode 4]
Integrated turbine and foundation installation	• Concepts have been developed in-house by vessel designers, and the best approach is further development with the active participation of a turbine manufacturer. [modes 2a, 2b, 2c] • Collaborative projects, probably with partnerships with research and technology organisations, can be useful in understanding how the acceleration limits of nacelle components can be extended and how onshore logistics can be optimised. [modes 2a, 2b] • Demonstration is a key step and a challenge due to the high costs of tooling, for instance a specialised transport and installation barge. [mode 3] • De-risking of early post-demonstration commercial projects is likely to be important, as small-scale demonstrators may be insufficient to develop the market, due to concerns about logistics risks on larger projects. [mode 4]
HVDC infrastruc-ture	• An outstanding area is the introduction of HVDC nodes that enable the current point-to-point connections to be replaced by an integrated grid. In-house RD&D with testing facilities will be important. [modes 2c, 2d] • Much of the RD&D will take place in-house by suppliers of grid infrastructure, but relevant expertise lies in the supply chain, in academic institutions, and in research and technology organisations. Collaborative research will be valuable in bringing the technology to market. [modes 1a, 1b, 2a, 2c] • Market development support to establish a market for internationally traded energy using interconnectors that also connect to offshore wind farms will help. [mode 4]
DC power take-off and array cables	• Beyond what discussed above for HVDC infrastructure, DC power take-off at the turbine does not represent a significant technical challenge, and leading turbine manufacturers have the capability to bring this to market with in-house RD&D, testing and through collaboration with existing suppliers. [modes 2b, 2c, 2d] • DC array cables need further, mainly in-house, RD&D to optimise cost. [mode 2c]
Site layout optimisation	• Layout optimisation requires greater investment than developers can make for a single project, and RD&D enablers can play a valuable role in driving this forward. [mode 2a] • Progress is being made in aspects of site layout optimisation, and there is a valuable role for research and technology organisations and RD&D enablers – in partnership with developers with a significant pipeline of projects – to lead work to consolidate progress and enable benchmarking. [modes 1b, 2a, 2b, 2c]

Note: All areas of innovation require commercial diffusion (mode 5).

7. RECOMMENDATIONS

The eight high-potential-impact technologies can be grouped, as in Table 27: These groupings help define what actions stakeholders should take in order to bring them to market. Of course, technology innovation in many other offshore wind-specific areas and areas not specific to offshore wind also will play an important role in meeting the industry goals discussed. Examples of these are included in Table 29: Beyond these technology developments, there is an important role for regulatory and certification bodies in enabling international collaboration and establishing good practice and common standards.

Table 29: Grouping of technologies

Technologies driven mainly through:	Example technologies
RD&D by established offshore wind industry players	Future generation turbines Repowering of sites HVDC infrastructure DC power take-off and array cables Site layout optimisation Wind resource characterisation Jacket foundation manufacturing Higher-voltage array cables Substation installation Reducing electrical transmission infrastructure High-wind-speed blade installation Quiet foundation piling Onshore turbine pre-commissioning Condition-based maintenance strategies Wind farm-level control strategies
RD&D by newer offshore wind industry players	Floating foundations Airborne wind Integrated turbine and foundation installation Suction bucket foundations Self-installing gravity base foundations Personnel transfer to turbines Remote and automated maintenance solutions
RD&D by players outside the offshore wind industry	Aerodynamic modelling Communications Control theory Electronics Metallurgy Materials Smart grid / energy management and energy storage Tribology Weather forecasting

Technologies driven mainly through RD&D by established offshore wind industry players

Tougher to implement

These technology innovations are likely to be brought to market by established offshore wind industry players which have the experience, capability, market presence and size required to achieve commercialisation.

Policy makers have a key role to play in establishing the market conditions for private investment in RD&D, including market conditions that support demonstration projects for new turbines.

Policy makers and grid operators need to establish frameworks allowing international and interstate supergrid development and associated electricity market arrangements.

There is an argument for imposing conditions on developers of commercial-scale projects, either by governments or landowners, that they incorporate one or more locations where novel technology can be demonstrated.

Research and technology organisations can play an important role in enabling provision of suitable test equipment, recognising that DC technology is relevant also to industries beyond offshore wind.

Research and technology organisations also can help by ensuring that all areas of the industry progress to market in step; for example, there is little value in developing next-generation turbines if required innovations to install them have not been developed.

Research and technology organisations and R&D enablers also need to maintain technology and LCOE roadmaps and to monitor progress, in order to steer R&D focus in an environment of evolving need.

Funders should focus on quantifying the cost of energy impact, the potential market share and the impact on other industry goals of innovations, so that funding has the best chance to have maximum impact. This could be facilitated through the use of simplified cost modelling tools, such as that used by the UK government in recent public competitions for R&D funding (DECC, 2015).

Funders also should maximise the benefit of grant funding for SMEs through an element of funded Incubation support to help progress route to market, undertake benefits analysis, and facilitate relationships with potential customers, partners and investors.

Promotion of collaborative research and RD&D networks will help maximise the LCOE benefit through increased academic and SME involvement, as will public grant funding. The major existing players are likely to draw from the research communities around them, rather than interacting with competitors.

Investors have a key role to play, especially with SMEs which also are likely to seek parallel access to public funding. Again, they can bring strong discipline in focusing on quantifying the LCOE benefit and developing robust routes to market.

Other stakeholders also may have an important role in facilitating onshore and offshore prototype demonstration sites for larger turbines, whether relating to leases, planning approval or other potential constraints. Often the development time for such sites exceeds the time-risk horizon of potential users, such that RD&D can be held up by the lack of sites.

Easier to implement

Some technology innovations driven by established offshore wind industry players can be commercialised without significant cost or disruption. Less direct intervention is needed to support RD&D for this type of RD&D. What is more critical is for policy makers to ensure confidence in a sufficient market to drive activity as a way of driving competitive RD&D and cost reductions. In addition, regulatory activity may be needed to enable repowering of sites, for example regarding extension of leases and planning approvals. Such regulatory changes can take a long time, so early progress is recommended so as not to dampen the market.

Researchers should seek collaboration in order to combine best-in-class thinking and benchmarking between activities to maximise the positive impact on the industry.

There may be limited opportunity for investors to drive activity because there is often a good business case for internally funded RD&D, but investors in projects at different stages of development should be aware of the potential impact on the cost of energy.

RD&D enablers have an important role to play in flagging opportunities, supporting partnerships and facilitating shared learning, both within the industry and from more mature sectors.

Technologies driven mainly through RD&D by newer offshore wind industry players

These technology innovations are likely to be brought to market by newer offshore wind players seeking to disrupt the market.

Established turbine manufacturers and vessel owners have invested significant amounts in product, infrastructure and skills development. Innovations in this group could make such investment redundant, meaning that any market uptake is highly disruptive.

Typically, there is a greater market disconnect at play, and innovations will not be commercialised without intervention.

Policy makers have a key role in creating the market, as discussed above. In addition, they have a role in addressing regulatory issues, for example relating to temporary, very high structures in ports (for integrated turbine and foundation installation) or aircraft and radar issues (for airborne wind).

Due to the number of innovators seeking to progress, RD&D funders will need to pick winners through competitive processes to leverage private investment in part-scale or full-scale prototypes. Such processes need to consider objectively both the quality of innovation (including the impact on the LCOE) and the ability of the organisation (and its potential collaborators) to commercialise.

R&D funding also needs to connect innovators with industry end-users in order to ensure the most direct route to market, taking account of vested interests.

It also is important that RD&D funding balances support for lower-impact, easier-to-implement innovations and game-changing technologies.

Investors also have a key role to play, which evolves from providing high-risk, early funding through to de-risking demonstration and other later-stage activity. Again, they need to bring focus on quantifying the market benefits of technology and communicating these in ways that clients and other investors will relate to.

Other stakeholders also may have an important role in addressing regulatory issues and in facilitating onshore and offshore demonstration.

Technologies driven mainly through RD&D by players outside the offshore wind industry

There are many areas of technology development that positively impact offshore wind, especially with regard to the LCOE (goal A), but that may be driven by players with minimal knowledge of the offshore wind application. This generally is because their technology is used in a wide range of industries.

It is important for policy makers to understand these links, so that a fuller impact of RD&D in these technologies is appreciated in allocating funding and driving relationships between sectors.

As the offshore wind sector grows, it may become increasingly relevant for researchers to understand the demands of the offshore wind application. The same trend relates to components in onshore wind turbines, where the wind industry is now the largest industrial purchaser of a range of technologies including large castings and industrial-grade carbon fibre.

Funders have an important role in facilitating cross-sector collaboration in relevant areas, such that offshore wind benefits from new technologies and the developers of those technologies access a further new market.

Investors in these technologies will benefit from facilitating engagement with the offshore wind industry, especially with stakeholders that can communicate new opportunities widely across the sector.

General recommendations for policy makers

In addition to the recommendations discussed above, policy makers have an important role in creating a climate for investment in technology across the offshore wind industry, which involves:

- Giving as much clarity over the future market size and long-term policy direction as possible, for it is confidence in sustainable market volumes that drives most technology innovation (BVG Associates, 2015a).

- Facilitating competitive environments in which cost-of-energy reduction is both rewarded through the right to deliver new projects and supported through the provision of targeted public R&D funding.
- Ensuring that public R&D funding is targeted on areas of greatest anticipated cost-of-energy impact and supplemented by incubation support to ensure that innovation meets evolving industry needs and reaches market as rapidly as possible.
- Supporting information sharing within the industry, including the establishment of common language and nomenclature with which to define cost elements, to enable comparison of results from different studies.
- Supporting skills development.
- Supporting supply chain development in order to enable commercialisation of technology.

All stakeholders should ensure that they remain fully informed on technology and industry trends and ensure that new technologies are exposed to best practice in the industry. The IRENA's *Innovation Outlook* series, comprising a number of reports such as this one, will help policy makers in this regard.

Policy makers should sustain international collaborations, and IRENA serves as a platform for international co-operation for its Member Countries, as well as for researchers, funders, investors and other stakeholders.

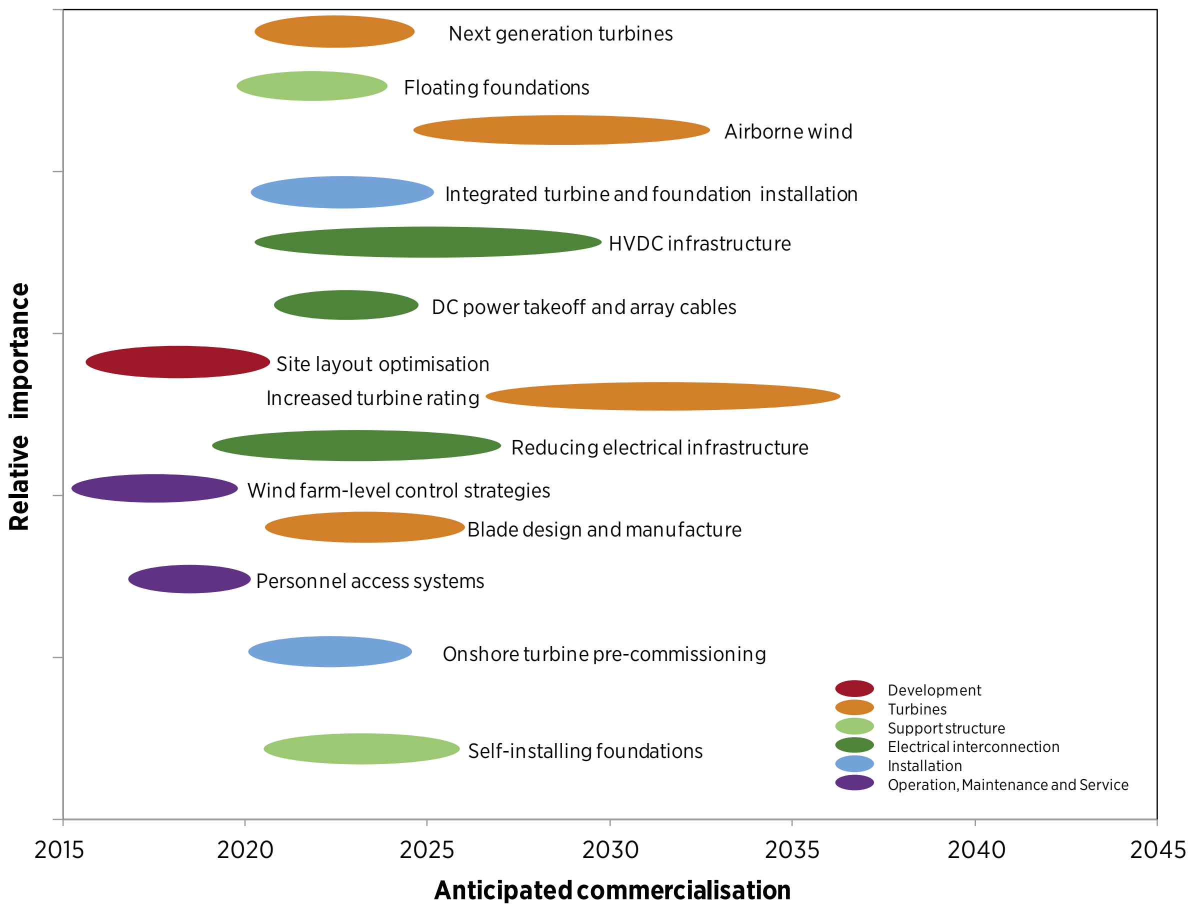
It may be helpful to establish a framework that defines the roles played by different stakeholders, to help maximise the chance of collaboration to facilitate efficient industry development.

To help policy makers understand the expected pace of specific developments, Figure 45 shows a projected commercialisation timeline for the offshore wind supply chain elements.

Key findings

- The RD&D landscape is diverse, with collaborations ranging from purely academic and purely in-house, to corporate initiatives, to various blends between the two.
- There is a role in RD&D for established players and new entrants in delivering in the most high-potential-impact technology innovation areas.
- There also is a role for regulatory and certification bodies in enabling international collaboration and establishing good practice and common standards.
- R&D funders can learn lessons from previous offshore wind activities and other sectors, especially around providing incubation as well RD&D grant funding, and encouraging information sharing.
- One of the most important roles for policy makers is to provide clarity over future markets and to provide stable, predictable policy frameworks. They also have a role in adapting the market to accept some innovations.
- A wide range of innovations will positively impact the sector over the next 30 years, ranging from detailed innovations in underpinning technologies driven by players outside of the sector that will be easily incorporated as a matter of course, to potentially game-changing innovations that need significant regulatory change and new supply chains to implement.

Figure 45: Anticipated timing and relative importance of technology innovations, 2016-2045



Note: Relative importance is judged based on the potential impact of the innovation on the goals discussed in Section 4. See also caveat before Table 27: Repowering of sites, although considered of importance in Table 27, has little technology content and thus is not shown.

REFERENCES

ABB, 2014. ABB launches world´s most powerful underground and subsea power transmission cable system. Press release. Zurich, 21 August. *http://www.abb.com/cawp/seitp202/0cea859b5b6e1776c1257d3b002af564.aspx.*

BOEM, n.d. Lease and grant information. US Bureau of Ocean Energy Management. *www.boem.gov/Lease-and-Grant-Information/ (accessed May 2016).*

BOW (BOW Terminal B.V.), n.d. Breakbulk and offshore wind terminal. *www.bowterminal.nl* (accessed May 2016).

BVG Associates, 2007. UK Offshore Wind: Moving Up a Gear. British Wind Energy Association, London.

BVG Associates, 2011. Offshore Wind: Forecasts of Future Costs and Benefits. RenewableUK, London.

BVG Associates, 2012. Offshore Wind Cost Reduction Pathways Study: Technology Work Stream. The Crown Estate, London.

BVG Associates, 2014. Future Renewable Energy Costs: Offshore Wind. KIC InnoEnergy, Ag Eindhoven, The Netherlands.

BVG Associates, 2015a. Approaches to Cost-Reduction in Offshore Wind. Committee on Climate Change, London.

BVG Associates, 2015b. Offshore Wind Port Readiness Evaluation: Report 1: An Evaluation of 10 Virginia Ports. Virginia Department of Mines, Minerals and Energy, Richmond, Virginia, USA.

BVG Associates, 2015c. Offshore Wind: Delivering More for Less. Statkraft UK, London.

Carbon Trust, 2014. Detailed Appraisal of the Offshore Wind Industry in China. Carbon Trust, London.

Committee on Climate Change, 2015. Power Sector Scenarios for the Fifth Carbon Budget. Committee on Climate Change, London.

DECC, 2015. DECC Offshore Wind Programme: Simple levelised cost of energy model, revision 3. (UK Department of Energy and Climate Change. *www.demowind.eu/LCOE.xlsx* (accessed May 2016).

DNV GL, 2015. WindFarmer wind farm design software. *www.dnvgl.com/windfarmer* (accessed May 2016).

EC Harris, 2012. Offshore Wind Cost Reduction Pathways Study: Supply Chain Work Stream. The Crown Estate, London.

EMEC, 2011. Energy Bag to test at EMEC. European Marine Energy Centre. 15 December. *www.emec.org.uk/energy-bag-to-test-at-emec/.*

Eneco, n.d. Platform lands at Luchterduinen, *www.enecoluchterduinen.nl* (accessed May 2016).

Fitchner and Prognos, 2013. Cost Reduction Potentials of Offshore Wind Power in Germany. Prepared for the German Offshore Wind Energy Foundation and partners. Berlin.

Fraunhofer IWES, 2013. The Importance of Offshore Wind Energy in the Energy Sector and for the German Energiewende. Fraunhofer Institute for Wind Energy and Energy System Technology, Hannover, Germany.

GE Reports, 2015. The world's largest generator keeps the wind turbine operating even during a sea storm. 22 April. *www.gereports.ca/the-worlds-largest-generator-keeps-the-wind-turbine-operating-even-during-a-sea-storm/.*

GWEC, 2015. Global Wind Statistics 2015. Global Wind Energy Council, Brussels.

Hexicon, n.d. *http://www.hexicon.eu* (accessed May 2016).

IEA, 2015. Energy Technology Perspectives 2015: Mobilising Innovation to Accelerate Climate Action. International Energy Agency, Paris.

IRENA, 2015. Renewable Energy Technology Innovation Policy: A Process Development Guide. International Renewable Energy Agency, Abu Dhabi, UAE.

IRENA, 2016. REmap 2030: Roadmap for a Renewable Energy Future, 2016 edition. International Renewable Energy Agency, Abu Dhabi, UAE.

Kite Power Solutions, n.d. *www.kitepowersolutions.com* (accessed May 2016).

Korean Institute for Material Science, n.d.

LORC, n.d. Greater Gabbard Offshore Windfarm. *www.lorc.dk/offshore-wind-farms-map/greater-gabbard* (accessed May 2016).

Makani, n.d. *www.google.com/makani* (accessed May 2016).

MHI Vestas Offshore Wind, 2014. MHI Vestas to ship four V164s. reNEWs. 7 February. *http://renews.biz/69628/mhi-vestas-seals-v164-deal/.*

Nenuphar, n.d. *www.nenuphar-wind.com/en* (accessed May 2016).

OffshoreWIND.biz, n.d. Buyers guide A2Sea. *http://www.offshorewind.biz/tag/a2sea/* (accessed May 2016).

ORE Catapult, 2016. Cost Reduction Monitoring Framework 2015: Qualitative Summary Report. Offshore Renewable Energy Catapult, Glasgow, Scotland, UK.

PriceWaterhouseCoopers et al., 2015. Cost Reduction Options for Offshore Wind in the Netherlands FID 2010-2020. TKI Wind op Zee, Utrecht, The Netherlands.

RenewableUK, 2012. Potential for Offshore Transmission Cost Reductions – A Report to The Crown Estate. The Crown Estate, London.

Scottish Energy News, n.d. Mabey Bridge lands deal for 30 onshore wind turbine towers with Holland's EWT. *http://www.scottishenergynews.com/mabey-bridge-lands-deal-for-30-onshore-wind-turbine-towers-with-hollands-ewt/.*

Siemens, 2011. New AC grid access solution from Siemens: lighter, faster, cheaper. Press release. Copenhagen, 11 March, *www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2015/energymanagement/pr2015030151emen.htm&content%5b%5d=EM.*

Siemens, 2012a. *www.siemens.com/press/pool/de/pressebilder/2012/photonews/300dpi/PN201204/PN201204-01_300dpi.jpg* (accessed May 2016).

Siemens, 2012b. *www.siemens.com/press/pool/de/pressebilder/2012/photonews/300dpi/PN201209/PN201209-01_300dpi.jpg* (accessed May 2016).

Siemens, 2013. *http://www.siemens.com/press/en/presspicture/?press=/en/presspicture/pictures-photonews/2013/pn201301.php* (accessed May 2016).

Siemens, 2014. SCOE – Society's Costs of Electricity: How Society Should Find Its Optimal Energy Mix. Siemens Wind Power, Brande, Denmark.

Siemens, 2015. Fathoming new depths with service vessels. *http://www.energy.siemens.com/hq/en/energy-topics/energy-stories/sov.htm* (accessed May 2016).

Siemens, n.d. Pioneering wind farm off the Suffolk coast opened officially by UK Energy Minister. Press release. Frimley, UK, 7 August. *www.siemens.co.uk/en/news_press/index/news_archive/2013/greater-gabbard-offshore-wind-farm-opened-by-michael-fallon.htm.*

Think Defence, 2013. An offshore problem. 7 April. *www.thinkdefence.co.uk/2013/04/an-offshore-problem/.*

Thomson, Camilla R., Harrison, Gareth P., 2015. Life Cycle Costs and Carbon Emissions of Wind Power – Executive Summary. ClimateXChange, Edinburgh, Scotland, UK.

University of Strathclyde, 2015. Large scale offshore wind energy systems the multi-rotor solution. Poster presented by Jamieson, P., Chaviaropoulos, P.K., Voutsinas, S. University of Strathclyde, Glasgow, Scotland, UK.

US DOE, 2014. Top 10 things you didn't know about offshore wind energy. US Department of Energy, 6 May. *http://energy.gov/articles/top-10-things-you-didn-t-know-about-offshore-wind-energy.*

WindEurope, 2011. UpWind: Design Limits and Solutions for Very Large Wind Turbines. European Wind Energy Association, Brussels.

WindEurope, 2013. Deep Water: The Next Step for Offshore Wind Energy. European Wind Energy Association, Brussels.

APPENDIX A:

Inventory of operating offshore wind farms

Table 30 shows the characteristics of the wind farms commissioned between 2001 and 2015 with a project size of 30 MW or larger. Earlier or smaller projects have been omitted from this list due to their status as demonstration projects.

The average water depth is for the lowest astronomical tide (LAT) at the site. All wind speeds listed are the annual average at 100 metres above mean sea level. The port distances are to OMS port.

Table 30: Inventory of operating offshore wind farms[1]

Year of commissioning	Country	Project name	Project capacity (MW)	Individual turbine rating (MW)	Average water depth (m)	Average distance from port (km)	Average wind speed (m/s)
2001	DK	Middlegrunden	40	2	4.5	3	7.8
2002	DK	Horns Rev 1	160	2	17	30	9.9
2003	DK	Samsø	23	2.3	12	8	9.0
2003	DK	Rødsand I (Nysted)	165.6	2.3	7	20	9.0
2003	UK	North Hoyle	60	2	12	18	8.8
2004	UK	Scroby Sands	60	2	7.5	8	9.1
2005	UK	Kentish Flats	90	3	5	9	8.8
2006	UK	Barrow	90	3	18	13	9.8
2007	NL	Egmond aan Zee	108	3	6	30	9.8
2007	SE	Lillgrund	110.4	2.3	6	1	9.0
2007	UK	Burbo Bank	90	3.6	5	15	8.9
2008	BE	Thornton Bank 1	30	5	28	30	10.2
2008	NL	Prinses Amaliawindpark	120	2	22	30	9.9
2008	UK	Inner Dowsing	97.2	3.6	18	60	9.3
2008	UK	Lynn	97.2	3.6	18	60	9.3
2009	DK	Horns Rev 2	209.3	2.3	18	30	9.9
2009	UK	Gunfleet Sands	108	3.6	8	20	9.1
2009	UK	Gunfleet Sands 2	64.8	3.6	13	21	9.2
2009	UK	Rhyl Flats	90	3.6	9.5	31	8.6
2009	UK	Robin Rigg East	90	3	10	14	9.5
2010	BE	Bligh Bank (Belwind) Phase I	165	3	26	40	10.2
2010	CH	Donghai Bridge	102	3	7	4	7.5
2010	DK	Rødsand II	207	2.3	9	9	9.0
2010	UK	Robin Rigg West	90	3	10	14	9.5
2010	UK	Thanet	300	3	22.5	13	9.4
2011	CH	Rudong Intertidal 1A	102	2.3	4.5	4	7.5
2011	CH	Rudong Intertidal 1B	48.3	3	4.5	4	7.5
2011	DE	Baltic 1	48.3	2.3	17	16	8.8
2011	DE	Bard 1	400	5	40	87	10.0
2011	UK	Greater Gabbard	504	3.6	29	62	9.8
2011	UK	Ormonde	150	5	19.5	24	9.8
2011	UK	Sheringham Shoal	316.8	3.6	19	26	9.7

Year of commissioning	Country	Project name	Project capacity (MW)	Individual turbine rating (MW)	Average water depth (m)	Average distance from port (km)	Average wind speed (m/s)
2011	UK	Walney 1	183.6	3.6	26	34	10.0
2011	UK	Walney 2	183.6	3.6	26	34	10.1
2012	BE	Thornton Bank 2	147.6	6.15	20	28	10.2
2012	CH	Rudong Intertidal 2A	50	2.5	4.5	4	7.5
2012	CH	Rudong Intertidal Extension	60	2.5	4.5	4	7.5
2012	DK	Djursland Anholt	399.6	3.6	17	18	8.8
2012	UK	Lincs	270	3.6	13	58	9.3
2012	UK	London Array 1	630	3.6	13	40	9.5
2012	UK	Teesside	62.1	2.3	11	7	8.2
2013	BE	Thornton Bank 3	147.6	6.15	20	28	10.2
2013	DE	Meerwind Ost/Sud	288	3.6	24	23	9.8
2013	SE	Kårehamn	48	3	22.5	9	8.7
2013	UK	Gwynt y Môr	576	3.6	23	28	9.2
2014	BE	Northwind (Bank zonder Naam/ Eldepasco)	216	3	21	37	10.2
2014	DE	Borkum Riffgat	108	3.6	18	14.5	9.9
2014	DE	Borkum West II phase 1 (Trianel)	200	5	30	65.6	9.9
2014	DE	Butendiek	288	3.6	19	34	10.0
2014	DE	Dan Tysk	288	3.6	27	70	10.0
2014	DE	Global Tech 1 1	200	5	32	77	10.0
2014	DE	Global Tech 1 2	200	5	40	77	10.0
2014	DE	Nordsee Ost	295.2	6.15	23.5	38	9.8
2014	UK	West of Duddon Sands	388.8	3.6	18.5	28	10.0
2015	DE	Amrumbank West	288	3.6	23	40	9.8
2015	DE	Baltic 2a (previously Kriegers Flak 1)	140.4	3.6	30	32	8.8
2015	DE	Borkum Riffgrund 1	312	4	26	34	9.9
2015	UK	Humber Gateway	219	3	14.5	42	9.5
2015	UK	Westermost Rough	210	6	20	36	9.5

1 *BE: Belgium; CH: Switzerland; DE: Germany; DK: Denmark; NL: Kingdom of the Netherlands; SE: Sweden; UK: United Kingdom of Great Britain and Northern Ireland*

APPENDIX B:

Key actors in offshore wind

This appendix describes key actors in the offshore wind industry. It includes companies, government agencies, private institutions and public institutions that play important roles within key markets in Asia, Europe and North America. It considers workshop test facilities, but not onshore or offshore sites for the operational testing and demonstration of turbines and other wind farm components. The list is not exhaustive, as there are many organisations involved across the various offshore wind technology elements. Main focus areas follow the elements used throughout the report, but other categories introduced are:

- Enabler for government and other bodies that do not supply services directly to wind farms
- Finance
- R&D for research and technology organisations and universities.

Table 31: Key actors in offshore wind[1]

Actor	Country	Type of organisation	Description	Main area of focus
A2SEA	DK	Company	Supplier of foundation and turbine transport and installation, and O&M logistics for offshore wind farms.	Installation OMS
Aalborg University	DK	Academic	Involved in the research of floating foundation and other offshore wind technologies.	R&D
ABB	CH	Company	Supplier of electrical components, such as transformers for onshore and offshore substations. Also works in other sectors.	Electrical interconnection
ADEME	FR	Government / public agency	Broad mandate that includes oversight of offshore wind energy.	Enabler
Adwen	FR/ES/DE	Company	Manufacturer of offshore wind turbines. Joint venture between Areva and Gamesa.	Turbine
American Bureau of Shipping	US	Company	Provider of ship classification services.	Installation
BHS (Federal Maritime and Hydrographic Agency)	DE	Government / public agency	Responsible for the leasing of the seabed and for planning approval of maritime activities, including shipping, tourism and offshore wind farms.	Enabler
Bilfinger Mars Offshore	PL	Company	Manufacturer of jackets, monopiles and transition pieces for offshore wind farms.	Foundation
Bladt	DK	Company	Manufacturer of jacket foundations and transition pieces for offshore wind farms. Also supplies other sectors.	Foundation
Bureau of Ocean Energy Management (BOEM)	US	Government / public agency	Responsible for the leasing of the seabed for maritime activities, including oil and gas and offshore renewable energy.	Enabler
CENER	ES	RTO	Research institute with turbine blade and drivetrain test facilities. Research areas cover wind, solar and biomass energy.	RD&D

Actor	Country	Type of organisation	Description	Main area of focus
China Huaneng Group	CN	Company	State-owned developer of Chinese offshore wind projects.	Wind farm development OMS
China Longyuan Power Group Corporation	CN	Company	Developer of solar, biomass, geothermal and wind energy. To date onshore wind has been more of a focus, but the company is expected to develop more offshore wind farms in China.	Wind farm development OMS
China Shipbuilding Industry Corporation	CN	Company	Shipbuilder and supplier of installation vessels. Also owns Haizhuang offshore wind turbine company.	Installation vessels Turbine
China Three Gorges	CN	Company	Primarily develops and operates hydropower plants, although it also develops wind projects and pumped storage power station. Has invested in a European offshore wind project.	Wind farm development OMS
Class NK	JP	Company	Provider of ship classification services.	Installation
Clemson University	US	Academic	University with turbine drivetrain test facilities.	RD&D
CREII (China Renewable Energy Engineering Institute)	CN	Public institution	Policy, research and information service centre supporting standards and international collaboration.	RD&D Enabler
CRIST Shipyard	PL	Company	Shipbuilder and supplier of vessels for offshore wind farm construction and servicing.	Installation OMS
CT Offshore	DK	Company	Supplier of array cable installation for offshore wind farms.	Electrical interconnection
Cwind	UK	Company	Supplier of PTVs and personnel to offshore wind farms. Works across onshore and offshore wind, although offshore wind is the core activity.	Installation OMS
DTU	DK	Academic	University involved in the research of offshore wind technologies.	RD&D
DBB Jack-up	DK	Company	Supplier of specially designed vessels for major component replacement for offshore wind farms.	OMS
Deepwater Wind	US	Company	Developer of offshore wind projects, including the first offshore wind farm installed in the United States.	Wind farm development
DEIF	DK	Company	Supplier of SCADA-systems for remote monitoring and control of onshore and offshore wind farms.	Turbine OMS
DNV GL	NO	Company	Provider of energy and marine classification services and technical consultancy.	Most areas
Dong Energy	DK	Company	Utility developer of wind and thermal power projects and oil and gas exploration and production. Offshore wind is a core activity, with projects across Europe and rights to develop in the United States.	Wind farm development OMS
E.ON Climate and Renewables	DE	Company	Developer of wind, biomass and marine renewable energy projects. Offshore wind is a core activity, with projects across Europe.	Wind farm development OMS

Actor	Country	Type of organisation	Description	Main area of focus
Ecole Centrale de Nantes	FR	Academic	University involved in the research of floating foundation technology. Also involved in the research of other offshore wind technologies.	R&D
ECN	NL	RTO	Research institute focusing on energy systems, including offshore wind.	R&D
EDF Energies Nouvelles	FR	Company	Utility developer of wind and solar projects across Europe. Parent company EDF Energy is a key developer of nuclear projects in the UK.	Wind farm development OMS
EDP Renewables	ES	Company	Developer of wind projects in Europe and North America.	Wind farm development OMS
Energinet.dk	DK	Government / public agency	Transmission operator. Also funds related RD&D.	Enabler Electrical interconnection
European Commission	Europe	Inter-governmental agency	Inter-governmental agency that co-ordinates and supports research and innovation.	Enabler
European Investment Bank	Europe	Public institution	Bank of the European Union which makes investments in a range of sustainable projects, including offshore wind.	Finance
Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB)	DE	Government / public agency	Responsible for producing and implementing energy development plans and industrial policies. The ministry is concerned primarily with climate policy, conserving the diversity of fauna and flora, efficient use of resources and energy as well as protecting people's health from environmental pressures.	Enabler
Fraunhoffer IWES	DE	RTO	Research institute focusing on wind energy systems technology. It also has blade and drivetrain test facilities.	RD&D
Fred Olsen	NO	Company	Parent company of several key players in offshore wind, including OMS, installation, foundations and fabrication.	Foundation Installation OMS
GE Grid Solutions	FR	Company	Supplier of electrical components, such as transformers for onshore and offshore substations. Also works in other sectors.	Electrical interconnection
GE-Alstom	US	Company	Manufacturer of onshore and offshore wind turbines. Alstom was acquired by GE in 2015.	Turbine
GeoSea	BE	Company	Supplier of foundation, turbine, export cable and array cable installation and personnel for offshore wind farms. Also works in other sectors.	Installation
Goldwind	CN	Company	Manufacturer of onshore and offshore wind turbines.	Turbine
Guangdong Electric Power Design Institute	CN	Company	Project development, electrical system design, foundation selection and design, and overall project management.	Wind farm development

Actor	Country	Type of organisation	Description	Main area of focus
Hitachi Zosen	JP	Company	Designer and developer of floating offshore wind farms. Also works in other sectors.	Wind farm development Foundation
Iberdrola	ES	Company	Developer and operator of renewables, hydroelectric, nuclear, coal and natural gas combined-cycle power plants.	Wind farm development OMS
JDR Cable Systems	UK	Company	Supplier of array cables for offshore wind farms. Also works in other sectors.	Electrical interconnection
Jiangsu Longyuan Zhenhua Marine Co	CN	Company	Designer and supplier of offshore wind installation vessels and equipment and foundations.	Foundation Installation vessels and equipment
KIMS-WTRC	KR	RTO	Research institute with facilities for blade testing. It includes the Wind Turbine Technology Research Center (WTRC).	RD&D
Knowledge Centre WMC	NL	RTO	Research institute with facilities for blade testing. Works in the wind, tidal, offshore oil and gas, marine, civil engineering and automotive industries.	RD&D
Lloyds Register	UK	Company	Provider of energy and marine classification services.	Most areas
LORC	DK	RTO	Research institute with facilities for drivetrain testing. Focused on offshore renewables.	RD&D
LS Cables	KR	Company	Supplier of export and array cables to offshore wind farms. Also works in other sectors.	Electrical interconnection
Massachusetts Clean Energy Center's Wind Technology Testing Centre (MassCEC WTTC)	US	RTO	Research institute with facilities for blade testing. Works across onshore and offshore wind.	RD&D
MHI Vestas	DK	Company	Manufacturer of offshore wind turbines but not onshore wind turbines. Joint venture between MHI and Vestas.	Turbine
MingYang	CN	Company	Manufacturer of onshore and offshore wind turbines.	Turbine
Ministry of Economic Affairs	NL	Government / public agency	Responsible for producing and implementing energy development plans and industrial policies.	Enabler
Ministry of Economy, Trade and Industry (METI)	JP	Government / public agency	Responsible for producing and implementing energy development plans and industrial policies.	Enabler
MPI Offshore	NL	Company	Supplier of foundation and turbine installation and personnel for offshore winds.	Installation
National Energy Administration (NEA)	CN	Government / public agency	Responsible for producing and implementing energy development plans and industrial policies, including for coal, oil, natural gas, nuclear and renewable energy.	Enabler

Actor	Country	Type of organisation	Description	Main area of focus
NREL	US	RTO	Research institute focusing on renewable energy. It includes the National Wind Technology Center (NWTC).	RD&D
Nexans	FR	Company	Supplier of export and array cables to offshore wind farms. Also works in other sectors.	Electrical interconnection
NKT	DE	Company	Supplier of export and array cables to offshore wind farms. Also supplies to other sectors.	Electrical interconnection
Offshore Renewable Energy (ORE) Catapult	UK	RTO	Research institute with capacity for turbine blade and drivetrain test facilities. Offshore wind is a core activity alongside tidal and wave device testing.	RD&D
Planning Inspectorate / Marine Scotland	UK	Government / public agency	Responsible for examining planning applications for nationally significant infrastructure projects.	Enabler
Powerchina Huadong	CN	Company	Large state-owned engineering business active in wind farm design and survey.	Wind farm development
Principle Power	US	Company	Designer of floating offshore wind foundation.	Foundation
Prysmian	IT	Company	Supplier of export and array cables to offshore wind farms. Also works in other sectors.	Electrical interconnection
Romax Technology	UK	Company	Supplier of software and predictive maintenance services to onshore and offshore wind farms. Also works in other sectors.	Turbine OMS
RWE Innogy	DE	Company	Utility developer of wind, hydro, solar and biomass projects in Europe. Offshore wind is a core activity.	Wind farm development OMS
SDIC (State Development and Investment Corporation)	CN	Company	State-owned investment holding company that has invested in European offshore wind projects.	Investment
Seajacks	UK	Company	Supplier of foundation and turbine installation and personnel for offshore wind farms. Also works in other sectors.	Installation
Senvion	DE	Company	Manufacturer of onshore and offshore wind turbines.	Turbine
SEwind	CN	Company	Manufacturer of onshore and offshore wind turbines.	Turbine
Shanghai Investigation, Design & Research Institute	CN	Company	Large technical institute active in wind farm design and survey.	Wind farm development
Siemens Power Transmission	DE	Company	Supplier of electrical components, such as transformers for onshore and offshore substations. Also works in other sectors.	Electrical interconnection
Siemens Wind Power	DE	Company	Manufacturer of onshore and offshore wind turbines.	Turbine
SIF Group / Smulders	NL/BE	Company	Manufacturers of monopiles and transition pieces for offshore wind farms. Both companies also supply to other sectors.	Foundation
Sintef	NO	RTO	Research institute with wind energy team and energy laboratories.	RD&D

Actor	Country	Type of organisation	Description	Main area of focus
Statkraft	NO	Company	Developer of wind, hydropower and natural gas projects. Offshore wind is a core activity.	Wind farm development OMS
Statoil	NO	Company	Designer of floating offshore wind foundation. Also develops energy projects including offshore wind farms.	Wind farm development Foundation OMS
The Crown Estate	UK	Government / public agency	Leaser of the seabed for marine activities, including wind, wave and tidal power, carbon capture and storage, gas storage, marine aggregates and minerals, cables and pipelines.	Enabler
The Department for Business, Energy & Industrial Strategy (BEIS)	UK	Government / public agency	Responsible for producing and implementing energy development plans, industrial policies, subsidy mechanisms and tariffs (formerly the Department of Energy and Climate Change (DECC).	Enabler
University of Maine	US	Academic	University involved in the research and design of floating offshore wind foundations. Also involved in the research of other offshore wind technologies.	RD&D
University of Stuttgart	DE	Academic	Involved in research on floating foundation technology and other offshore wind technologies.	R&D
University of Tokyo	JP	Academic	Involved in research on floating foundation technology and other offshore wind technologies.	R&D
US Department of Energy	US	Government / public agency	Responsible for funding RD&D in electric power, energy sources and efficiency, science education and climate change. The Department of Energy Wind Program is committed to developing and deploying a portfolio of innovative technologies for clean, domestic power generation to support an ever-growing industry, targeted at producing 20% of US electricity by 2030.	Enabler
Van Oord	NL	Company	Supplier of foundation, turbine, export cable and array cable installation for offshore wind farms. Also works in other sectors.	Installation
Vattenfall	SE	Company	Developer of biomass, coal, hydro, natural gas, nuclear and wind projects. Offshore wind is a core activity.	Wind farm development OMS
VBMS	NL	Company	Supplier of export and array cable installation for offshore wind farms. Also works in other sectors.	Installation
Wpd	DE	Company	Developer of onshore and offshore wind farms.	Wind farm development OMS
Zhongtian Technology Submarine Cable Co.	CN	Company	Supplier of offshore wind farm cables. Market leader in China for 200 kV cables.	Electrical cables

1 *BE: Belgium; CH: Switzerland; DN: China; DE: Germany; DK: Denmark; FR: France; IT: Italy; JP: Japan; KR: the Republic of Korea; ES: Spain; NL: Kingdom of the Netherlands; NO: Norway; PL: Poland; SE: Sweden; UK: United Kingdom of Great Britain and Northern Ireland; US: United States of America.*

APPENDIX C:

Levelised cost of electricity

Underpinning the study of the cost reduction potential for offshore wind, there is a robust method of calculating the LCOE from wind farm element costs, energy production, wind farm life and WACC. The formula for calculating the LCOE is described in Section C.1. The definitions of each cost element and the assumptions underpinning the analysis are presented in Sections C.2 to C.4. A summary of results for projects commissioned in years 2001, 2015, 2030 and 2045 are provided in Section C.5.

The values used for the cost of each wind farm element, energy production, wind farm life and WACC for the baselines in this study were based on a combination of the following:

- Data presented in the references to this study, plus the background data gathered for the subset of these studies that were undertaken by BVG Associates.
- Further insight from a detailed study comparing results from other analyses:
  - *The Crown Estate Offshore Wind Cost Reduction Pathways Study: Technology Work Stream*, BVGA for The Crown Estate (BVG Associates, 2012)
  - *The Crown Estate Offshore Wind Cost Reduction Pathways Study: Supply Chain Work Stream*, EC Harris and BVGA for The Crown Estate (EC Harris, 2012)
  - *Potential for Offshore Transmission Cost Reductions*, RenewableUK for The Crown Estate, 2012 (Renewable UK, 2012)
  - *Cost Reduction Potentials of Offshore Wind Power*, Fichtner and Prognos for The German Offshore Wind Energy Foundation, 2013 (Fitchner and Prognos, 2013)
  - *The Importance of Offshore Wind Energy in the Energy Sector and for the German Energiewende*, Fraunhofer Institute for Wind Energy and Energy System Technology (Fraunhofer IWES, 2013)
  - *Future Renewable Energy Costs: Offshore Wind*, BVGA for KIC InnoEnergy, May 2014 (BVG Associates, 2014)
  - *Offshore Wind: Delivering More for Less*, BVGA for Statkraft (BVG Associates, 2015)
  - *Approaches to Cost-Reduction in Offshore Wind*, BVGA for the Committee on Climate Change (BVG Associates, 2015a)
  - *Cost Reduction Options for Offshore Wind in the Netherlands FID 2010-2020*, PwC, DNV GL/Ecofys for TKI Wind op Zee, 2015 (PriceWaterhouseCoopers et al., 2015)
  - *Cost Reduction Monitoring Framework 2015: Qualitative Summary Report*, Offshore Renewable Energy Catapult. (ORE Catapult, 2016)
- Engineering-based models provided to BVG Associates by a range of industry players or established in-house, based on industry engagement.
- Publicly stated cost points for specific wind farm elements on specific projects.
- Trends in wind farm element costs and LCOE against key parameters, established over time.
- In-house processes to moderate and rationalise data.
- Feedback from senior industry contacts on costs and cost breakdowns.

As an example, the cost of installation of a jacket foundation on the intermediate deep site is based on:

- Industry feedback on current preferred processes and vessel types.
- An in-house model taking into account vessel and equipment day rate costs based on industry dialogue.
- Typical times for different operations involved in installing the foundation that depend on key site parameters, including mobilisation/demobilisation, load-out, transit, waiting for weather, positioning and different elements of the physical installation process.

Likewise, the impacts of opportunities on the cost of each wind farm element, energy production, wind farm life and WACC for the different sites for projects commissioned in 2030 and 2045 are based on:

- Quantitative and qualitative dialogue with senior industry figures to understand the drivers of cost of energy reductions.
- In-house models established to explore the impact of innovation on cost of energy.
- Publicly available material, both providing top-down perspectives and bottom-up detail on specific opportunities for cost reduction.
- In-house processes to moderate and rationalise data in order to provide a balanced and robust forward view.

The interested reader is pointed to *The Crown Estate Offshore Wind Cost Reduction Pathways Study: Technology Work Stream* (BVG Associates, 2012) for further information on the underpinning methodology.

C.1: Definition

Levelised cost of electricity (or LCOE or "cost of energy") is defined as the revenue required (from whatever source) to earn a rate of return on investment equal to the discount rate (also referred to as the WACC) over the life of the wind farm. Tax and inflation are not modelled. The technical definition is:

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

Where:

I_t	investment expenditure in year
M_t	operations and maintenance expenditure in year
E_t	energy generation in year
r	discount rate; and
n	lifetime of the project in years.

C.2: Element definitions

Definitions of the scope of each element are provided in Table 32:

Table 32: Definitions of the scope of each element

Type	Element	Definition	Unit
CAPEX	**Development**	Development and other work to obtain planning approval paid for by the developer up to the point of works completion date (WCD). Includes: • Internal and external activities such as environmental and wildlife surveys, met mast (including installation) and engineering (pre-FEED) and planning studies up to FID • Further site investigations and surveys after FID • Engineering (FEED) studies • Environmental monitoring during construction • Project management (work undertaken or contracted by the developer up to WCD) • Other administrative and professional services such as accountancy and legal advice, and • Any reservation payments to suppliers. Excludes: • Construction phase insurance • Suppliers own project management.	USD/MW

Type	Element	Definition	Unit
CAPEX	**Turbines (including tower)**	Payment to wind turbine manufacturer for the supply of nacelles and their sub-systems, the blades and hub, and the turbine electrical systems to the point of connection to the array cables. Includes: • Delivery to nearest port to supplier • Five-year warranty • Commissioning costs. Excludes: • O&M costs • RD&D costs.	USD/MW
	Foundations	Includes: • Payment to suppliers for the supply of the support structure comprising the foundations (including any anchors, transition piece and secondary steel work such as J-tubes and personnel access ladders and platforms) and the tower • Delivery to nearest port to supplier • Warranty. Excludes: • OMS costs • RD&D costs.	USD/MW
	Electrical interconnection	Includes: • Array cables and connectors • Export cables and connectors • Substation and its foundation • All materials delivered to nearest port to supplier (ex-works) • Installation of export cables substation (transmission assets) • Contingency and warranty. Excludes: • OMS costs • RD&D costs.	USD/MW
	Installation	Includes: • Transportation of all from each supplier's nearest port • Pre-assembly work completed at a construction port or other construction area before the components are taken offshore • All installation work for support structures, turbines and array cables • Commissioning work for all but turbine (including snagging post-WCD) • Scour protection (for support structure and cable array) • Subsea cable protection mats etc., as required • Contingency expected to be spent due to unforeseen factors up to works completion, but not assigned to a particular item. Excludes: installation of electrical connection (covered above)	USD/MW

Type	Element	Definition	Unit

OPEX	**OMS**	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
		• Reactive service in response to unplanned systems failure in the turbine or electrical systems.
		• O&M activities for the electrical connection
		• Fixed cost elements that are unaffected by technology innovations, including:
		  • Contributions to community funds
		  • Monitoring of the local environmental impact of the wind farm.
			USD/MW/yr

AEP	**Gross AEP**	The gross AEP is the forecast output of the turbines averaged over the wind farm life. Excludes aerodynamic array losses, electrical array losses and other losses. Includes any site air density adjustments from the standard turbine power curve.	MWh/yr/MW
	Losses	Includes: • Lifetime energy loss from cut-in / cut-out hysteresis, power curve degradation, and power performance loss • Wake losses • Electrical array losses to the offshore metering point • Losses due to lack of availability of wind farm elements. Excludes: electrical connection losses from substation to shore.	%
	Net AEP	The net AEP averaged over the wind farm life at the offshore metering point at entry to offshore substation.	MWh/yr/MW
Other		Financing costs and other non-technological issues, including project life, competition and other supply chain levers such as levels of competition in the supply chain.	
Decoommissioning		Decommissioning reverses the assembly process taking one year. Piles and cables are cut off at a depth below the seabed, which is unlikely to lead to uncovering. Environmental monitoring is conducted at the end. The residual value and cost of scrapping is ignored.	USD/MW

C.3: Site and technology definitions

Baseline costs and the impact of innovations are based on the typical site characteristics and technologies defined in Table 33 and the assumptions below the table. The choice of typical site characteristics and technologies was based on projects installed in the years around 2001 and 2015, then based on a view of the global market, looking forward.

It is recognised that there will be a range of site characteristics and technologies used on the range of projects commissioned at any given time. The technologies stated are anticipated to be ones used for a project with the site characteristics stated. As an example, in 2015, there also were projects with HVDC transmission, but these were on sites where the distance to the point of grid connection was greater than the typical stated in the table.

Table 33: *Typical site characteristics and technologies.*

Year of commi-ssioning	Average water depth (LAT) (m)	Distance to near-est construction and operation port and point of grid connection (km)	Average wind speed at 100 m above MSL (m/s)	Mainte-nance strategy	Trans-mission	Turbine rating (MW)	Rotor size (m)	Foun-dation type	Farm size (MW)
2001	10	20	9.0	Shore-based	HVAC	2	80	Mono-pile	60
2015	25	40	9.8	Shore-based	HVAC	5	134	Mono-pile	300
2030	35	60	9.7	Off-shore-based	HVAC	10	190	Jacket	1 000
2045	40	70	9.6	Off-shore-based	HVAC	14	225	Jacket	1 500

Global assumptions

- Real (end-2015) prices, assuming European cost base (as this is where by far the greatest experience is available). It is recognised that over time, the geographical spread is anticipated to increase. As this report is focused on the impact of technology, the change in supply chain costs due to the geographical diversification is not modelled. It is anticipated that the increase in spread to incorporate markets with lower supply chain costs could further decrease the LCOE.
- Commodity and exchange rates at the average for 2015, except where explicitly discussed, and macroeconomic conditions unchanged between 2015 and 2045.

Development

- Turbines are spaced at nine rotor diameters (downwind) and six rotor diameters (across-wind) in a rectangle.
- With an increasing density of offshore wind farms, there is potentially a shading effect. This analysis assumes that this is primarily an issue for German developments and is not considered significant globally in the long term.
- The lowest point of the rotor sweep is at least 22 m above MHWS.
- The development and installation costs are funded entirely by the project developer.

Metocean

- A wind shear exponent of 0.12.
- Rayleigh wind speed distribution (Weibull distribution with shape factor, k = 2).
- No storm surge is considered.

Projects with commissioning in 2015

- Turbines are certificated to Class IA of international offshore wind turbine design standard IEC 61400-3. They have a three-bladed upwind rotor, a mid-speed gearbox, a mid-speed permanent magnet generator and a full-span power converter.
- Ground conditions are "typical" for sites in Europe, namely 10 m dense sand on 15 m stiff clay, only occasionally with locations with lower bearing pressure, the presence of boulders or significant gradients.
- Array cables of three core 33 kV AC in fully flexible strings are used, with provision to isolate an individual turbine.
- Installation is carried out sequentially by the foundation, array cable, then the pre-assembled tower and turbine in a five-lift operation. A jack-up vessel collects components from the construction port for turbine installation. A single jack-up is used for monopile installation and for collecting components from the construction port. Array cables are installed via J-tubes, with separate cable lay and survey and burial.
- OMS access is by PTVs, while jack-ups are used for major component replacement.

C.4: CAPEX spend profile

The spend profile of the CAPEX is as defined in Table 34:

Table 34: CAPEX spend profile.

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

Year 1 is defined as the year of first full generation.

AEP and OPEX are assumed as constant for each year during the lifetime of the plant.

C.5: Element cost breakdown

The values of the cost elements and other relevant parameters in 2001, 2015, 2030 and 2045 are given in Table 35:

In addition to Figure 8 (for 2001) and Figure 9 (for 2015), the contribution to the cost of energy is shown in Figure 31 and Figure 32 for 2030 and 2045. Note that the value for decommissioning is given as the cost at the end of life rather than the discounted value.

Table 35: Breakdown by cost element in different years.

Element		2001	2015	2030	2045
Development	USD/MW	144 000	128 000	59 000	48 000
Turbine	USD/MW	1 024 000	1 952 000	1 651 000	1 580 000
Foundations	USD/MW	538 000	771 000	702 000	649 000
Electrical interconnection	USD/MW	443 000	754 000	645 000	617 000
Installation	USD/MW	1 095 000	829 000	395 000	238 000
Contingency	USD/MW	184 000	368 000	294 000	272 000
CAPEX	USD/MW	3 430 000	4 800 000	3 750 000	3 400 000
OPEX	USD/MW/yr	235 000	135 000	75 000	55 000
Decommissioning	USD/MW	680 000	623 000	536 000	51 000
Net capacity factor		35%	46%	50%	52%
WACC		12.0%	9.0%	7.5%	6.8%
Lifetime	yr	20	22	28	32
LCOE	USD/MWh	240	170	95	74

APPENDIX D:

Patent, journal and conference paper activity

This appendix describes the analysis of patents, journal articles and conference papers. The analysis informs the choice of technology innovations described in the main report, especially Section 5.

Evaluation of the patent landscape offers a historical perspective on technology development and provides visibility to future technologies which are under development but are not yet commercialised. The remainder of such future technology intelligence comprises other sources such as conference proceedings, technical papers and journal publications that are indicative of technology opportunities.

Patent tracking and analysis provides a proxy for the level of R&D investment made in certain innovations. It is important, however, to combine all sources when analysing the evolution of technology and predicting future trends so that the patent analysis can be understood in a larger context.

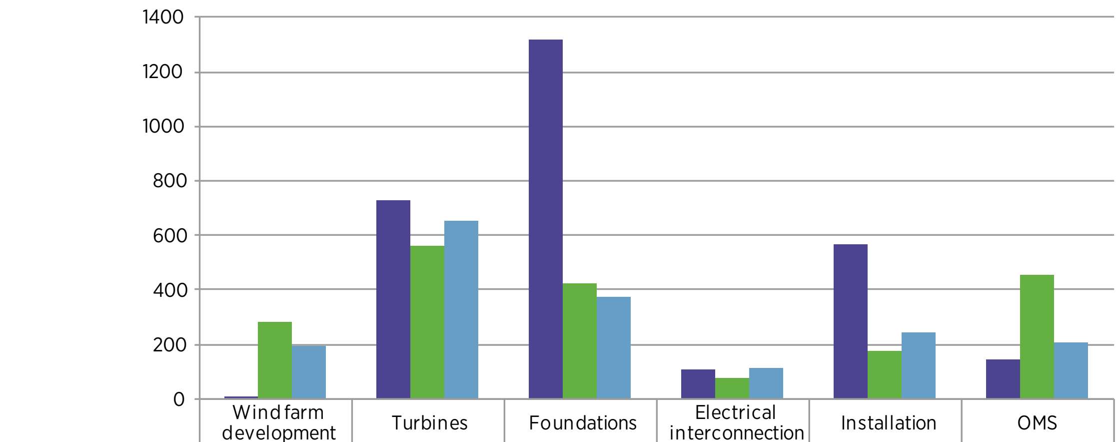
Supporting references

The patent landscape in wind is comprised of over 40 000 global patent filings which bear relevance to mainstream horizontal-axis, utility-scale turbine technology. Currently, offshore-specific patent filings comprise only 7% of the global patent filings in wind, with a total of 2 867 global patent filings.

Additionally, 1 972 journal publications, thesis papers and technical publications, along with 1 784 conference proceedings and poster presentations from established international conferences covering offshore wind over the past 20 years, are included in the evidence base.

These datasets have been aggregated and analysed over the last five years to build the most comprehensive archive of wind industry technology development intent available. Public patent databases were used to build patent landscape data, while various public and paid data sources were used for the technical journals and conference proceedings. All information was subsequently analysed by technical experts to determine the degree of relevance to the industry and to categorise the content according to a standard industry taxonomy that goes beyond the categorisation by such information archives. The patent landscape was specifically scrubbed to ensure elimination of false positive patent filings in the dataset which mention

Figure 46: Patent activity, journal articles and conference papers relating to offshore wind, 2001-2015



	Wind farm development	Turbines	Foundations	Electrical interconnection	Installation	OMS
Patents	2	729	1317	108	569	142
Journal references	278	560	423	78	176	457
Conference papers	197	651	372	114	245	205

wind turbine technology but are not directed towards it. The data scrubbing also ensures that those innovations which are labelled as "offshore" are dedicated specifically to that market segment. Most conventional patent search tools are incapable of discerning that level of fidelity without the involvement and co-ordination of technical experts.

Areas of patent and journal activity

Figure 46 shows the allocation of patent activity, journal articles and conference papers by technology element in offshore wind for the period 2001-2015.

Historically, most patented innovations are focused on dual-use wind turbine technology covering onshore and offshore application equally. As the offshore market segment emerges as a greater portion of revenue contribution for companies involved in the wind industry, then more dedicated R&D expenditure on offshore specific technology development and the requisite patent protection will be made. This increase in R&D spend will result in an increase in offshore-specific annual patent filings as companies seek to protect their key and competitively differentiating technologies.

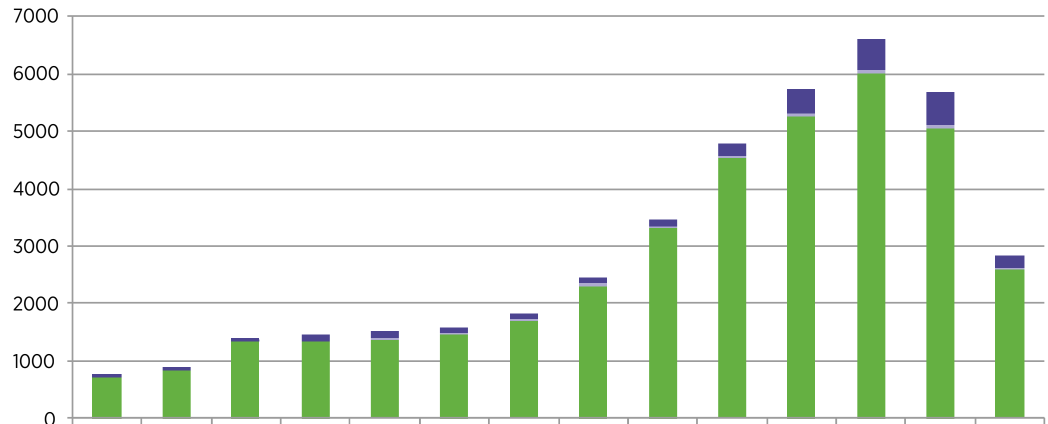
Annual patent filing trends show an increase in overall wind-industry related filings as well as offshore-specific technology patents. Unfortunately, high barriers to market entry in offshore wind have led to many orphaned innovations on foundations, turbines and installation techniques. Nevertheless, the overall correlation between market adoption of the technology and the level of investment in R&D can be seen clearly over time. There is a noticeable dip in patent filings in 2013. As the global wind market went through a period of re-organisation during a commercial pause, there was a drop in R&D expenditure and a corresponding drop in patent filings associated with protecting the resulting innovations produced by that R&D spend.

The breakdown of patent filings by country / patent filing jurisdiction indicates the extent to which the industrialised world has enabled R&D in wind energy technology development. Yet, many companies do not file patents universally in all markets in which they are selling their products or offering their services. As a result, the geographical trends in patent filings have shown a distinct focus on established markets where there are enforceable legal protections afforded through the patents which the owners obtain.

Recent offshore technology development focus has come from Asia with significant re-investment of profits from thriving onshore wind businesses in China, coupled with the increased interest in floating offshore wind in Japan.

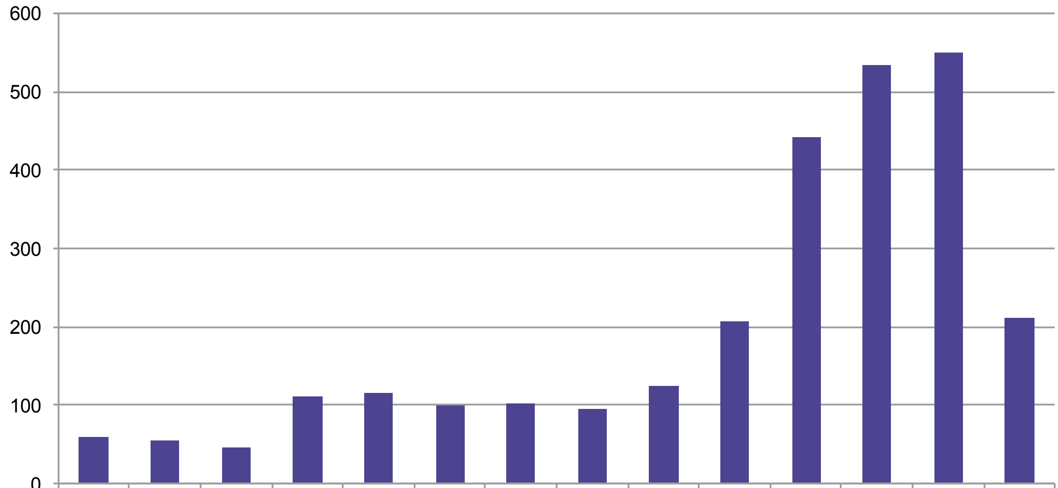
European innovations in offshore technology development have been focused more recently on lowering OMS costs along with standardising installation procedures using purpose-built vessels.

Figure 47: Annual patent filings for onshore and offshore wind, 2000-2013



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13
Offshore	58	55	45	110	114	100	102	96	123	207	443	535	549	212
Onshore	6	6	19	14	15	31	16	42	34	49	39	61	64	33
Dual Use	700	831	1330	1341	1381	1451	1713	2310	3300	4534	5265	5998	5049	2593

Figure 48: Annual patent filings for offshore wind, 2000-2013



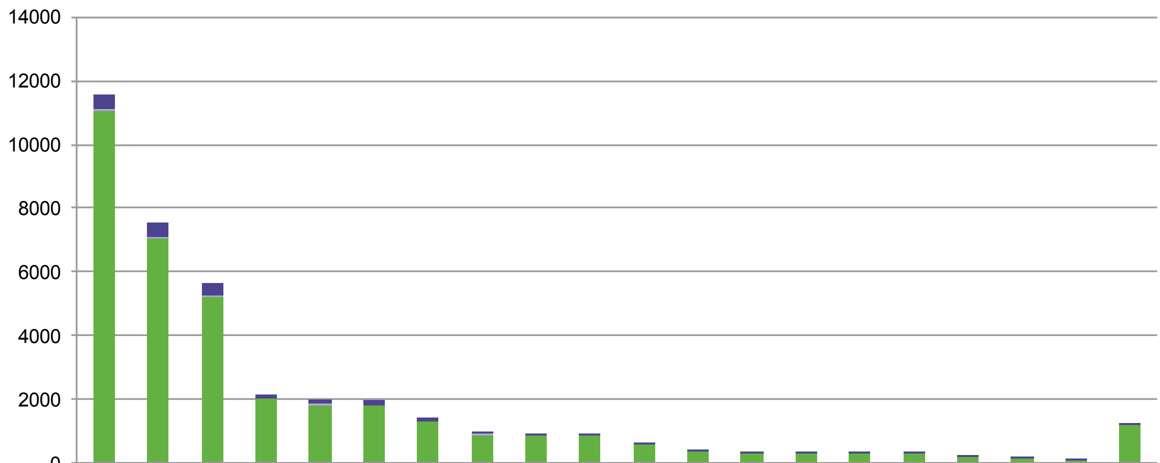
	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13
Offshore	58	55	45	110	114	100	102	96	123	207	443	535	549	212

The United States has a significant portion of the offshore innovation market as well, with many companies focused on capturing high-value patents on key technologies and installation methods.

The analysis of the evolution of technology only enables accurate forecasting of future technology trends when the CAPEX, OPEX, AEP and LCOE impact of each newly patented innovation are considered. To assess potential, this needs to be measured against the RD&D and non-recurring engineering and commercialisation costs required to implement new technologies.

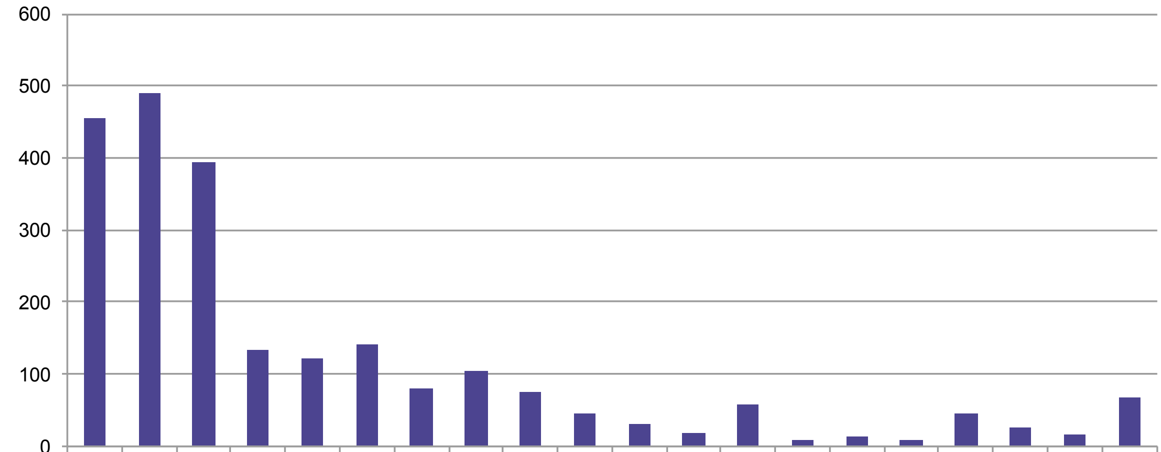
Patents which are filed today will take many years before the technology can be fully commercialised, if at all. It is possible to determine future technologies which will

Figure 49: Patent filings for onshore and offshore wind by country, 2000-2013



	US	EU	CN	DE	CA	JP	AU	KR	DK	ES	AT	BR	UK	MX	NZ	IN	NO	FR	NL	Other
Offshore	455	490	394	132	121	141	78	103	75	45	31	18	57	8	12	9	45	25	15	68
Onshore	78	55	52	31	35	20	29	14	5	11	6	5	1	8	12	4	1	1	1	24
Dual Use	11046	7025	5192	2008	1820	1797	1299	883	841	835	583	366	311	322	289	286	208	117	69	1176

Figure 50: Patent filings for offshore wind by country, 2000-2013



	US	EU	CN	DE	CA	JP	AU	KR	DK	ES	AT	BR	UK	MX	NZ	IN	NO	FR	NL	Other
Offshore	455	490	394	132	121	141	78	103	75	45	31	18	57	8	12	9	45	25	15	68

prove to be bankable through a standardised evaluation process for each proposed innovation, whether declared in a patent filing or published paper, involving:

- Tracking of the technology readiness level (TRL) for each proposed innovation.
- Determination of the non-recurring engineering cost for technology development and commercialisation (RD&D and commercialisation costs).
- Benchmarking of the incremental cost and performance benefit for the introduction of a new innovation (*i.e.*, CAPEX, OPEX, AEP and LCOE impact).

The 6 623 patents, technical publications and conference proceedings which refer to specific offshore wind technologies were analysed in accordance with the methods outlined above within the 26 categories outlined in the 6 sub-sections. Specific technology trends are then summarised.

Wind farm development

Wind farm development is poised to undergo a transition to incorporate much more site optimisation. The literature survey suggests that holistic cost models which measure impacts of aerodynamic wake interactions, array cable length and other factors on annual energy production are starting to be developed and utilised. These techniques, combined with operational data from existing offshore wind parks as well as SCADA and CMS system analysis, will lead to fully integrated production models with price-optimised electricity delivery.

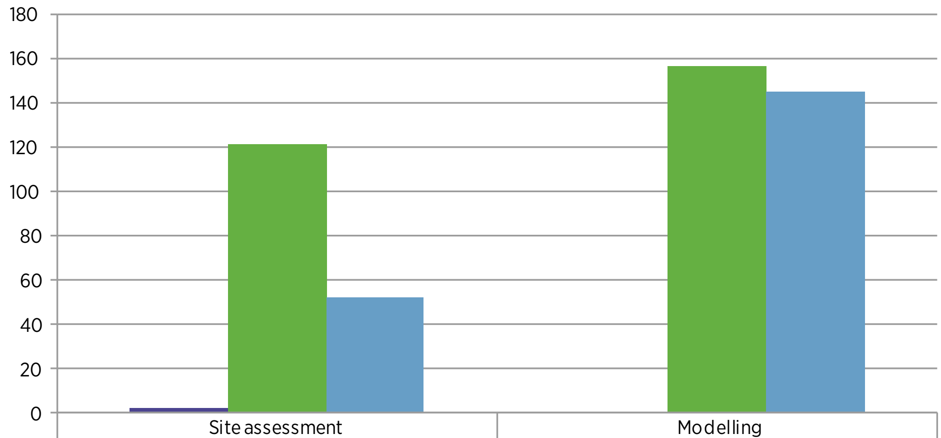
LiDAR technology and predictive weather modelling techniques will enable this approach. Turbine placement as well as rotor size and power rating can be "tuned" for optimisation of energy production at a given project site. Combining LiDAR inputs from multiple sources, including airborne and floating buoys, to provide a robust 3D representation of the complex flow field dynamics is thought to be key to improving predictive weather models and production forecasts.

Outlook 2016-2030

Given the limited number of patents in this area, the significant number of papers and publications seem to be suggesting more complex evaluation techniques, with LiDAR measurements being combined from multiple sources and locations within a specified development zone.

Recent conference presentations show a technique in which airborne LiDAR and floating LiDAR used in combination will provide more fidelity of site performance. This increased fidelity will allow for better

Figure 51: Patent activity, journal articles, and conference papers on wind-farm development, 2001-2015



	Site assessment	Modelling
Patents	2	0
Journal references	121	157
Conference papers	52	145

site engineering and turbine placement, potentially skewed from the conventional grid layout in order to increase energy output and mitigate wake interactions.

Future wind park design, including physical layout, type of electrical system infrastructure, turbine technology, as well as installation and service methods will benefit from a system engineering philosophy. Complex site optimisation models are already under development and have been the subject of more than 35 different papers and conference presentations already.

Outlook 2031-2045

Improved on-turbine, forward-pointing wind data measurement capabilities which are enabled by LiDAR, combined with analytics on that accumulated data set, allows for development of enhancements to weather modelling techniques which will enable improvements in site performance optimisation. It is likely that artificial intelligence-based or quantum computing solutions will be used for weather modelling in this time frame, although little discussion has occurred on the adaptation of this relatively new technology by the wind industry to date.

Future capabilities in weather prediction also should enable more site tailoring, which is already in the experimental stage. The modularisation of components in wind turbine design enables a range of options in hub heights, rotor diameters and power ratings to be utilised within the bounds of a single site.

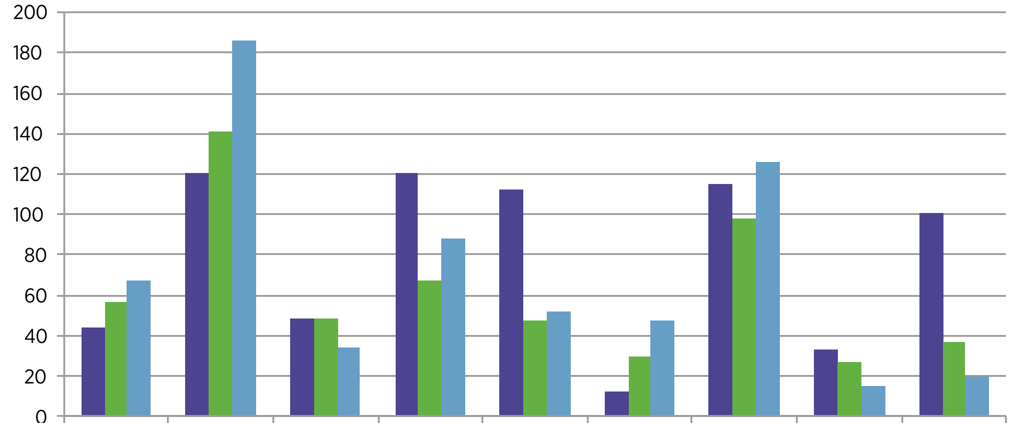
Turbines

In conjunction with the wind farm development techniques outlined above, the turbine technology of the future will make a shift towards modular platform architectures to enable site-optimised design. Common platform architecture is set to become more pervasive as companies seek manufacturing and supply chain cost efficiencies and to help further drive down OPEX. The patent landscape in particular indicates this shift, with 76% of the offshore turbine patent filings in the past 10 years pointing towards turbine designs which are offshore-specific.

Multiple journal articles and conference papers suggest that as turbines grow towards 10 MW and above there is likely to be a shift towards low-to medium-speed generators using a two-stage or single-stage gearbox or no gearbox at all. This shift in architecture is due largely to the torque capacity limits of conventional gearbox technology when scaled to a power output range of 15-20 MW. More than 20 different patents have been filed on differing drivetrain and turbine architectures to date.

Additionally, a spike in patent filings around the full power conversion electrical system architecture and the desire for a “converter-less” substation connection

Figure 52: Patent activity, journal articles and conference papers on turbines, 2001-2015



	Blades	Controls	Generator	Drivetrain	Nacelle	Electrical	Pitch System	Yaw System	Tower
Patents	44	120	48	120	112	12	115	33	101
Journal references	56	141	48	67	47	29	98	27	37
Conference papers	67	186	34	88	52	47	126	15	19

system is likely to push the industry in this direction in the future. This converter-less architecture uses DC power generation from the wind turbines along with DC array cables and a passive rectification and inversion system at the substation. The evaluation of lowest total cost suggests that this type of approach will reap benefits for turbine as well as electrical interconnection CAPEX, and a reduced part count improves OPEX as well.

As the desire for increased capacity factors drives rotor growth, the industry already has filed five different patents on a turbine architecture with a tension wheel or cable-stayed rotor solution. These radical architectures will enable rotor diameters in excess of 200 m for power ratings of 12 MW and higher. Additionally, patent analysis reveals that new innovations around materials and their usage are set to have a profound impact. Metal-composite hybrid structures already are being investigated for use in blades, towers and transition pieces, and they offer significant cost benefits compared to carbon fibre without sacrificing strength or suffering a significant weight penalty.

Outlook 2016-2030

Based on the analysis of all data sources, intermediate-term offshore turbine technology will comprise advances in materials science, electrical system architecture and drivetrain technology. Specifically, turbines will comprise composite hybrid blades (whether metal or carbon fibre), a turbine control system architecture fully utilising optical cables, model predictive control strategies, a medium-voltage electrical system, a two-stage gearbox with permanent magnet generator or a radial flux direct drive architecture, and full power conversion.

The patent landscape of turbine technology has been fairly comprehensive, with dozens of patent filings covering each of the technologies outlined above. For offshore applications, the hybrid blades appear to be a preferred solution for the industry based upon the need for higher strength with lower material costs. Metal-composite hybrids are seen as a cost effective substitute for carbon fibre.

The fibre-optic controller architecture is a natural evolution of the control system in the shift towards digitally managed assets which are fully integrated on an Internet of Things (IoT) platform. Similarly, the evolution of the control software itself appears to be driving towards not just model-based controls, but model predictive controls which can offer an anticipatory capability.

The move from low- to medium-voltage electrical systems within the wind turbine has been discussed in papers for several years already, but it is expected to take root in the desire for comparable efficiency at higher power levels.

Direct-drive, single-stage or two-stage drivetrain solutions are more likely to take root as the industry moves towards higher rate power levels, *i.e.*, from 6-8 MW to 10-12 MW. Several studies presented at industry conferences in the past few years have suggested that three-stage gearbox and DFIG architectures are not cost effective when scaled to these power levels.

The concept of a flexible and competitive platform architecture that is robust enough to withstand the rigors of the offshore environment is also a focus.

Outlook 2031-2045

Future offshore wind cost-competitiveness necessitates offshore-specific solutions. Based on the viability analysis of the technologies offered in the patents and papers, the offshore turbine of the future could comprise self-healing structures, composite towers, neural network control strategies, a transverse-flux generator with a tension wheel rotor and integrated hub. Many of these technologies have been developed only conceptually; however, with significant levels of financial commitment to mature the technologies, they are likely to be commercialised.

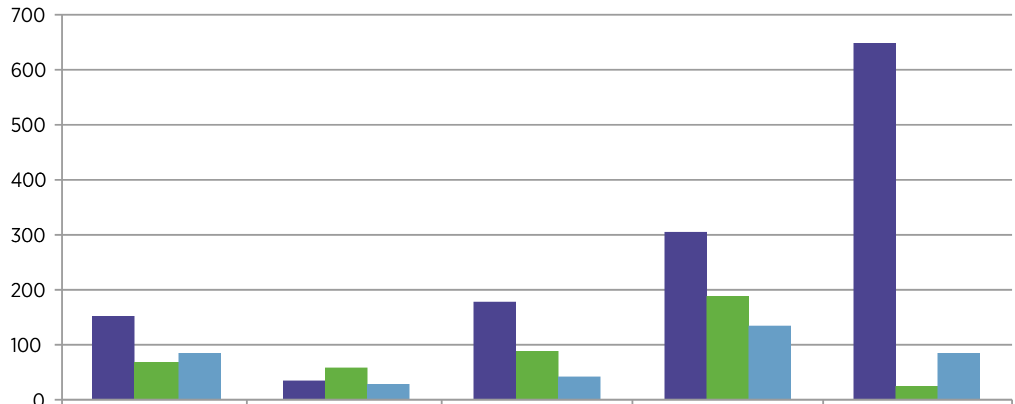
Particular among them are the three different patents on the tension wheel or cable-stay rotor architecture. Moving towards this large ring generator structure will enable alternative generator arrangements besides the conventional radial flux type which is commonly used today. More than 50 patents have been filed on transverse flux generator architectures, although only a handful have acknowledged the potential for use in large wind turbine platforms.

Foundations

The historical reliance on different concepts in different water depths has not proved to be a cost-optimal approach. The literature survey clearly identifies the intent to move towards a "one size fits all" foundation solution which would enable more manufacturing economies and other ancillary benefits.

A few patent filings on monopile technology suggest a move towards concrete-reinforced solutions, similar to how the oil and gas industry establishes wells.

Figure 53: Patent activity, journal articles and conference papers on foundations, 2001-2015



	Monopile (incl. guyed monopile)	Gravity base (incl. skirted gravity base)	Jacket (incl. tripod)	Floating (incl. tension leg platform)	Other (incl. transition piece, etc.)
Patents	151	36	178	304	648
Journal references	67	58	87	188	23
Conference papers	84	29	41	135	83

For relatively shallow water solutions it is likely that monopile technology will continue to be used, but for other sites, guyed monopiles may impact.

Gravity base technology may remain a niche use. Literature and analysis widely suggests that sites which might use a gravity base or a skirted base solution are likely to be displaced by tension-leg platforms or other tethered floating structures.

Additionally, jacket structures are likely to evolve beyond conventional oil and gas structures which previously have been adopted towards lower-cost concepts for offshore wind. From the patent landscape and literature survey, which shows a combination of materials and structural arrangements to minimise total cost, there are more than 90 different proposed configurations for such structures. In the longer term, the industry consensus from an analysis of the publications indicates that these structures also will be reduced in usage as the industry shifts significant volume towards floating solutions in depths beyond where monopiles are cost-effective.

More than 150 different floating platform innovations have been proposed in the patent landscape and literature. Given their ability to also enable cost savings on installation by leveraging full quayside assembly, tow-out for installation and tow-in for service, the industry appears to show significant interest in floating foundations for a range of water depths. Studies have suggested that the manufacturing scale which can be achieved from the semi-submersible type solutions could enable the desired "one-size-fits-all" approach.

Outlook 2016-2030

The industry has recognised that floating foundations have significant potential to enable CAPEX and OPEX benefits if there is a concentrated focus on achieving manufacturing scale which will drive down those costs. The patent landscape and many of the published papers suggest an opportunity for cost reduction with a move towards solutions that are purpose-built for offshore wind instead of adaptations of onshore wind or leveraging oil and gas technologies which can be over-designed for wind industry use.

From a review of the references, the industry consensus appears to be that in the near term, developments in monopiles, gravity bases and non-monopile steel structures such as jackets will continue to reduce costs. Research further suggests that as the industry moves to a more system-engineered approach to offshore design, then floating foundation solutions will mature and also reduce in cost. As a result, more widespread deployment of semi-submersible, tension-leg platform and, to a lesser degree, spar solutions can be expected.

Many papers suggest that by 2030, the industry will shift focus to a "one-size-fits-all" solution based upon the semi-submersible or TLP architecture. This focus is necessary to ensure that manufacturing scale is achieved in foundations, which will allow for the significant cost reductions predicted. Additionally, this shift enables a push towards integrated turbine and foundation installation and logistics, which has been suggested, but not yet utilised.

Outlook 2031-2045

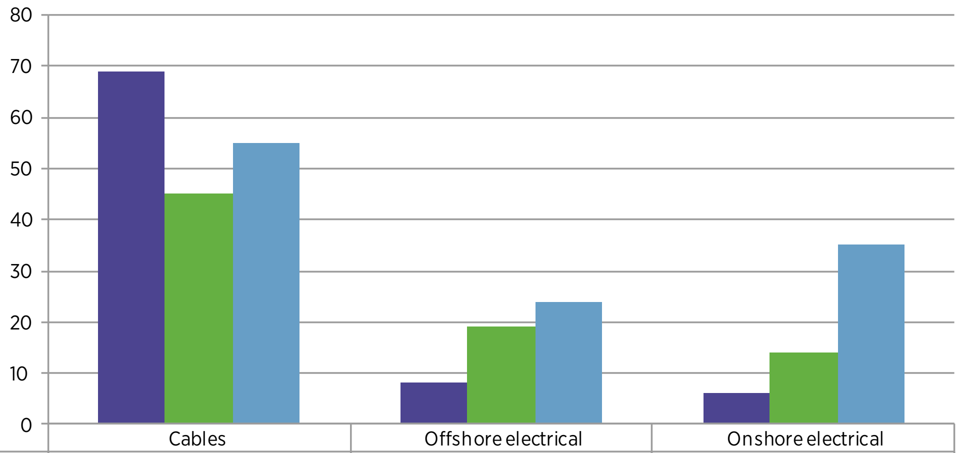
Foundation structures which can be assembled quayside and used in integrated installation methods and back-to-base service process are most likely to emerge as the cost-effective solution at scale. Quayside assembly ensures a level of quality control that cannot be guaranteed away from shore, and the development of integrated tower and foundation solutions that can be fully deployed as a single structural unit will be the preferred solution. Floating foundation design concepts are likely to provide the greatest benefit in this approach, and over 40 different patents and research papers have suggested specific ways to implement such a holistic foundation solution, acknowledging the integrated installation and logistics challenges.

Despite several patents on the subject, the push towards massive, multi-turbine platform floating structures which have been proposed for future use is unlikely to prove cost-effective. The turbine spacing requirements of larger rotor diameters will drive the material cost too high for this conceptually appealing concept. Such high costs will render these structures useful only for niche applications.

Electrical interconnection

Electrical interconnection has already moved from medium voltage to high voltage, and from AC- to DC-based solutions, with more than 45 patents and over 150

Figure 54: Patent activity, journal articles and conference papers on electrical interconnection, 2001-2015



	Cables	Offshore electrical	Onshore electrical
Patents	69	8	6
Journal references	45	19	14
Conference papers	55	24	35

papers discussing this topic. Analysis of the early-stage technology developments along with the associated patents suggests that this evolution will continue as the transition to high-temperature superconducting (HTS) technology is already under way. HTS is likely to be used in both inter-array and export cables while more advanced materials are under investigation.

Ultimately, materials science will dictate changes in cable use from HTS to a next-generation technology such as graphene- or germanene-based cables, but more research is required in this area before a clear technology winner emerges. Only a handful of papers exist on this topic since the application of materials to wind is still an emerging area. Nevertheless, an analysis of the materials which are being developed suggests a potentially dramatic impact on the installation and OPEX for the offshore wind industry due to reduced life-cycle maintenance costs on cables which comprise self-healing properties enabled by these advanced materials.

This shift also is underpinned by the drive towards a "converter-less" turbine architecture, putting more emphasis on a centrally managed substation converter and transformer system which integrates HVDC outputs from multiple turbines in the wind park. More than 10 patents and more than 30 papers have suggested that this technology is not only possible, but is a more cost-effective solution than conventional technology.

Outlook 2016-2030

With the low number of patents and other references dedicated towards HVDC technology and the associated electrical infrastructure, it has been difficult to forecast the evolution of this technology through the evaluation of the publications and patent references. Several patents already are suggesting that cables can shift towards copper-less solutions, but this technology is still at a comparatively low state of technology maturity.

This time frame is likely to be governed by the emergence of high-temperature superconducting (HTS) cable technology by 2030. The configuration of HVAC for array infrastructure with HVDC for export will shift towards HVAC for array infrastructure with HTS for export cables and eventually will evolve to HTS for both array and export cables.

Offshore substation complexity and footprint will be reduced significantly, although the cost and reliability-risk of additional cryogenic cooling systems for the HTS cables and electrical systems will offset some of the benefits. The removal of active rectification systems and regulation of frequency and voltage through active inversion systems will play a role in CAPEX reduction of the electrical systems. The ability to provide and manage ancillary services as well as to integrate energy storage capabilities could also be key for future success.

Outlook 2031-2045

Cables made from advanced materials such as carbon nanotubes, graphene, germanene, etc. will see significant investment in innovation due to the potential for transmission efficiency of conventional copper without the temperature rise and other thermal management requirements. These advanced materials will enable a shift away from copper or HTS solutions, as cables themselves are reported to be getting "smart" as well. More than 10 different references suggest that cable management with advanced materials will provide for frequency and electricity flow management which can regulate temperatures, provide redundancy as well as behave as a power shunt or short circuit capability without requiring extra hardware.

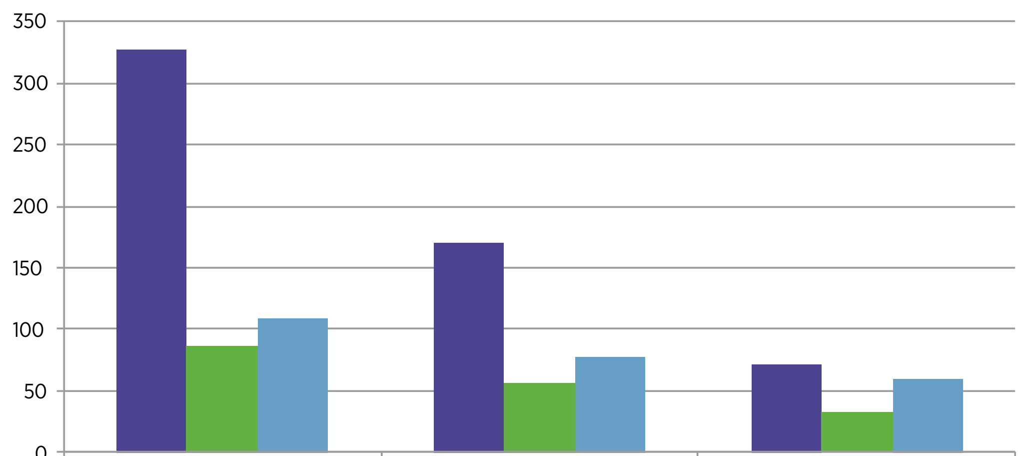
The limited publication of patents and other journal references on electrical system infrastructure provides little guidance on the potential evolution in this area beyond the 2030 time frame. The few references suggest a move towards DC power generation systems which would require a fundamental shift in infrastructure compared to AC generation and export. This approach would allow for a "converter-less" wind turbine with only a DC-to-AC active inverter system at the substation. Such an approach could have a profound impact on CAPEX cost for the electrical systems and positively impact the turbine as well.

Installation

Due to vessel size and capacity, the offshore wind industry has traditionally utilised partial turbine assembly in-port and load out of sub-assemblies, with final assembly at sea. Both the literature and the patent landscape suggest that installation trends are transitioning from partial quayside construction of turbine sub-assemblies to full quayside turbine assembly. This shift will have a profound impact on vessel type and mission specification versus the approaches that are employed today.

Presently, there are over 125 different proposed aspects of partial turbine assembly codified in patents and journal publications, but many of these innovations are largely defensive in nature, meaning that the existing vessel owners and EPCI contractors are largely influencing the landscape. Additionally, more than 70 patents have been filed by organisations new to the industry that seek to drive the industry towards this full quayside assembly technique. The ideas range from larger vessels and barge cranes capable of installing full

Figure 55: Patent activity, journal articles and conference papers on installation, 2001-2015



	Partial assembly	Full assembly	Future techniques
Patents	327	170	72
Journal references	87	56	33
Conference papers	109	77	59

pre-assembled turbine and foundations to structures delivered and deployed by airship.

Outlook 2016-2030

The industry is focused on evolving the standard at-sea installation techniques with the use of more quayside component assembly. Conventional vessel solutions will still continue to have their place, although the cost of upgrading to vessels that can handle larger turbines and foundations is likely to be prohibitive versus the shift towards full assembly.

The reported benefit from analysis of the studies undertaken has been that quayside turbine assembly will significantly increase vessel utilisation and therefore the cost of installation. Additionally, the pre-assembly of the turbines in a more quality-controlled environment will introduce a contribution to turbine reliability. The recent trend in patent filings is favouring full assembly techniques, with over 50 patents on the subject matter published within the past 18 months alone.

Outlook 2031-2045

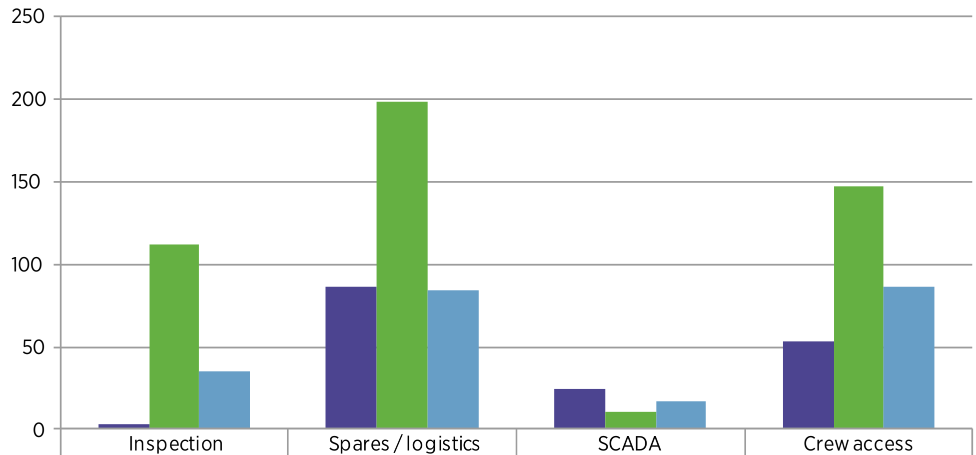
Longer-term solutions will benefit from revolutionary thinking to achieve the deployment of complete turbine and foundation structures which are fully assembled quayside. Although only a few patents and papers reference full assembly, these types of solution will require further development of vessel designs and logistics. The level of onshore work and quality control possible by utilising full quayside assembly is highly advantageous versus the cost of ocean-based component assembly.

One noteworthy patent identifies an opportunity to conduct full installation of an assembled turbine and foundation structure with delivery by an airship or dirigible. The dirigible option offers a particularly compelling business case but would require a radical departure from conventional installation methods. The cost per tonne mile is unlikely to be cheaper than conventional seafaring vessel deployment techniques, but the precision hover and loiter capabilities would enable a singular sky-crane for installation as well as turbine or sub-component service. As with other technology areas, full life-cycle cost analysis will need to be undertaken.

Operation, maintenance and service

Operation, maintenance and service is seeing a shift from time-based maintenance solutions to a condition-based approach. Hundreds of patents and technical publications have discussed the aspects of increasing revenue by adjusting wind farm power output based on price-optimal timing, extending the life of wind parks to minimise unscheduled service maintenance and

Figure 56: Patent activity, journal articles and conference papers for OMS, 2001-2015



	Inspection	Spares / logistics	SCADA	Crew access
Patents	3	86	24	53
Journal references	112	198	10	147
Conference papers	35	84	17	86

streamlining spare parts inventory in accordance with identified service requirements and known upcoming component replacements.

The development of condition-monitoring technology and advanced SCADA data analytics has enabled more robust analysis and the establishment of decision making based upon a turbine operational envelope rather than just sticking to fixed operational setpoints. The move towards IoT-enabled platforms will push the condition-based maintenance solution capability to the forefront of offshore asset management, as has been discussed in numerous papers. This aspect of technology will see significant cross-over with onshore wind and other sectors, so innovations in onshore wind also will be relevant in this area.

Crew access to perform maintenance also will see significant cost efficiencies as the industry matures. Conventional vessel-mounted gangway solutions are evolving to improve safety and increase operating envelope. Helicopter-based crew access is becoming more common as the cost benefit has improved. Different proposed maintenance and access solutions using helicopters have been patented, including video and thermographic inspection of blades. Permanent offshore crew quarters could become more commonly used, as has been suggested in a few papers and patents, but the cost associated with fixed offshore structures for crew and OMS facilities may be prohibitive on some sites.

Outlook 2016-2030

Condition-based maintenance solutions will become the norm as turbine output optimisation based on remaining useful life, predictive maintenance scheduling, and spares demand scheduling all look to have an impact. Remote inspection technologies including optical / video camera-based blade tower inspection, tower climbing inspection “robots”, remote controlled aerial vehicles and wireless data transmission technologies will play important roles in the future.

Despite only a few offshore wind-specific patents on this platform architecture thus far, the IoT will play a key role in the data acquisition, analysis and communication of relevant information which will be used for control and determination of optimal service strategies. The shift to this architecture will take place over several decades, but certainly newly installed turbines and wind parks will be able to benefit more immediately from this emerging technology.

Structures incorporated into the foundation to ensure vessel interlock will enhance safety during crew transfers. The transit cost per worker per operating MW is improving for helicopter-based crew access and retrieval. More widespread use of this solution is expected.

Outlook 2031-2045

Little public domain information exists on the anticipated technology solutions for OMS in this time frame. Technical solutions from other industries are anticipated to penetrate the wind industry. As with the other aspects of technology, the OPEX-reduction potential of such technologies has been evaluated to determine the likelihood of adoption in wind.

Virtual reality and 3D visualisation capabilities will be put into use to ensure optimal time-efficiency of repairs. The evolution of sensor systems enabled by the IoT platform will allow pinpoint accuracy and visualisation of potential reliability issues before they affect operational performance. This will enable accuracy of just-in-time spare parts inventory management and deployment of service personnel and resources only when required.

There are a few patents on vessel deployment and crew access strategies which bear note, although the implementation of such strategies is likely to take some time. Offshore services may see the use of motherships with crew transfer vessels, as part of a flexible deployment structure. Modular access solutions will benefit from being foundation-mounted instead of vessel-mounted to reduce vessel dead weight.

APPENDIX E:

Wind farm development timeline

This appendix describes a typical development timeline for an offshore wind farm commissioned in 2015. Some of these steps rely on technology discussed in the main body of the report. The descriptions below focus on the non-technology aspects of offshore wind farm development.

Agreement for lease

An agreement for lease gives the developer exclusivity rights to develop and undertake ancillary activities in relation to the potential wind farm. A lease is only finally awarded after a project has received the necessary planning approvals from the relevant planning authority.

There have been two main approaches used for projects currently in development:

- In Germany and the UK, the leasing body (Germany's Federal Maritime and Hydrographic Agency or the UK's The Crown Estate) identified and awarded agreements for lease. Some pre-development work was undertaken by governments or leasing bodies, although it typically was limited. For UK Round Three zones, the DECC undertook a strategic environmental assessment (SEA) to inform locations for agreement for lease by The Crown Estate. Once an agreement for lease was reached, the developer assumed the responsibility, cost and risk of wind farm development.
- In Belgium, Denmark, France and the Netherlands, the leasing body completed a significant amount of development activity including wind farm design, surveys and stakeholder engagement before agreement for lease. This allowed developers to enter into competitive agreement for lease tenders with less development risk and a greater understanding of the site characteristics.

Wind farm design and surveys

Described in Section 3.1.

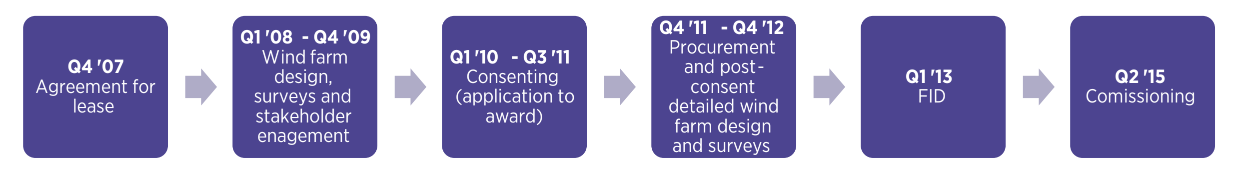
Stakeholder engagement

Stakeholder engagement has been run in parallel with wind farm design and surveys and was undertaken by the developer. Stakeholders engaged included governments, businesses and members of the public.

Obtaining planning approval

Analysis from wind farm design, surveys and stakeholder engagement has informed the detailed applications required for applications for planning approval. The process has varied between countries but typically was undertaken at a national level, although in some cases by municipalities if the leased area was within 12 nautical miles. Developers have sought to maintain flexibility in wind farm design in the process of gaining planning approval (both for future proofing and procurement purposes), although the scope for this has varied among jurisdictions.

Figure 57: Development timeline for a typical offshore wind farm commissioned in 2015



Procurement

Procurement of wind farms has been via two main approaches, or a combination of these:

- Multi-contracting. Developers have contracted individual work packages for the supply and install of key components. This approach has allowed developers to project manage the wind farm construction and installation in-house, but it increases interface risk between work packages.
- Engineer, procure, construct and install (EPCI) contracting. Developers have contracted combined work packages which has allowed them to reduce interface risk between work packages and to make the project more attractive to investors, but often at a higher base cost.

Final investment decision

The final investment decision is a major project wherein the finance partners commit capital to the project. This in turn enables the supply chain to make investments and enables installation to commence.

Commissioning

Commissioning follows installation and is the process of completing final checks and sign-offs before the wind farm begins operating.

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