Low
Carbon
Innovation
Coordination
Group

Technology Innovation Needs Assessment (TINA)

Offshore Wind Power
Summary Report

February 2016

Background to Technology Innovation Needs Assessments

The TINAs are a collaborative effort of the Low Carbon Innovation Co-ordination Group (LCICG), which is the coordination vehicle for the UK's major public sector backed funding and delivery bodies in the area of 'low carbon innovation'. Its core members (at the time of this document's completion) are the Department of Business, Innovation and Skills (BIS), the Department of Energy and Climate Change (DECC), the Energy Technologies Institute (ETI), the Engineering and Physical Sciences Research Council (EPSRC), Innovate UK, Scottish Enterprise, and the Scottish Government.

The TINAs aim to identify and value the key innovation needs of specific low carbon technology families to inform the prioritisation of public sector investment in low carbon innovation. Beyond innovation there are other barriers and opportunities in planning, the supply chain, related infrastructure and finance. These are not explicitly considered in the TINA's conclusion since they are the focus of other Government initiatives.

This document summarises the Offshore Wind TINA analysis. The TINAs apply a consistent methodology across a diverse range of technologies, and a comparison of relative values across the different TINAs is as important as the examination of absolute values within each TINA.

The TINA analytical framework was developed and implemented by the Carbon Trust with contributions from all core LCICG members as well as input from numerous other expert individuals and organisations.

Disclaimer – the TINAs provide an independent analysis of innovation needs and a comparison between technologies. The TINAs' scenarios and associated values provide a framework to inform that analysis and those comparisons. The values are not predictions or targets and are not intended to describe or replace the published policies of any LCICG members. Any statements in the TINA do not necessarily represent the policies of LCICG members (or the UK Government).

Department for Business Innovation & Skills

Department of Energy & Climate Change

energy technologies institute

EPSRC Engineering and Physical Sciences Research Council

Innovate UK Technology Strategy Board

Scottish Enterprise

The Scottish Government Riaghaltas na h-Alba

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CARBON TRUST

Key findings

Offshore wind has tremendous potential to replace aging power plant, reduce reliance on imported gas, and meet greenhouse gas emissions and renewable energy targets. Innovation is critical to enabling the deployment and cutting the cost of offshore wind, with an estimated saving to the energy system of c. £33 billion (£18-57 billion)[1] to 2050. Investment in innovation can also help create UK based business opportunities that could contribute an estimated c. £19 billion (£12-30 billion)[2] to GDP to 2050, 80% of which would come from domestic activity, while supporting c. 31,000 (19,000-55,000) direct jobs per year by 2050. Significant private sector investment in innovation, catalysed by public sector support where there are market failures and barriers, is needed to unlock these opportunities.

Potential role in the UK's energy system	• The UK has a large offshore wind resource, estimated at over a third of the total European potential[3]. • The offshore wind sector is advancing quickly and has already deployed large scale farms on numerous sites. • While it is more expensive than onshore wind, it is more scalable. Moreover, while its cost-competitiveness in the future against nuclear and carbon capture and storage (CCS) is uncertain, it is currently deployable sooner and faster than either of these. This means that offshore wind is a low carbon alternative to combined cycle gas turbines (CCGT) that can be deployed at the required scale to replace aging power plants ready for decommissioning. • How much and how quickly offshore wind is deployed will depend in part on how successful innovation is in reducing costs. The improvement potential is very large, with various sources suggesting that offshore wind could cost-effectively deliver c. 10-30% of total electricity generation by 2050.
Cutting costs by innovating	• Recent strike prices agreed in the contracts-for-difference mechanism[4] and other analysis[5] suggests that though still relatively high, offshore wind costs are decreasing quickly. • Innovation (learning-by-research-and-development (R&D)) together with savings in the supply chain and finance (learning-by-doing) have the potential to drive down costs by over c. 30% by 2025 relative to projected baseline costs (which increase as the assumed mix of sites used becomes more challenging) and by close to c. 60% by 2050. This could reduce the cost of energy, in 2015 GBP, to as low as c. £86/MWh by 2025 and to c. £56/MWh[6] by 2050. • Depending on deployment levels, successfully implementing innovation in offshore wind could deliver cumulative cost savings of c. £33 billion (bn) (£18-57 bn) to 2050.
Green growth opportunity	• The UK could become one of the leaders in a global offshore wind market with a cumulative size of c. £430 bn (£300 bn - £1 trillion) to 2050 capturing c. 10% of the total market (tradable and non-tradable). • If the UK successfully competes in the global market to achieve a c. 10% market share, then

[1] Cumulative (2015-2050) 2015 GBP discounted values for medium (low-high) UK deployment scenarios and a high innovation scenario. Unless otherwise stated all figures are in real, 2015 GBP.

[2] Cumulative (2015-2050) 2015 GBP discounted GVA for medium (low-high) global / UK deployment scenarios and a high innovation scenario.

[3] Estimate by the Energy Technologies Institute (ETI), *Offshore Wind* (2014).

[4] DECC, Contracts for Difference (CFD) Allocation Round One Outcome, February 2015.

[5] ORE Catapult, Cost Reduction Monitoring Framework – Summary Report to the Offshore Wind Programme Board, 2015.

[6] The equivalent LCOE values in 2012 GBP are c. £83/MWh by 2025 and c. £54/MWh by 2050.

	the offshore wind industry could contribute c. £19 bn (£12- 30 bn) direct gross value added (GVA) to the UK economy to 2050, split c. 80% towards activity in the UK and c. 20% towards exports.
The case for UK public sector intervention	• To unlock this opportunity there is a strong case for targeted public sector intervention to catalyse private sector investment. There are critical and significant market failures and barriers to innovation in development, installation, foundations, and operations and maintenance (O&M). The UK cannot exclusively rely on other countries to develop the technologies within the required timescales, particularly in development, deep fixed foundations, and condition-based monitoring for operations and maintenance. • The main market failures and barriers relate to: – The lack of coordination between different players in the value chain to share essential performance information and the lack of incentive that any one player in the industry has to incur the costs of investing in innovations that will ultimately benefit the industry as a whole. These failures primarily affect the development of improved wakes and loads models used in the planning stage for new wind farms, the development of new foundations, including floating foundations, and development of new O&M techniques. – Insufficient investment by industry because of the high uncertainty of demand. A high degree of demand uncertainty reduces the incentive to invest in innovations that only offer a payback if demand is sufficiently high. This particularly affects innovations in installation and O&M. Here, for example, development of a new installation vessel has several years lead-in time and would be very costly – it is therefore only justified if the pipeline of demand is sufficient. – The aversion of individual developers to including innovations in their farms due to the increase in cost (e.g. planning changes, higher cost of capital) and risk. This particularly affects trialling of new foundations, including floating foundations, and serial manufacture of foundations and is compounded by a lack of / limited access to test sites. • The link between deployment support and innovation support should be acknowledged when considering how to address the market failures and barriers. In order for the offshore wind industry to develop new innovations, investors must see a clear business case for the level of inherent risk in the projects they undertake. This is crucially linked to the demand / deployment pipeline – both its scale and visibility, which includes deployment support. While acknowledging its importance the TINA does not analyse this link. • In general the UK cannot rely exclusively on other countries to develop necessary innovations to bring down the cost of offshore wind. Offshore wind represents a larger share of renewable resource for the UK than many other countries and development needs to occur earlier to be applicable in the UK compared with other countries given deployment projections. This is particularly the case with development and O&M innovations. The UK may also have particular innovation needs for fixed foundations in deeper water that are unlikely to be prioritised in the short term by other countries.
Potential priorities to deliver the greatest benefit to the UK	• Innovation areas offering the biggest benefit from UK public sector support are: – Novel designs including both fixed and floating concepts for low-cost foundations particularly for water depths of greater than 35m and to support larger turbines; and development of serial manufacturing techniques for foundations. – Remote condition-based monitoring, control and maintenance systems; O&M access systems. – Improved wakes and loads models for layout optimisation, advanced resource measurement tools, and data sharing methods. – Installation methods for deeper waters and higher sea states. – Optimised / next generation transmission systems (e.g. high-voltage direct current -

  HVDC) and improved, lower cost materials, cabling concepts, and installation techniques.
  – Innovative materials and components for higher power rating and more reliable turbines.
- Supporting all the innovation areas identified would require support in the hundreds of millions of GBP of public sector funding over the next 5-10 years.

Table 1 - Offshore Wind Power TINA summary

Sub-area	Variant / Focus	Value in meeting emissions targets at low cost £bn[7]	Value in business creation £bn[8]	Direct jobs supported in 2025 / 2050[9]	Key needs for UK public sector innovation activity / investment
Development	Tools for layout optimisation and yield improvement	2.9 (1.6-5.2)	0.7 (0.5-1.7)	1,200 / 1,000	• Development of improved load and wakes models, to feed into layout optimisation models. • Creation of industry-led data pooling and dissemination campaigns.
	Wind resource measurement				• Studies into advanced measurement techniques. • Validations of floating / scanning light detection and radar (LiDAR) and other tools.
Installation	Installation methods for larger / deeper farms	3.2 (1.7-5.7)	4.7 (2.7-7.5)	4,900 / 5,900	• Demonstration of novel installation techniques (onshore or offshore) and testing of new installation vessels.
Turbine	High power / yield / reliability turbines	15.7 (8.7-26.3)	1.8 (1.3-2.3)	2,100 / 1,700	• Support in obtaining consent for an onshore test site for large (10MW+) turbines. • Early Technology Readiness Level (TRL) research into blade materials, power converters etc. • Testing turbine components.
Foundations	<35m depth	0.9 (0.7-1.5)	2.4 (1.8-3.2)	3,000 / 2,500	• Development of serial manufacturing processes.
	>35m depth	2.7 (1.2-4.9)			• Development of novel foundation designs – concept development, demonstration of foundations tailored for larger turbines in 35-60m water depths. • Development of serial manufacturing processes and fabrication facilities / assembly hubs.
	Floating	n/a[10]			• Development and demonstration of floating foundations.

[7] 2015-2050 value in meeting emissions at low cost estimates are built up from combining deployment scenarios taken from ETI's Energy System Modelling Environment (ESME) with a high estimate of how much learning by R&D can reduce costs. Learning by R&D estimates are taken from an extensive literature review combined with expert interviews and Carbon Trust analysis.

[8] 2015-2050 value in business creation is an estimate of the direct GVA in the UK supported by offshore wind deployment and is built up using global deployment scenarios taken from the International Energy Agency's (IEA) Energy Technology Perspectives 2014 multiplied by relevant capital, operating, and decommissioning costs for each year that assume the highest level of cost reduction. Estimates of the share of global activity that is accessible to the UK and estimates of the UK's competitive position deliver a share of global turnover by sub-area that the UK could capture. Office for National Statistics (ONS) figures for the relevant share of GVA in turnover for each sub area then deliver an estimated GVA figure, which is discounted following HM Treasury's Green Book (2011) guidance. Finally, figures are adjusted downwards by 50% to account for displacement of other economic activity.

[9] Jobs supported in 2025 and 2050 are based on direct jobs only using ONS figures for jobs per £ million turnover for each sub area based on the turnover captured by the UK. Figures quoted for 2025 and 2050 are for the medium deployment scenario.

[10] Floating foundations could have a major impact on cost reduction, however stakeholders interviewed for this analysis had a very broad range of estimates of this potential impact and were in general uncertain on whether this technology would be deployed. Floating foundations are not included in the main part of modelling used in this analysis however they are acknowledged as a potential breakthrough technology and are the subject of recent specific studies see *PelaStar Cost of Energy: A cost study of the PelaStar floating foundation system in UK waters* (prepared by Glosten for ETI, January 2015) and *Floating Offshore Wind: Market and Technology Review* (prepared by the Carbon Trust for the Scottish Government, June 2015).

Sub-area	Variant / Focus	Value in meeting emissions targets at low cost £bn[7]	Value in business creation £bn[8]	Direct jobs supported in 2025 / 2050[9]	Key needs for UK public sector innovation activity / investment
Collection & Transmission	Inter-array cables	3.3 (1.8-5.7)	0.5 (0.4-0.7)	600 / 500	• Design and testing of innovative high voltage inter-array cables.
	Transmission systems				• Design and testing of innovative transmission systems (next generation High Voltage Alternating Current (HVAC) / HVDC, novel substation concepts.
O&M	Remote control, monitoring and maintenance	3.5 (1.9-6.3)	8.8 (5.6-14.7)	10,700 / 19,100	• Development and testing of novel sensors, algorithms and control systems for remote monitoring and condition based maintenance. • Creation of anonymised data sharing programmes.
	Access systems	0.8 (0.4-1.4)			• Design and testing of novel vessels and transfer systems for rougher sea states.
Total	**Value:**	**33 (18-57)**	**19 (12-30)**	**22,500 / 30,700**	**5-10 year investment programme in the low-mid hundreds of millions of GBP (programmes of material impact in individual areas in the millions to tens of millions on GBP).**

Benefit of UK public sector activity/investment[11]	
	High
	Medium
	Low

[11] Benefit of UK public sector activity / investment also takes into account the extent of market failure and opportunity to rely on another country but without considering costs of the innovation support.

Offshore wind has an important role to play in the UK energy system

The UK has a large offshore wind resource, estimated at over a third of the total European potential[12]. While it is more expensive than onshore wind, it is more scalable and is dealt with as major infrastructure in planning terms. Moreover, while its future cost-competitiveness against nuclear and CCS is still uncertain, it is currently deployable sooner and faster than either of these. This means that it is a low carbon alternative that can be deployed at the required scale to replace aging power plants ready for decommissioning.

Nevertheless, how much and how quickly offshore wind is deployed (especially in the medium to long run) will depend on how successful innovation is in reducing costs. The improvement potential from innovation is very large (detailed below), and various energy system modelling exercises suggest that offshore wind could cost-effectively deliver c.10-30%[13] of total electricity generation by 2050.

However, technological innovation cannot work in isolation. Private sector investment in R&D activities is contingent upon there being security of future deployment at scale, a point repeatedly emphasised by industry. Other important forms of cost reduction, notably standardisation, economies of scale and improved financing structures, are also linked to the overall capacity installed. Therefore, the degree to which costs come down depends on a number of "exogenous" factors that influence the deployment rate: the degree of deployment support, the cost of alternative generation technologies, the degree of public acceptability of onshore wind and nuclear, the (relative) technical success of CCS, the availability of biomass for energy use, overall energy / electricity demand, and the success of energy efficiency and demand reduction measures[14].

We have considered three indicative deployment levels of offshore wind, described below, which are aligned to different views on the exogenous factors affecting the future energy system (these scenarios aim to capture the full range of feasible deployment scenarios, and are neither forecasts for the UK nor targets for policy makers[15]).

- **Low scenario** (11GW by 2025, 17GW by 2050) if there are few constraints on nuclear, CCS and onshore wind, energy demand is relatively low (through successful energy efficiency and demand reduction measures), large amounts of biomass are available for energy needs, and electrification of heat and transport is relatively limited.
- **Medium scenario** (16GW by 2025, 31GW 2050) if there are moderate constraints on nuclear, CCS and bioenergy, or that energy demand is moderate and electrification occurs extensively in heat and transport energy. This scenario is aligned with the 2030 capacity value for offshore wind in the scenario based on the decarbonisation assumption of 100gCO_2/kWh in DECC's Electricity Market Reform (EMR) Delivery Plan[16]. This scenario also passes through 10GW of capacity in 2020 roughly consistent with capacity based on farms that will already have been built or where there is medium or higher confidence that they will have been built by 2020, according to 4C Offshore analysis[17].
- **High scenario** (25GW by 2025, 57GW by 2050) if no CCS is deployed and there are strong constraints on biomass, or energy / electricity demand is relatively high.

The medium deployment scenario (16GW by 2025 and 31GW by 2050) is used as the main basis for the

[12] Estimate by ETI, *Offshore Wind* (2014).

[13] Assuming a 42% capacity factor and total UK electricity generation of 615TWh in 2050.

[14] Successful deployment of offshore wind will also depend on other factors affecting the energy system such as grid upgrades and connections. Our analysis of deployment potential took those factors (and their cost) into account, including ensuring that the proportion of variable offshore wind generation was feasible within an optimised energy system – but this TINA does not look at the innovation and other challenges related to these developments.

[15] By trying to capture the full range of uncertainty over the medium to long term to inform innovation policy, these indicative deployment levels were not precisely aligned with UK government short and medium term targets.

[16] DECC, Electricity Market Reform Delivery Plan (2013).

[17] See http://www.4coffshore.com/

following analysis with the low and high deployment scenarios quoted in brackets throughout.

UK energy system with offshore wind

The above deployment scenarios were generated based on customised runs of ETI's Energy System Modelling Environment (ESME). ESME determines how much capacity is required across the generation mix to meet energy demand and emissions reduction targets at lowest cost based on the constraints outlined above. All scenarios meet energy demand and carbon emission constraints.

The medium deployment scenario envisages a UK electricity system which has around 150GW of overall installed electricity capacity by 2050. Within this scenario the most dominant low carbon technologies are nuclear (36GW) and CCGT with CCS (30GW).

In the high deployment scenario, in the absence of any CCS, there is a high proportion of renewables across the c. 204GW of capacity. This amounts to 57GW of offshore wind, 20GW of onshore wind and 24GW of solar. It also includes 56GW of nuclear capacity.

Energy storage, flexible back-up capacity, smart grids and / or interconnectors are important enablers for offshore wind energy to ensure security of supply despite the intermittent nature of wind power production. Long distance power evacuation from offshore wind using HVAC and potentially HVDC transmission will be particularly important in this respect.

Continuing early stage research into innovative distributed energy storage, innovation and deployment support of bulk storage (other than Pumped Hydro), and continued early stage and deployment-end innovation support for smart grid technologies is essential in lowering the cost of integrating a growing capacity of renewable electricity (including offshore wind) into the UK network.

Cutting costs by innovating

Current costs

The current levelised cost of energy (LCOE) of offshore wind in the UK is between c. £129-133/MWh[18] in 2015 GBP for a typical 'Round 2' site reaching Final Investment Decision (FID) in 2014, depending on depth. However, costs are very site-specific, driven not just by water depth but also distance to shore, wind speed, access to grid connections, and soil conditions[19]. For the purposes of the TINA we have assumed that low-cost 'Round 2' and 'Round 3' sites based on the portfolio of currently identified sites are likely to be developed first, leaving higher cost 'Round 3' wind farms to increasingly be constructed in more challenging areas, again based on the portfolio of currently identified sites[20],[21],[22]. Compared to a typical near-shore shallow-water site, moving to water depth of 40-60m can increase the cost of energy by c. 15-20%, while moving beyond 100km offshore can increase the cost of energy by another c. 15-20%[23]. However, this can be compensated for by higher wind speeds which improve the capacity factor; LCOE reductions of up to c. 20% can be achieved if the site is in a high-wind speed area. It should be emphasised that the above assumptions and their implications for how baseline costs increase over time as deployment ramps up, are based on the current portfolio of available sites, with all forthcoming analysis based on this portfolio.

Therefore, innovation must tackle not only the cost challenges of shallow-water near-shore sites, but also deliver new technologies for more challenging 'Round 3' sites and beyond. The sensitivity of cost to water depth for both near- and further-from-shore sites and distance to shore will need to be reduced. Many new technologies for more challenging sites will also be applicable to less challenging (both shallow and near-shore) sites, so decreasing the costs of deployment whatever the final mix of sites that are developed.

For this analysis we consider wind farms over the next few years to be relatively close to port (<60km) and in shallow water (<35m depth). By 2020 farms are increasingly in deeper water and further from port.

While capital expenditure (CAPEX) costs have risen over the past decade due to a combination of changes including increased health and safety restrictions, the move to more difficult sites (see above), and changes in the value of the pound, costs in recent years have once again started to decline. This is primarily a result of innovation in turbines leading to greater power

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[18] For further context to the starting costs (c. £129-133/MWh) compared with the 2015 Contracts-for-Difference (CfD) auction prices (c. £114-120/MWh): The strike prices in the CfD auctions (and the base used for the £100/MWh by 2020 target used in the Crown Estate's Offshore Wind Cost Reduction Pathways Study) are expressed in 2012 GBP whereas the TINA costs quoted here are in 2015 GBP. Converting TINA costs to 2012 GBP gives a range of c. £124-128/MWh. Furthermore, CfD prices are for delivery years of 2017-19 whereas the TINA starting costs are for FID 2014. Sticking with the 2012 base, for FID 2015 the TINA comparison would be c. £123-127; FID 2016 would make the TINA comparison c. £118-123 (all in 2012 GBP). FID 2015 and FID 2016 would still be consistent with delivery years 2017-2019. A further factor to consider when making comparisons is the administrative strike prices the year before the CfD auctions took place that were set at £155/MWh for projects commissioning in 2015/16, before falling to £150/MWh for those commissioning in 2016/17, and £140/MWh for those commissioning in 2017/18 and 2018/19 (again in 2012 GBP). Please note that other sources may show different estimates.

[19] The Crown Estate, Offshore Wind Cost Reduction Pathways Study (2012).

[20] Note that 'Round 2' and 'Round 3' in this context do not refer precisely to Crown Estate seabed zoning but to the general move to more expensive sites after cheaper sites have been developed.

[21] Site types have been defined in line with The Crown Estate's Offshore Wind Cost Reduction Pathways: Technology Work Stream (2012) and BVG's, Future renewable energy costs: offshore wind (2013).

[22] As confirmed in BVG, Towards Round 3 (2012): "Additional costs [are] associated with the majority of Round 3 Projects".

[23] EEA, Europe's onshore and offshore wind energy potential (2009), modified using Carbon Trust expert analysis: Taking an increase from 30-40m depth to 40-50m as raising costs by 13% and making a simplifying assumption that depth increases costs at the same percentage rate per 10m of depth, 50-60m would be c.25-30% more expensive than 30-40m. Assuming that some sites will be in the range 40-50m and some 50-60m we have approximated this as 15-20%, erring towards the lower end so as not to overstate the cost-reducing impact of innovation and recognising shallower sites will be prioritised over deeper sites.

Similarly, moving from 50-100km to 100-200km increases costs by c.20%. We have approximated this as 15-20%, erring towards the lower end so as not to overstate the cost-reducing impact of innovation and recognising closer sites will be prioritised over sites that are further away.

ratings, improvements to extra-large monopole foundations and O&M processes, as well as extended design life and reduced financing costs (e.g. cost of debt, equity, and insurance)[24].

Offshore wind systems can be split into six major technology sub-areas: development (wind resource measurement and turbine / array modelling), installation, the turbine, foundations, collection & transmission, and operation & maintenance. The turbine constitutes the largest share of the cost of energy (29%) followed by O&M, the foundation, installation, and collection & transmission (about 16-18% each) with development the lowest cost element (4%) as detailed in Table 2. It is important to note that these shares are not necessarily proportional to the potential for cost reduction. For example, innovations in technologies for the development phase can have a significant impact on the yield, leading to a greater reduction in the LCOE than their share of the LCOE might suggest.

The TINA analysis focuses on new windfarms, at least as far as CAPEX is concerned, however retrofitting technology improvements to existing windfarms (not quantified in this analysis) are also likely to yield benefits e.g. upgrading the range of wind speeds existing farms are able to operate within. Similarly, the TINA has not included consideration of extended life / repowering of wind turbines / farms.

[24] See Offshore Renewable Energy Catapult, Cost Reduction Monitoring Framework – Summary Report to the Offshore Wind Programme Board, 2015.

Table 2 - Overview of Offshore Wind Power sub-areas

Sub-area	Descriptions	% LCOE
Development	• Development involves the detailed planning and scoping for windfarms including measuring wind resource, designing the farm, and gaining resource consent. • Fixed meteorological masts are used to measure the wind resource and oceanographic conditions, using anemometry and LiDAR. Floating LiDAR systems have been deployed for validation. • Iterative processes are used to design array layouts, based on relatively simple Front-End Engineering Design (FEED) studies.	4%
Installation	• Vessels that jack-up from the seabed are used to transport and install most foundations and turbines – these may be oil & gas vessels or they may be specialised for offshore wind. Dynamic positioning (DP2) vessels have also been used to a certain extent, but this is not yet the norm. • Often down-time due to stormy weather can reach over 30%.	16%
Turbines	• Current turbines are less than or equal to 6-8 MW, with 3 blades on a horizontal axis. Many designs still use gearboxes to drive the generator, but some have removed the high speed stage to reduce the gearbox size, and others have adopted direct-drive drive trains. • AC power take-off systems (converting from AC to DC and back to AC again) use silicon components which are often a cause of turbine failure. • Most blades are made of glass fibre; carbon fibre is a lighter but costlier alternative. • Pitch control is used to control the rotor speed and loads; more complex algorithms are being introduced to balance wake and turbulence loads, improving energy production. • Turbines are installed in arrays to create large wind farms. • The turbine tower is usually a standard design for a specific turbine, not specialised for the foundation.	29%

Sub-area	Descriptions	% LCOE
Foundations	• Monopile foundations (steel tubes) are used for shallow waters (generally <35m depth), although jackets may be used for larger turbines (8MW+). Some concrete gravity bases have also been used. • Foundations for 35-60m water depth and larger turbines are more sophisticated and tend to be fixed to the sea floor, e.g. jackets and tripods, though this could change with further developments in floating foundation concepts. Currently these are more expensive, often optimised for the oil and gas industry, and are not yet standardised for serial manufacture. However standardisation is likely to occur in the future, and the development of tension-leg platforms moves the industry away from oil and gas experience.	17%
Collection & Transmission	• Inter-array cables tend to be three core 33kV AC cables. • Currently HVAC cables are used to link turbines to an offshore substation, with power clean-up at each turbine. • HVAC cables are also used to transmit power to the onshore substation, as current wind farms are relatively close to shore (within 60-80km). • Some far-from-shore farms in Germany have used HVDC transmission systems, although they have experienced several problems, mainly related to foundation designs not being adequately optimised to interface with collection and transmission systems leaving to substantial delays in new farms coming on stream.	16%
O&M	• Currently small crew transfer vessels are used to access turbines from the shore; these work best in calm seas. Some farms have helicopter access. • Accommodation vessels have been used in a limited number of cases. • Operators are required by manufacturer warranties to follow time-based planned maintenance strategies. After the warranty period some operators are using Condition-Based Maintenance (CBM) methods, although these are not widely used. • Individual turbine control systems are used to adjust operational parameters; intervention on a larger scale (e.g. on the farm as a whole) requires human operation.	18%

Sources: KIC InnoEnergy (2014) Future renewable energy costs: offshore wind; Expert interviews.

In addition to the above, the interaction between environmental forces and the technology (e.g. metocean conditions at all lifecycles of the project), and where necessary mitigation of environmental impacts (e.g. biofouling) are recognised as having an important bearing on project costs. Innovating, streamlining and front-end loading environmental considerations can assist in minimising environmental impacts and keeping project costs down. Although some of the relevant technologies in this area are covered under the ‘Development’ category above, this is more with a focus on increasing the yield of the farm rather than how these actions can lower costs directly e.g. through smoothing regulatory compliance.

Floating foundations are a particular area of interest for their capacity to lower the cost of wind farms in deeper water and also to potentially open up new sites for wind farms. While the TINA analysis did examine the impact of floating foundations on the LCOE (see Chart 1 below), the widely varying estimates of the potential impact of floating foundations from stakeholders interviewed for the TINA led to their exclusion from the main scenario analysed for assessing the value in meeting emissions targets at least cost. Nevertheless, floating foundations remain an area of active research interest and have been the focus of recent studies see, for example, *PelaStar Cost of Energy: A cost study of the PelaStar floating foundation system in UK waters* (prepared by Glosten for ETI, January 2015) and *Floating Offshore Wind: Market and Technology Review* (prepared by the Carbon Trust for the Scottish Government, June 2015).

Cost savings through learning-by-R&D and learning-by-doing

Offshore wind power is a relatively nascent technology compared to the gas, coal and nuclear technologies that make up the majority of our current generation mix. Offshore wind power has been deployed at scale since 2002. It has been proven to operate in harsh offshore conditions. Nevertheless offshore wind technologies are still largely based on modified onshore wind turbines and offshore oil and gas foundations. Further technological innovation is required at both a system level and in each sub-area to reduce costs and enable deployment in deeper water, further offshore.

Innovation opportunities over the next 10 years could bring down the deployment costs of offshore wind by up to c. 30%, with further savings after 2025 could bring down costs even further – up to c. 45% by 2050[25]. However, it is worth reiterating that realising cost savings from R&D cannot happen in isolation from deployment. Large cost savings from R&D will only occur if developers see a reliable pipeline of demand justifying the investment – and risks – of developing and trialling new innovations.

Figure 1 shows the impact of innovation and learning-by-doing on reducing the offshore wind 'average' levelised costs to 2050. The yellow line, which represents baseline costs with no cost reduction increases over time as the proportion of more challenging sites in deployment increases. This baseline projection is not a prediction of actual costs for sites that will eventually be developed but rather a modelling exercise based on currently identified sites.

Cost reductions to 2025 are based on expert judgment of optimistic but feasible cost reductions from innovation in each segment of the value chain (development; installation; turbines; foundations; collection and transmission; and O&M). The cost reductions from innovation are further augmented with assumed learning-by-doing, which is simply modelled as a ratio to the cost reductions from innovation identified by experts according to the maturity level of each value chain component. The ratios of learning-by-doing to learning-by-R&D by maturity level follow the approach of Jamasb (2007).

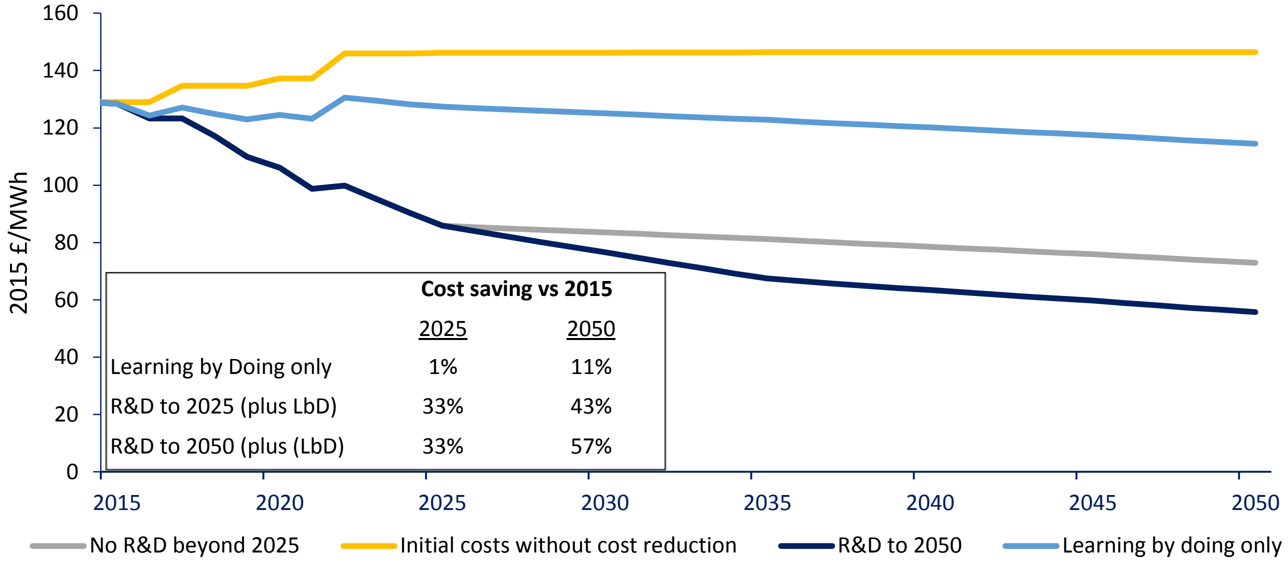
Cost reductions from 2025 to 2050 are based on an overall learning rate drawn from literature of a 12% reduction in costs for every doubling in global capacity[26], which in the medium deployment scenario reaches 228 GW by 2050.

To understand the impact on average costs, cost reduction modelling is coupled with assumptions regarding what proportion of wind farms each innovation type is applicable to and the degree of market penetration each innovation achieves

[25] These figures are for reductions from only R&D. Reductions from R&D and learning-by-doing raise this to 40% and 60% respectively.

[26] RenewableUK, Offshore wind forecasts of future costs and benefits, (2011); Carbon Trust, Offshore Wind – Big Challenge, Big Opportunity, (2008).

.Figure 1 - Potential impact of innovation on 'average' levelised costs[27] 2015-2050 with learning-by-R&D and learning-by-doing



Sources: KIC InnoEnergy (2014) Future renewable energy costs: offshore wind; BVG (2012) Offshore wind cost reduction pathways Technology work stream; Offshore Renewable Energy Catapult Cost Reduction Monitoring Framework Summary Report to Offshore Wind Programme Board (2015); EWEA (2014) Strategic Research Agenda / Market Deployment Strategy; RenewableUK (2011) Forecasts of future costs and benefits; expert interviews; Carbon Trust analysis; ESME.

[27] Note that the yellow baseline in Figure 1 represents initial 'average' costs for 'Round 2' and 'Round 3' sites, further differentiated by water depth (under or over 35m) based on the known current portfolio of available sites. Some adjustments to the profile of baseline costs were made to recognise that even though the proportion of 'Round 3' sites being used will increase quickly, at least initially many of these 'Round 3' sites will have cost characteristics similar to average 'Round 2' costs.

Some technologies such as sensors and smart control are noted in the analysis for their potential to decrease CAPEX or operating expenditure (OPEX) but not for their capacity to increase the range of wind conditions within which turbines could operate. These effects would result in higher yields but their impacts are not quantified in the TINA analysis. However, the yield impact of layout optimisation tools, wind resource measurement techniques, and high power / yield / reliability turbines are included.

Cost savings through learning-by-doing are possible, through standardisation, economies of scale in the supply chain, and improved financing structures. Note that learning-by-doing is not analysed in detail here, but is derived using the ratios described in Jamasb (2007). These ratios are based on learning-by-doing rates being correlated to both deployment levels and technology maturity, with more learning-by-doing occurring (compared with learning by R&D) the more mature a technology area becomes.

Combining these learning-by-R&D and learning-by-doing effects, the cost of energy from offshore wind power could be as low as c. £86/MWh by 2025 and c. £56/MWh by 2050 (see Figure 1).

These estimates include maximum innovation potential, combining learning-by-R&D (driven by R&D spending) and learning-by-doing (achieved in the model through the incremental learning associated with increased deployment alone)[28], and are shown in the bottom path in Figure 1. This path is steeper than a base case scenario with only learning-by-doing (without focused R&D activity). The path in-between these in Figure 1 incorporates the maximum innovation opportunities to 2025, followed by learning-by-doing only.

Estimates of learning-by-R&D in 2025 were derived from a bottom-up assessment of highest potential cost and yield improvements identified and potentially commercialisable by ~2025, as shown in Chart 1. Full innovation to 2050 is a top-down assessment of the long term potential for cost reduction and yield improvement, based on learning rates in this and similar industries[29].

[28] As defined in Jamasb, T. (2007). Technical Change Theory and Learning Curves: Patterns of Progress in Energy Technologies, The Energy Journal, Vol. 28, Issue 3, 45-65.

[29] Sources RenewableUK (2011) Forecasts of future costs and benefits; Van de Zwaan et al. (2011) Cost reductions for offshore wind power: exploring the balance between scaling, learning and R&D; U.S. Energy Information Administration AEO (2012) Electricity Market Module.

Chart 1 Potential cost savings from innovation (learning-by-R&D) by sub-area

Sub-area	Type	Innovation impact potential on levelised cost by ~2025[1]	Innovation impact potential on levelised cost by 2050	What is needed (source of improvement potential)
Development	Layout optimisation Wind resource measurement techniques	c. 3.5%	c. 4%	▪ Improved wakes and loads models to feed into multi-variable layout optimisation, mesoscale modelling, weather forecasting and logistics planning ▪ Advanced resource measurement tools, e.g. new applications of scanning LiDAR
Installation	Installation methods for larger / deeper farms	c. 6.0%	c. 7%	▪ Alternative piling methods ▪ Improved sea fastening and rigging methods. ▪ Innovative installation vessels for work in rougher sea states
Turbine	High power / yield / reliability turbines	c. 17.0%	c. 19%	▪ Higher power turbines, optimised rotor diameters ▪ Improved blade materials, power take-off and aerodynamic control ▪ Holistic design ▪ Power degradation prevention
Foundations	<35m depth >35m depth Floating[2]	c. 3.5% c. 5.0% c. 10.0%	c. 4% c. 6% c. 19%	▪ Innovations in monopiles (e.g. soil modelling) ▪ Methods for serial manufacture of jackets (e.g. welding) ▪ Suction bucket technology ▪ Dynamic cables, anchoring systems, floating foundation concepts (e.g. tension leg platforms, spar-buoy)
Collection & Transmission	Inter-array cables and transmission systems	c. 4.5%	c. 5%	▪ Higher voltage inter-array systems ▪ Next generation (optimised) HVDC / HVAC systems and other novel concepts (e.g. variable frequency) ▪ Infrastructure innovations, e.g. turbine-mounted platforms, substation design
O&M	Remote monitoring, control and maintenance Access systems	c. 4.0% c. 1.0%	c. 5% c. 2%	▪ New sensors and algorithms for remote monitoring and condition-based maintenance ▪ Improved logistics planning tools, power forecasting tools and experience-based decision support methods ▪ Safe access vessels and transfer systems for higher sea states
Total impact on levelised cost		c. 30%	c. 45%	

[1] The innovation impact potential represents the high end of a low-medium-high range of what experts deem to be "aspirational but feasible" to 2025 and then a learning rate of 12% from 2025 to 2050. For the total impact on LCOE these estimates are combined with assumptions on the applicability and market penetration of innovations in each area of the value chain.

[2] The impact of floating foundations on costs, while potentially substantial, was subject to major uncertainty in the TINA analysis and is not included in the total impact on levelised cost.

Sources: KIC InnoEnergy (2014) Future renewable energy costs: offshore wind; BVG (2012) Offshore wind cost reduction pathways Technology work stream; EWEA (2014) Strategic Research Agenda / Market Deployment Strategy; expert interviews.

Value in meeting emissions targets at lowest cost

Based on our estimates for cost and efficiency improvements, and our scenarios for deployment (taking into account emissions constraints), we calculate the potential savings in energy system costs through innovation.

In our medium deployment scenario, the identified innovation opportunities lead to a saving of c. £33bn in deployment costs over 2015-2050. As shown in Figure 2 below; c. £27bn, is from learning-by-R&D improvements achievable by 2025[30]. An additional c. £6bn is saved from ongoing learning-by-R&D post 2025. The c. £33bn cost saving from R&D is in addition to the c. £16bn cost saving from learning-by-doing. These savings estimates use an 'inflexible deployment' counterfactual i.e. the deployment costs for this technology without cost reduction are compared with the deployment costs with cost reduction without considering any feedback between costs and deployment.

The savings opportunity can be further broken down by each sub-area, as shown in Figure 3. The greatest cost savings / system benefits are from improvements in turbines, foundation and O&M processes.

[30] Note that only c. £6 bn of the c. £27 bn in savings is realised by 2025 with the remainder realised by 2050.

Figure 2 - Potential cost savings from 2010 to 2050 – assuming inflexible deployment[31]

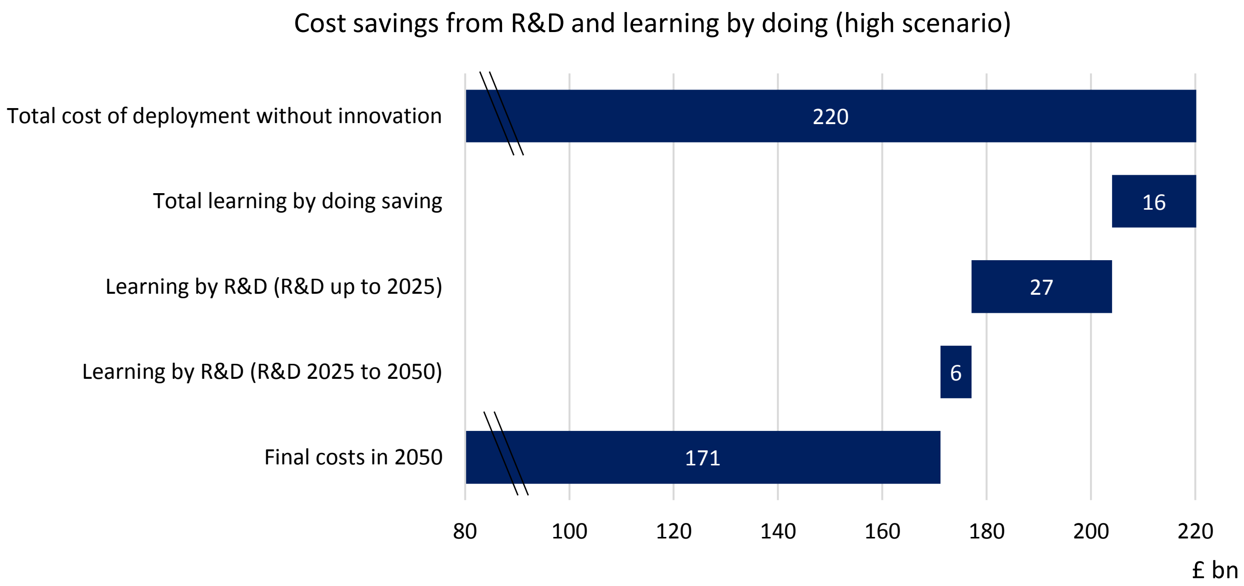
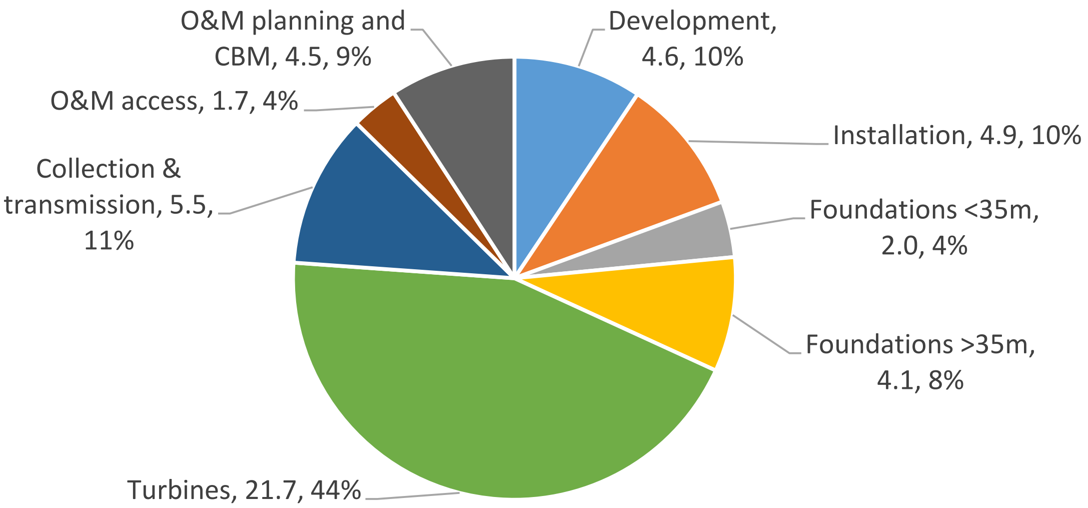


Figure 3 - Potential cost savings in £ bn and as a percentage of total (learning-by-doing plus learning-by-R&D) from 2015 to 2050 by sub-area (medium deployment scenario)



Sources: KIC InnoEnergy (2014) Future renewable energy costs: offshore wind; BVG (2012) Offshore wind cost reduction pathways Technology work stream; expert interviews (including input from ETI, developers, supply chain organisations and academia), Carbon Trust analysis.

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[31] Cumulative levelised cost of offshore wind capacity installed between 2015 and 2050 (medium scenario), discounted to 2015 using the social discount rate, 3.5% to 2045 and 3.0% 2045-2050. Costs are calculated using a medium deployment scenario, derived using the ESME model, and with the requirement that deployment reaches 10GW by 2020 – the capacity found to be "achievable" in the EMR Delivery Plan (DECC 2013)). Note that the cost savings calculated were not fed back into the ESME model to further refine the outputs. This is the total actual cost of deployment (medium scenario); it does not represent the additional cost over the best high-carbon alternative.

Green growth opportunity

Global offshore wind market

Estimates of global deployment of offshore wind by 2050 range from around 140GW to over 500GW (IEA's Energy Technology Perspectives 2014).

- **Low scenario** (37GW by 2025, 142GW by 2050) if the world stays on a path to a 6 degrees Celsius increase in global average temperatures and / or few constraints on nuclear and CCS, and / or electricity demand is relatively low
- **Medium scenario** (48GW by 2025, 228GW by 2050) if the world shifts to a 4 degrees path and there are few constraints on nuclear and CCS
- **High scenario** (101GW by 2020, 504GW by 2050) if the world keeps on a 2 degrees path and there are strong constraints on nuclear and CCS

The cumulative, discounted global market turnover by 2050 could grow to c. £430bn (£300bn to £1 trillion).

The UK could be one of the market leaders

The UK is well positioned to become one of the leaders in the global offshore wind market, achieving a market share of c. 10% in 2050. It can leverage its capabilities from the offshore oil and gas, maritime, aerospace and other sectors which allow the UK to create a strong position in foundations, installation, O&M and turbines.

The overall global shares that the UK captures will be determined by how much of the global market is tradable versus non-tradable; how much of the tradable market is accessible to UK-based firms, and what market share UK-based firms capture of the accessible, tradable market. The non-tradable share of the global market that relates specifically to deployment in the UK is 100% captured by UK-based firms[32].

[32] Each of these judgements (tradable v non-tradable; accessible tradable market; and the market share captured by the UK) differ for each part of the value chain.

£19 billion (£12-30 billion) contribution to the UK economy

Estimates of GVA supported by the offshore wind sector (and the estimates that follow relating to jobs) relate to direct activity only and are driven by deployment. Indirect GVA (i.e. supply chain), induced GVA (activity stimulated elsewhere in the economy), and GVA not directly connected to deployment (e.g. R&D activity) are not included in these estimates. The major advantage of the simplicity of the TINA approach is that it is able to be replicated across different technologies easily.

Global and European level deployment figures used in the calculations are taken from the three scenarios outlined in the IEA's Energy Technology Perspectives 2014 and noted above. UK deployment figures are taken from the low / medium / high deployment scenarios used in the analysis of the benefit of cost reduction and are based on customised ESME runs.

If the UK successfully competes in a global market to achieve the market share above, then offshore wind could contribute c. £0.7 bn (£0.4 – 1.2 bn)[33] in direct GVA per annum in 2050, a cumulative contribution[34] of c. £38 bn (£24 - 61 bn)[33] to 2050. The breakdown of cumulative GVA by value chain component is given in Figure 4.

It may be appropriate to apply an additional displacement effect since part of the value created from offshore wind will be due to a shift of resources away from other industries. Expert opinion has roughly assessed this effect to be between 25% and 75%, so we have applied a flat 50%. Including this displacement factor, offshore wind would still make a net contribution of c. £0.3 bn (£0.2 - 0.6 bn) in direct GVA per annum in 2050, a cumulative contribution of c. £19 bn (£12 - 30 bn) to 2050.

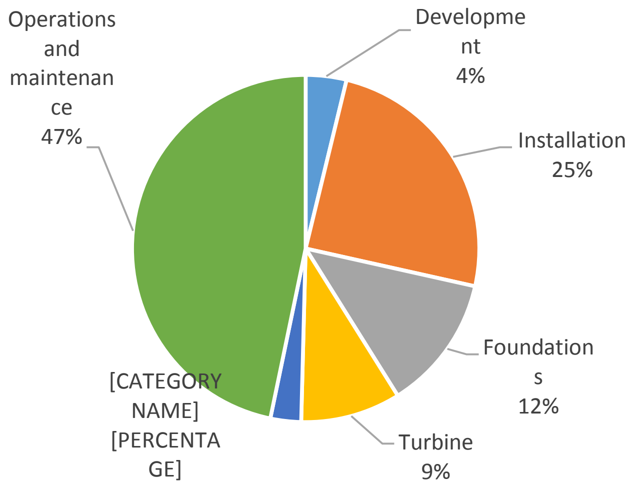
Approximately 80% of direct GVA is estimated to come from domestic activity and c. 20% from export activity. There is variation in export intensity across

[33] Estimates based on medium (low – high) deployment scenarios.

[34] Discounted at 3.5% to 2045, and 3.0% between 2045 and 2050, in line with HMT Green Book (2011) guidelines.

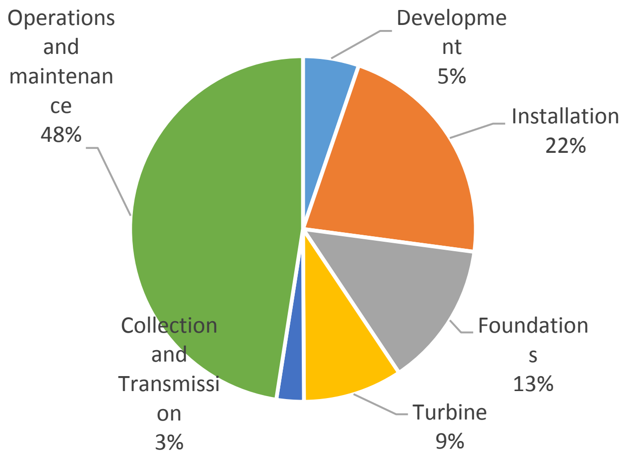
components in the value chain with development being more heavily weighted towards the export market (c. 75%) and installation and O&M more heavily weighted towards activity in the UK (both more than 85%).

Figure 4 - Cumulative GVA breakdown by value chain component



Direct jobs in 2025 are estimated at c. 22,500 (13,800 -38,600)[35]. As with GVA, job intensity varies across the value chain. c. 10,700 (48%) of jobs are in O&M whereas only c. 600 (3%) relate to collection and transmission. Figure 5 gives a breakdown of jobs in 2025 by value chain component. Direct jobs in 2050 are estimated at c. 30,700 (18,800 - 55,000).

Figure 5 - Jobs in 2025 breakdown by value chain component



[35] Estimates are based on turnover figures generated by costs multiplied by deployment levels with ONS figures for jobs per million GBP of turnover for each segment of the value chain then applied. Other estimates may vary.

The case for UK public sector intervention

Public sector activity is required to unlock this opportunity – both the c. £33bn reduction in the costs to the energy system to 2050 from learning-by-R&D, and the c. £19bn cumulative direct GVA to 2050 from new business creation.

Market failures impeding innovation

A number of overall market failures inhibit innovation in offshore wind. The main market failures and barriers relate to:

- The lack of coordination between different players in the value chain to share essential performance information and the lack of incentive that any one player in the industry has to incur the costs of investing in innovations that will ultimately benefit the industry as a whole (coordination failures / positive externalities). These failures primarily affect the development of improved wakes and loads models used in the planning stage for new wind farms, the development of new foundations, including floating foundations, and the development of new O&M techniques.
- The high degree of demand uncertainty reduces the incentive to invest in innovations that only offer a payback if demand is sufficiently high (negative externalities). This particularly affects innovations in installation and O&M where for example development of a new installation vessel has several years lead-in time and would be very costly – therefore only justified if the pipeline of demand is sufficient.
- The disinclination individual developers have to including new innovations in their wind farms due to the increase in cost (e.g. through planning changes, higher cost of capital) and risk. This particularly affects the trialling of new foundations, including floating foundations, and serial manufacturing of foundations.

These are further detailed in Table 3 below.

Table 3 - Market failures by value chain component

Sub-area	What market failures or barriers exist?	Assessment
Development – **Improved wakes / loads models**	**1. Lack of coordination between different players in the value chain (e.g. turbine original equipment manufacturers (OEMs), foundations manufacturers and developers) hinders innovation** – no one player is incentivised to incur the costs of innovation activities that will benefit the industry as a whole while accruing only a portion of those benefits and while risking a loss of competitive advantage *(coordination failures / positive externalities).* This hinders yield optimisation. **2. Skills deficiencies in an area of increasing technical complexity can limit progress in R&D and how innovation is used.** **3. Legislation issues** (e.g. search & rescue and other regulations) can complicate the investment process and increase CAPEX, OPEX, and decommissioning costs.	*Critical failures*
– **Improved wind resource measurement**	**4. Risk aversion** of investors' engineers can reduce acceptance of new resource measurement technologies.	*Moderate failure*

Sub-area	What market failures or barriers exist?	Assessment
Installation	**5. High demand uncertainty for offshore wind farm development results in reduced investment in innovations** (*negative externalities)*. • This is particularly true for installation vessels, given that they have a long lead time (3-4 years) and high costs (~£100m) which may only pay off over multiple installations. • Cable installers will continue to use practices from the oil & gas industry because demand uncertainty hinders specialisation. **6. Limited incentive for collaboration between OEMs, installers, foundation manufacturers and vessel owners** makes it more difficult to optimise installation processes (see point 1).	*Significant failure*
Turbine	**7. Test sites are lacking due to high capital costs, demand uncertainty and private sector coordination failures** – no single player has the incentive to pay the consenting costs for a site for large (10MW) turbines (though a planning application has been lodged for a 10MW onshore testing site in Denmark) as the site would serve multiple suppliers (*negative externalities / coordination failures, positive externalities).*	*Moderate failure*
	8. Risk aversion of technology and project investors to using novel turbines is exacerbated by a poor understanding of type certificates. **9. Demand uncertainty, upfront capital costs and long product lead times (5-10 years) can limit investment in novel concepts and prevent new firms from entering the market, reducing competition** (*negative externalities, imperfect competition, high barriers to entry).* • Turbine OEMs will only invest in developing a larger turbine if they are certain of a return on their investment. Furthermore, the current level of demand means the market can only support a limited number of manufacturers, dampening competition. • New entrants need a track record of operating hours, but investment required to get to this point without an order book is high.	*Minor failure*
Foundations • **<35 m depth** • **>35m depth** • **Floating foundations**	**10. Test sites for novel foundations are lacking** (see point 7). **11. Demonstration on a commercial site can increase the cost, time to construct, and risk associated with a wind farm** (see point 8), therefore developers are reluctant to test new foundations.	*Moderate failure*
	12. Lack of collaboration in the value chain due to the multi-contract approach – prevents data sharing and holistic design (see point 1). **13. Lack of incentives for innovation in e.g. serial manufacturing processes** (see point 5).	*Critical failure*

Sub-area	What market failures or barriers exist?	Assessment
Collection & Transmission – **Improved inter-array connections**	**14. Skills limitations and inappropriate standards** (for e.g. cable burial) limit innovation. **15. Benefits from improved cable / transmission technology may be copied by other developers, hence reducing incentives** (see point 1).	*Minor failure*
– **Improved offshore substations / transmission systems**	**16. See 14 and 15 above** **17. Market in novel transmission technologies is dominated by a small number of large companies** (e.g. Siemens, ABB, JDR) due to large infrastructure requirements (*i.e. barriers to entry and immateriality).* **18. Coordination failures (*positive externalities / transaction costs)*:** Offshore Transmission Owners (OFTOs) operate transmission assets, but all the development risk falls upon developers. This barrier is further exacerbated by uncertain demand for projects (see point 5), especially for HVDC technologies, as these require larger farms or connection of multiple farms at once where a return is only likely when there is a long pipeline of projects.	*Moderate failure*
O&M – **Improved condition monitoring / better planning**	**19. Lack of collaboration between companies** (see point 1) – O&M companies, project developers and turbine manufacturers do not want to share performance and product warranty data needed to improve. **20. Innovation is driven by developers at the farm level**, so the industry as a whole may not always benefit. **21. Uncertainty on future offshore wind demand** (see point 5) has particular effect since investments in new technologies are substantial for the relatively small O&M play.	*Critical failure*
– **Improved access technologies**	**22. See point 21 above.**	*Moderate failure*

Source: Expert interviews, Carbon Trust analysis.

Ability of the UK to rely on others

For most offshore wind sub areas, the UK cannot exclusively rely on other countries or sectors to intervene in tackling these market failures and develop the necessary innovations to bring down the cost of offshore wind.

Overall, the UK has an earlier and greater need than other countries:

- Offshore wind comprises a much larger share of UK renewable resource than in most other countries and the UK is a leader in the deployment of offshore wind. This means that while other countries may eventually invest in innovations that could be applied in the UK, in order to be applied to a greater share of UK deployment innovations will need to be developed by the UK first.
- UK R&D programmes have been among a handful of leaders in offshore wind. This is important for retaining the (unquantified) link between investing in R&D and creating value in business creation.

With respect to specific components in the value chain, the UK has specific needs in:

- **Development** – the UK has similar needs to Denmark and other countries with high deployed capacity and relative resource. However, the UK is important because of its lead in deployment and strong academic base and programmes (e.g. SUPERGEN).
- **Installation** – the Netherlands and Denmark also have some far from shore farms or potential sites, however, these are much more extensive in the UK (Round 3 sites). There is some overlap on installation vessels with the oil and gas sector – but these need to be adapted for use in offshore wind. The Netherlands leads on installation vessels but the UK has strengths in installation techniques.
- **Foundations** – the UK has a greater need than most others for 35-60m foundations and a potential specific need for 60-100m foundations. The UK could potentially rely on others, such as Japan, which sits on a continental shelf that drops steeply away, for very deep water (100m+), possibly floating foundations.

Turbine – turbine development is being driven primarily by private companies in Denmark and Germany. Some supporting technologies such as materials and power systems are developed in the UK.

- **Collection and transmission** – Germany is using HVDC for its far-from-shore farms but they have encountered challenges and the application may not be directly convertible to the UK because the responsibility for connecting offshore generation to the grid rests with developers in the UK rather than the grid operator, meaning the synchronisation problems in Germany would not occur in the UK.
- **Operations and maintenance** – Data sharing programmes (e.g. SPARTA) are being led by the UK, which is also very strong academically in this area and in safety. While O&M challenges exist for other countries, UK farms are in tougher conditions than most other early adopters of offshore wind.

Potential priorities to deliver the greatest benefit to the UK

The UK needs to focus its resources on the areas of innovation with the biggest relative benefit to the UK and where there are not existing or planned initiatives (both in the UK and abroad). The LCICG has identified and prioritised these innovation areas.

Innovation areas with the biggest relative benefit from UK public sector activity / investment

The LCICG has identified the areas of innovation with the highest relative benefit from UK public sector activity / investment[36]. The identification of these areas assumes that the sites developed are based on the currently identified portfolio of sites. The highest relative benefit areas identified are novel foundations for deep (>35m depth) water, improved O&M technologies for remote control and maintenance, and improved wakes and loads models for layout optimisation, followed by improved installation techniques for larger and deeper farms, high yield and reliability turbines, advanced transmission systems, and novel access systems (see Table 4).

These have been prioritised by identifying those areas that best meet the following criteria:

- Value in meeting emissions targets at lowest cost;
- Value in business creation;
- Extent of market failures or barriers; and
- Opportunity to rely on others.

[36] Without considering costs – these are considered in the final prioritisation on pages 27-29.

Table 4 - Benefit of UK public sector activity / investment by sub-area and technology type

Sub-area	Type	Value in meeting emissions targets at lowest cost (£ bn)	Value in business creation (£ bn)	Extent of market failure	Opportunity to rely on others	Benefit of UK public sector support (without considering costs)
Development	▪ Models for wakes / loads	c. 2.9 (1.6-5.2)	c. 0.7 (0.5-1.7)	Critical failure	No	**High**
	▪ Wind resource measurement			Moderate failure	No	**Low-medium**
Installation	▪ Improved installation methods for larger / deeper farms	c. 3.2 (1.7-5.7)	c. 4.7 (2.7-7.5)	Significant failure	Maybe	**Medium-high**
Turbine	▪ High power / yield / reliability	c. 15.7 (8.7-26.3)	c. 1.8 (1.3-2.3)	Minor failure	Yes for turbine design and manufacture; no for materials and supporting technologies.	**Low-medium**
Foundations	▪ <35m depth	c. 0.9 (0.7-1.5)	c. 2.4 (1.8-3.2)	Minor failure	Maybe	**Low**
	▪ >35m depth	c. 2.7 (1.2-4.9)		Critical failure	Not really	**High**
	▪ Floating	N/A[37]		Critical failure	Maybe	**Medium**
Collection & Transmission	▪ Inter-array cables	c. 3.3 (1.8-5.7)	c. 0.5 (0.4-0.7)	Minor failure	Maybe	**Low**
	▪ Transmission systems			Moderate failure		**Medium**

[37] Due to the highly uncertain impact of floating foundations on cost reduction and whether it will be included in deployment, floating foundations are not included in the modelling used in this analysis. Nevertheless as other more specific studies have highlighted, floating foundations could potentially have a major impact on costs and face many of the same market barriers as fixed foundations. Mitigating this is the interest other countries e.g. Japan may have in developing this technology, therefore the overall prioritisation of floating foundations is rated as 'medium'.

Sub-area	Type	Value in meeting emissions targets at lowest cost (£ bn)	Value in business creation (£ bn)	Extent of market failure	Opportunity to rely on others	Benefit of UK public sector support (without considering costs)
O&M	▪ Remote control, monitoring and maintenance	c. 3.5 (1.9-6.3)	c. 8.8 (5.6-14.7)	Critical failure	Not really	**High**
	▪ Access systems	c. 0.8 (0.4-1.4)		Moderate failure	Maybe	**Medium**

Existing innovation support

The UK is supporting many of the areas highlighted above. This is through a combination of policies to incentivise demand, supply-side innovation programmes to 'push' technology and support for enablers. Table 5 provides further detail.

Table 5 - Summary of current / recent UK public sector support

Market pull (demand side)	Examples of technology push (supply side) and enablers
▪ The Scottish Government has introduced an enhanced Renewables Obligation Certificate (ROC) scheme to incentivise testing and demonstrations of innovative, new-to-market turbines (2.5 ROCs) and in particular pilot projects consisting of non-fixed turbines e.g. floating turbines or those deploying 'tension line' deployment systems (3.5 ROCs). ▪ UK revenue support through **Feed-in Tariffs** is now operated through a competitive Contract for Difference auction. The recently completed CfD Allocation Round One saw two offshore wind projects come in at £119.89/MWh and £114.39/MWh – all strike prices are in 2012 GBP. This compares to the previous contracts that were agreed at £140-155/MWh[38] in 2014 under the Final Investment Decision enabling for Renewables (FIDeR) that preceded the CfD Allocation Round One. ▪ Carbon price, via the **EU Energy Trading Scheme (ETS).**	**Offshore Renewable Energy Catapult (ORC)** – up to £10m per annum over five years (£50m) from Innovate UK, headquartered in Glasgow with an operational centre in the North East of England (Northumberland) and now incorporating NaREC – the National Renewable Energy Centre. Project areas include/have included: ▪ Using **standardisation** to drive cost reduction and innovation; ▪ **Offshore cables** – looking at how HVDC networks and best practice in cable design and installation; ▪ The **System Performance, Availability, and Reliability Trend Analysis (SPARTA)** project working with the **Crown Estate** and wind farm owners / operators **Carbon Trust Offshore Wind Accelerator (OWA)** – 2008 to 2015; c.£30m in funding to accelerate cost reduction and increase reliability and yield in a consortium with nine major developers, looking across electrical systems, cable installation, foundations, wake and wind resources measurement, and access systems. The aim of the OWA is to reduce the cost of offshore wind by 10% in time for cost savings to be realised in time to impact on large scale deployment across Round 3 sites. The OWA is funded two-thirds by industry and one third by **DECC** and the **Scottish Government**. **DECC and Innovate UK's Offshore Wind Component Development and Demonstration Scheme** has supported development of technologies across components including installation, turbines, foundations, collection and transmission, and operations and maintenance. The **Scottish Government** is also supporting the **Hywind project** that has now secured agreement for lease (AfL) and is seeking consent from Marine Scotland. This project will demonstrate technological improvements, the operation of multiple units, and cost reductions in a park configuration for floating turbines. **Scottish Enterprise** runs the £15 million **Scottish Innovative Foundations Technologies Fund** that is available to companies to encourage manufacture of next generation wind foundation prototypes in Scotland and to support cost reduction within the sector. **ETI offshore wind programmes** – has funded a number of studies, with over £40m invested since 2007. The ETI is a public-private partnership between global energy and engineering companies, academia, and the

[38] This range is representative of the contracts agreed for two offshore wind farms: Dudgeon (£150/MWh), which is due to begin generating power in 2017, and Beatrice (£140/MWh), which is due to begin generating power in 2019 and takes stock of the strike prices administratively set at £155/MWh for projects commissioning in 2015/16, £150/MWh for those in 2016/17, and £140/MWh for those in 2017/18 and 2018/19 prior to the introduction of the CfD auctions.

	UK government. Recent studies have included: ▪ The **Very Long Blades project** demonstrated technologies required for the world's longest wind turbine blades (£15.5 million from ETI); ▪ **Floating Platform System FEED study**. **Structural Lifecycle Industry Collaboration** project – Collaborative joint industry project established by a group of ten offshore wind operators undertaking research into the specific behaviour of wind turbine structures in the offshore environment and supported by **DECC**. **EPSRC's SUPERGEN Wind Hub**, which brings together leading wind energy academic research groups in UK to address the medium term challenges of scaling up to multiple wind farms in the UK. SUPERGEN includes better understanding wind resources and their interaction with farms; the layout of the farms; their components and their connection with the grid. Other projects supported by grants from **EPSRC** including: • Offshore wind farms in shallow water at the University of Cambridge looking at the **monopile foundations** in shallow water; • **Offshore wind farm availability** at the University of Strathclyde

N.B. In addition EU funding is being invested in offshore wind in the UK.

Sources: Carbon Trust, Crown Estate, DECC, EPSRC, ETI, Innovate UK, Renewable Energy Catapult, Scottish Enterprise, Scottish Government.

Potential priorities for public sector innovation support

In the sections above, we identified the key innovation needs and the market barriers hindering these innovations. This analysis points to a number of priorities for public sector innovation support:

- Novel designs for low-cost foundations for water depths of greater than 35m including floating concepts but especially fixed concepts.
- Novel designs for larger turbines.
- Development of serial manufacturing techniques.
- Remote condition-based monitoring, control and maintenance systems and O&M access systems.
- Improved wakes and loads models for layout optimisation, advanced resource measurement tools, and data sharing methods.
- Installation methods for deeper waters and higher sea states.
- Optimised / next generation transmission systems (e.g. HVDC) and improved, lower cost materials, cabling concepts, and installation techniques.
- Innovative materials and components for higher power rating and more reliable turbines.

Table 6 outlines how the potential innovation priorities align against each technology sub-area, the scale of potential public funding needed for each, current or recent relevant activities / investment in each area, and potential future activities. Figure 6 gives a timeline of these potential future activities over the next 10 years.

To realise the full benefit from innovation over the following 5-10 years will require on-going support to existing areas, scaling up a subset as they move from design to demonstration, as well as adding a prioritised set of new programmes. The public sector investment required however is a fraction of the value that offshore wind innovation could bring to the UK economy, including helping to unlock c. £33 bn (£18 - 57 bn) savings in meeting energy and emissions targets at lowest cost, and the c. £19 bn (£12 - 30 bn) value add creation to UK GDP.

As well as supporting innovation in each of the individual areas above, public intervention can help collaboration and integration across them. It can also facilitate the commercialisation of innovative concepts created by research institutes and small companies through entrepreneurial support programmes (generally across many technology areas). Public intervention can join up innovation programmes with supply chain and infrastructure development. Where appropriate this includes helping to focus activity into centres of excellence where there are collective benefits.

Finally, while it is not examined in the TINA, it is also important to note the link between deployment support and innovation support, when considering how to address the market failures and barriers identified. In order for the offshore wind industry to contemplate developing new innovations investors must see a clear business case for the level of inherent risk in the projects they undertake. This is crucially linked to the demand / deployment pipeline – both its scale and visibility, which includes publicly provided deployment support.

Table 6 - Potential offshore wind innovation priorities and support

	Potential innovation priorities	Indicative scale of public funding[39]	Examples of current activities / investments	Future potential activities
Development ▪ Wakes / loads models	▪ Improved models for wakes and loads	▪ Low millions	▪ Carbon Trust Offshore Wind Accelerator wake effects programme (modelling) ▪ SUPERGEN	▪ Further programmes for wakes models; new programmes for loads models
	▪ Industry-led data sharing campaigns	▪ Low millions	▪ None	▪ New programmes to provide incentives for sharing data
▪ Wind resource measurement	▪ Studies into advanced wind resource measurement techniques, and validations of floating / scanning LIDAR	▪ Low millions	▪ Carbon Trust Offshore Wind Accelerator floating LIDAR programme ▪ SUPERGEN	▪ Support for new studies into novel measurement techniques. ▪ Additional support for validation.
Installation	▪ Improved installation methods for larger / deeper farms	▪ High millions	▪ Carbon Trust Offshore Wind Accelerator funding design work for new installation vessels ▪ DECC / Innovate UK's Offshore Wind Component Technologies Development and Demonstration Scheme.	▪ Additional support for testing
Turbine	▪ Onshore demonstration sites of novel turbines	▪ High millions	▪ DECC / Innovate UK's Offshore Wind Component Technologies Development and Demonstration Scheme.	▪ Expand existing and support new sites.

[39] Provides an order of magnitude perspective on the scale of public funding (existing and future) potentially required over the next 5 to 10 years to address each need.

	Potential innovation priorities	Indicative scale of public funding[40]	Examples of current activities / investments	Future potential activities
Foundations ▪ >35m	▪ Programme to develop novel concepts for deeper water ▪ Programme to develop innovative technologies for serial manufacture of deeper water foundations ▪ Incentives for on-farm offshore demonstration of novel concepts (e.g. suction caissons)	▪ Low millions ▪ High millions ▪ Low tens of millions	▪ Carbon Trust Offshore Wind Accelerator – supporting 7 foundation designs ▪ Scottish Innovative Foundations Technologies Fund ▪ DECC / Innovate UK's Offshore Wind Component Technologies Development and Demonstration Scheme	▪ Incentives for developers to demonstrate novel technologies on their farms ▪ Funding for developing serial manufacture technologies
Floating foundations	▪ Programmes for the demonstration of floating concepts	▪ High tens of millions	▪ Hywind project ▪ ETI's Floating Platform System FEED study	▪ Funding for demonstrating and developing floating foundation concepts.
Collection & Transmission	▪ Studies into next generation HVDC / HVAC / other technologies ▪ Demonstration of novel HVDC / HVAC / low frequency system components	▪ Low millions ▪ High tens of millions	▪ Carbon Trust Offshore Wind Accelerator – high voltage array design, HVDC / HVAC optimisation studies ▪ The ORE Catapult's work on offshore cables ▪ ETI transmission to shore project ▪ SUPERGEN ▪ DECC / Innovate UK's Offshore Wind Component Technologies Development and Demonstration Scheme.	▪ Additional support for developing and testing

[40] Provides an order of magnitude perspective on the scale of public funding (existing and future) potentially required over the next 5 to 10 years to address each need.

	Potential innovation priorities	Indicative scale of public funding[41]	Examples of current activities / investments	Future potential activities
O&M ▪ Planning, remote maintenance & control systems	▪ Support for R&D and use of sensors and control systems for remote monitoring and condition-based maintenance ▪ Programme for data pooling and coordination of sharing.	▪ High millions ▪ High millions	▪ ETI Condition Monitoring programme ▪ The ORE Catapult and the Crown Estate's SPARTA (data sharing) project ▪ SUPERGEN	▪ Further support for sensor / algorithm development at early TRL levels ▪ Support for and coordination of data sharing
▪ Access technologies	▪ Programme to design and trial novel vessels / access systems	▪ High millions	▪ Carbon Trust Offshore Wind Accelerator is funding design work for access and transfer technologies ▪ DECC / Innovate UK's Offshore Wind Component Technologies Development and Demonstration Scheme	▪ Further support for testing novel vessels and access systems

N.B. In addition the Devolved Administrations have a number of active programmes and EU funding is being invested in offshore wind in the UK.

Sources: Carbon Trust, Crown Estate, DECC, EPSRC, ETI, Offshore Renewable Energy Catapult.

[41] Provides an order of magnitude perspective on the scale of public funding (existing and future) potentially required over the next 5 to 10 years to address each need.

Figure 6 - Timeline of innovation activities and public sector funding needs by value chain component