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Technology development report

Joint Research Centre

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Contact information

Name: Roberto LACAL ARANTEGUI
Address: European Commission, Joint Research Centre, Petten, The Netherlands
Email: roberto.LACAL-ARANTEGUI@ec.europa.eu

Name: Matthijs SOEDE
Address: European Commission DG Research and Innovation, Brussels, Belgium
Email: Matthijs.SOEDE@ec.europa.eu

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Foreword on the Low Carbon Energy Observatory

The LCEO is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patent filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?

The project produces the following report series:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database).

How to access the reports

Commission staff can access all the internal LCEO reports on the Connected LCEO page. Public reports are available from the Publications Office, the EU Science Hub and the SETIS website.

Acknowledgements

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1 Introduction

1.1 Methodologies and data sources used

The purpose of this report is to provide an assessment of the state of the art of wind energy technology, to identify their development trends and needs and technological barriers and to define areas for further R&D in order to meet announced deployment targets and EU policy goals.

In order to undertake the different tasks set out for this report, different approaches have been employed, based primarily on scientific and technical literature review, expert judgements, existing KPIs identified by the sector, collection of techno-economic information and analysis of the information collected to provide an unbiased assessment of the wind energy sector. Wherever possible, the data coverage is up to mid-2018; however, some data were updated to the end of 2018 during the preparation of the public version of the report.

A literature review was carried out to assess the state of the art of the wind energy sector with a special focus on the most distinctive technological aspects of offshore wind turbines. Sub-technologies and research areas were used according to their priority, as shown in section 2.1. This also addressed the technology barriers to lower manufacturing and other costs from a technological point of view.

The analysis of EU-funded projects focused on H2020 projects although other projects were reviewed e.g. to assess the evolution of funding. Within H2020 some projects, thought to have the potential for more significant impact, were given particular attention. Selected international and national projects and those supported by international organisations were reviewed.

Table 1 presents the data sources employed for the current analysis.

Table 1 Data sources for the analysis.

Data sources	SOA	R&D	DT	BAR	PRI
Most relevant EU-funded projects (H2020)	✓		✓	✓	✓
EU Member State or regionally-funded projects	✓		✓		✓
Major international projects (IEA)	✓		✓		✓
National projects from major non-EU countries	✓		✓		✓
CORDIS database		✓			
Assessment of R&D initiatives /results		✓			

Headings: SOA: state of the art; R&D: research, development and demonstration initiatives; DT: technology development trends; BAR: technology barriers; PRI: future priorities

1.2 Technology: main characteristics

The blades of horizontal-axis wind turbines capture wind energy at rotational speeds of 10-20 RPM, and transform wind into mechanical energy, then an electric generator transforms it into electricity that is fed to the grid.

Wind turbines are normally grouped in wind farms in order to obtain economies of scale. Wind speed is the most important factor affecting energy production. Site wind speed is measured during several years and then carefully assessed before making the investment decision to build a new wind farm.

The wind speed varies depending on the year, the time of the year, location, topography and obstacles and it generally increases with height thus creating the wind shear profile.

Surface obstacles, such as forests and buildings, decrease the wind speed, which accelerates on the windward side of hills and slows down in valleys. For a given site, annual variations in electricity production of around 20 % are normal.

Generally, utility-scale wind power plants require minimum average wind speeds of 6 m/s. The power which can be extracted from the wind is proportional to the cube of the wind speed. Thus, a small difference in wind speed causes a large difference in available energy and in electricity produced, and eventually in the cost of the electricity generated.

Wind turbines start to capture energy at cut-in speeds of around 3 m/s (11 km/h) and the energy produced increases roughly proportionately to reach the turbine rated power at around 12 m/s (43 km/h), remaining constant until strong winds (above 25 m/s, 90 km/h) put at risk its mechanical stability and the turbine is forced to stop. The range of wind speeds is split into different classes for the objective of wind turbine design, as shown in Table 2.

Table 2 Main features of wind classes according to IEC 61400. Class S is at manufacturer's disposal. Source: [2]

Wind class turbine		I	II	III	IV
Annual average wind speed (m/s)		10.0	8.5	7.5	6
Extreme 50 year-gust (m/s)		70	59.5	52.5	42
Turbulence classes (%)	A:	18	18	18	18
	B:	16	16	16	16

There are two main market sectors: onshore and offshore, and from a technology point of view the latter can be further divided into floating and bottom-fixed. The differences are remarkable, due to the differences in the working environment (salinity and harsh sea conditions) and the complexity in accessing for installation and maintenance. In addition, as the wind is stronger and more stable at sea, wind turbine electricity production is higher offshore. Current onshore wind energy has room for further technology improvement, for sitting in remote areas (e.g. forests etc.), for facing extreme weather conditions, etc. -yet overall it is a mature technology. On the contrary, offshore wind still faces many challenges e.g. development of 10 MW+ offshore turbines, grid connection, more economic operations and maintenance (O&M) concepts etc.

There is a market for small turbines (up to 10 kW) for niche applications such as isolated dwellings, but this sector is unlikely to provide a significant share of the European electricity supply.

There is a continuous trend towards ever larger wind turbines from 10 kW in the 1980s to 10 MW today. The world’s more powerful turbine currently being manufactured, the Vestas V164-9.5MW, will set a new record next year when 23 of them are installed at the Northwester 2 offshore wind farm in Belgium [3]. New land-based turbines (97 % of all current installed capacity) are mostly rated either at the 2 – 2.5 MW or the 3.4 – 4.2 MW range and have rotor diameters in the 114 – 122 m or the 132 – 137 m ranges[1]. Supply-chain standardisation and economies of scale in turbine components are behind this trend, as is better land utilisation and reduced O&M costs. Both industry and academia see larger turbines (12 – 15 MW) as the future offshore machines [4–7].

Average investment costs for onshore projects showed a reduction to EUR 1 020/kW in 2004 and then climbed to reach EUR 1 410/kW in 2008 for 2009 installations. Subsequent excess of production capacity was the basis of both cost reductions and a crisis among turbine manufacturers in the period 2011-2013. Turbine prices in 2018 vary between EUR

[1] A sample of 73 wind turbine contract announcements in 2018, from Western manufacturers Vestas, Siemens Gamesa, Senvion, Nordex and GE, and covering 6.6 GW of sales, shows that 43% of the new turbines (per MW) are in the 2-2.5 MW range and 47% in the 3.4-4.2 MW range. Also, 30% of these turbines have rotor diameters in the 114-122 m range and 39% in the 132-137m range.

650 and 1100/kW depending on markets, India and China being cheaper, Japan more expensive [12], and on technology (low-wind turbines are more expensive). Other project costs include civil works, transport, electricity substations etc. and can add between 30 % and 70 % to the turbine cost to complete the total project cost. Recently wind farms are being built at or below EUR 1 000/kW [8–11][2].

Lack of data prevents showing a complete series of CapEx evolution for onshore projects. This gap has been covered with Figure 1, where the evolution of wind turbine prices from the current largest world manufacturers is shown.

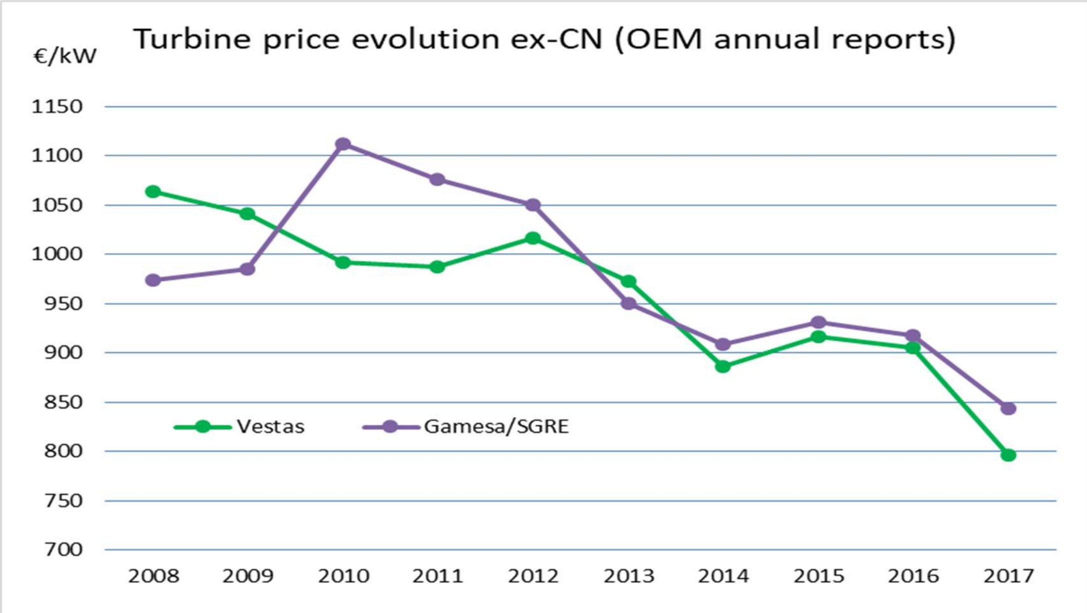

Figure 1 Evolution of turbine prices. Source: JRC based on annual reports of the turbine manufacturers (OEMs), excluding revenue from China. Note: Gamesa/SGRE data corresponds to Gamesa up to 2016. 2017 figure follows a different but compatible methodology, the average selling price of SGRE onshore turbines.

Offshore investment costs have been even more affected by supply chain limitations than onshore costs, and thus until very recently they have been less subject to price reductions. They climbed from EUR 2 200/kW in 2007 to EUR 2 490/kW in 2008 and even higher to EUR 4 500/kW in 2015, but they are reducing fast as reflected in Section 5.2.

Onshore operation and maintenance costs are around EUR 12 – 17/MWh and, over a 20-year operation period, constitute 30 – 40 % of total costs. They have presented a declining trend from the EUR 35/MWh of the old 55 kW turbines. Offshore O&M costs at EUR 15 – 33/MWh with an average of EUR 20/MWh in early UK farms [13], are higher mainly due to the high cost of getting access to the turbines, even when the higher production partly compensates for the difference.

The economics of the technology is undergoing a revolution because of the trend to replace feed-in tariffs with auctions and tenders [14]. Support prices have gone down radically as shown in a sample in Table 3 for onshore prices.

[2] Non-subsidised wind farms *El Tesorillo*, *El Marquesado* and *Goya* complex in Spain declared a cost of EUR 25 million for 26 MW, EUR 22.7 million for 23.8 MW and EUR 310 million for 300MW respectively.

Table 3 Feed-in tariff/premium support level and auctioned prices (€/MWh)

Country	FiT/FiP/TGC revenue	Auction price	Award date
France	85	65.4	1/03/2018
Germany	100	57.3	18/05/2018
Italy	110*	66	22/12/2016
Spain	73	Market	17/05/2017

Notes: Spain's auctions were awarded at a zero-subsidy level, which means that the winners will receive wholesale market prices. *In Italy former support was through tradable green certificates (TGC) which depending on the year were worth EUR 100 – 120/MWh

Wind energy supplied 346 TWh or 11.4% of the EU final electricity consumption in 2017[3], up from 7% five years earlier. According to these preliminary data, Germany with 103 TWh produced far more electricity from wind energy than the next two together: Spain with 48 TWh and the UK with 44 TWh. France, Italy, Denmark, Poland, Sweden, Portugal and the Netherlands produced each more than 10 TWh of wind electricity.

The contribution of wind power keeps growing. Estimates for 2020 suggest that between 14 and 15 % of EU electricity could be supplied by wind energy, and between 20 and 24 % by 2030. Thus, by 2030 wind energy could be the leading technology in the European electricity system.

In 2017 EU Member States commissioned an all-time record of 15.6 GW of wind turbines, 25 % above 2016 installations [15]. A total of 169 GW of wind turbines were operational in the EU at the end of last year. Our projections suggest that some 205 GW will be installed by 2020 and some 310 GW by 2030, with 13 % and 27 % of that capacity being offshore respectively.

During the last years, France and the UK turned up to be the major EU markets after the traditional leader Germany. In 2017 Germany installed 6.6 GW (470 MW were decommissioned) [16], the UK 4.27 MW and France 1.7 GW. Former leaders Spain and Italy installed 100 MW and 250 MW respectively [15].

The world wind energy market without China, in practice the part of the market available to European manufacturers, has grown 6% in 2017 (2016: -4.5%), from 31.3 to 33 GW [17,18]. The good year of the EU market increased its contribution to the global market from 23% in 2016 to 30%.

Denmark led in terms of wind electricity penetration with 43.2%, followed by Ireland (25.5%), Portugal (24.1%), Germany (19.2%) and Spain (17.9%). The UK, Romania, Sweden and Lithuania also produced more than 10% of their inland consumption from wind[4].

Wind turbines in the EU generated at an average capacity factor of 24.5 %, increasing from 21.9 % over the average of the 2005/2010 period. The highest average capacity factor was in Denmark (which produced offshore 35 % of the total, at a higher capacity factor) and Lithuania (31.5 %), 30 % in Finland and the UK and between 25 and 29 % in ten more countries. On average, the author estimates that a capacity factor of 23 % onshore and 45 % offshore is possible by 2020.

European investment in wind asset finance (a proxy for total investment) reached EUR 23.6 million, approximately one third lower than in 2016, mostly due to reduced financing of new offshore wind farms. Globally, wind energy asset finance reduced to EUR 92.3 million, a 10 % lower than in 2016 [19].

[3] Source: JRC based on 2016 and 2017 installed capacity from [15], and on wind generation and country consumption data from [86], scaled.

Investment in wind R&D rose 6% to USD 1.9 billion (EUR 1.68 billion) according to United Nations [19].

The JRC studied wind potentials in Europe and found that the surface available in the EU for a standard wind turbine would enable the installation of 3400 GW on land and 350 GW at sea which would generate 8400 TWh and 1300 TWh respectively. This has to be compared to the 2017 final demand of 2800 TWh in the EU[4] [20]. The analysis was drawn under a reference scenario respecting current legal requirements for exclusion zones and setback distances from dwellings.

[4] Specifically for offshore, there is a minimum distance to shore of 12 nautical miles. Offshore can only be installed in zones that have a sea depth of 50 meters or lower.

2 Technology state of the art and development needs

2.1 Priorities in sub-technologies and research areas

As shown in Table 4, the state of the art of wind energy technology is discussed in this report for two main wind energy technologies: onshore and offshore. Offshore wind energy is divided on two sub-technologies, fixed and floating foundations. Further, innovative designs such as airborne, vertical axis or two bladed wind turbines are considered under the "other" research areas.

Other research areas, e.g. components and materials of a more cross-technology nature, are included in Table 5. That research area category ("Other") is not described in RTD documentation. However, given that it has received the second largest funding of all research actions, it is necessary to list it in Table 5.

Table 4 Sub-technologies and priorities

Sub-technology	Priority
Onshore	High
Offshore (fixed)	High
Offshore (floating)	High
Small-scale wind	Medium/low

Table 5 Research areas

Action	Priority
1) New design of blades (longer, lighter materials, improved aerodynamics design, coatings)	High
2) New drive-train designs (increased energy density, improve loads, new gearbox design with higher reliability and torque density)	High
3) Reducing rare earths content (especially Dy) in permanent magnets	High
4) Innovative installation systems for offshore foundations, with a focus on cost reduction	High
5) Improving reliability, energy density, efficiency at partial loads, reactive energy output and quality of the electrical waveform of power converters	High
6) Next generation installation vessels	High
7) New design of towers (longer, new configurations, new materials)	Medium /High
8) New offshore foundations	Medium
9) New installation methods to reduce the noise generated in offshore installations	Medium
10) Response to extreme climate conditions (anti- and de-icing systems, hurricane protection, extreme heat, etc.)	Medium
11) Increased automation and higher manufacturing capability	Medium
12) Improved monitoring systems and enhanced maintenance strategies	Medium
13) Improved wind resource assessment techniques and modelling tools	Medium
14) New control strategies of power electronics	Low
15) Advanced control strategies to minimize wake effects	Low
16) Other: airborne, bladeless, vertical axis, non-technology issues	*Low*

2.2 Wind turbine technology

The main trend in turbine technology evolution is the reduction of turbine specific power, or the ratio rotor swept area to electricity generator, as shown in Figure 2.

The most modern onshore wind turbines feature increasingly lower specific power levels. These reach below 200 W/m^2 in the case of turbines for low- and medium-wind sites. Onshore turbines that have been commercially presented lately are mostly in the 3 – 4.5-MW range. Offshore, 8-MW turbines are being installed whereas several manufacturers are designing turbines above 10 MW [4,7,21]. The main technological characteristics of current turbines are:

- Blades are made using moulds with three kinds of materials: fibres (carbon, glass, occasionally wood), resins (epoxy, polyester, polyurethane) and structural (balsa wood, polyester foam, steel). The largest blade built to 2018 was the 88.4 m one for the prototype Adwen AD 8-180, now discontinued. GE is developing 107 m-long blades for the Haliade X which is rated at 12 MW.
- Pitch systems rotate in each blade independently, which allows better energy capture and, crucially, the turbine to reduce the loads that affect it.
- Drive train designs are more varied than ever, whereas direct-drive drive trains with permanent magnets (Siemens Gamesa Renewable Energy, SGRE) are fighting with medium-speed systems (Vestas) for supremacy offshore. Geared drive trains dominate onshore.
- Electricity generators with permanent magnets use less rare earths today, whereas the full-converter-based drive train is extending the use of the humbler induction generators, squirrel-cage machines.
- The use of gearboxes, whether in conjunction with medium- or high-speed generators, allows reducing the size of the generators and thus their cost.
- Power converters are able to adapt frequency and other characteristics of electricity generated, allowing more choice of generator types and providing better grid support.
- Innovative tower designs include prototypes reaching 178m, including a water reservoir for pumped hydropower storage [22,23].
- With regards to types of offshore foundation, monopiles are clearly leading the technology, whereas new offshore foundations based on jackets and/or suction buckets are being installed commercially.
- New vessels for offshore installation are being built again after only two were delivered in 2015 and 2016. Recent vessels are being upgraded to install larger turbines and foundations.
- Installation methods that reduce offshore noise to the sea are being tested.

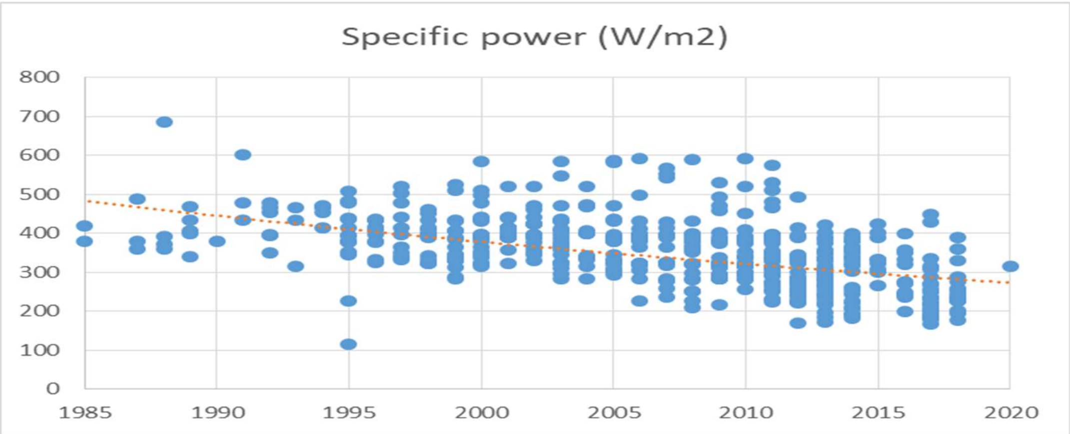

Figure 2 Trend to lower specific power in turbine prototypes. Turbines with lower specific power sweep larger areas for the same electric rating. Source: JRC database.

2.2.1 Blades

Blades are made of composites by using moulds designed by the turbine manufacturer or by the independent blade manufacturers. Blade factories have several manufacturing lines and each can use different moulds. This modularity allows independent blade manufacturers to make blades designed by their clients, with the exact profile required by a given turbine model.

A prime objective of blade design is longer blades yet with relatively lower mass, while containing or reducing costs. For example, carbon fibres are lighter but more expensive than glass fibres and one option is using them selectively, e.g. in spar caps or shells. In addition, a trend that gained weight in 2017 was designs that aim to facilitate manufacture.

Nowadays aerofoils are more rounded "for higher structural stability" [24] and blades have attached devices to improve their aerodynamic behaviour such as vortex generators, estimated to increase production by 1 -1.5 %.

Fibre surface treatments, including coatings, are used to protect against sand and water droplet erosion, aging from ultraviolet radiation, and to improve ice shedding efficiency in cold conditions.

Figure 4 Gaildorf wind farm featuring four turbines with up to 178-m hub height.
Source: Max Bögl

Figure 3 Artistic impression of a cable-stayed tower.
Source: Windpower Monthly [25]

Other state-of-the art technologies include aero-elastic tailored blades as passive control and load-reducing feature (SGRE), carbon pultrusions in blade shells adding robustness, and load sensors.

The newest individual pitch control (IPC) systems are abandoning the classic solution of rotating according to each blade position and are heading towards a rotation based on measuring the actual loads supported by each blade.

A technology that is ready for take-off but does not seem to come out of age is segmented blades.

The attractiveness of segmented blades for onshore wind is that it would allow to break the transport barriers for an increasing number of available low-wind sites. Several companies including Enercon, SGRE and Blade Dynamics (owned by General Electric) have developed segmented blades and have them commercially available, but the extra cost seems to be the element making them uncompetitive.

2.2.2 Towers

The traditional battle for height between concrete, concrete-steel hybrid and lattice towers is lately enriched with new technologies. These include Vestas' large-diameter steel tower (LDST) which reached hub heights comparable to concrete (137-166m and above) and a new 137-m prototype cable-stayed tower which has been tested in Østerild (DK) since April 2017 [25] and is planning first-of-a-kind installation at 175 m high [26]. Independent tower manufacturer Max Bögl claims a new modular technology able to reach 200 m [27].

Figure 5 uses data from the Thai market to show how hub height has grown quickly of late. With 622 MW of larger projects, Thailand is an emerging market with ample tropical vegetation and other obstacles, which makes that manufacturers GE, SGRE and Vestas are offering their tallest towers.

Some or all the towers sections (i.e. the 3 – 7 cylindrical or conical parts that the tower is divided in) of pre-cast concrete towers have been segmented already for some time. For steel-based towers, this technique is re-visited regularly because of the need to facilitate transport and to reduce the overall demand for materials. However, they have the disadvantage that tower internals must be mounted on-site[5].

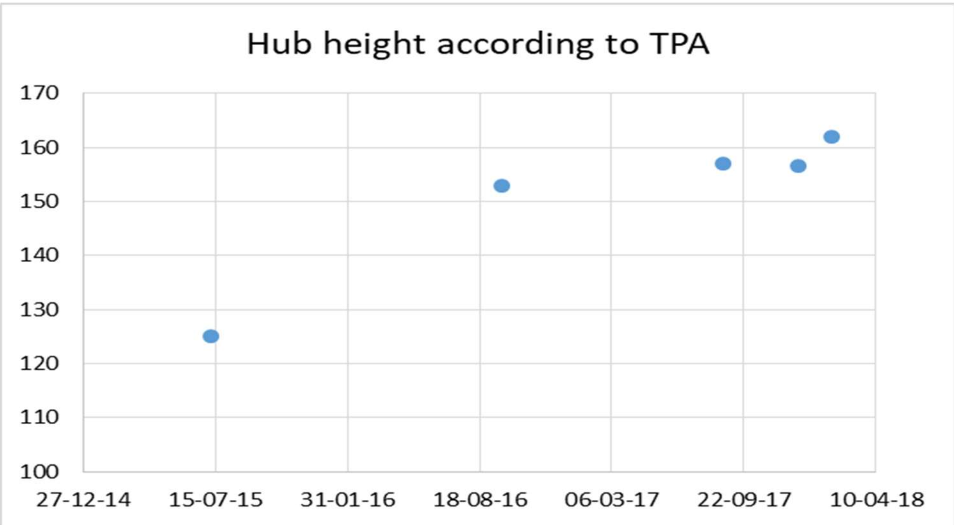

Figure 5 Evolution of hub heights in recently-published turbine purchase agreements (TPA), Thailand

2.2.3 Drive train

The variety of drive trains used onshore reaches from geared machines including squirrel-cage generators, doubly-fed induction generators (DFIG) or permanent magnet (PM)-based ones. Direct-drive machines include electrically-excited and PM generators.

Gearboxes have gone through a silent revolution from the poor situation in 2010, and the majority of the problems causing a large impact have been solved. Lately some models have significantly increased rated input torque without impacting outer mass and dimensions [28]. The Vestas V164 gearbox, the largest in the market, features torque-splitting technology for the low-speed gear stage [29].

This gearbox revolution is partly the reason why Vestas keeps using DFIG whereas traditional DFIG user Senvion is trying a non-DFIG but still a geared drive train similar to

[5] An illustrative video is available at http://video.vestas.com/m/12518185

Siemens' NetConverter®. SGRE has decided to use geared drive trains onshore and direct-drive ones offshore. Even when gearboxes still have relatively high O&M cost, the mechanical character of the component involves that condition monitoring systems are fully usable and most failures can be detected well in advance to allow preventive maintenance plans. This will allow gearboxes to progressively attain lower O&M costs.

Direct-drive (DD) turbines have also experienced significant innovations. For example, Enercon's new DD electricity generators will be made of aluminium form-wound coils instead of copper wire. This design is claimed to further allow production automation and weight reduction as aluminium is "significantly lighter than copper" [30].

One important focus of the industry is the optimisation and cost-reduction in processes for production, transport and logistics, and installation [30].

Other state-of-the art technologies include adaptive yaw system, a technology first used in automotive industry (SGRE), remote sensing replacing meteorological masts [31], and control systems [32].

Some manufacturers now install power electronics and the transformer in the nacelle, which facilitates installation and reduces losses in the down-tower cables and can help to reduce damaging harmonics in the case of DFIG machines.

2.3 Offshore wind technology

The recent offshore wind tenders with very low prices have been possible because of extreme supply chain optimisation, full confidence of financiers in the technology and their expectations in a rising wholesale market price for electricity, and a technology in continuous evolution towards larger turbines.

State-of-the-art project management based on experience of previous wind farm projects allows large developers to manage a large number of contracts in-house. This removed the premium paid to engineering, procurement and construction (EPC) contractors to take on contract interface risks. Also, project management benefits now from much better collaboration among suppliers, the developer and financiers, which permits the optimisation of the project and, crucially, to understand where project risks can best be managed and "which party or contractor is the best placed to manage them " [33].

2.3.1 Foundations

There are new methods for assessing the performance of offshore structures subject to extreme loads. These methods feature behaviour into the nonlinear range which will allow more thorough, performance-based design approaches to be implemented. Further, advances in modelling capabilities are for the first time allowing the support structure to be treated integrally with the foundation and turbine in the modelling and design space, promising increased efficiency and reliability [1].

Foundation design is being optimised and developers claim that the weight of monopiles could be reduced by at least half compared to those used at existing offshore sites [33]. Monopiles of up to 8.1 metres diameter were installed at Merkur (DE) and Hornsea One (UK), while new jackets tend to three instead of the former four legs (East Anglia One, UK). Suction buckets are coming of age as part of jacket structures, e.g. at the Borkum Riffgrund 2 offshore wind farm (OWF) in Germany 20 suction bucket jackets were installed, although they are still expensive compared to monopiles. Innovative foundations being tested include gravity-base monopiles (Blyth Demo, UK), steel jackets with concrete transition pieces (Nissum Bredning, DK), and gravity-base steel in icing seas (Pori Tahkoluoto, FI).

The first commercial-scale (although with only 5 turbines) floating systems was Statoil's Hywind project, it was installed in 2017 in Scotland. The two main elements of a floating system, the floater and the mooring system, are still in the initial adoption phase with multiple devices competing to become the established design. Floaters being tested include ballast-stabilised spar buoys (e.g. Hywind), mooring line-stabilised tension leg platforms (e.g. VertiMED), and buoyancy-stabilised platforms (e.g. Floatgen). Anchor and mooring systems include driven or drilled piles, gravity-base and suction anchors, torpedo embedded anchors and driven anchor plates [34].

The goal with both floaters and mooring system is reduced cost and flexible and economical fabrication and installation.

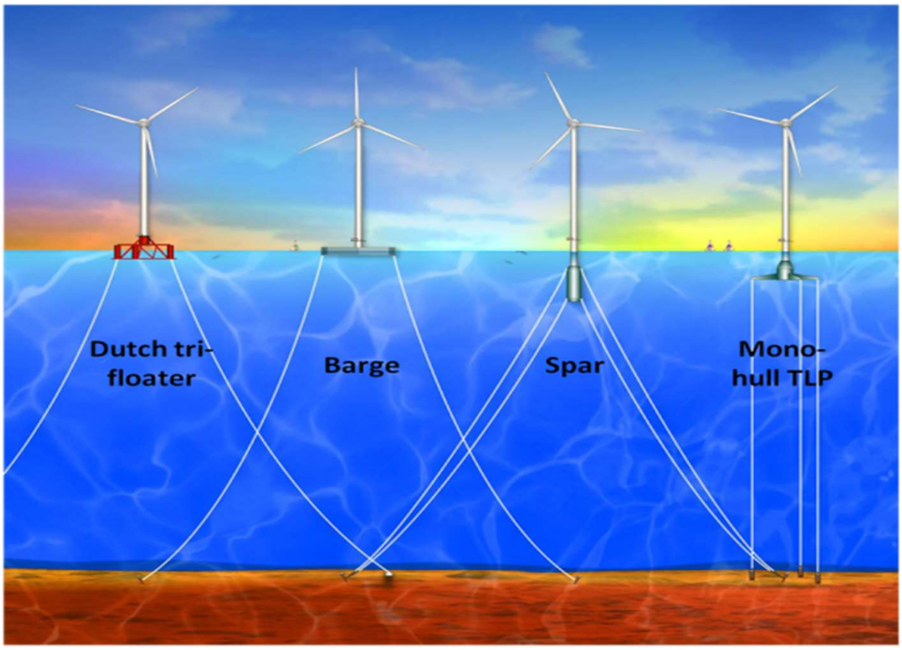

Figure 6 Most common offshore floaters.
Drawing courtesy Floating Wind Turbines [91]

2.3.2 Transmission, transport and installation

Power export technology will probably have dynamic rating system that can transmit more energy through the same cables. This kind of system, with continuous monitoring of cable temperature, allows "smaller conductor cross sections when using dynamic rating than with steady state rating of offshore wind farm power export cables" [35]. In other words, dynamic power rating allows the safe transmission of energy above the nominal power rating[6].

Already, wind farms are being permitted with electrical capacity above the export cable nominal one, e.g. Borssele I & II in the Netherlands will install 752 MW of turbines whereas the nominal export capacity is 700 MW.

Advances in power flow modelling allows reducing infrastructure at the new wind farms onshore and offshore substations [36].

During the last years factories were built at or near harbours (Cuxhaven in Germany, Hull and Isle of Wight in the United Kingkdom, Nakskov and Esbjerg in Denmark…) so that road transport of large and heavy wind turbine components to installation harbours have been eliminated.

[6] For a summary of the technology see the MARINET (an FP7 project) report "Development of new highly dynamic power cables design solutions for floating offshore renewable energy applications" [88]

A novel method of transporting main turbine components to the installation harbour was implemented by Siemens. It consists of "Ro-Ro", specially-designed vessels where components can be "rolled" into and out of without using cranes [37].

Increasingly, jack-up vessels formerly used for installing offshore wind farms are being hired as accommodation platforms during installation and commissioning [38,39]. This is cost-effective even when the vessel cost raises to EUR 125 000/day [39].

New vessels are being built with ever-larger offshore installation capabilities. These include GeoSea's Orion, a 216.5m long jack-up turbine installation vessel and Jumbo's Stella Synergy (185-m long) and OHT's Alfa Lift (216.3-m long) heavy-lift vessels. In the area of cable installation, new cable laying vessels with increased capacity were commissioned in 2016 and 2017 (NKT's Victoria, DEME's Living Stone) or were recently ordered (by Prysmian). In some cases (e.g. Living Stone) a dual cable-lane installation system will allow reducing installation time while carrying more cable on board (up to 10,000 tonnes of cable) [40]

3 R&D initiatives

This section looks at the R&D investment by the European programme Horizon 2020 (H2020) and compares it to that under FP7 for projects with public funding above a quarter of a million Euro. It also considers investments under other EU instruments (NER300, EEPR, KIC InnoEnergy) and refers to important international projects under the umbrella of IEA and joint industry projects promoted by DNV GL and The Carbon Trust (UK).

The analysis distinguishes between (a) wind energy-related investment i.e. projects that will result in the development of wind technology, or of wind and other technologies, and (b) wind energy share of the investment, i.e. a part of the total project budget when the project will benefit several technologies. For example, a project on reducing rare earths content in magnets is wind-related and will impact wind (the "wind share") but also electric vehicles and other sectors. In these projects, expert's opinion was applied in order to assess the breakdown of wind share versus that of other technologies.

For example, if the project potentially has impact on two technologies/sectors (of course, one of them is wind) a 50% split in the investment amount was assumed, and only the wind share was counted. In the cases when the project focuses on materials that can be used in a multitude of sectors, only a small share was considered applicable to wind, except when the project focuses on the use of the given material in the context of wind energy.

3.1 Private (corporate) investment

Corporate funding dwarfs public funding in R&D. For example, compared to the EUR 245 million wind share of R&D investment by EU programme FP7, the market leader wind turbine manufacturer Vestas invested some EUR 1 189 during the 7-year period of the duration of FP7 (2007-2013)[7].

Figure 7 shows recent figures for corporate R&D expenditure by leading wind turbine manufacturers. Other private R&D expenditure includes that by component manufacturers, installation companies and wind farm developers.

Expenditure by Gamesa until 2016 was replaced with expenditure by Siemens Gamesa Renewable Energy in 2017. Expenditure by Goldwind drastically increases in 2015 and the reason is unknown, this could be due to different accounting practices.

Whereas the high amount of corporate R&I projects is out of the scope of this report, it is perhaps interesting to note that developers in particular are running a significant number of R&D projects that share the focus on reducing the cost of energy.

For example, Equinor (formerly Statoil), operator of the floating wind farm Hywind Scotland, recently installed two LIDARs "in order to understand wake and turbulence effects from multiple floating wind turbines, measure turbulent wake spectra and to investigate the effect of wakes on yaw motions" [72]

At times, corporate R&D takes the form of joint testing (which could include development) of turbines or turbine components at a new wind farm. Offshore, this was the case for example at the Nissum Bredning offshore wind farm in Denmark, operational since 2018, testing new foundations (see Figure 8), "*a new 66kV voltage solution including a new transformer, cable and switchgear systems, along with further innovations regarding tower and controller settings*" [41]. A very detailed description of innovative elements being tested is available from Siemens "Nissum Bredning - Technical Report for 28 MW Pilot Project" [42]. An example onshore is the Viinamäki wind farm in Finland, where new cable-staying tower technology will be installed reaching 175 m (new record for steel towers) under a "*unique R&D collaboration (…) Vestas and TuuliWatti Oy have also partnered in a 10-year testing agreement at the site*" [26], see Figure 4.

[7] Source: JRC based on Vestas' annual reports

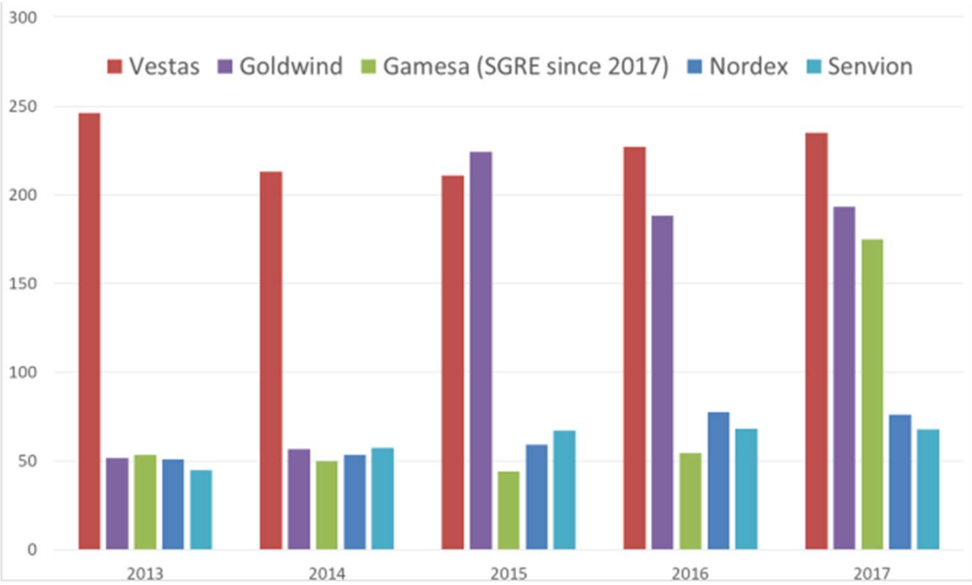

Figure 7 Research and development expenditure (mEUR) by some of the leading wind turbine manufacturers.
Source: JRC based on OEM annual reports and investor presentations

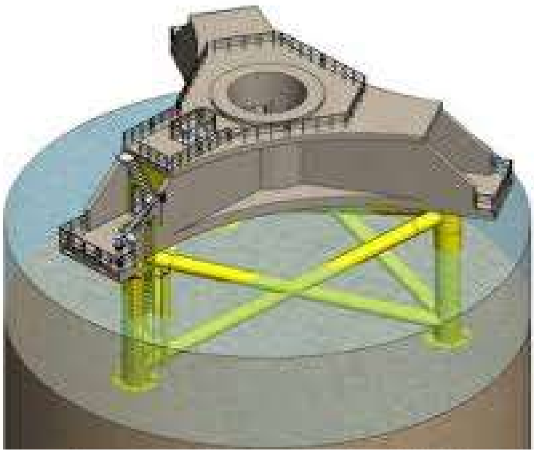

Figure 8 Three-legged jacket foundation with concrete transition piece. Courtesy Siemens

3.2 European projects - overview

Along with the main support instrument, Horizon 2020 (H2020), the European Union has supported wind technology research, innovation and deployment with other instruments: KIC InnoEnergy, EEPR, NER300, InnovFin and, formerly, FP7.

3.2.1 KIC InnoEnergy

The Knowledge Innovation Community (KIC) in the area of energy, KIC InnoEnergy, is part of the European Institute of Innovation and Technology (EIT). As such, KIC InnoEnergy aims to help “innovators and entrepreneurs across Europe to turn their ideas into products and services for the market” [43].

KIC InnoEnergy reported having supported a single wind-related project in the last years called WF Commercial. This project is linked to the WindFloat (floating wind platform) of American company Principle Power. This technology is being explored since a 2-MW Vestas turbine was floated out of Portugal on a WindFloat in 2011 and decommissioned in 2016. The successor project, 25-MW WindFloat Atlantic, is being developed with NER300 support although not without problems. Heavy delays were caused by the negative of the transport operator (REN, a private entity) to build the export cable, a problem that the Portuguese government addressed in early 2018 [44,45]. Issues are solved now and the first floating wind turbine is expected to be operational at the end of 2019.

With an unidentified cost, WF Commercial started in 2015 and is claimed to finish this year 2018. Based on a commercial presentation, it seems that KIC InnoEnergy supported MSc internships at Principle Power [46].

3.2.2 EEPR

The European Energy Programme for Recovery (EEPR) was designed to help containing the impact of the financial crisis by co-financing projects of European interest, of which some in the energy field [47]. Offshore wind was supported with EUR 565 million granted to the following projects:

- Kriegers Flak offshore grid connection between DK, SE, DE, & PL
- North Sea Grid (HVDC Hub) between UK, NL, DE, IE, DK, BE, FR, LU.
- Four German wind farms on deep water (Borkum West II – Bard I – Nordsee Ost – Global Tech I)
- A British experimental wind farm, Aberdeen (EOWDC)
- A Belgian wind farm on jacket foundations (Thornton Bank)

In its report COM(2018) 86 final [48], the European Commission highlighted that 4 of the projects (Nordsee Ost, Bard I, Borkum West II and Thornton Bank) have been implemented thus supporting large-scale testing, manufacturing and deployment of innovative turbines and offshore foundation structures. Whereas Global Tech I and HVDC Hub were eventually excluded, Kriegers Flak and a new grid-related project (Cobra Cable) are about to finish implementation.

3.2.3 NER300

The NER300 facility of the European Emissions Trading Scheme financed several wind projects with an innovation aspect: wind farms offshore Nordsee One and Veja Mate, onshore Blaiken and Handalm, and floating prototypes Windfloat, FloCan5, Vertimed and BALEA.

The four wind farms have already been commissioned, three of them during 2017 and Blaiken in 2013/2015. However, all the floating prototypes are delayed, with Vertimed and WindFloat Atlantic being expected to commission by the end of 2018 (see Annex to [49]) – something unrealistic for the latter at least.

3.2.4 InnovFin

"InnovFin – EU Finance for Innovators" is a joint initiative launched by the European Investment Bank Group (EIB and EIF) in cooperation with the European Commission under Horizon 2020. InnovFin "aims to facilitate and accelerate access to finance for innovative businesses and other innovative entities in Europe" [50].

Under this context, InnovFin Energy Demonstration Projects is a facility "to finance innovative first-of-a-kind demonstration projects at the pre-commercial stage that contribute to the energy transition" [51].

3.3 Horizon 2020

Horizon 2020, has supported some 77 projects affecting wind with a grant above 250 thousand euro. Of these, 37 projects focus exclusively on wind energy whereas the rest impact wind energy technology from the point of view of materials development, common areas with other renewables or non-renewable energies, etc.

Horizon 2020 is on its way to overtake FP7 in terms of total funding for R&D in wind technology. During the first three and a half years, Horizon 2020 has contributed nearly as much wind energy-related investment as FP7 did: EUR 373 M (H2020) vs. EUR 393 M (FP7). The share of those projects that focused specifically on wind energy follows a similar pattern: EUR 228 M (H2020) vs EUR 245 M. In terms of the number of projects funded, FP7 with 86 projects with an impact on wind technology is still ahead of H2020 (78 projects), but the latter still has two more years to run.

3.3.1 Research action focus

H2020 has allocated funding differently for different research actions while generally taking into account priorities.

Table 6 shows the breakdown of H2020 and FP7 according to the research areas described in Table 5. The table shows a split of public funding in both wind-related project and the wind share of wind-related projects.

The allocation of a project (and its budget) to a given research area is very problematic at times. In particular some large projects (e.g. RealCoE) embrace several research areas but there is no way to identify a sensible breakdown cost-research area. There are three forms to tackle this issue: (a) allocation of full budget to one of the research areas; (b) making up a breakdown using expert creativity, or (c) creation of a new research area hosting those projects. Here we have taken the first approach.

Figure 9 shows the split of project funding according to EC funding, both for the wind energy-related part of the project and for the non-wind part (e.g. wave/tidal) of the project, and to other funding. In the latter private funding finds itself along with Member State (MS) funding.

H2020 funding covers the majority or total R&I funding in all but the offshore foundation installation research area. The figure shows as well that strong synergies exist with other sectors (materials, wave & tidal, aviation) in the research areas blades, rare earths, power converters, towers, extreme climate conditions and manufacturing.

The following analysis is based on the H2020 wind share funding of projects unless indicated, e.g. by the term "total budget" which refers to the total project cost.

<u>Blades</u>

Research on blades and related components has focused on aerodynamics (AEROGUST), core blade materials (POWDERBLADE, AEROFLEX, FiberEUse, DACOMAT) including thermoplastics (ambliFibre), coatings (Riblet4Wind, EIROS), and lightning protection (LIBI, SPARCARB). Individual projects have total budgets from EUR 1.18 to 32.3 million, although only FiberEUse and RealCoE exceed EUR 10 million.

Flagship project RealCoE, here allocated to the blade research area, actually attempts to develop a prototype offshore 12 MW turbine. Led by Senvion with a budget of EUR 32 million, it is difficult to see how this ambitious objective will be achieved when development cost of new offshore turbines were reported at between EUR 200 and 350 million [52,53].

Table 6 Breakdown of wind-related and specific wind R&D investment in FP7 and H2020-supported projects (up to May 2018).

Research area from Table 5 Million euro	FP7 wind-related	FP7 wind share	H2020 wind-related	H2020 wind share
01) Blades	51.4	38.4	72.8	46.0
02) Drive train	12.6	12.6	21.2	12.8
03) Reducing rare earths content	10.2	4.8	22.9	6.6
04) Offshore found. installations	10.0	10.0	20.5	19.6
05) Power converters	12.3	6.1	43.3	20.7
06) Installation vessels	0	0	3.3	3.3
07) Towers	0	0	8.0	8.0
08) New offshore foundations	49.7	33.9	28.8	20.0
09) Noise in offshore installations	0	0	0	0
10) Extreme climate conditions	5.1	5.1	4.2	0.4
11) Manufacturing	4.6	3.9	4.9	0.7
12) Monitoring and maintenance	24.9	24.9	29.9	29.8
13) Resource assessment	18.9	18.9	7.9	3.9
14) Power electronics control strategies	0	0	0	0
15) Wake effects	10.9	10.9	13.8	13.8
16) Other	182.3	75.3	91.9	42.7
Total	446	306	449	**294**

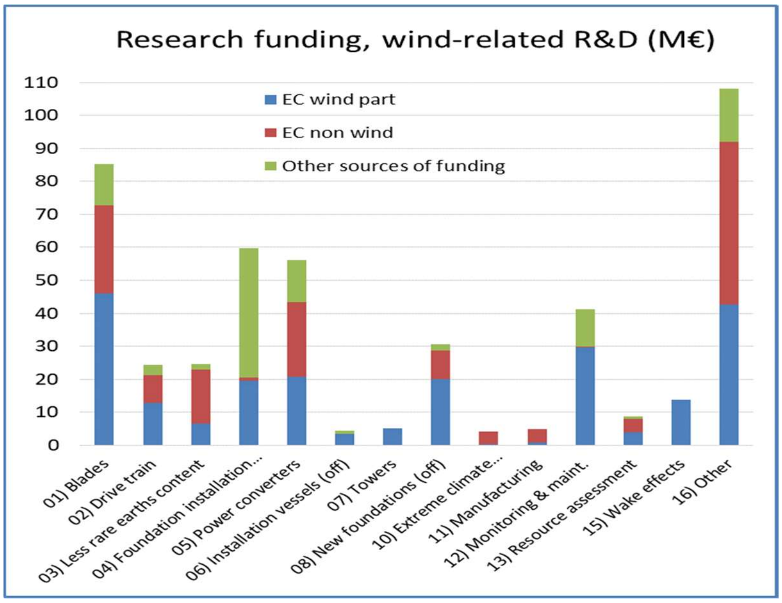

Figure 9 Funding breakdown (EC wind part, EC non-wind, other sources) of H2020 R&D projects according to research area.
Note: funding from "other sources" could also be split into wind/non-wind part, but it has not been done for clarity. Source: CORDIS data and JRC estimation of EC wind/non-wind shares

Drive train

Three out of four projects in the drive train action belong to the materials area under MSCA, and thus they focus on PhD education on superconductors (EASITrain), modelling (DyVirt) and fatigue management (INFRASTAR). Only a part of the project budget is considered to impact wind energy. The fourth project is EcoSwing, flagship research (EUR 14 million) in superconductors applied to future electric generators.

The reduction or elimination of rare earth content in permanent magnets (PM) and thus in PM electric generators (PMG) is the subject of four projects for a total budget of EUR 24.5 million. Of these, two projects explore non-PM generators (AMPHIBIAN and ReFreeDrive), one explores low-rare earth content PMG (NEOHIRE) and the latter and REE4EU focus as well on recycling rare earths.

Installations offshore

Improvements to the installation of offshore foundations and turbines is researched mostly under two special projects, both ERA-NET co-funds between the EC and participating MS. DemoWind and DemoWind2. With a total budget of EUR 57.6 million, these projects do not make enough information publicly available as to allow the current type of assessment. In addition, DemoWind web site [54] last accessed (24/5/18) showed information of May 2016 or earlier. Therefore, no information was available that could contribute to this analysis.

Consultancy VBG reported that projects WFCT on wind farm control strategies (Carbon Trust, see section 3.5.2) and SPWTT on software to improve offshore activities were awarded funding in the 2016 DemoWind 2 call. Other DemoWind projects were, according to a VBG newsletter: Blyth Offshore Demonstrator 'float and submerge' gravity base foundations (FSF); EnerOcean's wind integrated platform for 10+ MW power per foundation; IGEOTEST's robotic submarine geotechnical site investigation for offshore wind; Magnomatics' compact high-efficiency generator; Seaplace's compact holistic efficient floating turbine; SGRE development, manufacturing and in-field validation of the world’s largest offshore wind turbine blade, and SGRE wind turbine life-minded production management solution.

Because of lack of information, a breakdown of the DemoWind projects could not be allocated to the respective research actions or TRLs.

In addition to DemoWind, SME project OptiLift aims at commercialising a sensor, “motion reporter” that would facilitate installation operations.

Power conversion

Wind-related research on power conversion is the domain of two projects: GreenDiamond, looking at 10-kV transistors, and the flagship PROMOTioN which aims at improving the technology and reducing the cost of high-voltage direct current (HVDC) connection.

Installation vessels

A single project, the EUR 4.4 million NEXUS, will review the design, testing, and construction of vessels for servicing offshore wind. Although this is not a project focused on installation but service vessels, it is included here because functions of both overlap to a large extent.

Towers

Project ELICAN develops a self-erecting telescopic tower for a 5MW turbine under research action 7, new design of towers. Also TELWIND, which aims at scaling up to 6-8 MW both a self-erecting tower and a novel floating-to-site foundation, includes an action 7 element even when the project is assigned here as action 8.

It is interesting to note the absence of EU funding on some of the most exciting innovative tower projects. This was the case formerly for Vestas’ Large Diameter Steel Tower (LDST) [55] and currently for Max Bögl’s tower plus storage (see above) [22,27].

New offshore foundations

Research action 8 has funded seven projects so far. Two of these (ELISA and TELWIND[8]), by the same project leader, see above. Two projects look at materials, and in particular concrete: EUR 6 million EnDurCrete aims to "develop a new cost-effective sustainable reinforced concrete for long lasting (…) applications". The new product's market includes ports, tunnels as well as offshore foundations. Also, the EUR 8 million LORCENIS aims at developing "long reinforced concrete for energy infrastructures with lifetime extended up to a 100% under extreme operating condition". Finally, three more projects (POSEIDON, LIFE50plus and –more modestly- ICONN) explore floating foundations.

Because these projects develop expensive hardware, there is a relatively high risk of failure. For example DEMOGRAVI3[9] was originally funded with EUR 19 million EC contribution, being the flagship project in this category. Unfortunately the project failed after a key member of the consortium pulled out. It aimed at developing a full-scale demonstration in real-life conditions of a towed-to-site gravity foundation made of concrete and steel.

Extreme climate conditions

The response to extreme climate action was loosely funded with two projects at the basic science level. THUNDERR aims to modelling thunderstorms to be used for infrastructure modelling and design (including wind turbines). PHOBIC2ICE focuses on ice formation in aircraft but it can have an impact on turbine design. Similarly, the subject of manufacture improvements funded materials-related project LASIMM under the factory of the future theme. LASIMM aims at hybridising 3D and traditional manufacture of large engineering parts.

Improved monitoring and enhanced maintenance

This action funded 12 projects and a total budget of EUR 41 million. The flagship project is EUR 16 million ROMEO (EUR 10 million funded by H2020) aiming at developing an O&M information management and analytics platform for reducing offshore wind O&M costs. In addition to the projects focusing on a traditional area of research (condition monitoring: WINDMIL, BladeSave, CMDrive; software: Cloud Diagnosis II, ZephyCloud-2; training and education: AWESOME), new areas that arise as for example the use of drones in O&M in particular for blade maintenance (Liftra Crane, WEGOOI), the issue of offshore cable damage (SENTRY), or application of robotics to blade inspection (SheaRIOS).

Resource assessment

In the area of resource assessment, a floating LIDAR platform (FloatMastBlue) is the flagship project, whereas HPC4E, CloudBrake and WakeOpColl contribute to the basic science in the area.

Wind farm control

Wind farm control strategies is an action covered with three projects in the basic science to technology proof-of-concept level. The projects, CL-Windcon, TotalControl and UPWARDS, have budgets between EUR 4 and 5 million covered in full by H2020

Non-priority areas

Horizon 2020 has invested significantly on the non-priority "other" group (EUR 91.9 million with a EUR 42.7 million wind share) which includes three projects on grids MIGRATE, InnoDC and EU-SysFlex (EUR 48 million total budget of which EUR 11 million would be the wind impact), three on airborne wind research (AMPYXAP3, AWESCO and REACH), two on small turbines (IRWES, Eciwind) in addition to bladeless turbines (VORTEX), integration

[8] http://esteyco.com/projects/elisa/elican.html https://cordis.europa.eu/project/rcn/199304_en.html
[9] http://demogravi3.com/ https://cordis.europa.eu/project/rcn/199361_en.html

with hydrogen production (Haeolus) and recycling of blades (EcoBlade). Non-technology issues area also dealt with, including social acceptance (WinWind), markets for renewable energy (AURES, IndustRE, CrowdFundRES, and BestRES), infrastructure (MARINERG-i), consenting (RiCORE) and education and training (MARINET2, AEOLUS4FUTURE and also a part of InnoDC) are also supported.

No projects were identified on research areas 9 (new installation methods to reduce noise installing offshore foundations) and 14 (new control strategies of power electronics). Figure 10 summarises the distribution of H2020 at funding compared to the priorities.. Some of the priority actions receive significant funding, whereas reducing rare earth content and installation vessels are left to the private sector. Interestingly, the latter action seems appropriate because most of the technological advances in installation vessels seem to be more engineering-related than science-related. The new vessels needed to install the largest, newest turbines are being built in China (Cosco Nantong, China Merchants), although they tend to be finished in European yards. Therefore, it is unclear to which extent European research funding would benefit these technologies.

It can be discussed that not all research areas need the same level of funding in order to succeed. In effect, hardware-related research, e.g. offshore foundations, tend to be costlier than other research. In addition, even having the same priority does not mean that the impact of the different areas on LCOE reduction would be similar, thus it can be argued that some areas need higher funding.

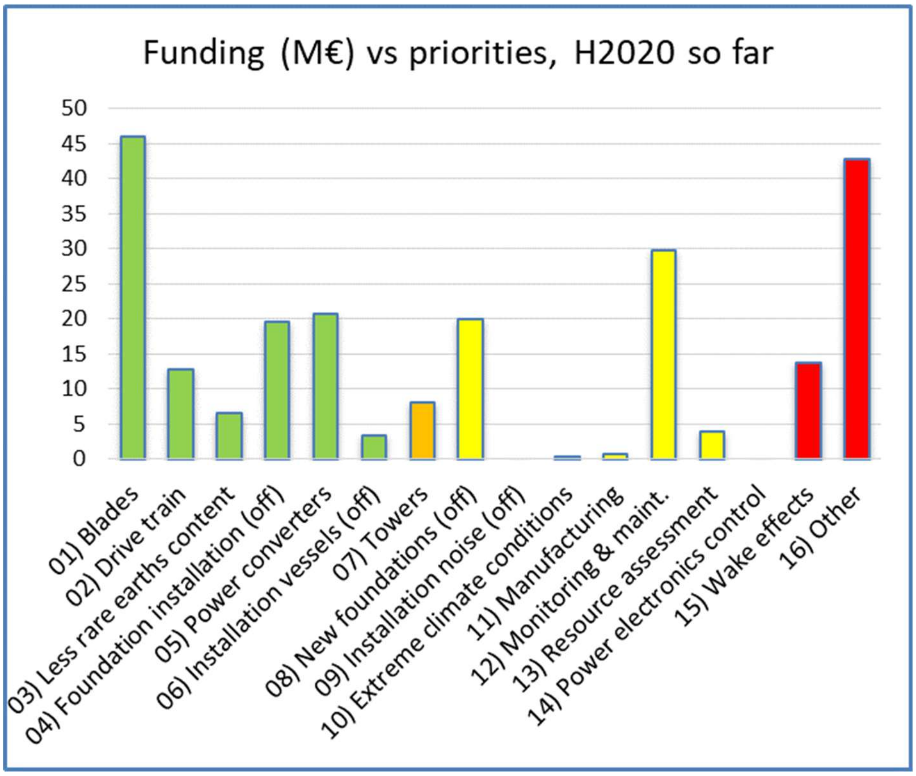

Figure 10 Distribution of H2020 funding by research area. Priority areas (green) receive significant funding, but towers (medium-high priority, orange) receive relatively much less. Two medium-priority areas (yellow) also receive significant funding as do the low-priority wake effects and non-priority airborne and others (red).

3.3.2 Fitting H2020 funding within the SET Plan Integrated Roadmap

The SET Plan Integrated Roadmap presented in 2014proposed three programmes and six actions, as shown Table 7.

Table 7 Research programmes and innovation actions defined in the SET Plan

Programme	Action
Advanced Research Programme (ARP)	**Action 1**: New wind turbines, materials and components
	Action 2: Resource assessment
Industrial Research and demonstration programme (IRDP)	**Action 1**: Offshore technology
	Action 2: Logistics, assembly, testing and decommissioning
Innovation and market-Uptake Programme (IMUP)	**Action 1**: Grid Integration
	Action 2: Spatial planning, social acceptance and end-of-life policies

Relative to FP7 funding, H2020 so far has dedicated more funding to new turbines, materials and components (ARP1) and to maintenance and condition monitoring systems (MAINT) as shown in Figure 11. On the other hand, FP7 funded significantly more resource assessment (ARP2), in part because of the ERA-NET+ project NEWA (New European Wind Atlas). H2020 so far has provided less funding to grid integration (IMUP1), non-tech issues (IMUP2) and offshore technology (IRDP1), and none to logistics, installation and commissioning (IRDP2).

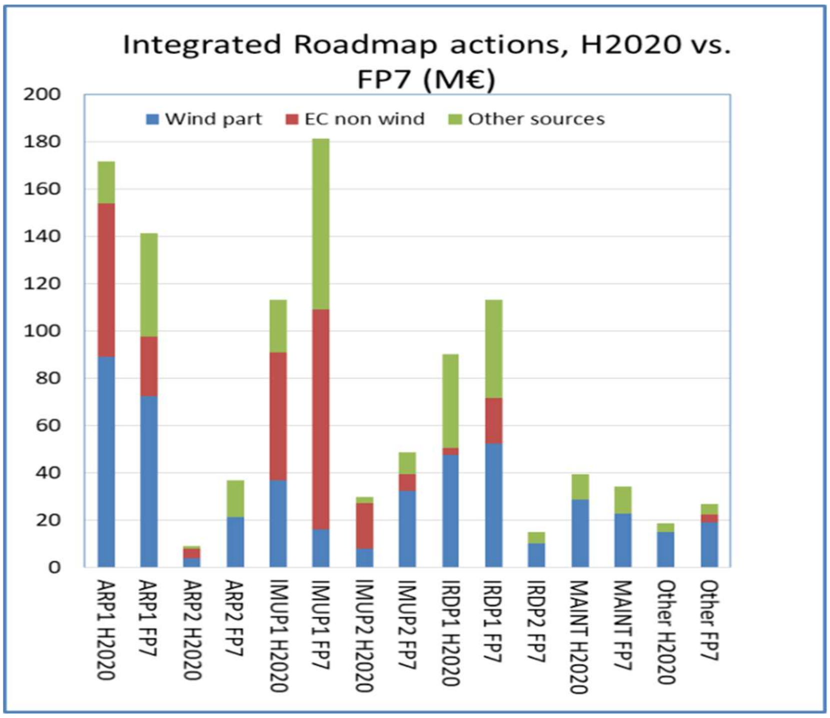

Figure 11 Research funding under the Integrated Roadmap structure, H2020 vs. FP7.
Source: JRC

3.4 Older projects (FP7)

Under the previous EU research programme, Framework Programme 7 (FP7), several projects finished in 2017: WALiD, MEDOW, SWIP, TowerPower, INFLOW, ACTIVEWINDFARMS, AVATAR, INNWIND.EU, LEANWIND, SPEED and CARBOPREC. Four more projects finished in 2018 (IRPWIND, SOPRIS, FLOATGEN and BEST PATHS) and one in 2019 (NEWA).

Interestingly, the total EU funding of these projects reach EUR 146 million, or 37% of the whole EU FP7 funding for wind-related projects.

3.5 Member State and international projects

National projects in the EU Member States focusing on wind technology tend to focus offshore (e.g. the Dutch GROW consortium and the British Offshore Wind Accelerator).

International projects used to be limited to IEA Technology Collaboration IEA Wind. Increasingly, public-private partnerships and private initiatives (joint industry projects, JIPs) are taking shape and leading to research projects driven by the private sector and very focused on well-identified, specific needs.

3.5.1 Netherlands: GROW programme

The Netherlands is very active in developing offshore wind technology mainly through public-private partnership. As an example, the GROW (Growth through Research, development and demonstration in Offshore Wind) programme [56] includes all Dutch companies active in the offshore installation sector, some research institution, utilities and pure-play wind companies. GROW "aims to reduce levelised costs of offshore wind electricity, to create added value for the Dutch economy and to strengthen the Dutch offshore wind industry" [57]

GROW's flagship project to date falls under research action four (innovative installation methods) and is called Gentle Driving of Piles (GDP). This project attempts to develop "a novel pile installation method based on simultaneous application of low-frequency and high-frequency vibrators exciting two different modes of motion of the monopile". A monopile was installed at Princess Amalia offshore wind farm in late May 2018 [58].

Currently, The Netherlands is supporting Offshore wind development via the TKI Wind op Zee program. It is made up of program lines that are focused on the development of technology, cooperation on the North Sea, and integration in the energy system, including large-scale energy storage and conversion[10].

3.5.2 UK Offshore Wind Accelerator (OWA)

This is the Carbon Trust's flagship collaborative RD&D programme to tackle technology barriers and needs for the deployment of offshore wind energy. The programme counts on nine developers plus the Scottish Government who contribute to fund research to fill gaps identified by their board of directors.

"The OWA is structured around five research areas: 'Access Systems', 'Cable Installation', 'Electrical Systems', 'Foundations', and 'Wake Effects and Wind Resource'. Each area is directed by a Technical Working Group consisting of highly skilled experts from each of the OWA partners. The working groups, managed by the Carbon Trust, meet regularly to discuss the challenges in each of the research areas and track the progress of ongoing projects." [59]

OWA has common projects, studies in general, and discretionary projects that are normally demonstration projects open to non-OWA partners. The latter include:

[10] Source: Matthijs Soede, DG R&D

- PISA - Pile Soil Analysis, a research project let by Ørsted, is aimed at investigating how monopiles behave in different soil and environmental conditions to refine the design methodologies reducing fabrication costs [60].
- VIBRO - Vibro Driving project to benchmark the performance of vibratory hammers against conventional piling method [60].
- JaCo - Improved Fatigue Life of Welded Jacket Connections, a GBP 2.4 million aimed at "optimising the design of jacket foundations through improved fatigue standards and validation of faster testing and fabrication methods" [61].
- Wind Farm Control Trials (WFCT) is a EUR 2.3 million project "with the aim of demonstrating new control strategies to improve energy yield and reduce operational and maintenance (O&M) costs" [62].
- BLUE PILOT, EUR 5.2 million including EUR 2.5 million from the Dutch government. "*The BLUE PILOT project will deploy the BLUE 25M Hammer, a new type of pile driver(...) The project will involve the development of validated underwater noise prediction models, which will allow the BLUE 25M Hammer to be used as an alternative for conventional hammers, resulting in direct savings on secondary noise mitigation measures. Furthermore, switching to a BLUE 25M Hammer will reduce the fatigue of conventional designed foundations, therefore increasing their allowable life span or reducing steel and cost for a similar life time*" [63].

These projects are already producing reports. For example, PISA demonstrated that monopile foundations for turbines can be reduced in size and made less expensive, for which it won an award from the British Geotechnical Association at the end of 2017. This result is being used in the design of the forthcoming Triton Knoll OWF [64]. The PISA project has already resulted in at least one spin-off, on cyclic loading [65].

3.5.3 UK Floating Wind JIP

The Carbon Trust leads as well a partnership with developers EnBW, ENGIE, E.ON, Iberdrola, innogy, Ørsted, Shell, Statoil, Vattenfall, Wpd Offshore, Eolfi, and Kyuden Mirai (JP). This joint industry project (JIP) has launched the following research projects [66]:

- Turbine Requirements & Foundation Scaling: Investigates turbine design requirements on floating structures and the impact of larger turbines (10-15 MW) on foundation design.
- Heavy Lift Offshore Operations: Investigates the feasibility, challenges, and technology development needs to undertake heavy lift offshore operations during installation and maintenance (i.e. floating-to-floating lifts).
- Dynamic Export Cable Development: Investigates the challenges and assist the development of high voltage (130-250 kV) dynamic export cables for use in floating offshore wind farms.
- Monitoring & Inspection: Investigates the requirements specific to monitoring and inspection of floating offshore wind assets in key geographic markets, including the identification of technology innovations to adopt less conservative requirements and reduce costs.

3.5.4 DNV GL-led JIPs

DNV GL is essentially a certification agency working on sea works and renewable energy. DNV GL is involved in several research projects with private and institutional partners also taking the form of joint industry projects.

- Cable Lifetime Monitoring: From mid-2018 to mid-2020 a monitoring system will be designed and developed to supervise the health of the cables during all stages of their lifetime, while outage costs caused by failures will be quantified in order to obtain key financial figures [67].

- Optimisation of O&M strategies for individual offshore wind farms. This project counts on industry to define every standard O&M operation and a way to adapt these to each individual wind farm [68].
- "Twisties": deployment of the Fast Feeder Vessel concept for offshore wind farm installation. The JIP will develop a Recommended Practice for the unitisation of project cargo using "Twisties", and in particular usage of the Twistie Turbine Cassette in offshore wind turbine storage, transportation and installation.

3.5.5 US Wind Technologies program

In the US, the Department of Energy Wind Energy Technologies Office "*invests in early-stage energy research and development (R&D) for U.S. land-based, offshore, and distributed wind power generation to lower wind energy costs, increase capacity, accelerate reliable safe energy production, mitigate market barriers, address environmental and human use considerations, and promote U.S. manufacturing innovation*" [69]

In its 2018 budget summary [69], the Wind Energy Technologies Office (WETO) defined its priorities as:

Resource Characterization and Technology R&D

• Atmosphere to Electrons (A2e) – Focus on optimizing performance and improving reliability of next-generation wind plants. Activities include atmospheric coupling research, complex terrain resource characterization, wind turbine wake-steering control, high-fidelity wind-plant wake modeling using U.S. Department of Energy high performance computing (HPC), and integrated system design.

• National Laboratory Facilities – The National Wind Technology Center and Scaled Wind Farm Technology Facilities will conduct A2e verification and validation experiments and component reliability testing.

• Technology Innovation – R&D and testing (RD&T) on controls, sensors, algorithms, materials, and low-specific power rotor design and manufacturing for tall wind applications, to lower costs and improve reliability and performance.

Mitigate Market Barriers

• Grid Integration and System Reliability – WETO R&D will focus on essential grid reliability services for wind systems and forecasting tools, as well as impact evaluations on large shares of wind energy in electricity markets to ensure that wholesale market design adequately compensates all participants for service.

• Wind/Radar Research and Testing – WETO will perform design and evaluation of technology solutions, algorithms and tool development to address wind/radar challenges in partnership with the Departments of Defense, Transportation, Homeland Security, and Commerce.

Modelling and Analysis

• WETO will focus on potential impacts of innovations in offshore wind substructures, operations strategies, and wind plant technologies developed through A2e.

In more detail, Dr Jim Ahlgrimm, US representative at the IEA Wind Executive Committee detailed in May 2018 the following areas of research [70]:

Tall Wind: Taller Towers & Bigger Blades

• Blades. Big Adaptive Rotor initiative to develop low-specific power rotors (larger swept area) for tall wind applications, with an improvement in energy capture of up to 15 percent.

• Towers. By increasing hub height from 80 meters to 140 meters, the area in the U.S. that has a minimum net capacity factor of 30% is increased by 68%

Wind Plant Optimization

• Wakes. R&D for next-generation wind plants to increase performance by reducing turbine-turbine wake interaction (current 20-30 percent energy reduction)

• Component and control innovations to reduce unsubsidized cost of wind energy by up to 50 percent by 2030.

Offshore Wind

• Resources. Collection and dissemination of wind and wave conditions data at U.S. offshore wind development sites.

• Installation. R&D to decrease technology costs and adapt to the unique U.S. conditions.

• Demonstration projects leveraging technologies that address U.S.-specific challenges.

• Assessment. Evaluation of supply chain limitations.

In addition, WETO is involved in exploring opportunities for distributed wind energy, for example in integration into microgrids.

3.5.6 China research and innovation in wind energy

Substantial search into Chinese wind energy R&I priorities failed to yield results. Conversation with our contacts in the Chinese Wind Energy Association failed as well. The only source available was the generic instruction 风电发展"十三五"规划 (Wind power development "13th Five-Year Plan" [71])[11]. Article 4 (III) on "Promoting independent technological innovation and industrial system construction" lists the following priorities:

- Continuously improve the ability of independent innovation, strengthen the construction of industrial service system, and promote industrial technology advancement, improve the quality of wind power development, and build a world-class horizontal wind power technology research and development and equipment manufacturing system.
- Promote independent innovation in industrial technology. Strengthen intelligence such as big data and 3D printing, the application of manufacturing technology to improve the performance and intelligence of wind turbines.
- Boost design and manufacture technology for breaking 10 MW high-capacity wind turbines and key components.
- Master wind loads optimization, intelligent diagnosis, fault self-recovery technology, master intelligent operation and maintenance of wind farms based on Internet of Things, cloud computing and big data analysis master the mastery of wind farm multi-units and wind farms.
- Break through marine wind farm design and construction of key sets of key technologies to master the foundation of offshore wind turbines integrated design technology and application demonstration.
- Encourage companies to take advantage of new technologies and reduce low operating management costs, improve the operational efficiency of stock assets, and enhance market competitiveness.
- Strengthen the construction of public technology platforms. Build a national public service platform for wind resources, provide high resolution wind resource data.
- Construction of an offshore pilot wind farm, the development and optimization of new units provides type test sites and field test conditions.
- Set up a 10 MW wind turbine drive chain ground test platform for the new unit and performance optimization provide testing and certification and technical research and development guarantees common technology platform service level.
- Promote the construction of industrial service system.

[11] Translations by Google Translate with the Support of a native Mandarin speaker.

- Optimize the consulting service industry and encourage the adoption of competition for the field improves the quality of consulting services.
- Actively develop operation and maintenance, technological transformation, specialized services such as power and electricity trading, and do a good job in market management and rule building.
- Spread new operating model and management tools to fully share industry service resources.
- Establish nationwide wind power technology training and talent training base to provide skills training for wind power practitioners, training and qualification ability identification, joint development of talents with enterprises, universities and research institutions
- Cultivate and improve the industrial service system.

3.5.7 Korea: a national mission

Korea has defined as a kind of national priority the design and construction of a large (8MW) offshore wind turbine.

With this goal, the Korea Institute of Energy Technology Evaluation and Planning (KETEP)[12] has granted some EUR 42 million to a consortium of companies with specific tasks:

- Doosan is the only active turbine manufacturer and will "direct the design, manufacturing and demonstration of the 8MW turbine" [72],
- Human Composites will manufacture the blades,
- Seil Engineering will design and manufacture the lower section, (assumed to refer to the tower)
- The Korea Institute of Material Science is responsible for blade design support and testing, and
- The Seoul National University (SNU) R&DB Foundation is responsible for devising measures to reduce blade noise.

The 4-years-long project has a funding level similar to the H2020 RealCoE, which aims at developing a 12-MW turbine. As mentioned above, this level of funding is much below the industry-declared level of funding necessary for the development of a large offshore wind turbine.

3.5.8 IEA Wind Technology Collaboration Programme

The IEA Wind Technology Collaboration Programme (TCP, formerly known as Implementing Agreement), promotes collaborative research at the early-TRL, basic-science levels.

As of mid-2018, the following research actions were ongoing:

- Task 19 Wind Energy in Cold Climates
- Task 25 Design and Operation of Power Systems with Large Amounts of Wind Power
- Task 26 Cost of Wind Energy
- Task 27 Small Wind Turbines at Turbulent Sites
- Task 28 Social Acceptance of Wind Energy Projects
- Task 29 MEXNEXT III Analysis of Wind Tunnel Measurements and Improvement of Aerodynamic Models
- Task 30 Offshore Code Comparison Collaboration Continued, with Correlation (OC5)
- Task 31 WAKEBENCH: Verification, Validation, and Uncertainty Quantification of Wind Farm Flow Model.
- Task 32 LIDAR: Wind Lidar Systems for Wind Energy Deployment
- Task 34 Working Together to Resolve Environmental Effects of Wind Energy (WREN)

[12] KETEP is a member of CORFA, Korea's Council of R&D Funding Agencies, established in 2009 with the objective to "efficiently support in description/evaluation and management of developments in energy technology" [89]

- Task 35 Full-Size Ground Testing of Wind Turbines and their Components
- Task 36 Forecasting for Wind Energy
- Task 37 Wind Energy Systems Engineering: Integrated Research, Design, and Development
- Task 39 Quiet Wind Turbine Technology
- Task 40 Downwind Turbine Technologies

Figure 12 shows the priority areas and execution of research under the umbrella of IEA Wind TCP

IEA Wind Tasks provide basic science (e.g. MEXNEXT); allow cross-platform validation of data (WAVEBENCH); publish reports (e.g. Task 26: Forecasting Wind Energy Costs & Cost Drivers), peer-review papers or Recommended Practices e.g. Wind Energy Projects in Cold Climates (Task 19); Wind Farm Data Collection and Reliability Assessment for O&M Optimization (Task 33); Floating Lidar Systems (Task 32). IEA Wind Tasks also organise technical meetings.

This work is sometimes carried out in coordination with other research entities and/or programmes, e.g. the Offshore Wind Accelerator in the case of the floating LIDAR recommended practice.

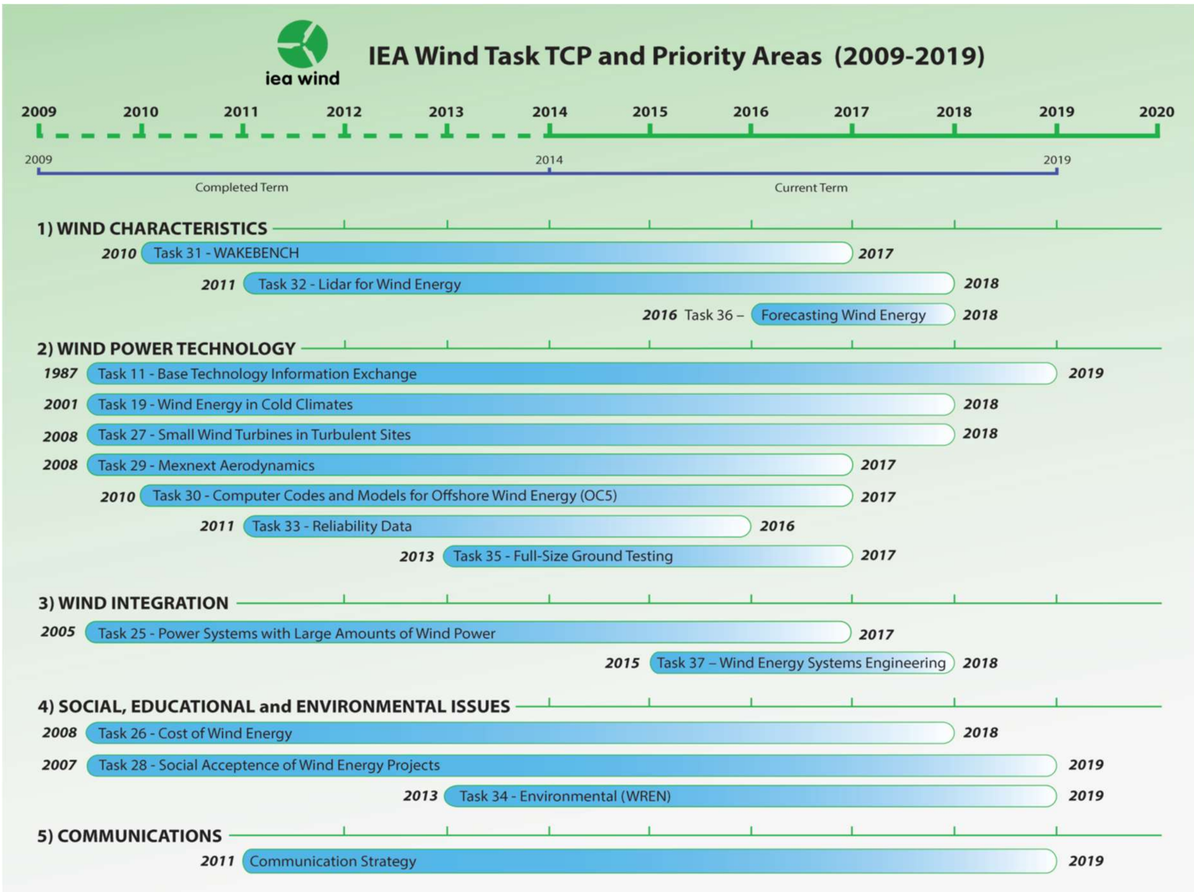

Figure 12 IEA Wind TCP research projects according to priority areas.
Source: IEA Wind TCP 2016 annual report [73]

4 Impact assessment of H2020-funded projects

In this analysis we consider the following indicators of impact:

- Advancement in the technology readiness level of the innovation
- Declared innovations
- Patents
- Peer-review papers

Broadly speaking, the objectives of high-TRL projects include the development of innovations, an element that cannot be measured as such.

4.1 Project analysis

ELISA, ELICAN, TELWIND

These projects present an interesting example of using different H2020 instruments. As explained above, the project sponsors developed a novel type of floating foundation under ELISA, supported by small and medium enterprise (SME) funding. Then, the ELICAN project funded under innovation action (IA) LCE-2015-2 added a telescopic, self-erecting tower, for a 5-MW turbine taking the set to TRL7. Later, the TELWIND project was funded under research and innovation action (RIA) LCE-2015-1-2 stage in order to scale up the whole structure to a 6/8 MW turbine and will result in a large-scale prototype at an earlier TRL (TRL5).

ELISA finished in May 2017, ELICAN and TELWIND are expected to finish by end 2018. All the deliverables will be confidential.

POSEIDON

This project aimed at developing a hybrid (wave and wind) floating platform. It involved "very demanding technological conception and complex technological, economic, territorial and commissioning requirements" [74].

HPC4E

Wind is the focus of work package 4 (WP4) of this ICT project. The aim was to analyse wind resource assessment and wind farm design, and to forecasts short-term prediction of wind electricity generation.

Expected results include:

- Algorithms to apply codes to run efficiently larger problems with higher fidelity to a better exploitation of various sources of energy.
- Tools and methodologies for wind energy evaluating with higher accuracy the technical and economic viability of wind farms, and to forecast the short-term production.

At the time of writing, the WP4 deliverables were not available.

WIndspector

WIndspector had as objective the development of a robot that could climb the blades in order to inspect for problems.

AMPYXAP3

This project concerns the design, construction and testing of the first article of an initial commercial PowerPlane, version AP3. This is second generation of airborne wind turbines, for altitudes between 100 and 600 meters. The project is based on a 2013 patent application.

The project was expected to finish in February 2017 but was extended until September 2019, more than double the initial duration.

VirtuWind

The project attempts to develop new telecoms technologies as a network to facilitate wind farm control. In essence, this is an innovation that would result in savings in capital and operating costs of the control network.

LIFES 50plus

This project targets development of two new floating concepts but has lost a key member of the consortium, Iberdrola. At the time of writing (2018) it is unclear how this could affect the work.

Riblet4Wind

This project aims to transfer technology used in the aeronautics sector for coating blades reducing resistance and improving energy production in particular at lower wind speeds. The ambition is a six percent increase in turbine efficiency. A very important by-product is a reduction of noise, because it would allow turbines to be installed in more sensitive areas, thus increasing the available land for deployment.

4.2 Analysis according to technology readiness levels

One of the key objectives of the H2020 programme is to help technologies to advance in the way to market. Thus, generally speaking, each H2020 project would push the given innovation one or two steps in the scale of technology readiness levels (TRL).

H2020 funded in particular wind research at the initial phases of innovation (TRL1-3) with 35 projects, whereas 20 projects in the central phases (TRL4-6) were funded as opposed to 16 projects in the most advanced phases. 7 non-technology projects were funded outside the TRL scheme.

However, in terms of total funding it is the middle phases (TRL4-6) that got higher funding at EUR 82.3 million, versus EUR 67 and 73.8 million in the initial and last TRL phases respectively.

A few large projects have extraordinary weight in the funding. RealCoE, a EUR 32 million project funded with EUR 25 million as an innovation action, constitutes 54% of the funding to 13 projects on blades.

PROMOTioN, a EUR 52 million high-voltage direct-current project with EUR 39 million funding from H2020 (of which 50% is considered to be wind share), constitutes 95% of the funding to the research action 5 (power converters).

The two DemoWind ERA-NET+ projects, funded with a total EUR 19 million from H2020 (and a further EUR 38.6 million from MSs), form the bulk of the research action Innovative installation systems for offshore foundations, with a focus on cost reduction. However, it has to be noted that DemoWind has the structure of a programme, not a project, and is actually funding projects in different research actions (e.g. blades, drive trains, new foundations). Unfortunately, lack of data prevents the consistent assessment of DemoWind projects.

4.3 Innovations from EU-funded projects

A registry of innovations resulting from EU-funded projects does not exist. Its assessment is therefore very limited.

DG CONNECT supports the Innovation Radar as part of the Digital Single Market [75]. The database is available in [76].

One innovation was listed for H2020 project VirtuWind (IA subprogramme on ICT) and one for VORTEX (SME subprogramme). Project ICONN (MSCA subprogramme) had three innovation listed but these belong to the wave energy part of the project.

DG CONNECT also has an internal Innovation Radar dashboard with additional information, were an additional innovation was found from H2020 project EIROS (RIA subprogramme on materials).

Clearly, EU-funded projects have much higher potential to develop innovations than the results of these sources show. This suggest that appropriate follow-up of innovations stemming from EU-funded projects is lacking.

4.4 Patents from EU-funded projects

Patents can be considered a proxy for innovations, with the benefit that general patent data are available.

Unfortunately, no records of patents resulting from EU-funded projects are available. However, many of the projects declared patents filed prior to the start of the project, which suggests that the projects were designed and run in order to test and/or implement a previously-filed and/or granted patent.

Having analysed all H2020 projects with initial ending date up to 31/08/2018, Table 8 shows those that referred to patents in their reporting to the Commission. With few exceptions (those in bold and italics), patent applications were filed prior to the project start date.

It is suggested that patent applications be notified to the EC when they originate in an EU-funded project, and recorded in a way that facilitates monitoring.

Table 8 H2020 projects implementing previous patents

Project	Start date	Area	Patent applications (date)
IRWES	4/2015	Small turbines	***EP20150837149 (30/12/15)*** ***NL2016888 (02/06/16)***
ELISA	6/2015	Floating foundation	EP12813291 (10/12/12) ***ES201630627 (13/05/16)*** ***ES201531355 (23/09/15)***
ELICAN	1/2016	Tower	EP11758478 (21/09/11)
TELWIND	12/2015	Floating foundation	***ES201631068 (02/08/16)*** EP12812901 (10/12/12) EP15800536 (27/05/15) EP15800580 (27/05/15)
AMPYXAP3	4/2015	Airborne	EP20120157057 (27/02/12)
LIBI	6/2016	Blades	EP14806532 (14/11/14) DK1400008591 (23/09/15)
VORTEX	6/2016	New concepts	20 patent applications claimed until April 2017

5 Technology development trends, barriers and needs

"One is to substantially reduce mass of the inner blades by switching from a full glass-epoxy structure to a sandwich design by integrating, for example, balsa wood." This sentence referred to blades, by Eize de Vries [77], neatly summarises the trends, barriers and needs in wind turbine technology: larger size, less mass, lower cost.

5.1 Expected developments

Wind turbines will continue growing in rotor size and electricity generator rating. To achieve this growth, a number of underlying technologies will have to develop, possibly including:

- Materials that will allow breaking the square-cube law [78] that applies to scaling up structures such as blades and towers.
- Design tools will help reducing over-engineering, designing for ease of transport, better reusing/recycling and even achieve optimisation through all life cycle stages of the wind farm, with the help of digitalisation.
- New manufacturing processes. Factories need to become more flexible, leaner. Approaches such as the robot factory by Tesla [79] will slowly permeate the wind sector, perhaps starting in component manufacture.
- Noise will be reduced based on materials (e.g. coatings) and new design tools (e.g. aerodynamics)

Some of these technological developments may not be demanded by the market unless the necessary legislative push is in place, e.g. design for recycling. Regulatory constraints are already showing an impact as it can be seen e.g. in noise reduction: Vestas' new V136-4.0MW (2018) has rated noise level of 103.9 dB(A) vs. 107 dB(A) of the old V90-3.0MW (2010). Operations and maintenance, especially offshore, will evolve towards more remote operation and higher importance of predictive maintenance.

Tools necessary to support those developments include artificial intelligence applied to big data; new, smaller sensors even at molecular level; and collaboration between/with the supply chain leading to an integrated yet modular wind turbine digital model. Digitalisation will trigger higher efficiency and lower costs along the entire value chain, turbine self-diagnostics and real-time wind farm optimisation. "Digitalization will transform the way we design and build turbines, as well as their operation and maintenance" [80].

5.2 Technology foresight

5.2.1 The JRC-EU-TIMES model

The JRC-EU-TIMES model offers a tool for assessing the possible impact of technology and cost developments [81]. It represents the energy system of the EU28 plus Switzerland, Iceland and Norway, with each country constituting one region of the model. It simulates a series of 9 consecutive time periods from 2005 to 2060, with results reported for 2020, 2030, 2040 and 2050. The model was run with three baseline scenarios:

- Baseline: continuation of current trends: it represents a 'business as usual' world in which no additional efforts are taken on stabilising the atmospheric concentration of GHGs; only 48 % CO_2 reduction by 2050.
- Diversified (Div1): usage of all known supply, efficiency and mitigation options (including carbon capture and storage -CCS- and new nuclear plants); 2050 CO_2 reduction target of 80 % is achieved.
- ProRES (Res1): 80 % CO_2 reduction by 2050 is achieved without the need for any new nuclear plants, nor for CCS.

In addition, a further 13 sensitivity cases were run. Nijs et al [83] present all the scenarios and the overall results.

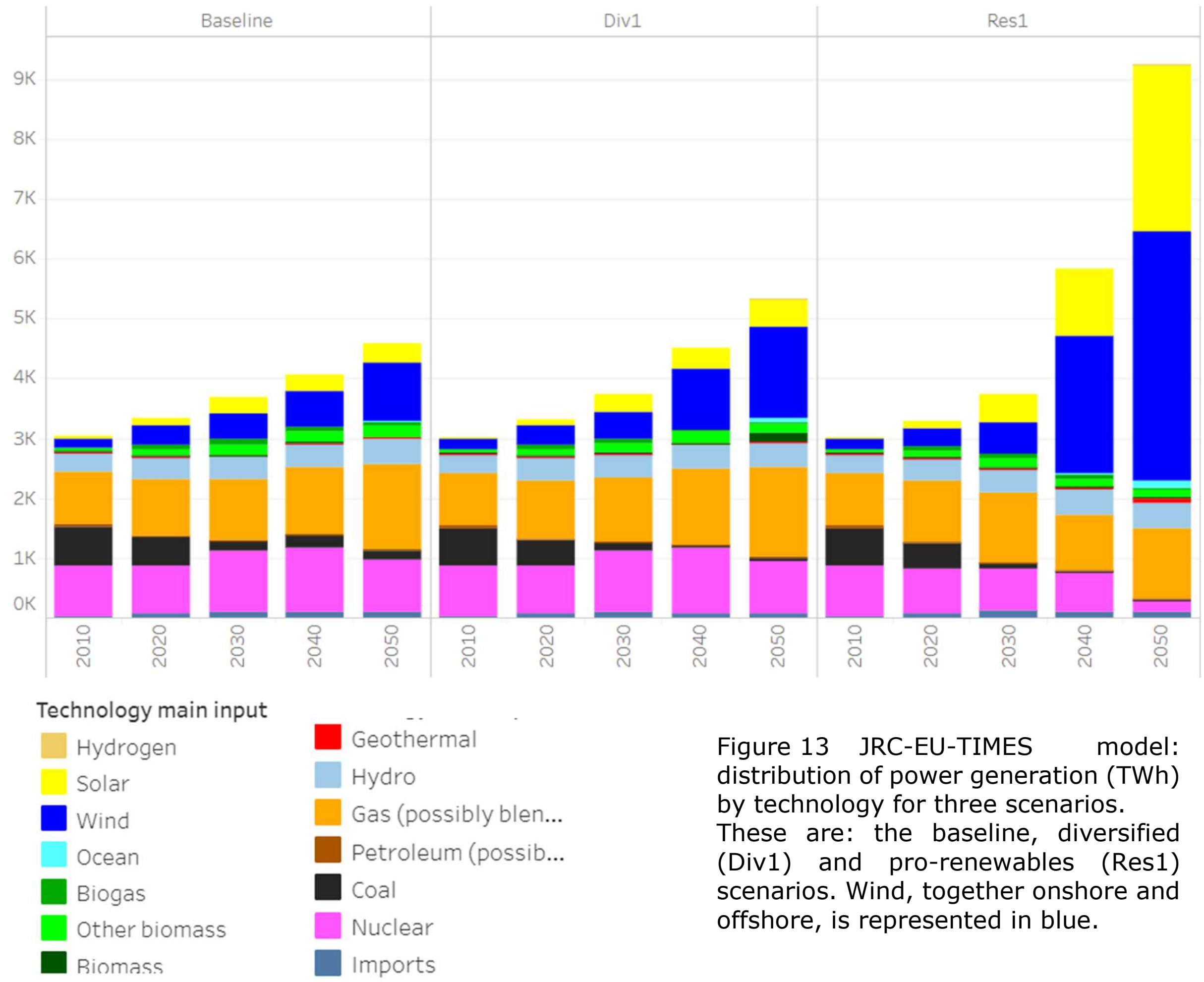

Figure 13 JRC-EU-TIMES model: distribution of power generation (TWh) by technology for three scenarios. These are: the baseline, diversified (Div1) and pro-renewables (Res1) scenarios. Wind, together onshore and offshore, is represented in blue.

5.2.2 Wind projections

This technology development report focusses on the 3 main scenarios and a series of sensitivity analyses to the ProRES (Res1) scenario: higher and lower learning rates. Further analysis including country breakdowns will be included in the technology market report. The extraordinary cost reduction over 2017/2018 (see section 1.2), has not been included into this TIMES run. One of the major questions raised by the model results is to what extent this can, if sustained, affect future deployment.

Figure 13 shows an overview of the results for the three main scenarios. The baseline represents a situation where natural gas is the predominant generation technology throughout the period, followed by nuclear, up to 2050, when wind surpasses it to rank second: 988 TWh from wind vs. 880 TWh from nuclear. It is noted that baseline scenario is likely to be conservative for wind energy. For example, the 2020 generation is projected to be 319 TWh whereas already in 2017 that figure was surpassed (see section 1.2). If recent trends continue, the baseline estimated 450 TWh by 2030 could be reached by 2022.

The other scenarios suggest a greater chance for renewables, and in particular wind and solar, to contribute more to the electricity mix. Perhaps the most notable feature is the large increase in electricity production in the ProRES scenario (Res1), reflecting a deep electrification of transport and the use of electricity to produce hydrogen and synfuels.

Non-energy products are not included in the model. Electrofuels are replacing diesel and kerosene where there is no hydrogen or electric alternative.

Among renewables wind plays the most significant role in all scenarios, and becomes the largest energy source in ProRES by 2040 and 2050. In the diversified scenario, with strong contribution from nuclear, wind contributes as much (1 022 TWh vs. 1 090 TWh from nuclear) by 2040, and clearly surpasses it by 2050 (1 526 vs. 885 TWh). As it can be expected, it is the ProRES scenario that presents the largest boost to the contribution of wind energy, which in this way would be the first electricity-generating technology overtaking gas already before 2040. The diversified scenario suggests that gas will continue being the largest contribution to the electricity mix up to 2050, when wind takes over the role of most popular technology. In terms of installed capacity, Figure 14 shows that the big jump occurs after 2030 and this is expected due to two factors: onshore repowering of existing projects with much larger machines; offshore much larger deployment due to lowering costs. The installed capacity by 2050 in ProRES is just over 1.5 TW, and a factor of more than 4 above that in the baseline scenario. In terms of the type of deployment, Figure 15 shows a breakdown between onshore and offshore for the three scenarios. This follows the costs: the cheapest form (onshore wind) dominates, with a smaller role for offshore wind.

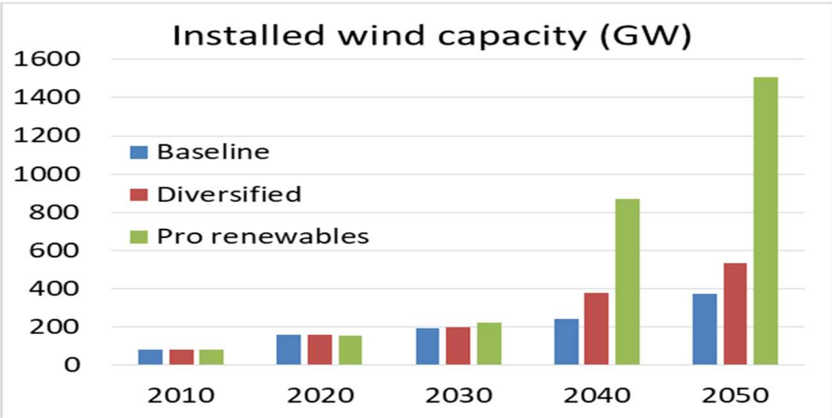

Figure 15 Development of the installed capacity for wind energy (both on- and offshore) under three scenarios

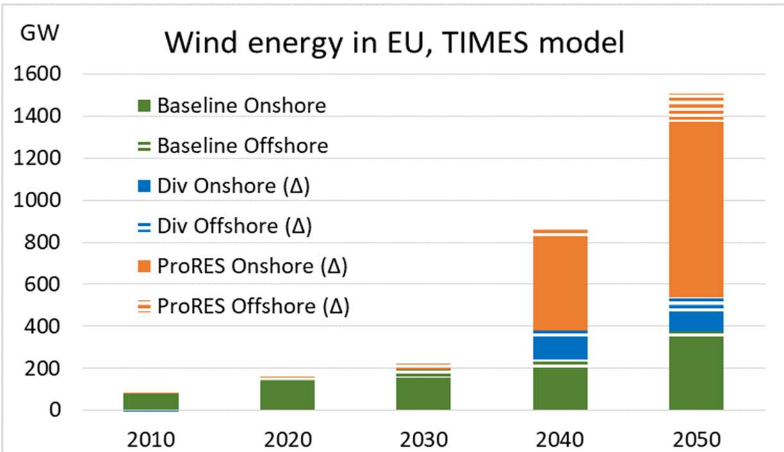

Figure 14 Wind energy deployment (GW) in the EU28 under different scenarios, differentiated between on- and offshore. Figures for the diversified scenario are incremental on the baseline, and for the ProRES scenario are incremental on the diversified one.

5.2.3 Sensitivity analysis

Because TIMES is heavily influenced by the learning rates assumed, the model explored how different learning rates (LR) could affect the scenarios. Two learning rates were explored related to the ProRES scenario, a lower and a higher LR cases.

Figure 16 shows the variations that can be expected in onshore wind energy generation if all technologies were running at a lower or higher learning rate, whereas Figure 17 shows the same information for offshore wind.

In both cases the model shows that the effect of different learning rates will be minimal before 2040. However, from then on this effect will be very significant.

The results for onshore seemingly run counterintuitively: the higher the learning rate the lower the production by 2040 and 2050. The reasoning behind is that onshore wind is mostly a mature technology with a relatively large installed base. A faster (higher) learning rate applied to all generation technologies would result in the less developed ones (e.g. offshore wind) developing faster and reaching competitiveness earlier. As a result of cheaper alternatives, onshore wind will not develop to the same extent in Europe by 2040 and 2050.

Incidentally, if similar LR sensitivities are applied to the diversified scenario, the effects are hardly felt: 1 058 TWh vs. 1 080 TWh under low LR and 1 127 TWh under high LR scenarios.

The situation offshore is very different, as shown in Figure 17. An improvement in the learning rate results in very significant increases in the contribution of the technology to the electricity mix, and this effect starts to be felt already by 2030. On the contrary, a reduction of the learning rate would not affect 2050 contribution that much.

This suggests that the assumptions on learning rates built in the model can be conservative. This sensitivity was put in the context of renewable energy[13], and the model shows that overall a higher learning rate will increase renewables' contribution in the diversified (3 056 TWh vs. 2 408 TWh of the base case), and ProRES (7 683 TWh vs. 7 313 TWh) scenarios. A low learning rate resulted in below-the-base-case contribution in both cases

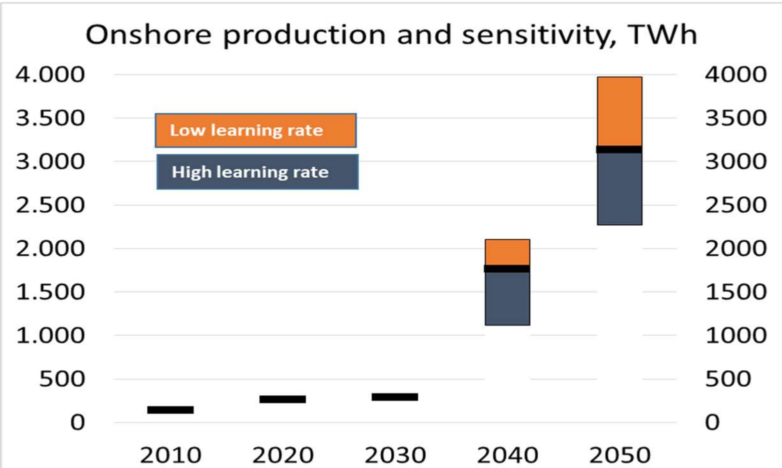

Figure 16 How onshore wind electricity generation could change based on all technologies reaching a lower and a higher learning rate, ProRES scenario.
Source: JRC-EU-TIMES

[13] The following technologies are here included as renewables: biogas, biomass, geothermal, ocean, solar and wind. Hydropower is excluded because it is a very mature technology that is not, according to the model, influenced at all by changes in the learning rates.

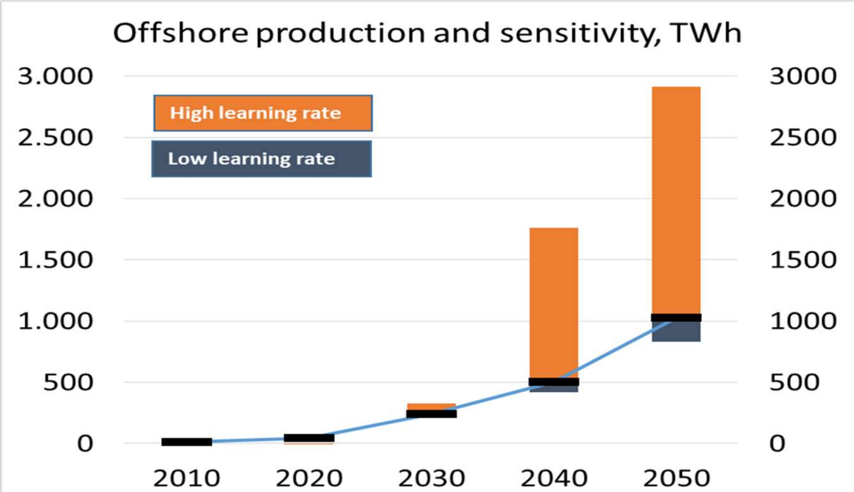

Figure 17 Offshore wind electricity generation based on a lower and a higher learning rate applied to all technologies, ProRES scenario. Source: JRC-EU-TIMES model

5.3 Technology barriers to large scale deployment, and corresponding needs

The main technology barrier preventing large-scale deployment is external to the wind energy sector. It is the absence of widespread storage technologies at affordable costs to cancel out the effect of natural variability of wind and allow the integration of large amounts of wind (and solar) electricity.

Wind energy technology based on the horizontal-axis wind turbine is a mature technology and, as such, there is not any unsurpassable technological barrier – and this was known as far back as 2003 [83].

Still, there are important non-technology barriers. These include legislation that does not support the technology such as electricity markets with too-long lead time between bidding and electricity delivery; local rules requiring a significant distance between turbines and nearest housing, etc. In some cases, there are land-use limitations, e.g. high population density in Luxemburg.

The industry frequently claims that the lack of an educated, trained workforce is one of the main barriers.

Technological barriers exist that hinder or slow down the improvement of the technology are very much related to costs. From this point of view, the following elements could be considered barriers:

- Materials that need to perform better whereas maintaining their cost affordable. These include coatings to prevent erosion, ice formation etc.; coatings that reduce blade maintenance; lighter plastics (thermoplastics, composites, etc.) to reduce the weight of blades while improving their stiffness and other properties; steels (or steel coatings) that let bearings, shafts and gears to suffer less damage in use.
- Blades and towers have become so large that transport is no longer possible to certain sites.
- Failures need to be better understood, documented, and researched.

There are higher technology barriers to the development of alternative wind technologies, including:

- Floating wind farms: mooring and anchoring systems; reduced use of materials in floaters.
- Airborne wind: proven and tested designs.
- Vertical axis wind turbines: reaching a broadly-accepted, efficient design.

For example, regarding materials for blades, a rule of thumb is that materials make 50 – 60 % of the cost of wind turbine blades whereas labour makes 20 – 30 %. This suggests that new materials are needed that are cheaper and/or allow more automated, lower-cost manufacture.

Materials are needed for coatings that protect blades for longer lifetime, in particular in the marine environment, so that expensive maintenance is avoided [84].

5.4 European vs. corporate interest

A non-technology barrier that is worth mentioning is the effect of the distinct interest of private companies versus European interests[14].

As discussed above -and it is natural- companies lead R&D investment, but will not share it with competitors because it is considered to give them competitive advantage.

Whereas it is part of our R&D structures that public funding focuses mostly on early stages of science, it is also of paramount European interests that EU companies support the creation of jobs in Europe – and this is not the trend nowadays[15]. Perhaps companies could do more if R&D was adequately supported and a way was found to make compatible competitive advantage and public interest. EU OEMs and component manufacturers would then be more open to share European R&D for the benefit of Europeans.

An example of private-public collaboration along these lines could be the development of cable-stayed monopiles based on Vestas' new cable-stayed tower [26], which has the potential to make monopiles reach depths where currently only jackets can be installed, and reduce costs.

5.5 Barriers to future energy technologies

Barriers to future technologies are identified in a recent report by the LCEO, *Workshop on identification of future emerging technologies in the wind power sector* [85], and a summary is included below:

- Airborne Wind Energy (AWE) is in its early stages of development. Barriers include the stability/reliability, the high complexity, the need for autonomous take-off and landing, as well as possible regulation issues and social acceptance.

- For offshore floating wind higher operations and maintenance costs might be expected. R&D needed on materials, advanced modelling tools and control systems.

- *Smart rotors* is a broad term that integrates both active and/or passive load alleviation features. Lifetime and cost of movable components and actuators were highlighted as an issue.

- Devices based on wind-induced energy harvesting from aeroelastic phenomena such as fluttering, vortex-induced vibrations and galloping have low efficiency and low power production.

- Wind turbine with tip-rotors could be designed to have lower weight, but it is anticipated that these may have issues regarding noise, erosion and centrifugal forces on the tip rotors.

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[14] As represented, for example, by the current Commission priority Jobs, growth and investment

[15] "Some EU OEMs follow a strategy to "develop" foreign suppliers in an effort to localise the supply chain. In these cases OEMs assign their own materials and quality development engineers to suppliers' facilities in order to ensure their technological development and competitiveness" [90].

- Hydraulic or compressed-air technologies as alternatives to electro-mechanical generation. feature lower efficiency.
- Multi-rotor system wind turbines would require standardisation of the rotor, and further research on active control and structural vibration alleviation.
- Alternative support structures for wind turbines face the high cost of prototypes and one-of-a-kind projects.
- Modular HVDC generators require improved stator designs to solve electro-mechanical issues.
- Wind computational models present high complexity which translates into a high need for research time and funding.

6 Summary and recommendations

This report aims to provide an assessment of wind energy technology, with particular focus on EU-supported R&D projects up to mid-2018.

In general, the projects supported by H2020 are contributing to technology advances that than ultimately reduce the cost of offshore wind energy. As a positive side effect, some of them may also contribute to lowering costs for land-based wind turbines, and will hopefully help European manufacturers to maintain world leadership. However, a number of projects also failed and/or were severely constrained. These include the cancelled DEMOGRAVI3, and EEPR (gravity foundations) projects, while others faced major problems. Often issues regarding consortia members proved critical e.g. lack of, or withdrawal of, a key partner.

The procedures for monitoring project results can be reinforced. For instance, reporting should define innovations more clearly so as to enable clear assessment of advances in technology readiness level and the extent to which the original performance objectives are met.

European companies such as Vestas, SGRE and Enercon are at the forefront of efforts to maintain EU technology leadership. Their ideas and support could help developing EU companies in their supply chain. Their involvement can be vital to reinforce the European industrial base, jobs and growth. In a similar way, leading wind farm developers (Vattenfall, Ørsted, etc.) are also in a strategic position to contribute on R&I planning, as in the case of the work of UK Carbon Trust in the offshore wind area.

It is recommended that support needs for each technology area are assessed in economic terms. By comparing these with current R&I investments, gaps can be highlighted for coverage in future H2020/Horizon Europe calls.

One future focus should be on technology transfer, between industry sectors, regarding materials, components and manufacturing processes. Expert workshops or similar techniques could help to identify items from other sectors (aeronautics, automobile, etc.) that can contribute to the further development of the wind sector. Cross-technology areas could include 3D printing e.g. for blade mould manufacture, or for prototype building of new components. R&I for manufacturing should be complemented with R&I for installation, as in some cases the cost of installing turbines is considerable. artificial intelligence also presents a huge prospective field to explore across technologies.

Four areas are critical to wind turbine blade technology: design, manufacturing, materials development and testing [1]. Future research could focus on lighter materials, mould manufacture (e.g. 3D printing as mentioned above), erosion-protection and anti-ice coatings, and reducing manufacturing costs. To these traditional long-term priorities, digitalisation has added the need for design at system rather than component level. This in turn requires deep collaboration where data sharing should reach a very high level, upstream with the supply chain and downstream with developers.

Options for modular blades increase with blade length, but these pose both cost and in-field assembly issues that need to be treated.

Better understanding of system loads, e.g. due to misalignments, bending moments, temperature variations and torque fluctuations [1], in larger turbines is important for improving the main mechanical and electrical components of the turbine, and for reducing the use of materials. Sensors have helped with this but they are not always suitable, e.g. internal sensors in the gearbox.

For offshore, higher standardisation of manufacture and installation is needed. In the area of offshore foundations, future research is suggested at the basic science level. This could include models for operational and extreme structural loads, methods for considering soil-structure interaction and subsurface effects on structural performance, design procedures for floating systems or coupled analysis (aero-hydro-elastic simulations). At a more advanced level, construction and installation capability for offshore systems still have room for research and development e.g. of lifting techniques, pile driving or drilling. Demonstration projects to prove numerical methods and environmental challenges would also be needed.

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List of abbreviations and definitions

AC	Alternating Current
ARP	Advanced Research Programme
BNEF	Bloomberg New Energy Finance
CapEx	Capital expenditure, expenses or capital cost
CCS	Carbon capture and storage
CF	Capacity Factor
CFD	Computational Fluids Dynamics
DFIG	Doubly feed induction generator
DoE	(US) Department of Energy
EESG	Electrically excited synchronous generator
HAWT	Horizontal axis wind turbine
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IMUP	Innovation and market-Uptake Programme
IRDP	Industrial Research and Demonstration Programme
LCoE	Levelised Cost of Energy
LR	Learning rate(s)
LiDAR	Light detector and ranging
NREAP	National Renewable Energy Action Plan
O&M	Operation and maintenance
OpEx	Operational Expenditure
SET-Plan	(European) Strategic Energy Technology Plan
SGRE	Siemens Gamesa Renewable Energy
TRL	Technology Readiness Level
VAWT	Vertical axis wind turbine
WETO	(US, DoE) Wind Energy Technologies Office

Annex: Wind Power Data Extract from JRC-EU-TIMES scenarios

Production and capacity figures for the scenarios described in section 5.2, the sensitivities and an additional scenario based on achieving the SET Plan objectives are shown below.

	Production (TWh)					Capacity (GW)				
	2010	**2020**	**2030**	**2040**	**2050**	**2010**	**2020**	**2030**	**2040**	**2050**
Baseline	**154**	**319**	**430**	**598**	**988**	**81**	**158**	**195**	**241**	**375**
Current offshore wind	10	42	32	2		3	12	9	1	
Current onshore wind	143	255	203	56		77	138	110	30	
Future offshore wind		17	111	148	157		4	28	37	38
Wind onshore CF15-20						0	0	0	0	0
Wind onshore CF20-25	1	6	83	88	75	0	3	47	50	42
Wind onshore CF25+			1	305	756	0	0	0	124	296
Div1	**154**	**321**	**431**	**1 022**	**1 526**	**81**	**158**	**196**	**380**	**536**
Current offshore wind	10	42	32	2		3	12	9	1	
Current onshore wind	143	255	203	56		77	138	110	30	
Future offshore wind		19	112	320	468		5	28	78	110
Wind onshore CF15-20						0	0	0	0	0
Wind onshore CF20-25		5	83	94	78	0	3	48	54	43
Wind onshore CF25+			1	549	980	0	0	0	217	382
Res1	**154**	**305**	**532**	**2 274**	**4 167**	**81**	**154**	**222**	**870**	**1 507**
Current offshore wind	10	42	32	2		3	12	9	1	
Current onshore wind	143	255	203	56		77	138	110	30	
Future offshore wind		2	211	504	1 027		1	54	125	246
Wind onshore CF15-20	0	0	0	10	17	0	0	0	7	12
Wind onshore CF20-25	1	6	85	208	242	0	3	49	115	131
Wind onshore CF25+	0	0	1	1 495	2 881	0	0	0	592	1 119
Res2_LowLR	**154**	**305**	**533**	**2 521**	**4 802**	**81**	**154**	**224**	**993**	**1 814**
Current offshore wind	10	42	32	2		3	12	9	1	
Current onshore wind	143	255	203	56		77	138	110	30	
Future offshore wind		2	205	416	830		0	52	102	197
Wind onshore CF15-20	0	0	0	10	24	0	0	0	7	16
Wind onshore CF20-25	1	6	92	275	444	0	3	53	152	237
Wind onshore CF25+	0	0	1	1 762	3 504	0	0	0	701	1 365
Res3_HighLR	**154**	**304**	**611**	**2 880**	**5 189**	**81**	**154**	**242**	**934**	**1 669**
Current offshore wind	10	42	32	2		3	12	9	1	
Current onshore wind	143	255	203	56		77	138	110	30	
Future offshore wind		2	255	1 721	2 886		0	67	430	706
Future floating wind			37	37	30			9	9	7
Wind onshore CF15-20	0	0	0	12	23	0	0	0	8	15
Wind onshore CF20-25	1	5	82	212	262	0	3	47	117	141
Wind onshore CF25+	0	0	1	839	1 989	0	0	0	339	799
Res4_SET	**154**	**305**	**537**	**2 390**	**4 172**	**81**	**154**	**224**	**919**	**1 540**
Current offshore wind	10	42	32	2		3	12	9	1	
Current onshore wind	143	255	203	56		77	138	110	30	
Future offshore wind		2	215	490	857		1	55	122	207
Wind onshore CF15-20	0	0	0	15	22	0	0	0	10	15
Wind onshore CF20-25	1	6	86	200	238	0	3	49	111	128
Wind onshore CF25+	0	0	1	1 628	3 055	0	0	0	646	1 190

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