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LOW CARBON ENERGY OBSERVATORY

WIND ENERGY
Technology development report

Joint Research Centre

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Contents

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 patents 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.

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Authors

Thomas TELSNIG

1 Introduction

1.1 Scope of report

The aim of this report is to provide an update of the state of the art of wind energy technology and to identify how EC funded projects contributed to technology advancements. Moreover, this version of the LCEO Technology Development Report complements the last version [JRC 2019a] which explained main characteristics on wind energy with detailed development trends of the main technical indicators in onshore and offshore wind.

A main focus is on the progress and technology readiness level (TRL) of R&D wind energy projects in the European context funded through the main European research funding instruments. Particularly for offshore wind energy, the progress within the SET-Plan[1] Implementation Working Group (IWG) for Offshore Wind is analysed against its research priorities.

As such, this report sets a clear emphasis on the technology status, research landscape and deployment and development trends in the European market and provides an outlook for wind energy under a scenario compatible with the SET-Plan targets and striving for full decarbonisation of the European energy system until 2050.

Table 1 presents the data sources employed for the current analysis of R&D.

Table 1 Data sources for this analysis

Data sources	SOA	R&D	DT	BAR	PRI
Most relevant EU-funded projects (H2020)	✓		✓	✓	✓
EU Member State or regionally-funded projects (SET-Plan)	✓		✓		✓
Major international projects (IEA)	✓		✓		✓
National projects from major non-EU countries (IEA)	✓		✓		✓
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

Following the main characteristics and market status presented in the following section (chapter 1.2), chapter 2 focuses on the state of the art and technology development trends based on the main technical indicators from the JRC Wind energy database. Chapter 3 provides an overview about R&D in wind energy based on H2020 funded wind energy projects, offshore wind R&D in the European Strategic Energy Technology Plan (SET-Plan), other European R&D support instruments and the IEA Technology programme for wind energy systems. Chapter 4 gives an impact assessment of H2020 projects completed in 2019 followed by chapter 5 providing a technology development outlook until 2050 under the assumption of achieving the SET-Plan targets and the targets formulated European Green Deal Investment Plan (striving for carbon neutrality by 2050) [EC 2020a]. Finally, selected conclusions are presented in chapter 6.

[1] SET-Plan: European Strategic Energy Technology Plan (SET-Plan) aims to accelerate the development and deployment of low-carbon technologies.

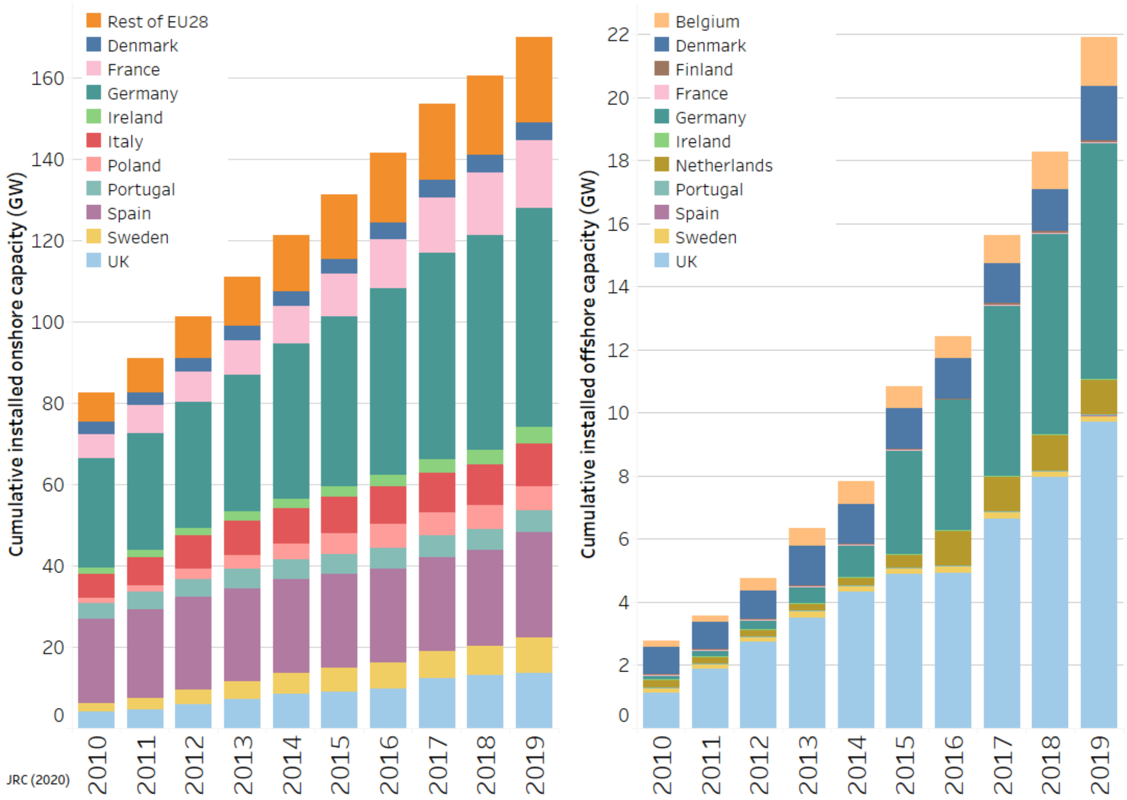
1.2 Main characteristics and current market status

Between 2010 and 2019, wind energy in the EU28 has grown from 85 GW to about 192 GW in cumulative installed capacity ranking second only superseded by China since 2015 [JRC 2019b]. In 2019, cumulative onshore wind deployment accounted for 170 GW experiencing an increase (9.6 GW) in annual capacity additions after moderate deployment in 2018 (7.5 GW) (see **Figure 1**). Still the record year of 2017 with about 12.7 GW of new onshore wind is out of sight as deployment rates continue to plunge in Europe's largest onshore market Germany (2.4 GW in 2018 and only 1.1 GW in 2019) as a consequence of long permitting procedures, increasing number of legal disputes and citizens protests [DWG 2019, FA Wind 2019, IEA Wind TCP 2019a].

The European offshore wind market represented 75% (21.9 GW) of the global market in terms of cumulative installed capacity (see **Figure 1**). China, Europe's strongest competitor, saw a record year in capacity additions (2.4 GW) resulting in a cumulative offshore wind capacity of about 6.8 GW, ranking third behind the United Kingdom (9.7 GW) and Germany (7.5 GW). Globally, 2019 was a record year in annual offshore wind additions with 6.2 GW installed across all markets. Moreover, it was a record year at European level with about 3.6 GW installed across five markets. In 2019 the United Kingdom (1.76 GW) and Germany (1.11 GW) accounted for 79% of the capacity deployed in European waters. The remaining capacity was deployed in Denmark (0.37 GW), Belgium (0.37 GW) and Portugal (0.008 GW).

In 2017, the 30 MW Hywind Scotland power plant marked the first multi-turbine floating offshore wind project in European waters followed by the Floatgen project (in 2018), the first floating offshore wind farm in France, which aims to demonstrate the technology's capabilities under Atlantic deep water conditions. The installation of a 25 MW floating wind farm in Portugal (WindFloat Atlantic (WFA) began in December 2019. Another 330 MW of floating offshore wind capacity in France, the United Kingdom, Spain and Norway is expected to become operational until mid-2020s [JRC 2019b].

Figure 1 Cumulative installed capacity of onshore wind (left) and offshore wind (right) in the EU28
Source: JRC based on [GWEC 2020]

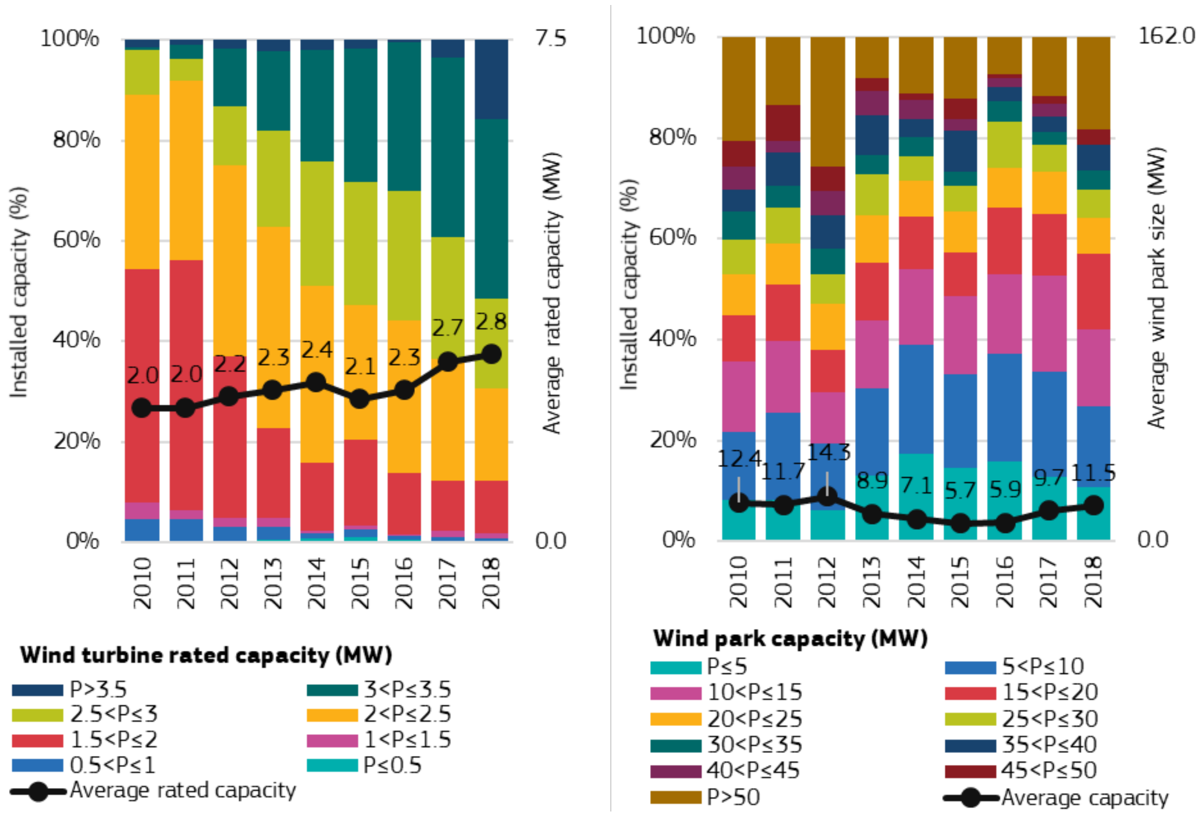


At both, onshore and offshore locations, wind turbines differ in terms of their turbine scale as well as in their quantity within a single wind park. The rated capacity of onshore wind turbines continues to increase towards models above 3 MW, increasing their annual market share within the EU28 from 2% in 2010 to about 51% in 2018 (see ***Figure 2***). Therefore, the average rated capacity increased by 40% in this period reaching 2.8 MW in 2018. The largest wind turbines deployed at onshore locations so far are two offshore wind turbines at the demonstration phase, namely the 12 MW GE Haliade-X Maasvlakte (Port of Rotterdam, Netherlands) producing first power at the end of 2019 and the 9.5 MW MHI Vestas V164 offshore turbine tested at Østerild (Denmark) in 2017.

The upper range of commercially available onshore wind turbines deployed at wind parks spans from 5 MW to 7.5 MW. However, only 760 MW of these large scale turbines have been deployed since 2010 (below 1% of the capacity deployed in this period) and some bigger models such as the 7.58 MW Enercon E-126 have been phased out. Difficulties for this product range in the European market most probably originate from the visual impact perceived and the increased setback distances needed for larger turbines. Moreover, all existing regulation concerning distances between wind turbines and settlements is related either to the physical size of the wind turbine or to the noise levels. Both of these metrics are related to the size (power) of the wind turbine: more powerful wind turbines tend to have larger poles or rotors and emit more noise [JRC 2017a]. Manufacturers of wind blades encounter this challenge by applying different add-ons and features on the surface or trailing edge of a blade (e.g. vortex generators, serrations or low noise tips) [Oerlemans et al. 2009, LMWindPower 2020, SiemensGamesa 2020].

The new turbine platforms of the major OEMs targeting the market for large scale onshore turbines are mostly in the 5 MW range (e.g. Enercon EP5, GE Cypress 5.3 MW, Nordex Delta4000, SiemensGamesa 5.X, Vestas EnVentus 5.6 MW) [WPM 2019a].

Figure 2 Evolution of rated capacity (left) and wind park size (right) of onshore wind in the EU28 [JRC 2019c]



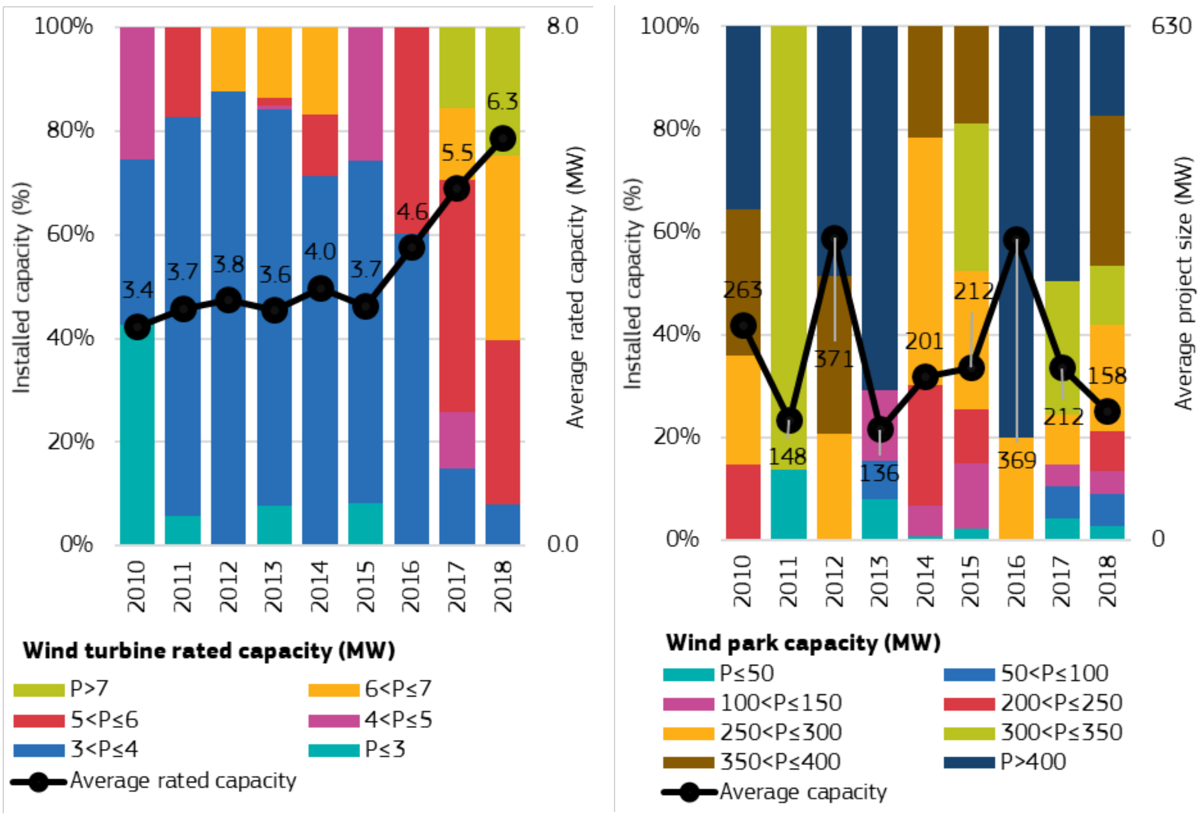
With 11.5 MW, the average capacity of onshore wind parks in Europe more than doubled since 2015 (see ***Figure 2***). Especially a decrease in small scale projects below 10 MW

can be witnessed, whereas wind parks above 50 MW gained ground (particularly in the UK and SE).

An even more rapid increase in rated capacity can be observed for offshore wind turbines. Since 2015 the average rated capacity of offshore wind turbines steadily grew to a value of 6.3 MW in 2018 which translates into a 70% increase within this period (see ***Figure 3***). The market share of offshore turbines below 6 MW significantly fell in the last two years, a development that will further accelerate as results from recent tenders show that projects, which are expected to be commissioned until 2022, will be installing offshore turbines with a rated capacity of up to 9.5 MW. Moreover, winning projects from offshore tenders with expected commissioning date in 2024/2025 (e.g. German Offshore tender April 2017) could implement already the next generation of 13-15 MW offshore wind turbines [JRC 2019b].

As compared to onshore wind, offshore wind parks show significant higher capacities with about 74% of the installed capacities in this decade being above 250 MW. The average project size capacity varies between 140 MW and 370 MW, with the higher values originating from years with a low number of projects (e.g. in 2011 and 2016, with only 4 projects each). Contrarily in the last two years multiple projects delivering first power of which some installed capacities were deployed in batches (e.g. Race Bank wind farm (UK) with about 500 MW in 2017 and 75 MW in 2018.)

Figure 3 Evolution of rated capacity (left) and wind park size (right) of offshore wind in the EU28 [JRC 2019c]



2 Technology state of the art and development trends

The current state of the art technology in wind energy uses horizontal-axis wind turbines to transform the wind resource into mechanical energy. The drive-train converts this mechanical power into electricity and includes depending on the drive train arrangement different components (gearbox, generator, converter, transformer)[2].

Wind turbines are designed to the wind conditions they are operating in. To ensure optimal operation, safety and to guarantee that wind turbines are fulfilling their planned lifetime, design requirements are provided in the international standard IEC 61400. The IEC 61400 standard classifies wind turbines into different wind speed classes and turbulence intensities. Wind classes I, II and III refer to high, medium and low wind speed conditions, respectively. Moreover, the IEC standard applies a representative turbulence intensity for turbine classification, which is defined as a high percentile of the expected natural variation (see Table 2) [DTU 2019a].

In the European market, onshore wind turbines for high wind speed locations (IEC I and IEC I/II) have continuously lost their market share to turbines of the lower wind speed classes, whereas the share of offshore wind turbines located at sites suitable for IEC class I remains constant (see Figure 4). The choice of the turbine location and thus the choice of wind class influences wind turbine design of sub-components such as blade length, specific power or drive train configuration.

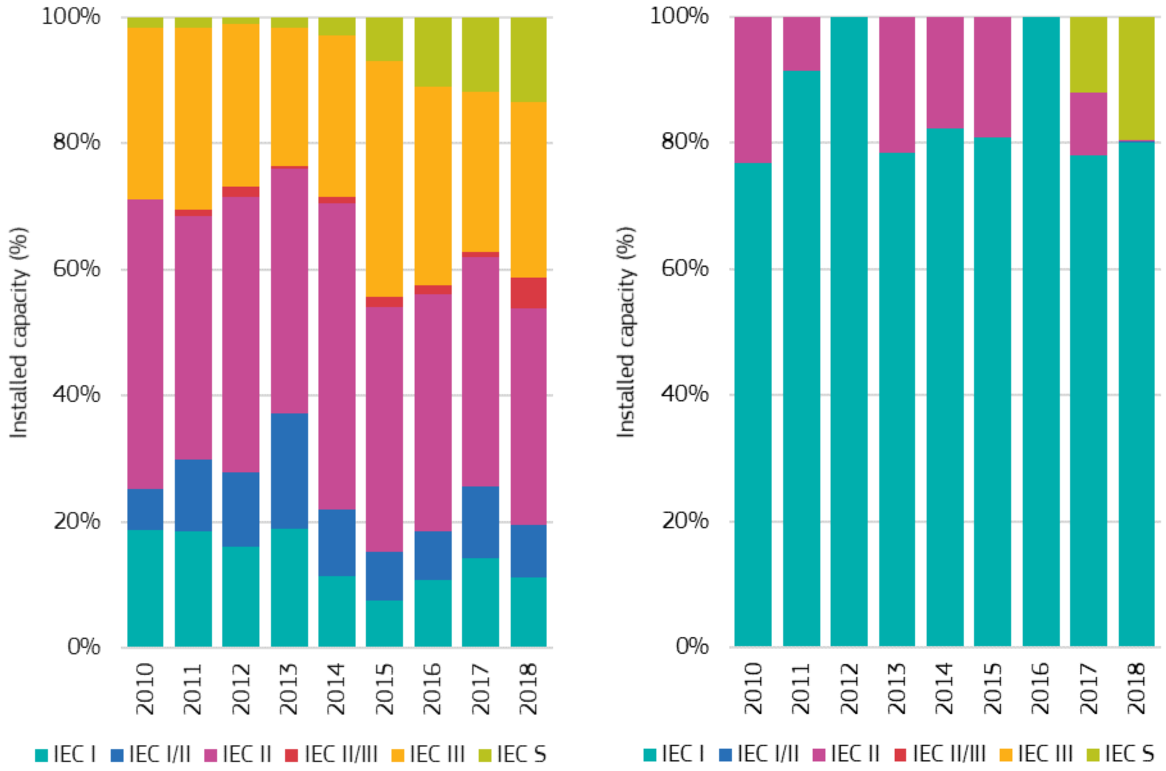
Table 2 Wind classes according to the IEC 61400 1 (Edition 4 (2019)) standard

Wind class		**I (high WS)**	**II (mid WS)**	**III (low WS)**	**S (User defined class)**	**T (Typhoon class)**
V_{ref} (m/s)		50	42.5	37.5		57
V_{ave} (m/s)		10	8.5	7.5		
I_{15}	**A+**	18 %			Values specified by the designer	Typhoon/hurricane conditions
	A	16 %				
	B	14 %				
	C	12 %				

Note: WS is wind speed, V_{ref} is the reference wind speed (average over 10 min), V_{ave} is the annual average wind speed and I_{15} is the turbulence intensity (at hub height at a wind speed of 15m/s)

[2] A full description of the different drive train configurations can be found in [Serrano-Gonzalez & Lacal-Arántegui 2016, Vazquez Hernandez et al. 2017]

Figure 4 Evolution of the share of installed capacity by IEC wind class of onshore wind (left) and offshore wind (right) in the EU28 [JRC 2019c]



2.1 Onshore wind

Since 2010 a clear downward trend can be witnessed in the specific power of onshore wind turbines deployed in the EU (see boxplots of historical data in Figure 5). The specific power of a wind turbine is defined through the ratio of the rated capacity of the turbine to the swept area of its rotor. Hence, this trend also meant a change in the turbine models deployed. In 2010, predominantly wind turbines with a rated capacity between 2 to 3 MW and blade lengths below 90m were among the top turbines deployed such as models from Vestas (V90-3.0MW and V90-2.0MW) and Enercon (E-82/2.0MW), resulting in an average specific power of about 370 W/m^2. Although there was an increase of rated capacity until 2018 the relatively stronger increase in blade length resulted in a decline of the average specific power to about 310 W/m^2, which translates into a decrease by 16% as compared to 2010-values. In 2018 the top 3 turbines deployed in the EU were the Vestas V126-3.45MW followed by Enercon's E-115/3MW and the Vestas V117-3.45MW.

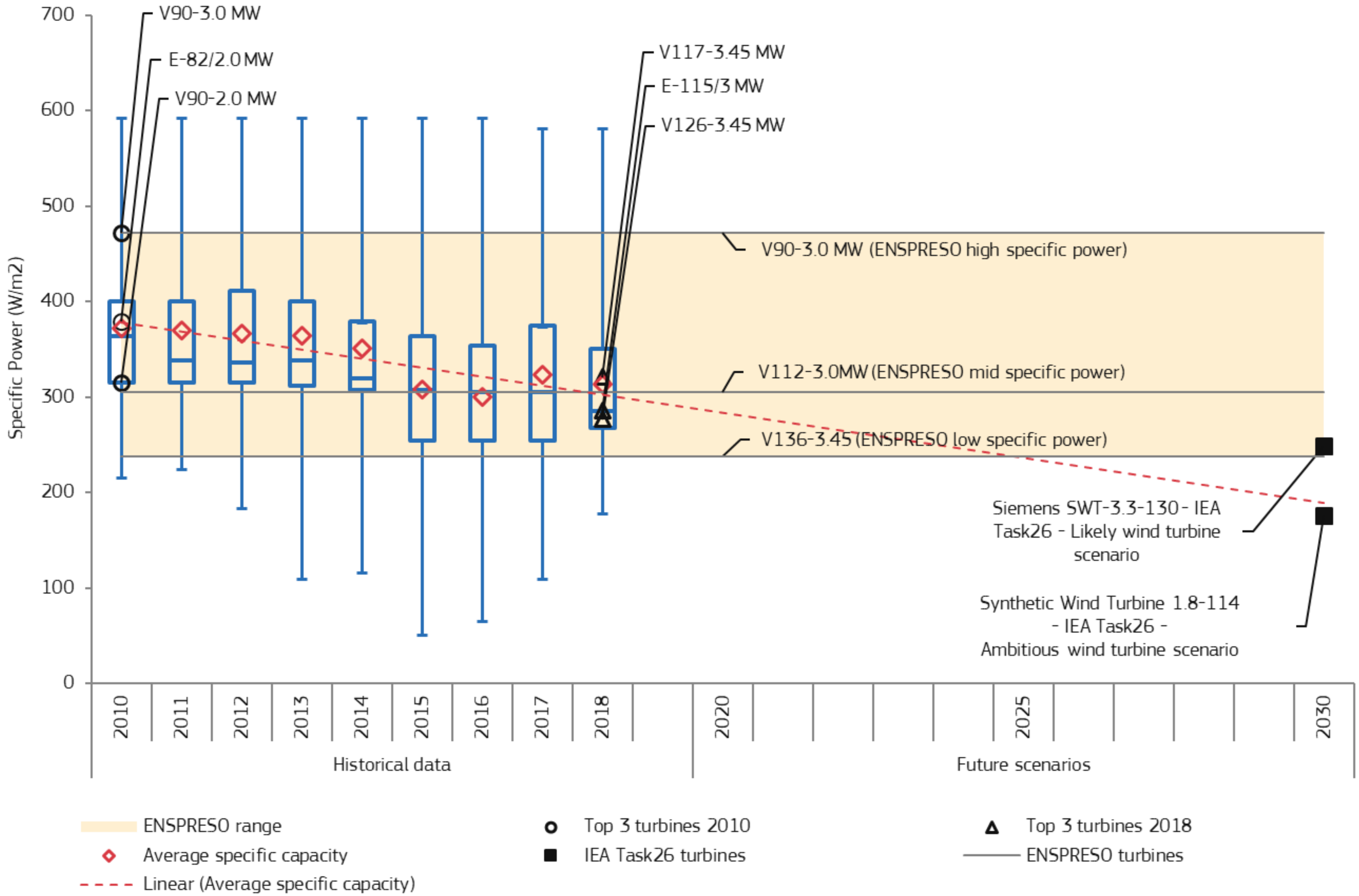
Assuming the continuation of this trend would result in an average specific power of about 180 W/m^2 by 2030. Figure 5 shows the current and/or future assumptions on the specific power from studies analysing the impact of different land-based wind turbine designs on grid integration (IEATask26 group) [Dalla Riva et al. 2017] or from the JRC-ENSPRESO (ENergy Systems Potential Renewable Energy Sources) database providing technical potentials for wind energy [JRC 2019d]. The JRC-ENSPRESO dataset defines three characteristic wind turbines spanning from a turbine model (Vestas V90-3MW) with high specific power (472 W/m^2) followed by a mid-specific power Vestas V112-3MW turbine (305 W/m^2, see also chapter 5.2 for results on the wind energy deployment outlook) to a V136-3.45MW turbine with a relatively low specific power (238 W/m^2). The study performed by IEA Task26 group uses as a reference turbine a GE 2.75-103 (330 W/m^2) within its 'Business as Usual' scenario. Apart from that, two future scenarios are defined: the ‘Likely’ wind turbine scenario considering a turbine technology (Siemens SWT 3.3-130) which will most likely characterise the European situation in 2030 with a specific power of 250 W/m^2 at a hub height of 125m, and an ‘Ambitious’ wind turbine scenario assuming a synthetic turbine based on the Gamesa G114-1.8MW with a specific power of 175 W/m^2 at a hub height of 150m.

In order to understand the effect of deploying wind turbines with different specific power, the capacity factor (CF) of three representative turbines is calculated. The following assumptions are made on turbine technology, turbine location and wind resource:

- High specific power turbine: Enercon E-82/2.0MW with a specific power of 379 W/m^2 deployed at a hub height of 80m (turbine model is both among the top3 deployed turbines and converging with the average specific power in 2010)
- Mid specific power turbine: Vestas V117-3.45MW with a specific power of 321 W/m^2 deployed at a hub height of 100m (turbine model is both among the top3 deployed turbines and converging with the average specific power in 2018)
- Low specific power turbine: IEA Synthetic-Gamesa 114/1.8MW with a specific power of 176 W/m^2 deployed at a hub height of 150m (representing an ambitous turbine model in terms of average specific power in 2030)
- Turbine location: Three different EU countries are selected as case studies in order to represent diverging wind resources across Europe: Croatia (South Eastern Europe – low wind resource), Spain (Western Europe – mid wind resource), Denmark (Northern Europe – high wind resource)
- Wind resource: For each country the hourly wind resource was derived for one specific site from the EMHIRES database for the year 2016 [Gonzalez Aparicio et al. 2016, Gonzalez Aparicio et al. 2017]. The site chosen represents the respective country’s median wind farm location based on its wind resource. Wind speeds at 50m from the EMHIRES database were extrapolated to the respective hub height by using the wind profile power law[3].
- Other: The calculation is performed in hourly time-steps for the single wind turbine. Thus, additional losses that appear in a multi-turbine wind park and which decrease the CF of an entire wind farm are not considered (e.g. wake effects, transmission losses, turbine availability…). Moreover, power curves are based on data from publicly available sources [WTM 2019].

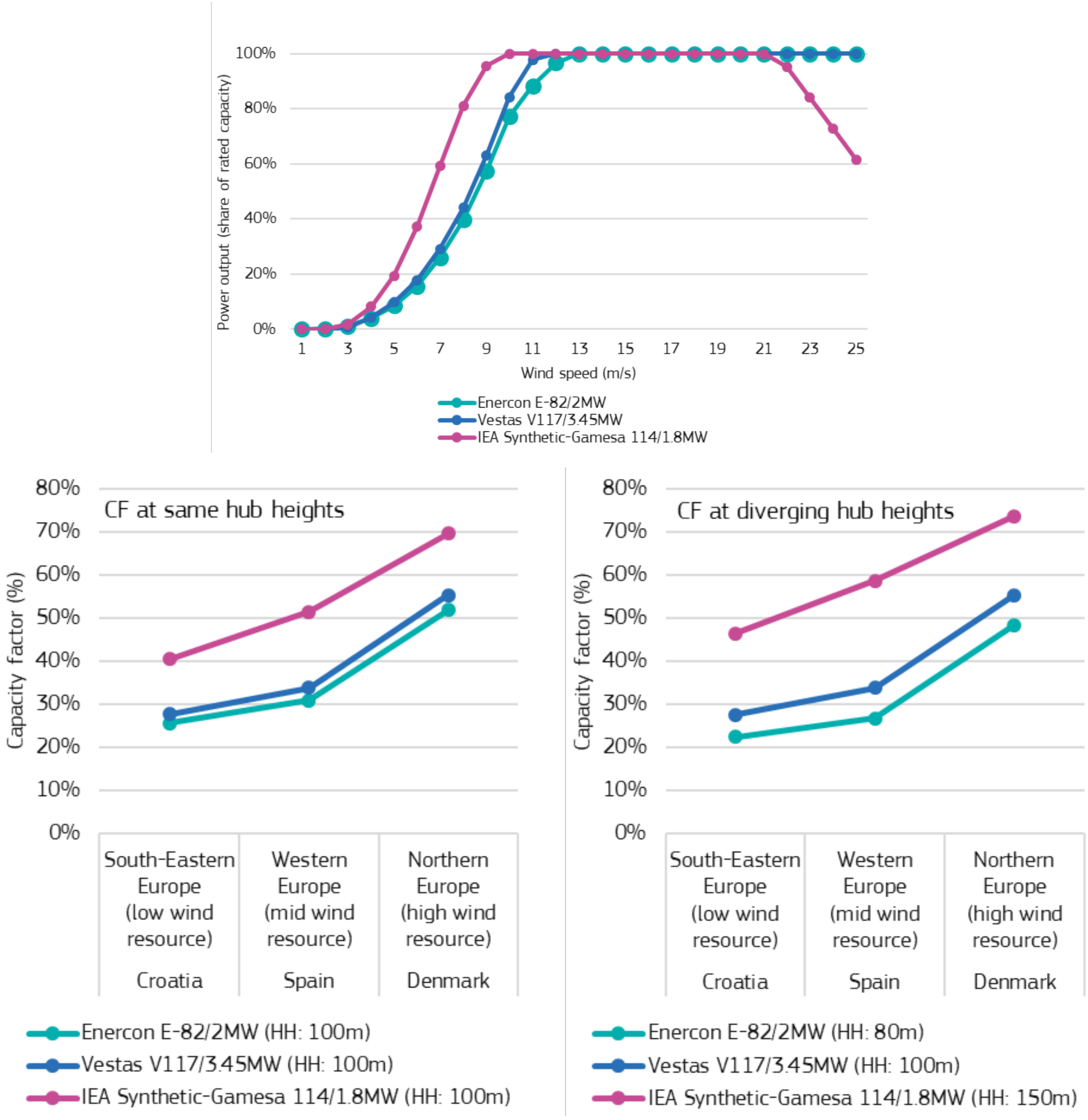
[3] $u = u_r \left(\frac{z}{z_r}\right)^{\alpha}$ where u is the wind speed at hub height z, u_r is the wind speed at a reference height z_r and α is the shear factor.

Figure 5 Evolution of specific power of onshore wind farms in the EU and scenario assumptions of the ENSPRESO dataset and the IEATask26 group [Dalla Riva et al. 2017, JRC 2017a, JRC 2019c, JRC 2019d]



A decrease in specific power allows to harvest the wind resource more efficiently in the lower wind speed range before reaching the rated capacity of the turbine (see Figure 6, left). As expected, our case studies show that the wind turbines operate below rated capacity most of the time during the year. Results of the Spanish case study (mid wind resource) show that turbines operate only between 1% and 26% (IEA Synthetic-Gamesa 114/1.8MW) at rated power when assuming the high specific turbine (Enercon E-82/2.0MW) and low specific power turbine, respectively. Similarly, this percentage of operating hours at rated speed ranges from 3% to 22% for the Croatian case study and from 12% to 48% at the high wind resource site in Denmark. Besides the influence of the turbines' specific power the applied hub height has a significant impact on the resulting capacity factor (e.g. as the average wind speed increases between 8% and 11% for the investigated case studies when moving from a hub height of 100m to 150m). Depending on the turbine model deployed the resulting capacity factors range from 22% to 46% in Croatia, 27% to 59% in Spain and 48% to 74% in Denmark (see Figure 6, right). Notably, the low and mid resource case studies benefit more in terms of capacity factor increase from applying a low specific power turbine than the high wind resource country Denmark because of the higher gains in the lower wind speed range.

Figure 6 Selected power curves (high to low specific power) and resulting capacity factors in three EU countries with diverging wind resources and hub heights (left:hub height at 100m; right: diverging hub heights)



Within this context, the trend to longer blades in Europe continues (see Figure 7, left), with about 76% of the installed capacity in 2018, deploying wind turbines with rotors diameters of more than 100 m (as compared to only about 2% in 2010). Therefore, the average rotor diameter within Europe increased by 31% since 2010 to about 108m. In the period 2010-2018, the average rotor diameter is found to be largest in Finland (121m) followed by Denmark (109m), Sweden and Germany (both 106m). In 2019, several Original Equipment Manufacturers (OEMs) announced or installed prototypes of their new onshore wind platforms targeting the 5 MW+ segment with increased rotor sizes (see Table 3).

Table 3 Onshore wind platforms in the 5 MW segment and their respective rotor size [WPM 2019b, WPM 2019c, WPM 2019d, WPM 2019e, WPM 2019a, WPM 2019f]

OEM	Platform	Rated capacity	Rotor diameters	Status
Vestas (DK)	EnVentus	5.6 MW	150m, 162m	Prototypes in 2019 and 2020
GE Renewable Energy (US)	Cypress	5.3 MW	158m (two-piece blade design)	Prototype installed end 2018
Enercon (DE)	EP5	5 MW	147m	Initial power rating of platform at 4.3MW which will be uprated to 5MW by 2020
Siemens Gamesa Renewable Energy (SGRE) (DE/ES)	5.X platform	5.8 MW 6.6 MW	155m, 170m	Prototypes in mid 2020 and Q3 2020 Installation of 6.6 MW foreseen in Q2 2021
NordexAcciona (DE)	Delta4000	5 MW	149m, 163m	Prototype in second half of 2020

Moreover, some manufacturers develop even larger rotor diameters for their new modularised onshore turbine models that target the low wind speed market. Market leader Vestas announced its modular, semi-integrated EnVentus platform in early 2019 with two rotor variants (150 m and 162 m, each at 5.6 MW) for medium- to high-wind speeds and low- to medium-wind speeds with prototypes planned for 2019 and mid 2020 [WPM 2019g]. In autumn 2019, NordexAcciona (DE) launched a 163m rotor for its Delta4000 5.X platform using a newly developed single-piece glass & carbon-fibre reinforced epoxy blades (NR81.5) with variable tip sections (this translates into a specific power of 240 W/m^2, assuming a rated capacity of 5 MW). NordexAcciona investigated a segmented blade solution but found that the single-piece blade option still offers benefits in terms of loads, lifetime performance and costs. A first prototype is expected for the second half of 2020 followed by a serial production in 2021 [Nordex-Acciona 2019, WPM 2019h, WPM 2020a]. In the lower rated power segment (below 3.4 MW) especially Chinese manufacturers offer new turbine models with very large rotors (e.g. as in the case of the Goldwind GW150-2.8MW machine, allowing a specific power of about 159 W/m^2 [WPM 2020b].

In order to improve blade lifetime several innovative techniques and materials currently at a low TRL (<3) might be pursued in the future. This might include new materials (fabric based) and automated manufacturing techniques (e.g. additive 3D printing processes for moulds and blades) [Watson et al. 2019].

Within Europe a wide variety of drive train configurations exists for onshore wind turbines showing a trend towards direct drive configurations and hybrid arrangements. The main distinction can be made from the presence of a gearbox, the type of generator (synchronous or asynchronous) and the use of a power converter. Table 4 summarizes the different types of drive trains following a redefinition of the classification provided by [Hansen et al. 2004] (see graphical representation of this classification in Annex 1, Figure 43).

Table 4 Types of drive train configurations based on [Hansen et al. 2004, Serrano-Gonzalez & Lacal-Arántegui 2016, JRC 2017b]

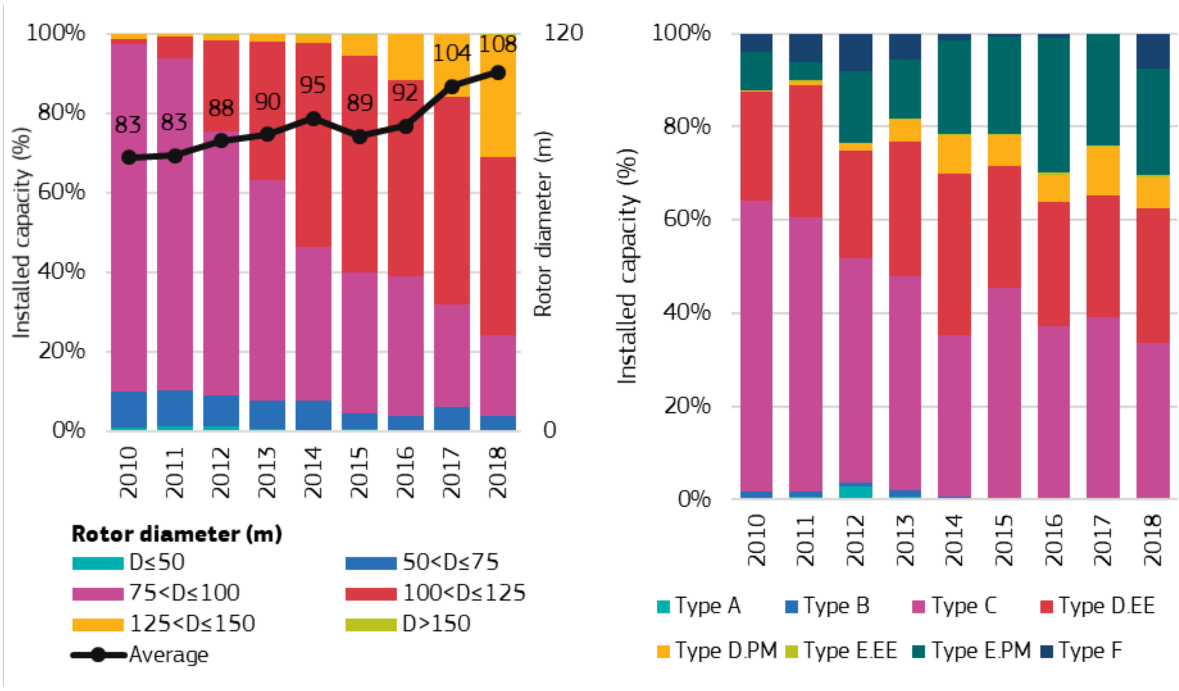
Type	Configuration	Gearbox/Gearless	Category
A	High-speed - Squirrel Cage Induction Generator (SCIG)	Gearbox	Geared high-speed WT
B	High-speed Wounded Rotor Induction Generator (WRIG)	Gearbox	
C	High-speed Doubly-Fed Induction Generator (DFIG)	Gearbox	
D-EE	Low-speed Electrically excited synchronous generator (EESG) with full power converter	Gearless (Direct Drive)	Direct drive WT
D-PM	Low-speed Permanent magnet synchronous generator (PMSG) with full power converter	Gearless (Direct Drive)	
E-EE	Medium/High-speed Electrically excited synchronous generator (EESG) with full power converter	Gearbox	Hybrid drive trains
E-PM	Medium/High-speed Permanent magnet synchronous generator (PMSG) with full power converter	Gearbox	
F	High-speed - Squirrel Cage Induction Generator (SCIG) with full power converter	Gearbox	

With 34% in 2018, type C shows still the highest market share among European onshore wind turbines (see Figure 7, right). Nevertheless, a strong decrease as compared to 2010-levels (62% market share) can be witnessed. Interestingly SiemensGamesa, one of the main OEMS, is phasing out its production of direct drive turbines (type D-PM) claiming to build on its globally established gearbox supply chain focused on DFIG-geared technology (type C) as part of their "one segment, one technology" philosophy [SGRE 2019a, WPM 2019i]. This could be an indication of a stronger focus towards onshore markets outside the EU.

The remaining geared high-speed wind turbine configurations (type A and B) were not deployed since 2013 in EU28 countries. Conversely, the share of direct drive configurations (type D-EE and D-PM) and the hybrid drive trains of type E-PM and F continuously grew until 2018. Type D-EE and D-PM increased their market share from 24% in 2010 to about 35% in 2018. Hybrid drive trains (type E-PM and F) increased their market share even stronger from 12% in 2010 to 31% in 2018. Moreover, drive trains with generators using permanent magnets (Type D-PM and E-PM) show almost a fourfold increase (30% in 2018) as compared to the beginning of the decade.

Looking ahead, JRC (2020) defines three scenarios (Low (LDS), Medium (MDS), and High Demand (HDS) scenario) to assess the future demands for the materials needed for the deployment of wind energy in the EU until 2050. For onshore wind configurations using permanent magnets (Type D-PM and E-PM) a market share of 52%, 59%, and 65% in 2050 is expected in LDS, MDS, and HDS, respectively [JRC 2020]. The analysis takes into account committed generation capacities, plant lifetime, information of existing market shares of sub-technologies and material intensity.

Figure 7 Evolution of rotor diameter of onshore wind turbines (left) and annual market share of installed capacity by drive train configuration in the EU28 (right) [JRC 2019c]



2.2 Offshore wind

Competitive tendering procedures have led to a decline in the costs for offshore wind projects. By mid-2019, ten MSs introduced competitive tendering procedures of which five countries (Denmark, the United Kingdom, Germany, the Netherlands and France) have executed tenders. Bid prices in these markets are plunging mainly as consequence of competition, technology advances, reduced financing costs and scalability. The latest increase in offshore wind rated capacity to about 6.3 MW in 2018 (see Figure 3) is expected to continue as some of the tender winning projects (e.g. in Germany) are expected to deploy next generation wind turbines in the 13-15 MW category [JRC 2017c, JRC 2019b]. Similarly, average installed rotor diameters rose to about 149m in 2018, an increase by about 47% as compared to 2010-levels (see Figure 8, left). Currently the offshore wind OEMs, GE Renewable Energy (GE) and SiemensGamesa RE (SGRE), introduced the first offshore turbines leading in terms of capacity and blade length. Regarding drive train technology, both manufacturers build on direct drive turbines (type D-PM). GE installed its 12 MW GE Haliade-X (rotor diameter: 220 m) in Maasvlaakte (Port of Rotterdam) which produced first power in November 2019. The prototype is undergoing a test and validation programme to obtain certification for the turbine by 2020. A second prototype build in Saint-Nazaire (France) will be shipped to a test site in the UK in order to perform a real-world test programme [WPM 2019j, WPM 2019k]. SGRE plans to install a prototype of its newly developed SG 10.0-193 DD (rotor diameter: 193m) at the test site in Østerild (Denmark) in the end 2019/beginning of 2020, followed by an envisaged serial production in 2022. The newly build test site will initially be used to test the 94m blades of the SG 10.0MW model but will enable SGRE also to test future offshore wind models with even longer blades. Potential upgrades to rated capacities of 14 MW and 11 MW are announced for both turbines from GE and SGRE, respectively [SGRE 2019b, WPM 2019l, WPM 2019m, WPM 2020c].

Smart rotor innovations enabling the development of even larger wind turbines (>20 MW) are showing differing TRL-levels. Research in this area is diverse and comprises new developments in active (Blades with movable parts (TRL 2-4); Circulation control systems (TRL 2-4); Active control systems (TRL 2-3)) and passive (Bend Twist Coupling (TRL 2-7); Segmented Ultra Morphing Rotor (TRL 4); Vortex generator (TRL 5-6)) control systems to alleviate loads on the rotor. Multi-rotor concepts are mostly at TRL 2-4. An exception can be seen in the multi-rotor concept from Vestas which is at TRL 5-6 [Watson et al. 2019], however end of 2018 Vestas dismantled the four-turbine prototype as the research project ended. Tests showed a 1.5% gain in annual energy production and a faster wake recovery (allowing to reduce wind turbine spacing) as compared to a conventional turbine [WPM 2018, van der Laan et al. 2019].

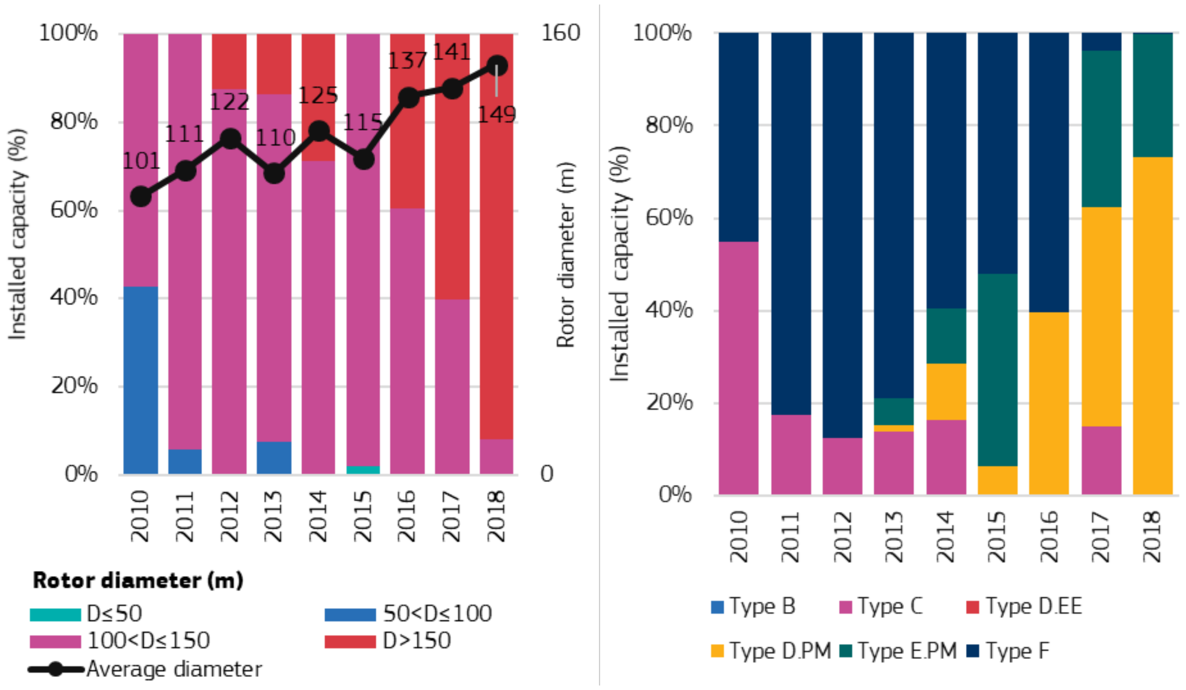
Together with this increase in size several innovations reducing the costs for blade repairs have been introduced lately by the industry. SGRE introduced leading-edge protection (LEP) upgrade solution made up of flexible precast, pre-curved polyurethane shell segments attached with a suitable offshore adhesive on the blade’s leading-edge. This targets especially the offshore wind models for which erosion becomes a more prevalent issue due to rainfall, larger rotor size and increased tip speed. The LEP concept includes a software tool capable to determine the potential degree of erosion and is currently going through a certification process at the certification body DNV GL. In a bigger context (Vestas, Siemens Gamesa, and Senvion, LM Wind Power, Ørsted) DNV GL launched the Joint Industry Project COBRA (COmprehensive methodology for Blade Rain erosion Analysis) to analyse damage caused to the leading edge of wind turbine blades by high-speed impacts of foreign objects [DNV GL 2019a, WPM 2019n, WPM 2019o]. Other technological blade developments in 2019 include a non-destructive blade inspection prototype by a Spanish start-up (Das-Nano) addressing blade faults through coating defects and the use of (Artificial Intelligence) AI and 3D-printing to develop a more resistant leading-edge protection [Das-nano 2019, WPM 2019p].

Generally, the average specific power of offshore wind turbines remains relatively constant between 300 W/m^2 and 400 W/m^2, as the technology targets the high wind speed class (IEC I). Since 2013, a continuous increase in drive train configurations using permanent magnets (type D-PM and E-PM) can be observed resulting in market shares above 80% in the last two years (see Figure 8, right). Assuming that this dominance of permanent magnet drive trains will persist, JRC (2020) assumes an EU market share of 95% in its HDS scenario, followed by 68% and 44% based on extrapolating historical time series or the uptake of new innovations in MDS and LDS, respectively [JRC 2020].

Latest industry innovations in drive train design propose an alternative to fault-prone roller bearings by replacing them with flexible conical journal bearings (‘FlexPad’ bearing, patent pending) capable to cope with main-shaft deflections during rotation [Schröder et al. 2019, WPM 2020d]. Moreover, the German technology developer Adion Technologies proposes a new hybrid gearbox concept (first patent to be granted in 2020) for next generation wind turbines (up to 20 MW) coping with the increased masses at these turbine ratings with a modular two-stage distributed gearbox [WPM 2019q].

At the very early stage (TRL 1-2) concepts of tip-rotors would offer the possibility to replace gearbox and generator by a fast-rotating rotor/generator located at the tip of each blade. As this concept targets weight and cost reduction it might be especially interesting for very large offshore rotors [Watson et al. 2019].

Figure 8 Evolution of rotor diameter of offshore wind turbines (left) and annual market share of installed capacity by drive train configuration (right) in the EU28 [JRC 2019c]



The upscaling in offshore wind asks for further innovations in the installation of wind turbines as crane capacity of jack-up and heavy lifting vessels increase (see also chapter 3.2.5 in [JRC 2019b]). An example is given by the Dutch maritime company GustoMSC introduced a Telescopic Leg Crane concept capable to lift 20 MW+ turbines, which will be installed in a self-elevating jack-up in 2022. Further, the Danish company Liftra is transferring its knowledge on self-hoisting cranes from onshore to offshore operations [Liftra 2020, WPM 2020e].

Today multiple floating designs exist which can be distinguished based on the used substructure concept giving the project its buoyancy (Spar-buoy, Semi-Submersible, Tension-leg platform, Barge or Multi-Platforms) (see ***Table 5*** and ***Figure 9***). So far, no concept prevailed over the others, however Equinor's spar-buoy concept was already deployed in a pre-commercial project. Given the variety of concepts JRC (2017d) estimates the TRL of offshore floating wind concepts in a range between 4 and 9 [JRC 2017d]. Spar-buoy and semi-submersible concepts reached already TRL 8-9 as they are already being built and tested at large scale. With a 2 MW floating prototype in France (Floatgen Project, generating 6 GWh in 2019 [WPM 2019r]) Ideol aims to demonstrate the capabilities of a concrete barge-type substructure ('Damping Pool' floating foundation) in a deep water setting. To date TLP designs have not yet reached this level of maturity [Watson et al. 2019].

A trend towards commercialisation of floating offshore wind farms was demonstrated through the deployment of the first multi-turbine floating wind farm by the energy company Equinor in 2017 (Hywind Scotland). Lately operational data (such as environmental data, motions of floating wind turbine and loads of the mooring system) to understand operation under real world conditions was shared within a collaboration with ORE Catapult in order to foster new collaborations within the floating offshore sector [OW 2019a]. The Hywind project was followed by Principle Power beginning to install three wind turbines in December 2019 of a 25 MW floating wind farm in Portugal (WindFloat Atlantic (WFA) [OW 2020].

Notably SeaTwirl S2, the only floating vertical-axis wind turbine (VAWT) close to commissioning, will be granted a patent for a divisible wind by turbine by the European Patent Office (EPO) upon payment of the patent fees. The same patent was secured in Sweden (in 2017), the USA (in 2019) and China (also in 2019). The patent protects a cost reducing solution which allows that the wind turbine is divisible above and below the house that holds the generator and bearing. Therefore, the entire generator and bearing housing can be replaced just above the water surface by boat [4COffshore 2020].

With 88 MW (eleven 8 MW SGRE-turbines), the next significant up-scaled project (Hywind Tampen) will be deployed close to the Gullfaks and Snorre fields to meet approximately 35% of the annual power requirement of five oil and gas platforms. This would mean also an increase in the design of the spar-buoy platforms (weight, draught and catenary length) as compared to the initial Hywind Scotland design as the project will be located 140 km from shore at a water depth of about 260-300 m [Equinor 2019, NSE 2019, OW 2019b, WPM 2019s]. In April 2020 and after achieving DNV GL's technology qualification, Seawind Ocean Technologies (NL) announced to install a two-bladed 6.2 MW floating demonstrator (Seawind 6-126) at the European Marine Energy Centre in Scotland until 2021, followed by a upscaled prototype (Seawind 12-225) in 2022. Commercial availability for these turbines is planned until 2023 and 2024, respectively [WPM 2020f].

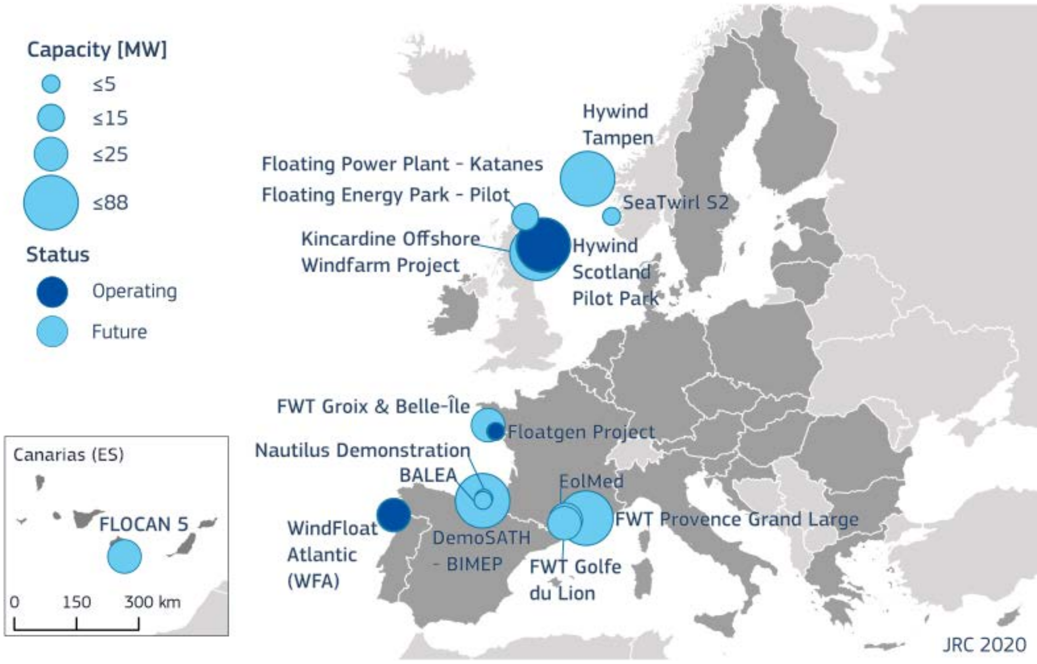
Floating hybrid energy platforms are still at a lower TRL (1-5), though the announced Katanes Floating Energy Park – Pilot (based on the P80 wind-wave energy platform) comprising a 3.4 MW wave converter and a 8 MW wind turbine could lift this system to TRL 6-7 by 2022 [OW 2018, FPP 2020].

Table 5 European floating offshore wind farms and demonstrators and the respective floating substructure concept used (announced and operational)

Project	Country	First Power	Capacity [MW]	# of turbines	Floating concept
Hywind Scotland	UK	2017 (operational)	30	5	Spar-buoy
Floatgen Project [1]	FR	2018 (operational)	2	1	Barge
WindFloat Atlantic (WFA)[2]	PT	December 2019 (partly operational)	25	3	Semi-Submersible
Kincardine Offshore Windfarm Project	UK	2021	50	5	Semi-Submersible
BALEA[2]	ES	Earliest 2021	26	4	
Nautilus Demonstration	ES	Earliest 2021	5	1	Semi-Submersible
DemoSATH - BIMEP[1]	ES	2021	2	1	Semi-Submersible
SeaTwirl S2 [3] **(VAWT)**	NO	2021	1	1	Spar-buoy
EolMed [4]	FR	2021	24.8	4	Barge
Seawind 6 demonstrator	UK	2021	6.2	1	Semi-Submersible
FWT Groix & Belle-Île	FR	2022	24	4	Semi-Submersible
FWT Provence Grand Large/VERTIMED[2]	FR	2022	25.2	3	Tension-leg platform
FWT Golfe du Lion	FR	2022	24	4	Semi-Submersible
Katanes Floating Energy Park - Pilot[5]	UK	2022	8	8	Semi-Submersible
Hywind Tampen	NO	2022	88	11	Spar-buoy
Seawind 12 demonstrator	UK	2024	12.2	1	Semi-Submersible
FLOCAN 5[2]	ES	2024	25	5	Semi-Submersible

[1] Funded by the EC's FP7 or H2020 programme
[2] Funded by the EC's NER300 programme
[3] Received a €2.48 million grant from the European Innovation Council's SME instrument
[4] Co-financed by the European Investment Bank
[5] Combined wind-wave generator. Project will be further developed to 47MW

Figure 9 Location of European floating offshore wind farms and large demonstrators (≥1MW) (announced and operational, as of December 2019)



2.3 Airborne Wind Energy Systems

Airborne wind energy systems (AWES) are concepts converting wind energy into electricity with the help of autonomous kites or unmanned aircraft, linked to the ground by one or more tethers. The technology might offer comparative advantages to conventional wind energy systems in terms of lower use of materials, higher capacity factors and lower production volatility. Moreover, it is expected that AWES will be realised in more remote and uninhabited areas which might also result in a niche use (off-grid) of the technology within first commercial projects. The most advanced prototypes are the M600 by Makani Power (600 kW) and the Ampyx AP3 (250 kW) using a fly-generation and a ground-generation concept, respectively. Ampyx currently joined forces with material science company DSM to design the tether using a high strength fiber (Dyneema) capable to generate up to 2 MW [Ampyx 2018, EC 2018a] . Makani M600 performed offshore test flights in August 2019 in the North Sea (NO) and will further optimise together with the energy company Shell the floating platform and the mooring system. However in February 2020 Alphabet, Makani's parent company, announced to drop its involvement in the project. As a consequence Shell currently explores options to continue developing the technology within their 'New Energies' strategy[Makani 2019, WPM 2020g]. Main challenges for AWES to move forward from TRL 3-5 are seen in the systems' reliability, in increasing the duration of autonomous flights, the durability of materials, conflicting regulations (interference with air traffic) and in the development of autonomous take-off and landing systems. Notably, the number of institutions involved (about 60) in AWES more than doubled since 2009 as a consequence of increased interest within the wind energy community and sustained funding through the EU research programmes FP7 (e.g. HAWE and Highwind project) and H2020 (e.g. AWESCO, AMPYXAP3, REACH, NEXTWIND, AWESOME, SKYPULL, TWINGTEC, TWINGPOWER) [Schmehl 2019].

2.4 Patent statistics

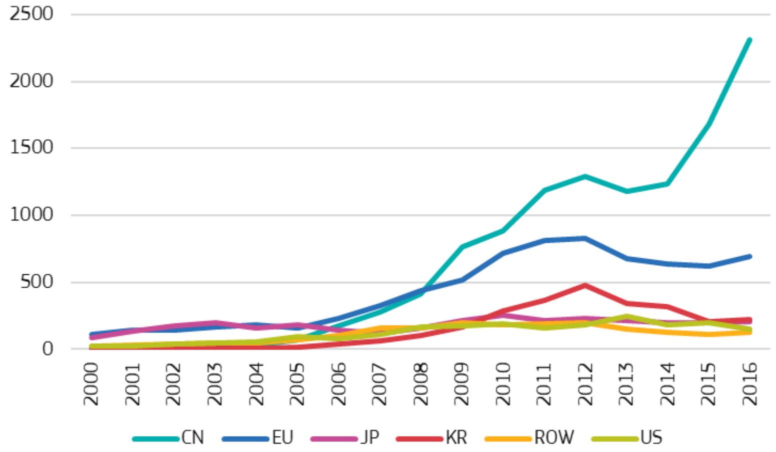
This section provides an update on the patent activity in wind energy technologies in the period 2000-2016. Results are analogous to earlier analyses (e.g. [JRC 2019b]), however particularly an improvement of the patent data with relation to the inventions filed in China was achieved. Possible differences with data reported previously are due to improvement in the JRC data processing of the raw patent dataset provided by EPO. This process increases data coverage, particularly for Asian countries that are often associated with incorrect or missing country codes, because of the incomplete provision of information from the national patent authorities. Furthermore, periodic revisions of the PATSTAT database run by the EPO (i.e. technological reclassification of patent applications or addition of new attributes to patent applicants) could potentially have an effect on the consistency and reproducibility of time series based on subsequent database versions [JRC 2017e, Pasimeni 2019]. Therefore, results are deviating in this respect from earlier patent analyses[4].

With a compound annual growth rate of 50% in the period 2000-2016, China currently ranks first in wind energy inventions[5] after overtaking the EU in 2009, who had been the world leader since 2006.

[4] Patent data are based on PATSTAT database 2019 autumn version [Pasimeni 2019]. The methodology behind the indicators is provided in [JRC 2017g].

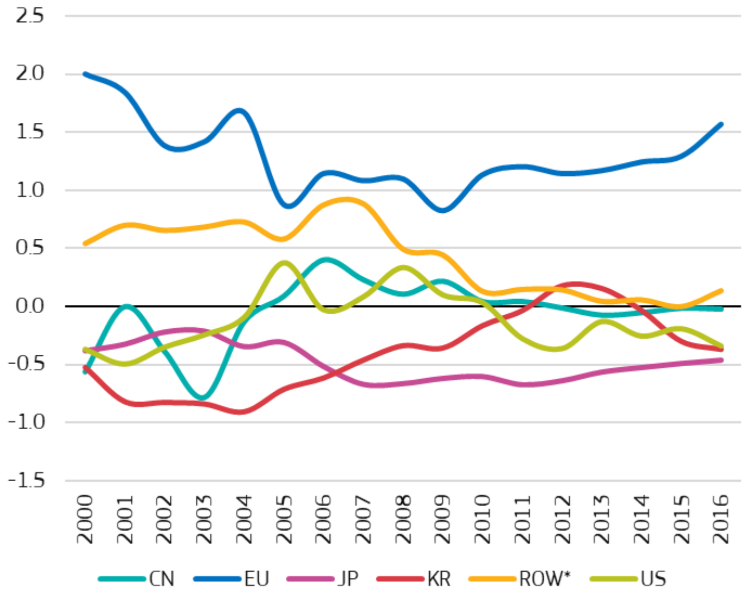
[5] Inventions or patent families include all documents relevant to a distinct invention (e.g. applications to multiple authorities), thus preventing multiple counting. A fraction of the family is allocated to each applicant and relevant technology.

Figure 10 International comparison of the evolution of inventions in wind energy
Source: JRC based on EPO data



Nevertheless, Europe has the highest specialisation index[6] (indicating the patenting intensity) in wind energy as compared to the rest of the world.

Figure 11 Specialisation index of the total inventions in wind energy
Source: JRC based on EPO data



Even though China has the strongest patenting activity, it is aimed for protection in the national market. As shown in ***Figure 12***, in the period 2000-2016 more than 70% of inventions filed on wind energy technologies were granted but only around 2% were high value inventions[7], i.e. protected in other patent offices outside China. Korea shows a similar trend, with more than 60% of inventions granted, but only 6% considered as high-value inventions. In contrast, around 60% of inventions in Europe and the United States were protected in other countries.

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[6] The specialisation index (SI) represents patenting intensity in a technology for a given country relative to geographical area taken as reference. For each country: SI = 0, patent intensity equal to the world; SI < 0, intensity lower than the world; SI > 0, intensity higher than the world. For more information please refer to [JRC 2017h]

[7] High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office.

Figure 12 International comparison of the inventions filed, inventions granted and high value inventions in wind energy technologies
Source: JRC based on EPO data

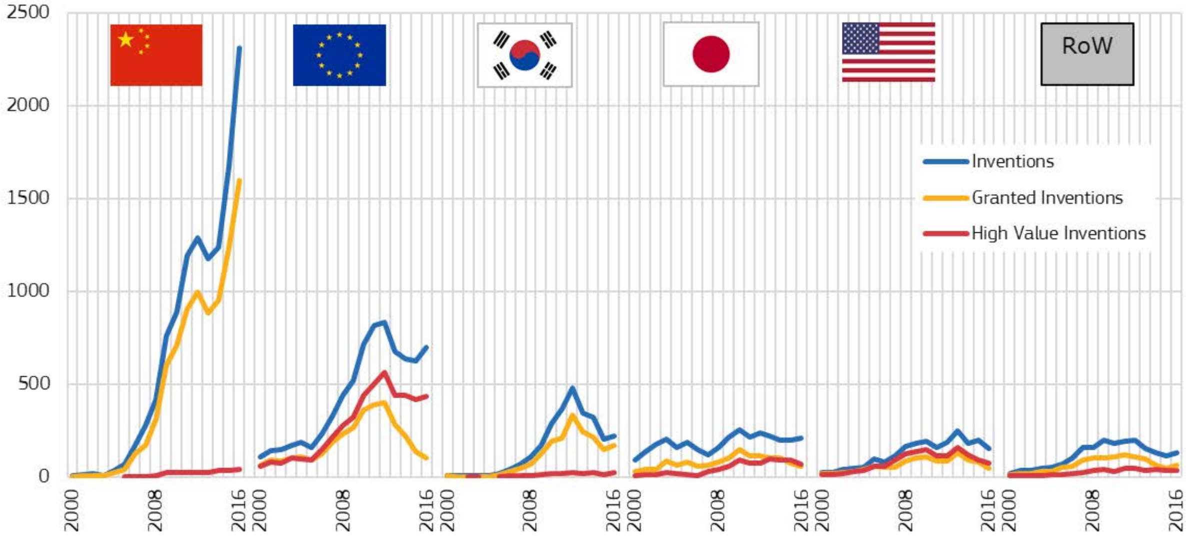


Figure 13 and Figure 14 show the technological trend of the filed inventions based on their Cooperative Patent Classification (CPC)[8]. Chinese companies stronger diversify their patent activity inventions in the last years which can be obtained through a steep increase in patenting in the CPC category 'grid-connected applications (Y02E 10/763)' since 2004 and more recently (since 2014) in 'onshore towers (Y02E 10/728)'. With 33% and 15% of the inventions filed in 2016, the strongest thematic focus of Chinese inventions is found in the categories 'Components or gearbox (Y02E 10/722)' and 'Control of turbines (Y02E 10/723)'.

Although European companies showed a remarkable increase in patenting activity since 2005 the topical direction of patents remains relatively unchanged. Throughout the investigated period, inventions within the category 'Blades and rotors (Y02E 10/721)' hold the highest share with about a quarter of the patents filed by European companies on wind energy.

The US, Japan and Korea show limited patenting activity as compared to China and Europe. Similarly as in Europe, inventions in the US are relatively stable throughout the different CPC categories with an emphasis on the category 'Blades and rotors (Y02E 10/721)'. In Japan a trend towards patenting in 'Components or gearbox (Y02E 10/722)' can be witnessed, whereas the CPC category 'Generator or configuration (Y02E 10/725)' lost shares since 2000. More recently, Japanese organisations show increased patenting activity in 'onshore towers (Y02E 10/728)' accounting for about 10% of the inventions filed in 2016. In Korea inventions filed in both categories 'onshore towers (Y02E 10/728)' and 'offshore towers (Y02E 10/727)' saw an increase in their share to 17% and 10%, respectively since 2010. Within the same period the share of inventions on 'Blades and rotors (Y02E 10/721)' decreased from 20% to about 12%.

[8] https://www.cooperativepatentclassification.org/cpcSchemeAndDefinitions/table.html

Figure 13 International comparison (CN, EU, JP) of the inventions filed by CPC category in wind energy technologies. Note: Analysis of inventions with a CPC code indicating wind turbine subcategory

Source: JRC based on EPO data

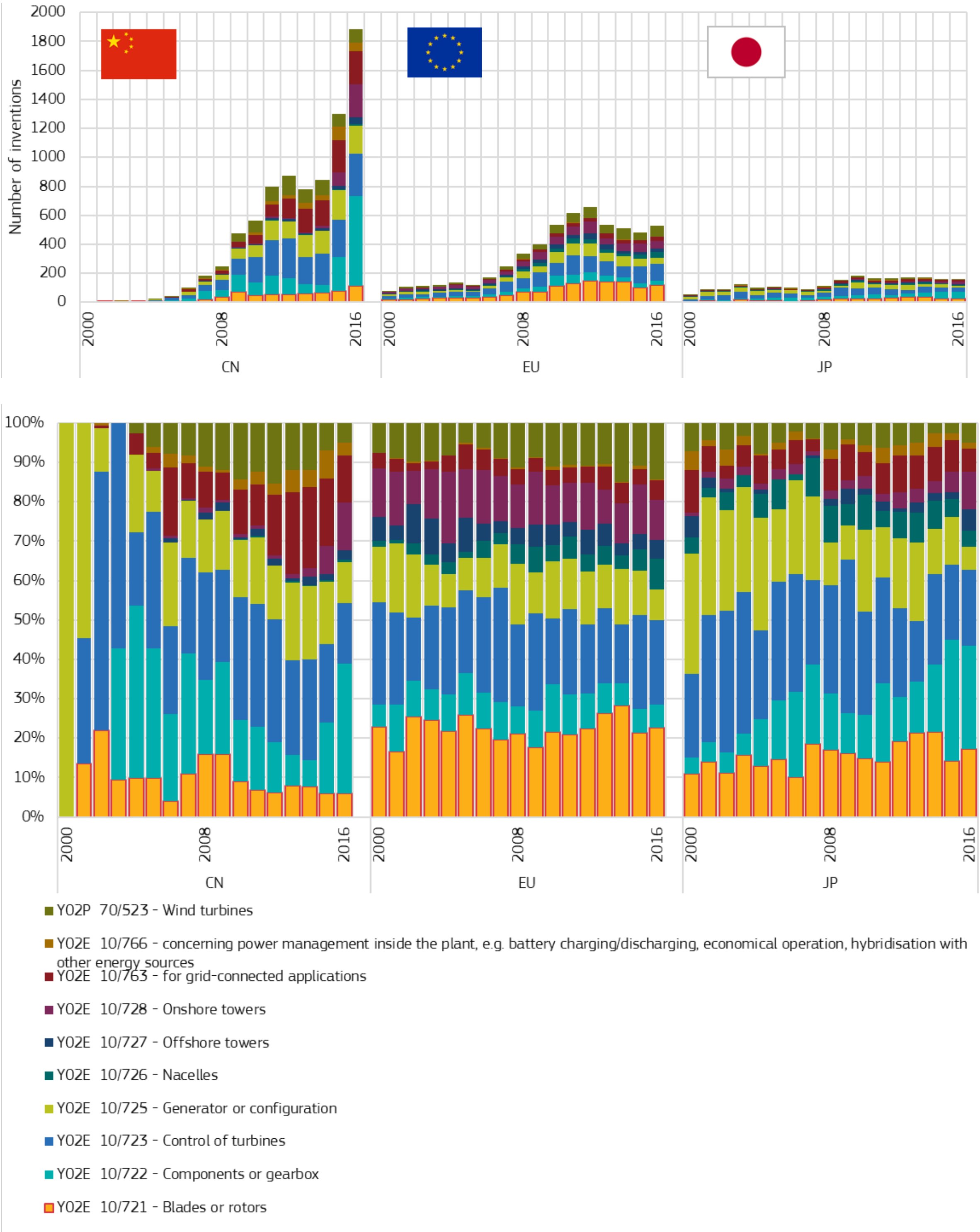
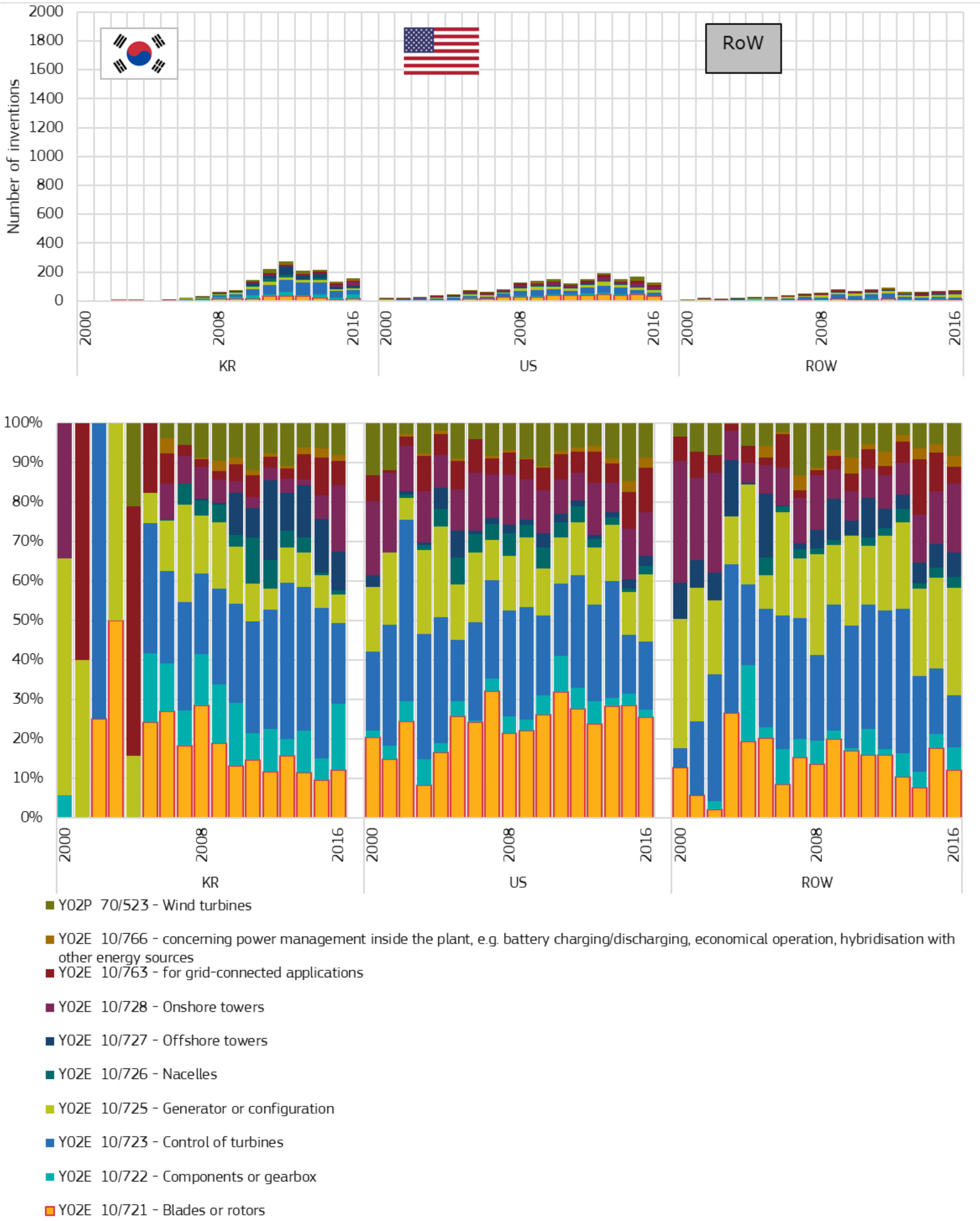
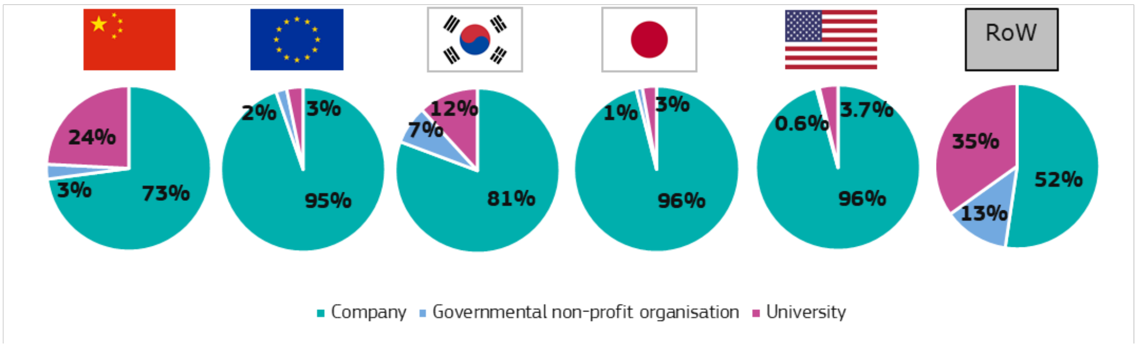


Figure 14 International comparison (KR, US, ROW) of the inventions filed by CPC category in wind energy technologies. Note: Analysis of inventions with a CPC code indicating wind turbine subcategory
Source: JRC based on EPO data



Regarding the sector activity, more than 90% of applicants were companies in the period 2000-2016, with the exception of China, where about 24% of inventions were protected by universities (***Figure 15***). The inventions from Chinese and Korean governmental non-profit organisations have also been increasing slightly in the last years, but still only represent a marginal share of the total.

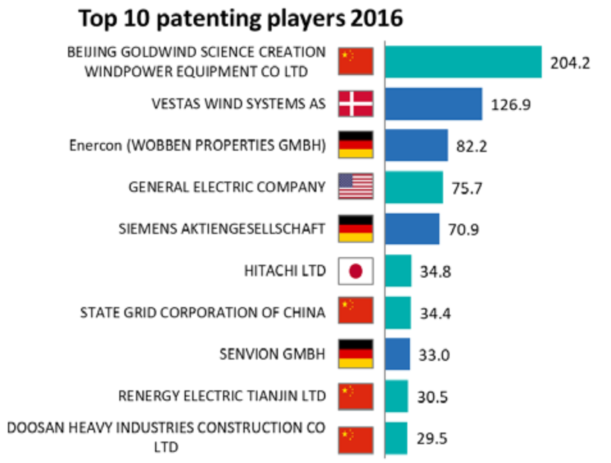
Figure 15 International comparison of the sector activity of the applicants of inventions
Source: JRC based on EPO data



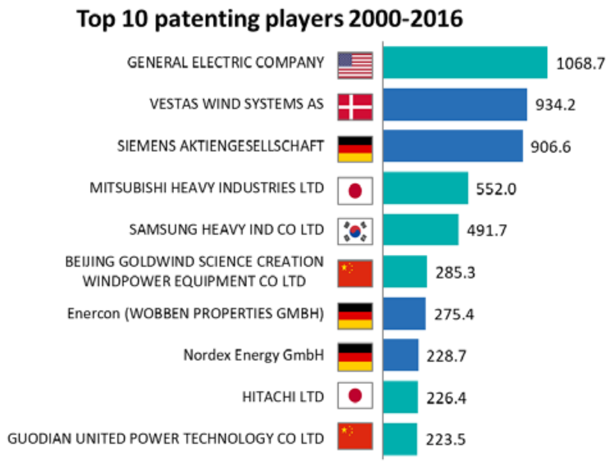
Not surprisingly, the parent companies of some of the leading OEMs rank among the top players in patenting activity. As shown in ***Figure 16***, in 2016, Goldwind was the leading company in number of wind energy inventions, representing 5.5% of global inventions, followed by Vestas Wind Systems A/S (3.4%) and Enercon GMBH (2.2%). Four out of the top 10 patenting entities were European companies (Siemens AG, Vestas Wind Systems A/S, Enercon GMBH and Senvion GMBH), covering altogether around 8.5% of wind energy innovations. Almost all of the top 10 in 2016 have a long standing presence in wind patenting activity since they also rank among the top 10 in terms of total inventions in the period 2000-2016. An exception can be seen in the leading Chinese companies (Goldwind, State Grid Corporation of China, Renergy Electric Tianjin and Doosan Heavy Industries and Construction) as they became only recently (in the period 2007 -2012) permanent members of the top 10.

Figure 16 Top 10 patenting players in 2014 (i), in the period 2000-2014 (ii) and recurrence in the period 2000-2014
Source: JRC based on EPO data
Note: European players highlighted with dark blue

(i)



(ii)



(iii)

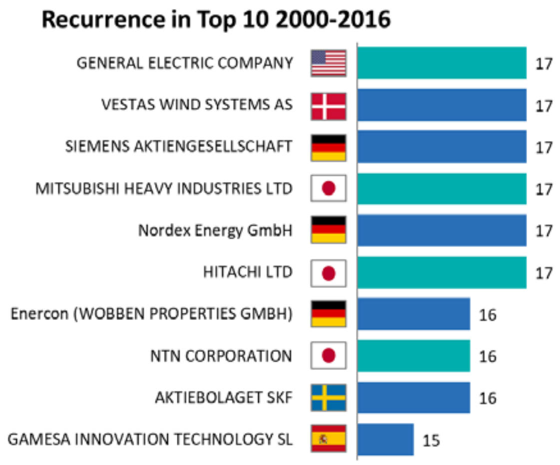


Figure 17 displays the evolution of the share of inventions protected in the major patent offices including national and international applicants. China is the most targeted market, with around 65% of inventions in wind energy protected in the Chinese patent office in 2016 and showing a strong increase in recent years. This trend seems to be driven by China's amendment of its patent legislation in 2000, more Chinese companies protecting their inventions, a growing domestic wind energy market, and the filing for protection of innovations by Chinese subsidiaries of foreign companies. The strong influence of domestic applications in China is visible when ***Figure 17*** is compared with ***Figure 18***. China was overtaken by the US in 2014 as the most targeted market when only international applicants are considered. However, in 2016 China became again the most targeted of international applicants mostly coming from South-Korea, the EU and Japan (see ***Figure 18***, right side).

Figure 17 Evolution of the share of inventions protected in the major patent offices (including national and international applicants Source: JRC based on EPO data

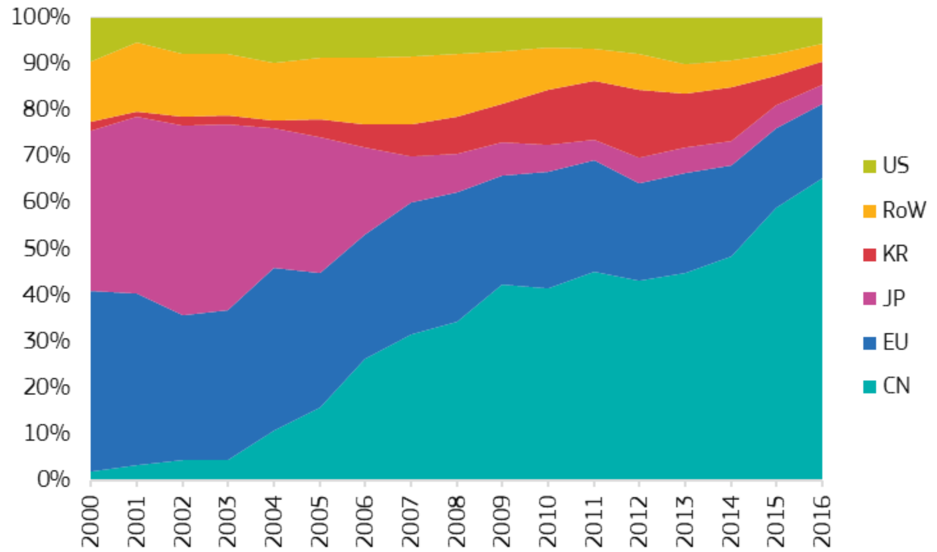
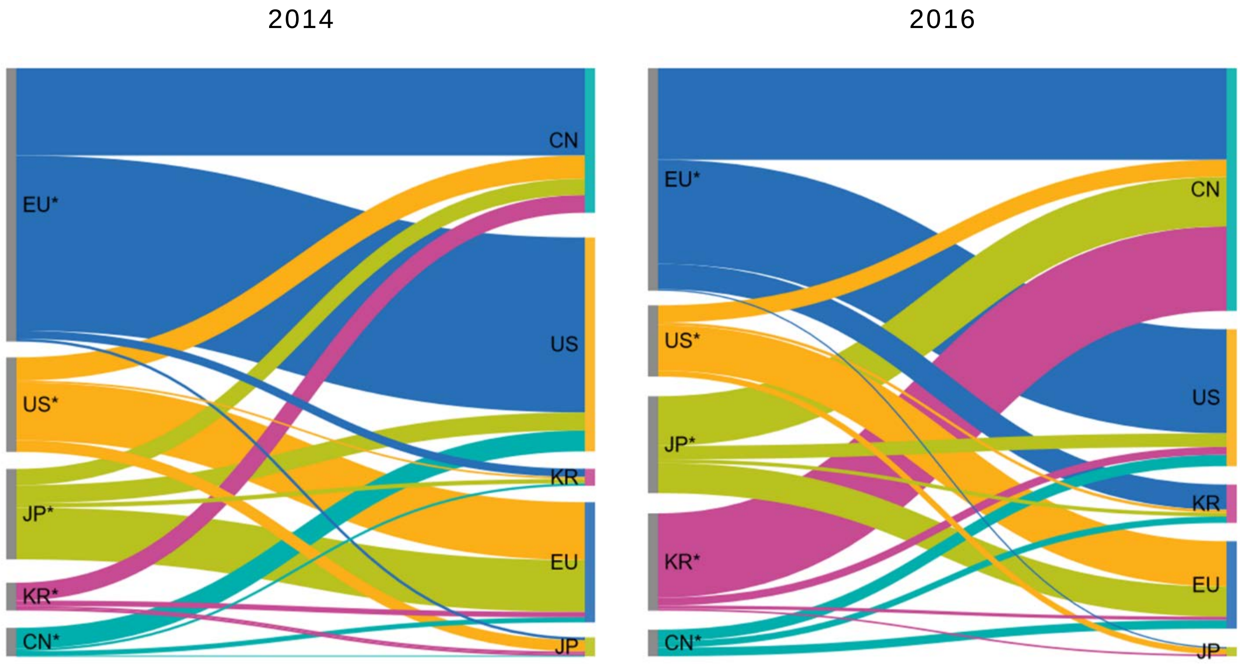


Figure 18 Comparison of the flow of inventions among the main patent offices (2014 vs 2016) (for flow of inventions in 2000 please see [JRC 2019b]) Source: JRC based on EPO data



The Korean patent office is also becoming a targeted destination but to a much lesser extent than China. In the period 2014-2016 the European market decreased from about 22% to 18% in terms of total inventions in wind energy protected in the European patent office. Moreover, the share of inventions protected in Japan has reduced significantly over the years.

Figure 18 shows the flow of inventions from the main players in terms of number of patents to the main patent offices.

The flow of patents has diversified mainly towards the patent offices of China, the United States and Korea in the last years (***Figure 18***).

European applicants keep the highest share of inventions protected in the United States and China in both 2014 and 2016, however Korea and Japan are lately catching up in the patents being protected in China.

The European patent office has become the main target of the Japanese applicants who protected more than half of inventions in Europe in 2014 and 2016. The number of inventions from American applicants has reduced almost half as compared to the year 2000 as a constant share of their inventions is addressing the Chinese patent office. Korean and Chinese applicants have only a limited number of inventions protected in Europe since the American patent office has become their main target.

3 R&D overview

This section gives an overview of the main R&D initiatives in the wind sector with a special emphasis on EU-funded research. The analysis monitors the R&D activities and investments in wind energy (see section 3.1) within the European H2020 programme until 2019 in order to complement previous analyses made on wind energy in the LCEO context (see last Wind Technology Development Report [JRC 2019a]). Moreover, as compared to previous studies this work adds two additional categories to analyse wind-related H2020 projects, namely 'Floating Offshore wind' and 'Airborne wind energy systems' given their increasing relevance within the wind sector. Section 3.2 provides information on the latest developments within the European Strategic Energy Technology Plan (SET Plan) and compares the ongoing SET-Plan R&D projects (including relevant national projects from major R&D programmes) against the SET-plan priorities formulated in the Implementation plan for offshore wind. This is followed by an analysis of wind energy R&D projects funded by European support instruments outside the H2020-framework (see section 3.3). The chapter concludes with highlighting the recent R&D foci and achievements of the IEA Technology Cooperation programme in wind energy systems (IEA TCP Wind) in order to give an overview of global R&D efforts (see section 3.4).

3.1 H2020 funded wind energy projects

3.1.1 Development and priorities of R&D investment in H2020

Horizon 2020 (H2020) is the biggest EU Research and Innovation programme with nearly €80 bn of funding available over 7 years (2014 to 2020). Moreover, it is the main funding instrument for energy research and development at the EU level, with a budget of about €6.0 bn ($7.2 bn). After the record year 2018, H2020 funded again a substantial number of wind energy projects (37) with a cumulated investment of €55.3 m ($61.9 m) (see ***Table 6***) [JRC 2019e].

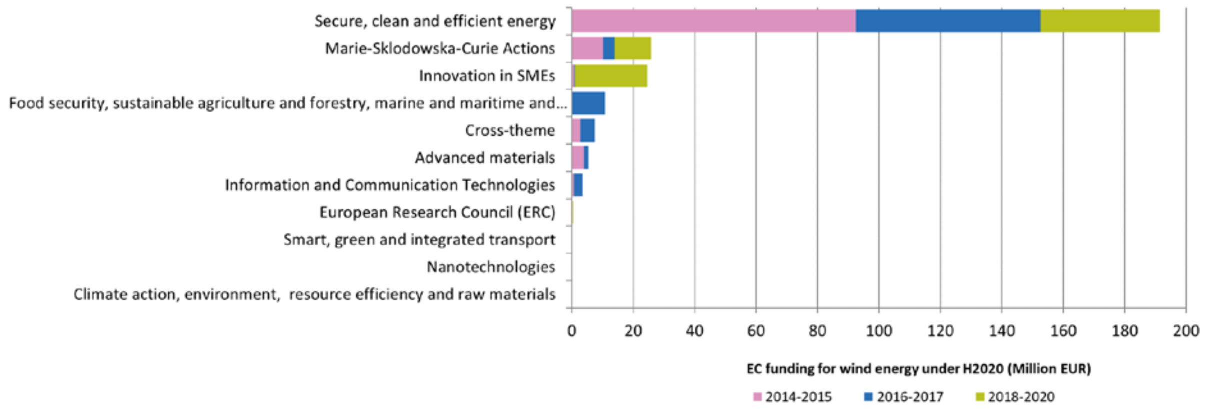
Table 6 Wind energy funding under H2020 granted to projects starting in 2019

H2020-funded projects	Total project cost Million EUR (Million USD)	EU contribution Million EUR (Million USD)	Number of projects
Wind-specific projects	58.7 (65.7)	50.7 (56.8)	32
Non-wind specific projects*	5.0 (5.6)	4.6 (5.1)	5
Total funding for wind energy	63.7 (71.3)	55.3 (61.9)	37

* In 2019, non-wind specific projects include the following projects in which wind energy play a minor part: TruePower, GiFlex, IGP and SUSMAGPRO. Since 2018 non-wind specific projects have been accounted with 25% of EC funding for wind energy.

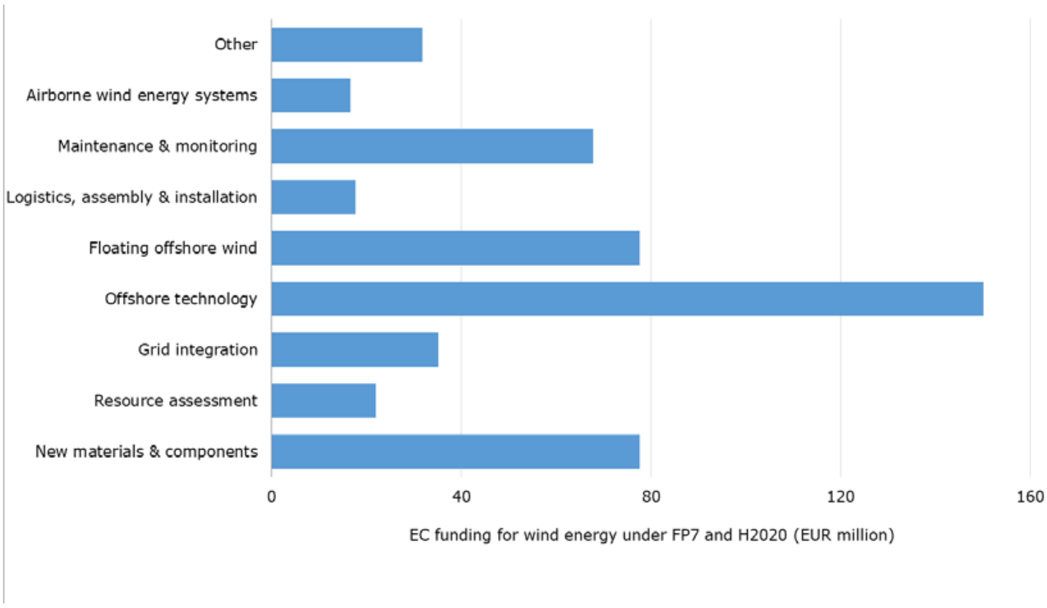
Since 2014 more than 71% of H2020 funding to wind energy projects has been allocated via the work programme "Secure, clean and efficient energy", identified by the European Commission as one of the priority societal challenges where targeted investment in research and innovation can have a real impact benefitting the citizen (***Figure 19***). Over the years, wind energy projects addressing other societal challenges such as advance materials, I&C technologies and marine research have received H2020 funding. Since 2018, H2020 also allocates increasing financial support to wind energy research projects coordinated by SME (Small- and Medium-sized Enterprises) and through the Marie Skłodowska-Curie Actions in order to generate, develop and transfer new skills, knowledge and innovation.

Figure 19 EC R&I funding for wind energy under H2020 programmes



The research and innovation (R&I) priorities of the EU include all aspects aimed to provide secure, cost-effective, clean and competitive energy supply, such as new turbine materials and components, resource assessment, grid integration, offshore technology, floating offshore wind, logistics, assembly, testing and installation, maintenance and condition-monitoring systems and airborne wind energy systems, among others. In the period 2009 – 2019, H2020 and its predecessor FP7 have granted funds of about €496 m ($556 m) to these aspects, putting the strongest emphasis in terms of funds on research in offshore technology (€150 m) followed by floating offshore wind, new materials & components and maintenance & monitoring (see ***Figure 20***).

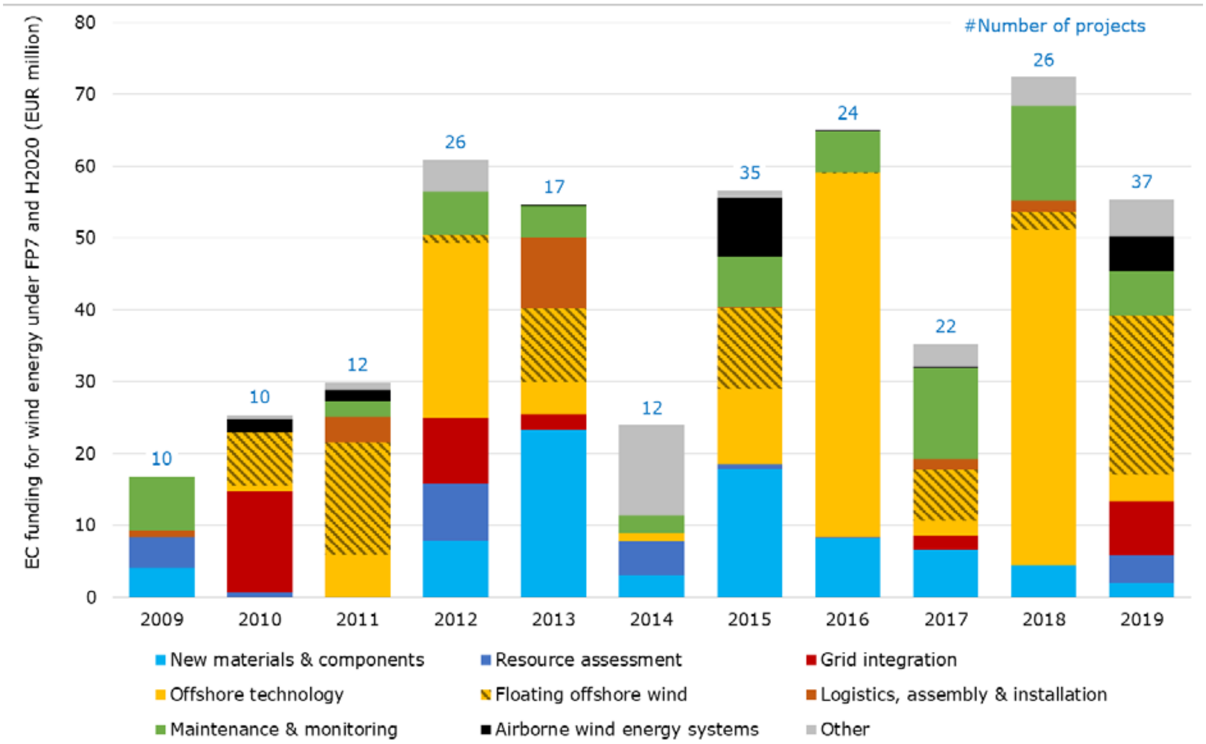
Figure 20 EC funding on wind energy R&I priorities in the period 2009 -2019 under FP7 and H2020



The focus of EU research funding in offshore wind under H2020 aims for the development of next-generation offshore wind turbines, further cost reduction and the uptake of commercial floating offshore wind platforms.

Figure 21 shows the development of R&I funding in the period 2009 – 2019 under H2020 funding program and its predecessor FP7 (see also list of projects in Annex 2, Table 29). Almost 47% of EC funding granted to wind energy projects starting in 2019 focused on offshore technology or floating offshore wind research. In particular, the EC is boosting the development of floating offshore wind concepts and solutions. FP7 programme funded seven research projects on floating offshore wind. Some projects such as FLOATGEN (see chapter 2, ***Table 5***) and DEMOWFLOAT demonstrated different floating concepts at pre-commercial scale in operational environment. H2020 has already allocated funding to 18 research projects on floating offshore wind since 2014. In total, the EC has granted more than €78m ($87m) to R&D projects on floating offshore wind solutions via FP7 and H2020 funding programmes since 2009.

Figure 21 Evolution of EC R&I funding categorised by R&I priorities for wind energy under FP7 and H2020 programs and number of projects funded in the period 2009-2019 (see also Annex 2) Note: The item "Other" includes some projects exploring emerging technologies such as social acceptance and critical rare earth elements among others. Funds granted refer to the start year of the project.



3.1.2 H2020 projects starting in 2019

A record number of 37 H2020-funded projects started in 2019. As in most of the previous years, most funds (€25.9 m) were granted to 12 projects addressing the R&I priority 'Floating offshore wind' or 'Offshore technology'. The following 8 projects coordinated by Dutch, French, Spanish and Swedish organisations with start date in 2019 focus on floating offshore wind research:

- COREWIND (Coordinator: ES) – aims to achieve cost reductions and to increase the performance of floating wind technology through the research and optimization of mooring and anchoring systems and dynamic cables (LCOE reduction of about 15% as compared to bottom fixed baseline). Simulations and experimental tests are performed (both in wave basin tanks and wind tunnel) of two concrete-based floater concepts (semi-submersible and spar) supporting large wind turbines (15 MW) at water depths greater than 40 m and 90 m for the semi-submersible and spar concept, respectively. A special focus will be also given to innovative installation techniques as well as to operation and maintenance (O&M) activities [EC 2020b].
- FLOTANT (ES) – aims to develop an innovative and integrated Floating Offshore Wind solution, optimized for deep waters (100-600m) capable to host a 10 MW

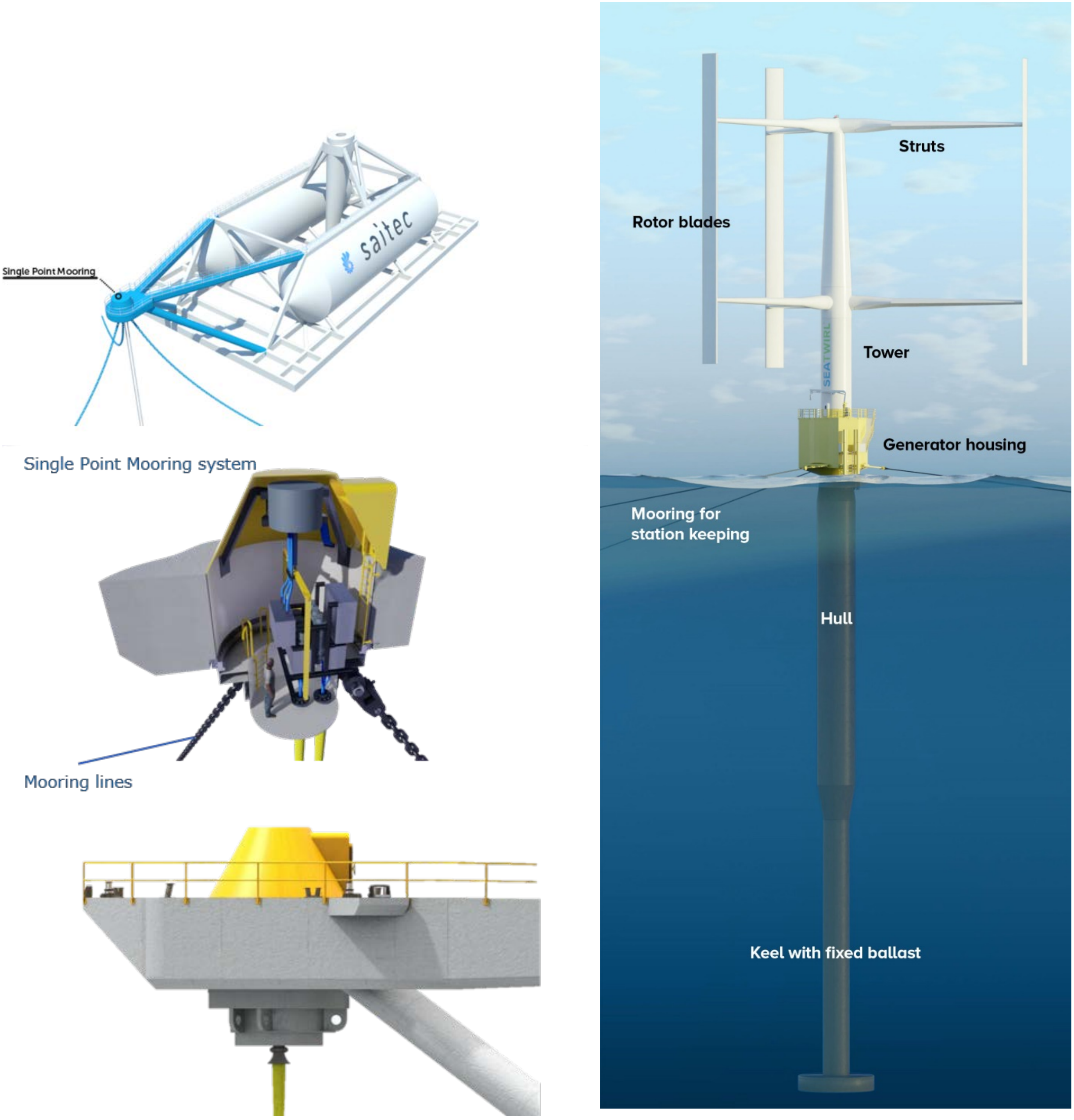
wind turbine generator. Moreover, the system is composed of a mooring and anchoring system using high performance polymers and based on Active Heave Compensation to minimise excursions, a hybrid concrete-plastic floater and a power export system with long self-life and low-weight dynamic cables. The project consortium claims to bring project technologies starting from TRL 3-4 to TRL 4-5. The project includes enhanced O&M strategies, sensoring, monitoring and the evaluation of the techno-economic, environmental, social and socio-economic impacts and targets an LCOE of 85-95 €/MWh by 2030 [EC 2020c, FP 2020].

- PivotBuoy (ES) – the project proposes to combine the advantages of the Single Point Mooring systems (pre-installation of the mooring and connection system using small vessels) with those of tension-leg systems (TLPs - weight reduction, reduced mooring length and enhanced stability). This allows reducing weight by 50% to 90% in floating wind systems compared to current spar and semi-submersible systems but also enabling a critical simplification in the installation of traditional TLP systems, which should allow a 50% LCOE-reduction for floating wind. The PivotBuoy concept is currently at TRL3 after its proof of concept in a wave tank at 1:64 scale [EC 2020d, PB 2020].

Figure 22 PivotBuoy tension leg platform

- SeaTwirl (SE) – this concept combines a vertical axis wind turbine with a smaller spar-buoy substructure. The project claims to realise reductions in both CAPEX, OPEX and DECEX which would lead to a decrease in LCOE of about 20%. Among others, the technical and environmental advantages of this concept are seen in the use of fewer moving parts, decreased space requirements and the use of the water’s buoyancy to carry the weight of the wind turbine. SeaTwirl will develop the S2, a 1-MW turbine (end 2021) which is planned to be followed by up-scaled models with a capacity of 7 MW (in 2025), 10 MW (in 2028) and >30 MW thereafter. The developers are especially targeting the off-grid sector such as isolated public municipalities (islands) and offshore industry companies (fish farms and Oil & Gas rigs)[EC 2020e]

Figure 23 Floater and Single-point mooring system – SATH Technology (left) and the SeaTwirl S2 concept (right)



- SATH (ES) – the aim of the SATH project is the demonstration in real conditions of a floating structure for offshore wind, which will allow a reduction in LCOE over the current floating technology. Within this project the SATH (Swinging Around Twin Hull) 1:6-scale prototype of a 10 MW wind turbine will be built and deployed for a 24-month offshore testing programme to de-risk a 2 MW demonstrator, known as DemoSATH/BlueSATH. The prototype, constructed in Santander (Spain), is to be installed on the Basque Marine Energy Platform (BIMEP) in 2021. The SATH design is based on a joined pair of cylindrical pre-stressed concrete hulls anchored to the seabed via a single-point mooring system that allows the unit to swing like a weathervane to face the wind. The concept has previously been put through an extensive part-scale testing campaign in wave tanks at the University of Cantabria's Instituto de Hidráulica Ambiental [Saitec 2019a, Saitec 2019b].

- EDOWE (NL) – the Economical Deep Offshore Wind Exploitation (EDOWE) project proposes introducing a concept of an innovative distributed multi-scale control and monitoring system in order to overcome the difficulties of effectiveness, robustness, integration and multi-scalability of optimal control and fault diagnosis system of floating offshore wind. In doing so, the project will address the undesirable loadings on the blades, tower, floating foundations and other components, which results in mechanical failures, and electrical faults which could lead to operation interruptions and cause economic losses[EC 2020f].
- ASSO (FR) – intends to establish a sound framework for the feasibility and assessment of adhesive connections for floating offshore wind installations in the marine environment, including experimental tests and accurate numerical procedures. In particular the project will develop an innovative non-linear mechanical model (experimental tests, non-linear mechanical model and FEM analysis) able to investigate the influence of seawater on the performance of adhesive connections [EC 2020g].
- FLOAWER (FR) – the FLOAting Wind Energy network provides 13 Early Stage Researchers (ESR) with an interdisciplinary training with the aim to design better performing, economically viable floating wind turbines. A focus is set on the development of numerical and experimental tools for the wind resource and the subsystem design (heave-plates, load effects on floaters, substructure) of vertical and horizontal axis wind turbines in order to define cost-effective floating wind turbine designs. FLOAWER aims to strengthen European wind energy industry leadership and competitiveness through the involvement of 25 major academic and industrial partners, and research infrastructures ranging from lab scale (wind tunnel, wave tanks, etc.) to higher TRL facilities (pre-commercial floating wind turbines and farms) [EC 2020h].

Other H2020-funded offshore wind research investigates alternatives to conventional platform cooling, more resilient and lighter steel structures for offshore structures at deeper waters, structural safety of tall offshore towers and the creation of an offshore science network in Portugal. The COOLWIND (NO) project aims to demonstrate the replacement of state-of-the-art transformer platform cooling (using seawater) with a passive subsea cooler system (Future Subsea Controllable Cooler (FSCC)) in order to reduce operational costs and environmental impacts (mitigation of chlorination of seawater and less emissions).

Figure 24 Future Subsea Controllable Cooler (FSCC) for passive transformer platform cooling by Future Technology AS

The project proposes to bring the FSCC technology from TRL6 to TRL9 [EC 2020i, FT 2020]. HSS-WIND (UK) will investigate the application of high-strength steel (HSS) in offshore wind tubular platforms. Challenges in harsh deep-water environments include the proper estimation of fatigue behaviour and resistance of HSS welded tubular connections to prevent fatigue fracture and failure at the vicinity of the welds [EC 2020j]. OFFSHORE TALL TOWER (UK) aims to improve the structural safety of new and taller offshore towers under dynamic loads [EC 2020k]. Furthermore, the TWIND (PT) project will create a network of specialised scientists and trainers in offshore renewable energy, which will provide support to the rising offshore wind industry of Portugal. The project will be conducted by the Portuguese WavEC in coordination with specialised partners in Spain (F. Technalia R&I), the Netherlands (TU Delft) and UK (ORE Catapult) [EC 2020l, WavEC 2020].

In 2019 two major H2020 projects started which specifically focus on grid integration of wind energy. WinGrid (UK) aims to train the next generation of researchers on future power system integration issues associated with large-scale deployment of wind generation, focussing on the modelling and control aspects of wind turbine design, and the system stability issues and supervisory structures required for robust implementation [EC 2020m]. The HPCWE (UK) project addresses crucial computational challenges faced by wind energy industries in Europe and Brazil. The project aims to deliver a step change in the use of high-performance computing regarding wind flow simulations (integration of meso- and micro-scale simulations, and optimisation), reshaping almost every stage of wind energy exploration [EC 2020n]. Moreover, part of the RE-COGNITION (IT) project can be assigned to wind energy research. The project proposes a holistic, end-to-end Renewable Energy Technologies Integration Framework towards energy positive buildings with a focus on small and medium-sized buildings in Europe [EC 2020o]. In total, the EC granted more than €7.5 m to projects elaborating the grid integration of wind energy in 2019.

Within the R&D category 'Maintenance, condition monitoring systems' funds of about €6.2 m have been granted to 5 projects. The FarmConners (DK) project supports the implementation and industrialisation of Wind Farm Control (WFC) as an additional feature for the development and operation of wind power plants. The project promises an increase in power production and a decrease in structural loads while providing better integration of wind power in the grid [EC 2020p]. Windrone Zenith (PT) is developing a drone-based solution to provide 3-blade inspection in a single flight [EC 2020q]. In order to bring their technology within the next two years to the market the EOLOGIX (AT) project develops the eolACC condition-based monitoring on-blade sensor system capable to monitor blade crack detection, pitch angle measurements and blade icing detection. The developers claim cost reductions of up to €2.9 m over the lifetime of a turbine [EC 2020r, Eologix 2020]. WindTRRo (DK) develops a robot performing all the phases of wind turbine blade leading edge maintenance and repair, which might be an economic alternative for manual repair. First customers of the first fleet of robots are the leading wind OEMs SiemensGamesa RE and Vestas [EC 2020r, Rope Robotics 2020]. The PAVIMON (DK) project performs a feasibility study focused on the implementation of advanced artificial intelligence (AI) to analyse data from advanced sensor signals. The aim is to increase the resource efficiency of signal analysis and improve predictive capabilities [EC 2020s, Vertikal AI 2020].

Figure 25 Rope Robotics robot performing wind turbine blade leading edge maintenance and repair (left) and 100kW autonomous EnerKite EK200 for isolated grids.

Airborne wind energy systems received H2020-funding of about €4.8 m, mainly within the AWE (NO) and AWESOME (DE) project. AWE develops the KITEMILL kite and will implement a first demonstration park of five 30 kW units during this project at Lista (Norway) [EC 2020t, Kitemill 2020]. AWESOME aims to optimise and validate its EK200 -kite, a 100 kW unit, envisaged as the company's commercial market entry model (current estimates stress a LCOE range of about 70-120 €/MWh) [EC 2020u, EnerKite 2020]. The TwingTec (CH) project is targeting the off-grid market and remote communities with its vertically launched 100 kW drone (current LCOE estimates are at about 100-200 €/MWh) [EC 2020v, TwingTec 2020].

With zEPHYR (BE) only one project in 2019 can be assigned to the R&D category 'Resource assessment' yet with some substantial funding (€3.8 m). Within a multi-disciplinary training platform, the project proposes the development and application of advanced meso/microscale atmospheric models and the assessment of the impact of real terrain and local atmospheric effects on the predicted aerodynamic performance, structural dynamics and noise emissions. Moreover, human factors and the resulting inter-dependencies (visual vs. acoustic effects, age or occupation, etc.) are addressed [EC 2020w].

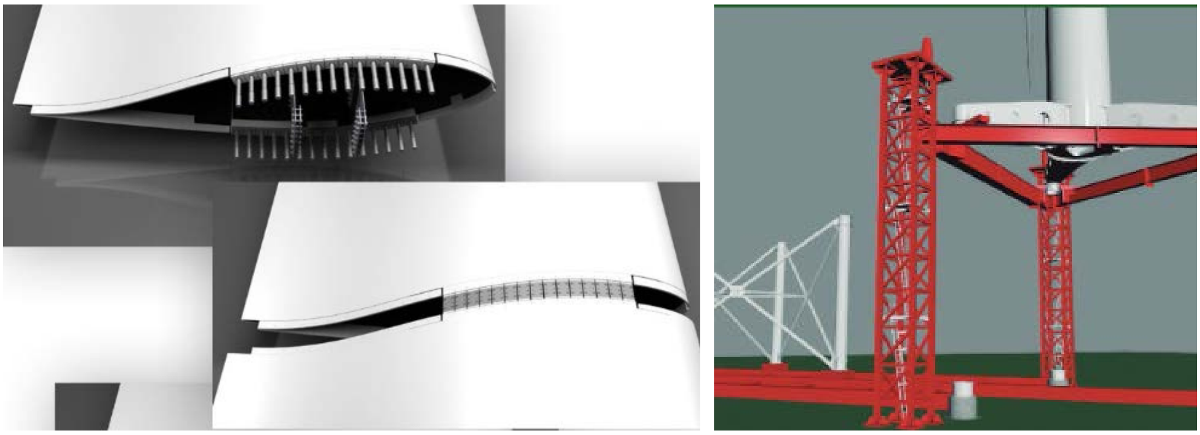
Apart from the NBTECH (ES) project (€1.7 m), all projects in the R&D category 'New turbine materials, components' started in 2019 received smaller H2020 funding (ranging from €50 000 to €150 000). The objective of the NBTECH project, led by the company

NABRAWIND, is the validation and demonstration of the functionality and reliability of its self-erecting tower concept (NABRALIFT) and modular blade system (NABRAJOINT) in real working conditions. A 200m tower is envisaged to be built in Navarra, Spain, with Acciona as promoter and hosting a 4.5 MW NORDEX turbine in order to introduce both systems into market [EC 2020x, NABRAWIND 2020]. SUNCOAT (UK) is the follow-up on the ongoing NICEDROPS project (ERC grant 714712) which developed a robust and flexible nano-engineered coating formulation and expands the latter by introducing water based coatings formulations, to make blades environmental friendly and VOC-free [EC 2020y, EC 2020z]. The MicroCoating (NL) project introduces a new blade coating technology by applying microstructures (in form of grooves, also known as sharkskin) on the blade reducing the air resistance by channelling the occurring air turbulences. The technology currently at TRL 6 was patented by the company Qlayers in 2018 and is planned to be commercialised in a wind project by December 2020 [EC 2020aa, Qlayers 2020]. In the Modvion (SE) project, the engineering company Modvion performs a feasibility study that will assess the technical and commercial aspects, as well as risks, of a commercial pilot of a modular, segmented wooden tower. The structural materials used are glue-laminated timber (GLT) and laminated veneer lumber (LVL). As a first step it is planned to install a 1:5-scale prototype tower with a 30-meter hub height near Gothenburg (expected to be completed by March 2020). However in end-2019 Swedish wind power company Rabbalshede Kraft AB signed a letter of intent to order ten modular wooden towers from Modvion for its Fagremo wind project [RN 2019, WPM 2019t, EC 2020ab].

Figure 26 Manufacturing of the 30m Modvion prototype tower

CWS's LEWIATH (FR) project targets the maritime transport sector. The company proposes its patented Wing-Sail combining reversible rigs, telescopic and free rotating masts and wing-sail automation. Within the project aerodynamic and market studies as well as the finalisation of the mechanical engineering of the V3-prototype are envisaged [CWS 2020, EC 2020ac]. Similarly, the SIDEWIND project (IS) aims for a low carbon shipping industry by incorporating horizontal turbines inside recycled cargo containers [EC 2020ad].

Figure 27 Segmented blade solution (left, NABRABLADE) and self-erecting tower concept (right, NABRALIFT)



Other H2020-projects starting in 2019 included the Vertical Sky (CH) project developing a large-scale vertical-axis wind turbine. The project developers claim that the main innovation of the system entails a self-optimising adjustment of the rotor blades which results in a significant reduction in noise levels. Together with the simplified logistics for transportation and installation it might be used in distributed applications and populated areas. In March 2019 the construction of a demonstration plant (750 kW, 32 m rotor diameter, 105 m total height) started in Grevenbroich (DE) [Agile Wind Power 2020, EC 2020ae]. Moreover, with the SETWind (DK) and the ETIP Wind (BE) projects two coordination and support actions (see chapter 3.2) facilitate the implementation of the SET-Plan Implementation Plan for Offshore Wind. They should also inform on EU's Research & Innovation policy to sustain Europe's global competitive edge in wind energy and deliver on the EU's Climate and Energy targets cost-effectively [EC 2020af, EC 2020ag, ETIP Wind 2020, SETWind 2020].

H2020 projects which are not exclusively wind-related include SUSMAGPRO (DE) developing a recycling supply chain for rare earth magnets in the EU. TruePower (CH) proposes a RES asset management platform to increase projects' revenues, GiFlex (CH) and IGP both strive for effective and increased integration of renewable generation through proposing an optimization framework or an intelligent machine learning grid platform, respectively [EC 2020ah, EC 2020ai, EC 2020aj, EC 2020ak].

3.2 Offshore wind R&D in the European Strategic Energy Technology Plan (SET-Plan)

3.2.1 Key issues, targets and R&I priorities

The European Strategic Energy Technology Plan (SET-Plan) aims to accelerate the development and deployment of low-carbon technologies. The communication on the Integrated SET-Plan identified offshore wind energy within its ten priority actions to accelerate the energy system transformation and create jobs and growth [EC 2015]. The SET-Plan has put forward a dedicated vision for each technology area by setting ambitious targets to be reached in the next decade(s) with the overall goal to place Europe at the forefront of the next generation of low-carbon energy technologies and of energy efficiency.

In 2018 an implementation plan for offshore wind with specific targets and priority actions has been developed by the Implementation Working Group (IWG) for Offshore Wind in order to meet the overall SET-plan targets. In total 14 implementation plans covering all the Energy Union Research & Innovation priority areas which were endorsed by the SET Plan Steering Group and the European Commission in 2018 [EC 2018b].

According to the IWG for Offshore Wind (supported by the H2020-funded SET-Wind project[9] [SETWind 2020]) three key issues need to be addressed in order to maintain European leadership in offshore wind:

- Offshore wind costs must be reduced through, but not only, increased performance and reliability in order to meet its full potential contribution to the European energy mix.
- There is a need to develop (floating) substructures or integrated floating wind energy systems for deeper waters and wind energy systems for use in other marine climatic conditions, to increase the deployment possibilities and to maintain and even improve the European position in the global market. Moreover, additional policy and research actions need to be developed.
- The added value of wind farms should be increased. For offshore wind energy to become a reliable source of energy, system integration will become ever more important. To improve the societal acceptance the ecological impact and spatial planning are crucial elements for the future development of offshore wind. Synergies with the declining oil & gas sector and co-operation with blue economy sectors have to be found.

The Implementation Plan (IP) for Offshore Wind defines 9 priority actions (both technological and non-technological) in order to reach the following two R&I targets:

1. Reduce the levelised cost of energy (LCoE) at final investment decision (FID) for fixed offshore wind by improvement of the performances of the entire value chain striving towards zero subsidy cost level for Europe in the long term.
2. Develop cost competitive integrated wind energy systems including substructures which can be used in the deeper waters (>50 m) at a maximum distance of 50 km from shore with an LCoE of <12 ct€/kWh by 2025 and <9 ct€/kWh by 2030.

To achieve this, the IWG estimates that a combined investment of €1090 m is needed until 2030 with a split in contributions of Member States 34%, EU 25% and Industry 41%.

3.2.2 Status of R&D progress

The progress made was monitored in 2019 based on the inputs received from the IWG and released during the 13th SET-Plan conference in Helsinki. The IWG confirmed that revision of the IP is needed. More specifically the first IP target was stressed to be still relevant, yet a new definition of the second IP target is needed as the outlined LCoE targets have already been achieved and new targets need to address the system value of the offshore wind. Moreover, the IWG perceives that most progress in R&I has been achieved in the IP R&I activities on 'Wind Energy Offshore Balance of Plant', 'Floating Offshore Wind' and 'Wind Turbine Technology' (see Table 7).

Table 7 Progress of R&I activities of the SET-Plan Implementation Plan for Offshore Wind as reported by the IWG for Offshore Wind

R&I activities of the endorsed IP	Progress
System Integration	● (yellow)
Wind Energy Offshore Balance of Plant	● (green)
Floating Offshore Wind	● (green)

[9] The SETWind project supports the implementation of the Implementation Plan. The project supports the continued work of the SET-Plan Implementation Working Group for Offshore Wind Energy and facilitate the implementation of the research and Innovation (R&I) priorities through cross-border coordination of nationally funded projects.

R&I activities of the endorsed IP	Progress
Wind Energy Operation and Maintenance	🟡
Wind Energy Industrialisation	🟡
Wind Turbine Technology	🟢
Basic Wind Energy Sciences	🟡
Ecosystem and social impact	🔴
Human Capital Agenda	🔴

Especially progress in floating offshore wind benefits from multiple ongoing projects and demonstration projects, yet the IWG sees significant efforts needed in basic research in that area. Only limited progress was stressed for the R&I activities 'Ecosystem and social impact' and 'Human Capital Agenda'. An update of the IP is envisaged until the end of 2020 in order to be presented at the 14th SET-Plan conference. The H2020 SETWind project will support this process and the IWG along its four main objectives [SETWind 2020]:

- Increase cross-border coordination of national research in wind energy

SETWind will facilitate that the R&I priorities defined in the Implementation Plan are translated into nationally (co-)funded projects coordinated across borders. SETWind aims to facilitate the successful submission of 10+ qualified proposals for cross-border projects (co-)funded by national funding agencies. For the development of cross-border projects the project developed a dedicated template for presenting proposals (see [SETWind 2019])

- Support the development of a "rolling agenda" of R&I priorities in the Implementation Plan

The Implementation Plan identifies a range of priority R&I actions. However, it recommends a "rolling agenda" since priorities will change as the wind energy sector progresses. To support this rolling agenda, SETWind will define and elaborate medium to long-term R&I targets for an updated rolling agenda and identify a lighthouse project requiring a wider concerted action between European stakeholders.

- Continue policy coordination between national funding agencies

The former TWG will remain as an Implementation Working Group for Offshore Wind (IWG) to continue the policy coordination in offshore wind energy R&I between national funding agencies. The SETWind project will support the work of the IWG by offering secretarial support to the IWG, which will also form the SETWind Steering Committee.

- Monitor and report on progress

SETWind will deliver an annual report on the progress towards the R&I investment targets as foreseen in the Implementation Plan. Furthermore, SETWind will also deliver reports on the national R&I policies for offshore wind energy to support the work of the Steering Committee.

The progress of R&I activities can also be observed by the number of projects reported by the IWG. ***Figure 28*** shows the reported IWG projects, their respective budget and their connection to one or more R&I priorities [JRC 2019f]. Apart from the earlier described H2020-funded projects a significant number of nationally funded projects are reported for the R&I priorities 'Wind Energy Offshore Balance of Plant', 'Floating Offshore Wind' and 'Wind Turbine Technology'. It becomes apparent that substantial budgets were allocated to the German funded marTech project (DE) (€35 m) investigating optimal anchoring of foundations and design of scour protection in a 1:10-scale wave tank [BMWi 2017] and to the H2020-funded RealLCoE project (DE) striving for accelerating the development of the next generation offshore wind turbines [EC 2020al]. Amongst others, both projects address the R&I category 'Floating offshore wind', a category which is also addressed by the INTERREG ARCWIND project (PT) studying the implementation of floating offshore wind in the Atlantic region [Keep 2020].

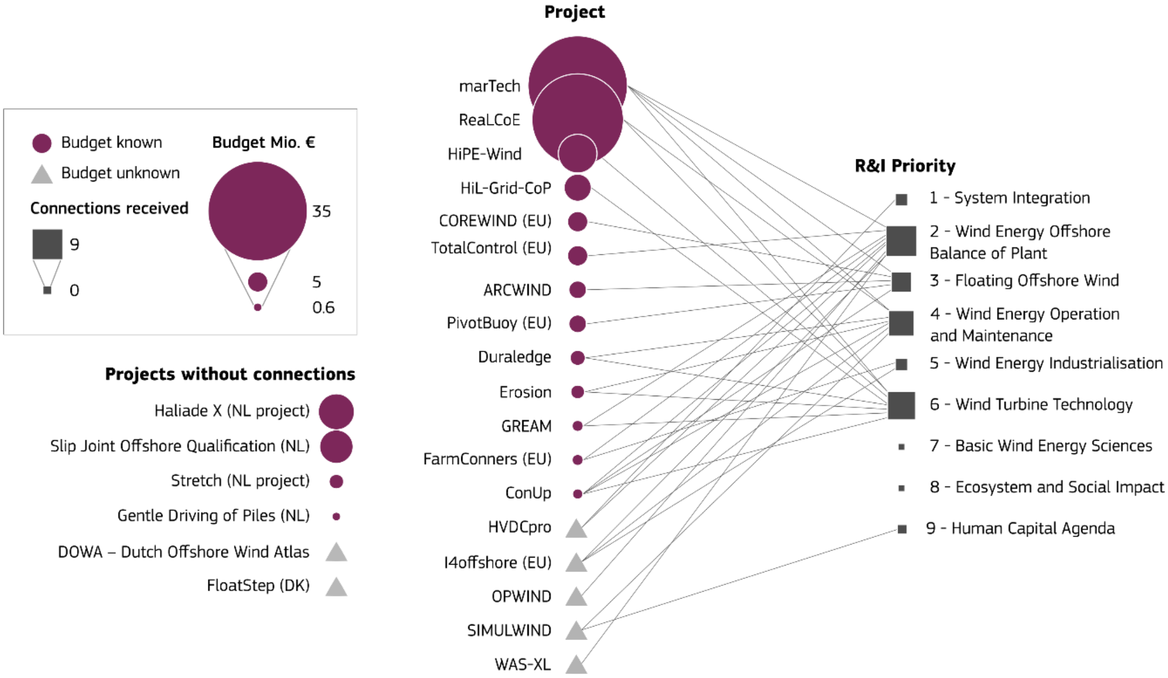
The IWG reported the SINTEF-led OPWIND (NO), WAS-XL (NO) and HVDCpro (NO) projects within the category 'Wind Energy Offshore Balance of Plant' with the latter being the only project also connected with the R&I priority 'System Integration'. OPWind aims to develop knowledge and tools for optimized operation and control of wind power plants, while WAS-XL is investigating wave loads and soil support for extra-large monopiles [SINTEF 2020a, SINTEF 2020b]. HVDCpro develops methods for assessing the value of and the requirements for inertia emulation from HVDC transmission schemes, thus seems to have a stronger focus on system integration than the aforementioned projects [SINTEF 2020c]. Both R&I activities 'Wind Energy Offshore Balance of Plant' and 'Wind Turbine Technology' are addressed by the BMWi- funded GREAM (DE) project investigating load-bearing characteristics of wind turbines and wind farm platforms [ForWind 2020]. Moreover, significant activity for turbine technology and O&M-related research is also reported with respect to electrical components and certification (Hil-GridCop (DE) and HiPE-WiND (DE)) and blade erosion (DURALEDGE (DK) and EROSION (DK)) [DTU 2020a, DTU 2020b, IWES 2020a, IWES 2020b]. With SIMULWIND, only one of the reported projects focused on the R&I activity 'Human Capital Agenda'. The project focuses on the training of personnel for operation and maintenance of wind energy farms, aiming at specifically developing a simulator able to show all main faults and solutions that can be found in both wind turbines and wind farms [RSC GmbH 2020].

Several projects (mainly from NL) were not reported as to be connected to specific R&I priorities, nevertheless some obvious linkages can be made outside the SET-Plan monitoring process as the following projects address multiple of the SET-Plan R&I priorities. Within the Haliade-X project in the Netherlands, TNO will perform extensive measurements on the Haliade-X 12MW offshore wind turbine in Maasvlakte, Rotterdam. The project is a partnership between TNO and GE Renewable Energy and LM Wind Power and can be assigned into the R&I priority 'Wind Turbine Technology'.

As an alternative to conventional grouting or bolting Van Oord and TU Delft are aiming in the Slip-Joint Offshore Qualification (NL) project for bringing this technology to TRL 8. The project is part of the Dutch GROW (Growth through Research, development and demonstration in Offshore Wind) programme and involves other industrial partners such as the DOT BV, Sif Group, Eneco (owner of the Princess Amalia offshore wind farm where the system is deployed) and Heerema Marine Contractors [Jorritsma 2019]. The Gentle Driving of Piles (NL) project is another initiative within the GROW programme. Its objective is to develop an efficient pile installation process by testing a novel pile installation method based on simultaneous application of low-frequency and high-frequency vibrators exciting two different modes of motion of the monopiles. This should improve drivability, reduce noise emissions, and ensure that the soil bearing capacity stays uncompromised. The project consortium includes research institutes (TU Delft, TNO, Deltares), marine contractors (Van Oord, Boskalis, IHC, Seaway Heavy lifting), project developers (Eneco and Shell), a monopile manufacturer (SIF) and a wind turbine developer (DOT BV). The main innovations introduced by both projects address the R&I priority 'Wind Energy Offshore – Balance of Plant'.

The STRETCH (NL) project aims for the development of a design suite as well as the testing capabilities for extremely large offshore rotors (diameters >220m). Based on the blade design developed earlier in the AVATAR-project (FP7 project until 2017) a project consortium involving TNO, LM Wind Power and GE Renewable Energy aim for a state-of-the-art rotor test facility for the next generation of offshore wind turbines. As such the project can be assumed to contribute to R&I priority 'Wind Turbine Technology'.

Figure 28 Reported SET-Plan projects addressing the R&I priorities of the SET-Plan Implementation Plan [JRC 2019f]



The DOWA (NL) project will produce a new and updated atlas available for use in tenders for new offshore wind farms off the Dutch coasts (e.g. Scheveningen and Egmond), thus contributing to the R&I priority 'Basic Wind Energy Scienes'. The project consortium includes TNO, the Dutch national weather service (KNMI) and Whiffle Weather Finecasting (a TU Delft spin-off focussing on weather modelling) [TNO 2019, TKI Wind op Zee 2020a, TKI Wind op Zee 2020b, TKI Wind op Zee 2020c, TNO 2020]. In its FloatStep (DK) project, DTU optimises the design of the floating wind turbine foundations that make it possible to place offshore wind turbines in very deep water. Together with project partners from research and industry (DHI, Siemens-Gamesa Renewable Energy A/S, Stiesdal Offshore Technologies, STROMNING and University of Western Australia) the project's objective is to bring the TetraSpar floater from TRL 5 to TRL 6-7 (R&I priority 'Floating Offshore Wind') [DTU 2019b, energiforskning 2020].

Other joint industry programmes not covered so far within the SET-Plan include additional projects from the Dutch GROW programme, the UK Offshore Wind Accelerator programme, the Offshore Renewables Joint Industry Programme (ORJIP Offshore Wind) (UK), the Floating Wind Joint Industry Project (Floating Wind JIP) (UK) and DNV GL's Joint Industry Projects (JIP) on Wind Energy. ***Table 8*** provides an overview of the most recent projects within these programmes, the consortium members and estimates which SET-plan R&I priorities would be addressed.

Table 8 Other joint industry research programmes addressing the R&I priorities of the IWG for Offshore Wind [DNV GL 2019b, DNV GL 2019c, DNV GL 2019a, Carbontrust 2020, GROW 2020]

Projects (Description)	Consortium	R&I priority addressed (JRC analysis)
GROW programme (NL)		
Corrosion Fatigue Life Optimisation (C-FLO) (Development and calibration of corrosion fatigue models for the optimisation of the design and maintenance of monopiles)	TNO, Deltares, Eneco, Innogy, Shell, Sif, TU Delft, Van Oord	2 - Wind Energy Offshore – Balance of Plant 4 - Wind Energy O&M
DOT3000 Power Train System (DOT3000 PTS) (Development of a seawater-hydraulic drive train)	DOT BV, TU Delft	6 - Wind Turbine Technology
Hydraulic Pile Extraction Scale Tests (HyPE-ST) (Testing the removal of piles from the soil at the end of their operational life)	DOT BV, TNO, Deltares, IHC, Innogy, Sif	2 - Wind Energy Offshore – Balance of Plant 8 – Ecosystem and Social Impact
Monopile Improved Design through Advanced cyclic Soil modelling (MIDAS) Optimal design of monopiles by accounting for the effects of repeated loading in offshore.	TU Delft, Deltares, Eneco, Innogy, IHC, Shell, Van Oord	2 - Wind Energy Offshore – Balance of Plant
WIND turbine COntrol strategies to reduce wind turbine blade Rain droplet Erosion (WINDCORE) (Development of wind turbine control strategies to reduce rotor speed under harsh weather conditions)	TNO, Innogy, Shell, TU Delft	4 - Wind Energy O&M 8 – Ecosystem and Social Impact
Offshore Wind Accelerator (OWA) programme (UK)		
PISA - Pile Soil Analysis (Monopiles behaviour in different soil and environmental conditions)	Ørsted, University of Oxford, Imperial College London, ESG	2 - Wind Energy Offshore – Balance of Plant
VIBRO - Vibro Driving project	Innogy	2 - Wind Energy Offshore – Balance of Plant
JaCo - Improved Fatigue Life of Welded Jacket Connections (Optimisation of the design of jacket foundations through improved fatigue standards and validation of faster testing and fabrication methods)	Ørsted, EnBW, Equinor, Iberdrola/Scottish Power Renewables, Vattenfall, Siemens Wind Power	2 - Wind Energy Offshore – Balance of Plant 5 - Wind Energy Industrialisation
Offshore Renewables Joint Industry Programme (ORJIP Offshore Wind) (UK)		
ORJIP Offshore Wind Stage 2 (Investigating the effects of offshore wind on the marine environment; Reduce the risk of not getting or delaying consent for offshore wind developments)	Innogy, Marine Scotland, Equinor, SSE Renewables, EDF, The Crown Estate, RWE, Shell, Crown Estate Scotland, SDIC, EDP, Carbon Trust	
Floating Wind Joint Industry Project (Floating Wind JIP) (UK)		
Floating Wind JIP – Stage 2 (Overcoming common technical challenges relevant to commercial-scale floating wind farms and de-risking technology challenges that are common to multiple floating wind concepts, particularly challenges for large scale floating wind arrays)		3- Floating Offshore Wind
DNV GL Joint Industry Projects (JIP) on Wind Energy		
ACE (Alleviating Cyclone and Earthquake Challenges for Wind farms) Joint Industry Project (Aligning wind turbine design methodologies for extreme environmental conditions)	CDEE, COWI, Jan de Nul, Kajima Corp, LOGE, Obayashi, Ørsted, Pacifico Energy, Shimizu, Vestas, wpd	8 – Ecosystem and Social Impact
Joint Industry Project to cut wind energy costs through LIDAR measurements	n/a	
Joint Industry Project - COmprehensive methodology for Blade Rain erosion Analysis (COBRA)	V estas, Siemens Gamesa Renewable Energy, LM Wind Power, Ørsted, Mankeweicz, Akzonobel, Aerox-CEU, Polytech, Hempel and PPG	4 - Wind Energy O&M

3.2.3 Connection to other research strategies on offshore wind

The fast-evolving technological development of the wind energy sector asks for regular updates of R&I priorities. Therefore, the IP for Offshore Wind recommends a 'rolling agenda' since priorities will change as the wind energy sector progresses. Besides the involved SET-Plan countries, EERA[10] and ETIPWind[11] are consulted in the development of updated R&I priorities[12] to ensure a balanced and appropriate involvement of the industry sectors, the research and innovation community and other principal stakeholders.

Table 9 shows the R&I priorities defined in the recent ETIPWind roadmap and the EERA JP Wind R&I strategy 2019. Both these strategies cover the entire wind sector (on- and offshore, providing knowledge at different TRL), yet an alignment of strategies for offshore wind within the SET-Plan IP might be appropriate as lately proposed by EERA in early 2020 [EERA 2020]. Moreover, some of the R&I priorities specifically address the following main challenges in the science of wind energy as identified by the IEA Wind Technology Collaboration programme [Veers et al. 2019]:

- Improved understanding of atmospheric and wind power plant flow physics
- Aerodynamics, structural dynamics, and offshore wind hydrodynamics of enlarged wind turbines
- Systems science for integration of wind power plants into the future electricity grid

Table 9 Comparisons of R&I priorities among the main research bodies/strategies [EERA 2019, SETWind 2019, Veers et al. 2019, EERA 2020]

ETIPWind 2019	**EERA 2019 strategy**	**IEA TCP Grand Challenges**	**Proposal EERA for SET-Plan IP**
Next generation technologies	Next generation wind turbine technology & disruptive concepts	Aerodynamics, structural dynamics, and offshore wind hydrodynamics of enlarged wind turbines	**Wind Turbine Technology**
Grid & system integration	Grid integration and energy systems	Systems science for integration of wind power plants into the future electricity grid	**Offshore wind farms & System Integration**
;Floating Wind	Offshore wind (bottom fixed & floating)		**Floating Offshore Wind & Wind Energy Industrialization**
Operation and maintenance	Operation and maintenance		**Wind Energy Operation, Maintenance & Installation**
Digitalisation, electrification, industrialisation and human resources	Sustainability, social acceptance, economics and human resources		**Ecosystem, Social Impact & Human Capital Agenda**
Offshore balance of plant			
	Fundamental wind energy science	Improved understanding of atmospheric and wind power plant flow physics	**Basic Wind Energy Sciences**

[10] European Energy Research Alliance (EERA)
[11] European Technology and Innovation Platform on Wind Energy
[12] R&I priorities of the current SET-Plan IP for Offshore Wind [EC 2018b]: System Integration; Wind Energy Offshore Balance of Plant; Floating Offshore Wind; Wind Energy Operation and Maintenance; Wind Energy Industrialisation; Wind Turbine Technology; Basic Wind Energy Sciences; Ecosystem and Social Impact; Human Capital Agenda

3.3 Other European R&D support instruments

3.3.1 KIC InnoEnergy

KIC InnoEnergy (part of the European Institute of Innovation and Technology (EIT)) aims to strengthen cooperation among businesses (including SMEs), higher education institutions and research organisations, form dynamic pan-European partnerships, and create favourable environments for innovations in the area of sustainable energy [EIT 2020a]. A focus is especially set on bringing innovations to the market (e.g. through its InnoEnergy Investment Rounds which target innovative products at a TRL greater or equal to 5, see [EIT 2020b])

KIC InnoEnergy reported having supported the company Principle Power in bringing its floating prototype WindFloat towards commercialisation through joining the Innovation Projects programme. KIC InnoEnergy invested €4 m in the project and worked with Principle Power on every aspect of advanced technology development and commercialisation, including engineering, third-party analysis and certification, business development and dissemination. A key area of focus has been to further reduce the levelised cost of energy to ensure that the WindFloat technology is in line with global price targets for commercial offshore wind projects [EIT 2020c].

In the KAStrion project (by Grenoble-INP (FR) and Polish EC Systems (PL)) KIC InnoEnergy provided support regarding intellectual property rights, facilitated knowledge exchange among industry experts towards project commercialisation. KAStrion has developed an independent condition-monitoring system (CMS) for both the electrical and mechanical parts of the wind turbine drive train. It uses multi-modal spectral monitoring technology and advanced algorithms for analysing current and vibration data; it provides pre-diagnostics and early fault detection for each turbine – without human intervention. The project developed the VIBstudio solution, which EC Systems is selling to customers around the world. InnoEnergy and EC Systems are now collaborating on two new innovation projects: Xsensor to develop wireless sensors for increasing the efficiency of power generation equipment; and FOGA, which is developing an interconnected, long-life smart battery system for off-grid applications [EIT 2019a, EIT 2019b, EC Systems 2020, EIT 2020d].

Moreover, ***Table 10*** summarizes the projects and innovations supported by InnoEnergy towards commercialisation (e.g. among others through finding appropriate commercialisation partners)

Table 10 Wind energy-related innovations supported by InnoEnergy towards product commercialisation [AMC 2020, EIT 2020e, NABRAWIND 2020, nnergix 2020, Pro-Drone 2020, Vertequip 2020, Windcrete 2020, WTS 2020, X1 Wind 2020] [Smartive 2020]

Project/Innovation	Description	Stage of development	Commercial solution (provider)
KAStrion	Independent condition-monitoring system (CMS) for the electrical and mechanical parts of the wind turbine drive train.	Commercialized	VIBstudio solution (EC Systems)
Xsensor	Wireless sensors increasing the efficiency of power generation equipment	Pre-commercial	(EC Systems)
FOGA	Interconnected, long-life smart battery system for off-grid applications	Pre-commercial	(EC Systems)
EOLOS FLS200	Floating buoy that uses LiDAR (light detection and ranging) technology to gather high-quality wind and ocean data from any offshore location	Commercialized	EOLOS FLS200 (Eolos solutions)
Cloud-based software	Combining satellite weather data and energy production values, providing customised solutions and specific monitoring designed for energy integration purposes	Commercialized	SmartMonitor (Nnergix)
AV SENSOR 2000R/4000R	Development of a line of wireless sensors, which will provide key information to improve the management and	Pre-commercial	AV SENSOR 2000R/4000R

Project/Innovation	Description	Stage of development	Commercial solution (provider)
	operation of power generation assets		(AMC)
AV MONITOR 4000	platform for online condition monitoring, failure protection and vibration-based diagnostics of machinery	Commercialized	AV MONITOR 4000 (AMC)
Windcrete	Spar type floating substructure designed to carry wind turbines of up to 10 MW in deep offshore marine environments. Pre-stressed reinforced concrete is shaped in a monolithic structure	Pre-commercial	(Windcrete)
X1 Wind	Floating system with significantly lower weight and easier to install (see also H2020-funded Pivot Buoy project led by X1 Wind)	Pre-commercial	(X1 Wind)
Nabralift	Self-erecting tower formed by a three column structure installed under the uppermost part of a wind turbine generator tubular tower, resulting in a hybrid support steel tower	Pre-commercial	Nabralift (Nabrawind)
Predictive (SMART CAST / SMART GEAR/ SMART SCADA)	IT platform solutions to monitor wind turbines to enable real-time online monitoring and control	Commercialized	SmartCast/SmartGear (Smartive)
Pro-Drone	Inspection of energy infrastructures, using cost-efficient, robust and automated airborne solutions	Commercialized	Pro-Drone (Pro-Drone)
S.T.E.P.	Technology that allows the worker to reach (both horizontally and vertically) any part of the structure with a simple harness and a remote control	Commercialized	S.T.E.P. (Vertequip)
Back-flow flaps (retrofit) on wind blades	Small flaps are adhered to rotors via adhesive technology. A passive model and pneumatically controlled models are planned to enhance the yield of wind energy facilities	Pre-commercial	(WTS Wind-Tuning-Systems GmbH)

3.3.2 European Energy Programme for Recovery (EEPR)

The EEPR (launched in 2009 by European Investment Bank Group) supports key investments in the context of the economic crisis and in order to promote the energy transition. With €3.98 bn the EEPR aimed to fund 44 gas and electricity infrastructure projects, nine offshore wind projects and six carbon capture and storage projects [EC 2016a, EC 2018c]. By February 2020 substantial progress was made in terms of offshore wind energy with six out of nine projects being operational and one project being commissioned by Q1 2020 (see ***Table 11***).

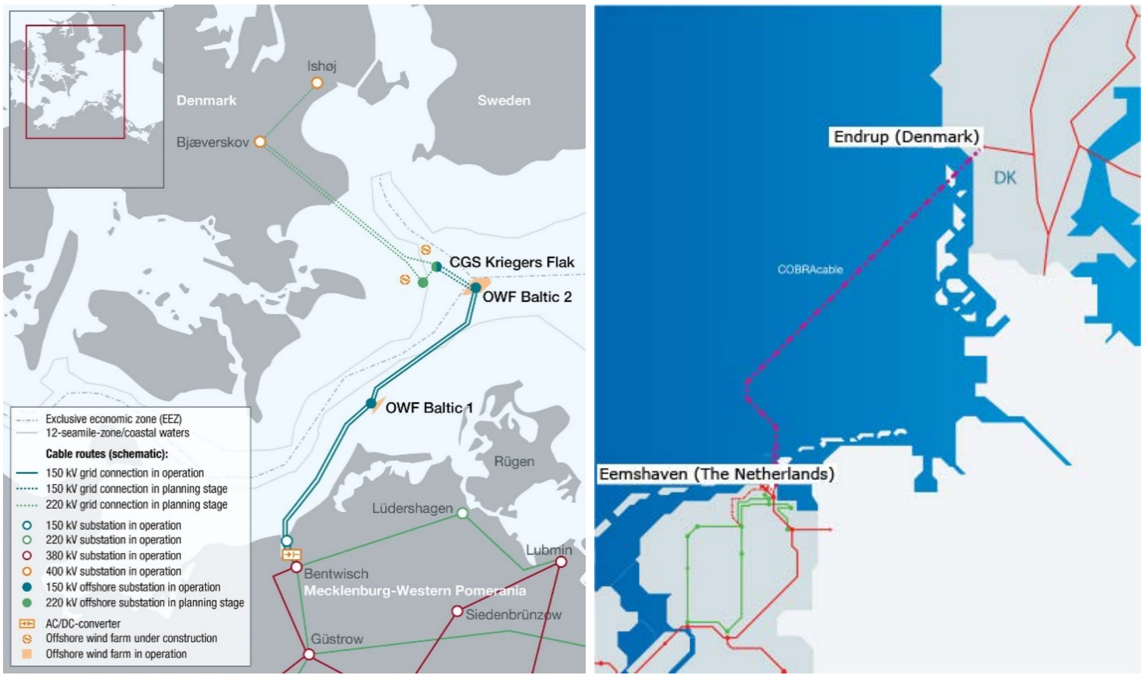
Two offshore wind grid integration projects (see **Figure 29**), Kriegers Flak (CGS) and COBRACable, are complete or close to completion, only the OffshoreHVDC hub project was terminated end of 2012 as the project coordinator wished to change the project significantly. Kriegers Flak (CGS) is close to being commissioned, the converter at the substation in Bentwisch (DE) is already in place, individual commissioning steps will slightly postpone the final commissioning and trial runs towards August 2020 [50Hertz 2020a, 50Hertz 2020b, 50Hertz 2020c]. The COBRACable subsea interconnector operates since mid-2019 and connects Eemshaven (NL) and Endrup (DK) with a ±320 kV HVDC bipole system [OW 2019c, OW 2019d].

Except Global Tech I all projects in the sector 'Offshore turbines and structures' have been completed, with the Aberdeen Offshore Wind Farm -Wind Deployment Centre generating first power in July 2018 [Vattenfall 2018]. Global Tech I was terminated in 2014 as the project struggled to obtain the permit for installing the gravity offshore foundations and in finding a co-investor.

Table 11 Status of EEPR funded offshore wind projects

Project	Description	Status	Grants Awarded (Cumulative payments received) [EUR]
OFFSHORE WIND-GRID INTEGRATION			
Kriegers Flak	Designing, installing and operating a Combined Grid Solution for the grid connection of the offshore wind farms to the Danish region of Zealand and the German state of Mecklenburg-Western Pomerania	ONGOING (Commissioning and trial run in Q1 2020)	150,000,000
COBRAcable	Realisation of a sub-sea power link (VSC-HVDC) between Denmark and The Netherlands	COMPLETED	86,540,000
OffshoreHVDC Hub	Addition of an intermediate offshore platform on a planned HVDC link for connecting offshore wind and marine generation in the North of Scotland	TERMINATED	(3,097,512)
OFFSHORE TURBINES AND STRUCTURES			
Thornton Bank wind farm	Optimised logistics for up scaling the far-shore deep-water Thornton Bank wind farm and demonstration of innovative substructures (jacket foundations) for deep water off shore parks	COMPLETED	10,000,000
BARD Offshore 1	Production of innovative tripile foundations and production and installation of innovative cable in-feed system for a 400 MW offshore windfarm	COMPLETED	53,100,000
Global Tech I	Design and serial manufacturing of gravity foundations for multi MW turbines, including an innovative and fast installation process	TERMINATED	(4,494,476)
Nordsee Ost offshore wind farm	Supply of innovative wind turbine generators (6.15 MW) for a 295 MW offshore wind farm	COMPLETED	50,000,000
Borkum West II	Supply of innovative wind energy converters and tripod foundation structures, including implementation of an innovative installation method, for the first phase of a 400 MW wind farm	COMPLETED	42,710,000
Aberdeen OWF - Wind Deployment Centre	Connection of a commercial offshore wind farm with a Deployment Centre, consisting of an ocean laboratory, environment monitoring and testing centre	COMPLETED	40,000,000

Figure 29 Location of interconnectors Kriegers Flak (Combined Grid Solution) and COBRACable [50Hertz 2020b, COBRACable 2020]



3.3.3 NER300 programme

The NER 300 programme took its name from the sale of 300 million emission allowances from the New Entrants' Reserve (NER) set up for the third phase of the EU emissions trading system (EU ETS). The funds from the sales have been distributed to projects supporting the demonstration of innovative CCS and renewable energy technologies. In total eight projects have been selected in the area of wind energy [EC 2020am].

The offshore wind projects Veja Mate (DE) and Nordsee One (DE) as well as the onshore wind projects Handalm (AT) and Blaiken (SE) have already been commissioned. However, with WindFloat (PT) only one of the four floating offshore wind projects is close to completion. Beginning of January 2020, a first platform including a 8.4 MW turbine was successfully connected and supplied power to the grid, the remaining two turbines are already assembled at quay side in Ferrol (PT) and are ready for being deployed at the site [GWS 2020, Principle Power 2020]. By mid-2019, the 25 MW FLOCAN 5 (ES) project at Canary Islands did not reach Final Investment Decision (FID), a full commissioning of the project might not happen before 2024 as the project is still required to provide a detailed Environmental Impact Assessment to analyse the impact of the anchoring system on the marine environment. After receiving state aid clearance from the EC [EC 2019a], the VERTIMED (FWT Provence Grand Large) (FR) project did not reach FID until Q4 2019 as there have been appeals against its authorisation (e.g. by Nacicca (Nature et Citoyenneté Crau Camargue Alpilles) raising concerns about negative impacts of the project on fish-eating birds)[Nacaccia 2018, Greenunivers 2019]. Commissioning of the project using a TLP-floater is expected by 2021 [EDF 2019, PGL 2019]. For the BALEA project (ES) no significant update could be observed. Still the project is delayed and all efforts are focused on ensuring the financial viability of the project [EC 2017]. However its future location, the open sea test platform 'Biscay Marine Energy Platform (BiMEP)', has obtained the permit from the Ministry of Agriculture, Fisheries and Food and Environment to host offshore wind development projects [TETHYS 2020].

The lessons learned from the NER300 programme will be taken into account by its successor the Innovation Fund (expected in June 2020) aiming for opening funding to energy intensive industries, decreasing financial risk exposure and allowing stronger synergies with other EU funding programmes [EC 2020an].

Table 12 Status and maximal funding of NER300 wind projects [EC 2020am]

Project	Status	Max NER300 funding [EUR million]
Veja Mate (DE)	COMPLETED	112.6
Nordsee One (DE)	COMPLETED	70.0
Handalm (AT)	COMPLETED	11.3
Blaiken (SE)	COMPLETED	15.0
WindFloat (PT)	ONGOING	30.0
FLOCAN 5 (ES)	ONGOING	34.0
VERTIMED (FWT Provence Grand Large) (FR)	ONGOING	34.3
BALEA project (ES)	ONGOING	33.4

3.3.4 InnovFin initiative

"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. One of the key factors constraining the implementation of R&I activities is the lack of available financing at acceptable terms to innovative businesses since these types of companies or projects deal with complex products and technologies, unproven markets and intangible assets. In order to overcome these difficulties, the EU and the EIB Group have joined forces to provide finance for research and innovation to entities that may otherwise struggle to access financing [EIB 2020]. Within this context 'InnovFin Energy Demonstration Projects' provides loans, loan guarantees or equity-type financing (typically between €7.5 m and €75 m) to innovative demonstration projects in the fields of energy system transformation bringing projects from pre-commercial level (at TRL 7-8 [EC 2016b]) to commercialisation. Up to €800 m are made available to help companies demonstrate the commercial viability of their projects and since 2016 five first-of-a-kind projects have been supported with loans totalling to about €167.5 m. With €60 m the largest loan so far was granted to the Windplus consortium (Energias de Portugal, REPSOL and Principle Power Inc.) building the innovative floating offshore wind farm 'WindFloat Atlantic' (PT) in order to harvest wind power in deep water areas [EC 2019b].

3.4 IEA Technology Cooperation programme on wind energy systems (IEA TCP Wind)

The IEA Technology Cooperation programme on wind energy systems (IEA TCP Wind) is to stimulate co-operation on wind energy research, development, and deployment (RD&D). Main objectives in view of the 2019-2024 Strategic Work Plan [IEA 2019a, IEA Wind TCP 2019b] include

1. research and sharing of best practices on the integration of wind power into energy systems in order to maximise the value of wind energy,
2. cost reduction of land-based and offshore wind to improve the economic performance of wind energy projects in both mature and emerging markets,
3. refining communication and technological tools to enhance the social support for, and environmental compatibility of, wind energy projects and to reduce barriers to wind energy deployment and
4. support of international collaborative research and the exchange of best practices and data.

16 research tasks were in place in 2018 (see ***Figure 30***). While Task 27 (Small Wind Turbines in Turbulent Sites) concluded at the end of 2018, two new tasks on 'Distributed Wind' (Task41) and on 'Wind Energy Digitalisation' (Task 43) were approved in 2019 [IEA Wind TCP 2019c].

Figure 30 Strategic priority and research tasks in the IEA Wind TCP in 2018 [IEA Wind TCP 2019b]

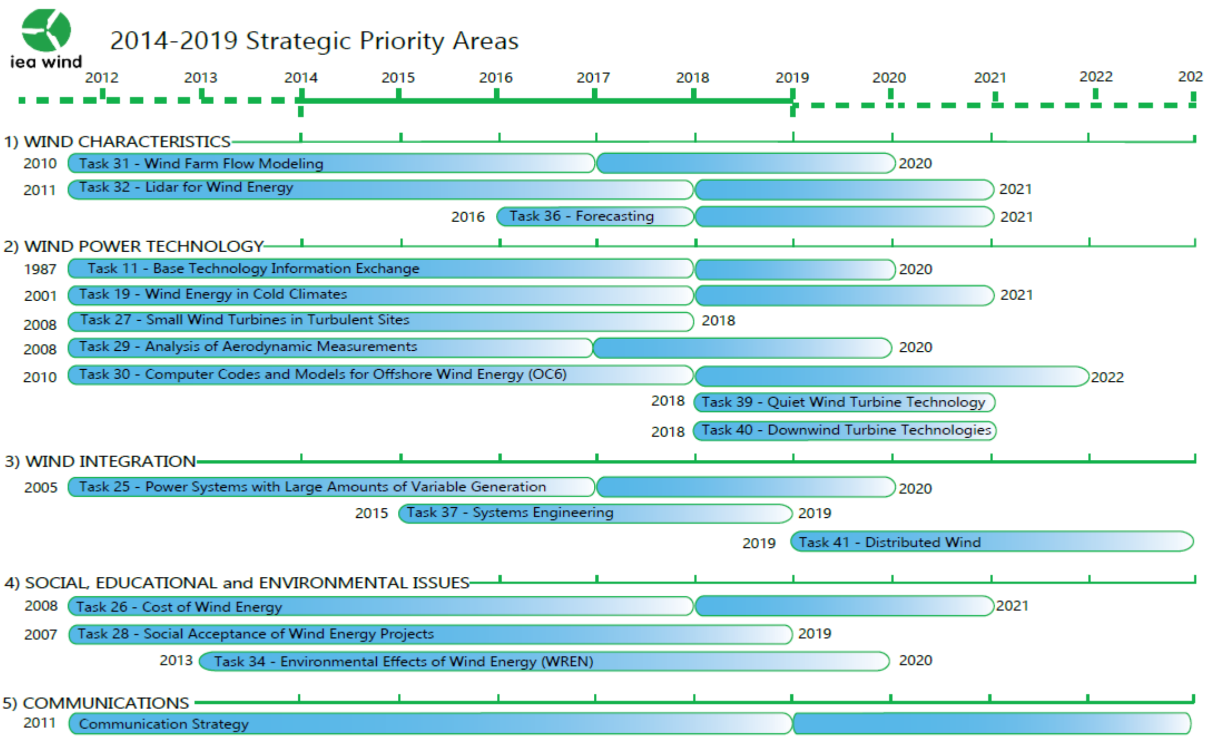


Table 13 lists the different research task in each of the main areas of work of the IEA TCP and gives an update on the latest progress, activities and topical experts meetings (TEM).

Table 13 IEA Wind TCP research tasks and selected achievements in 2019

Task	Description	Selected outcomes and achievements in 2019
WIND CHARACTERISTICS: Resource and site characterisation		
Task 31	WAKEBENCH	In 2019 an updated design of the verification and validation (V&V) framework is in development and a consolidated roadmap for wind and wake models will be produced [The Wind Vane 2019]
Task 32	Lidar[13] for Wind Energy	Publication of Several white papers (2-pagers) on the following topics: Wind Lidar, Increasing the impact of wind through digitalisation and the OpenLidar initiative. Moreover, a collaborative R&D Roadmap was published in order to give an overview on all Lidar related topics and meetings in this task [Clifton, Schlipf et al. 2019, Clifton, Vasiljevic, Wuerth et al. 2019, Clifton, Vasiljevic & Würth 2019, Clifton & Schlipf 2019]
Task36	Forecasting	Release of 'Recommended Practice on Forecast Solution Selection' [IEA Wind Task36 2019]
WIND POWER TECHNOLOGY: Advanced technology for wind energy		
Task 11	Base Technology Information Exchange	Release of a TEM workshop reports on Large Component Testing for Ultra-long Wind Turbine Blades. 3 TEMs on Reliability/Availability of electrical infrastructure, Wind Farm Control and Wind Plant Decommissioning, Repowering and Recycling
Task 19	Wind Energy in Cold Climates	Update of Task19 T19IceLossMethod IPS update. Task 19 has developed an open source Python code. The software and its documentation is available for download on [IEA Wind Task19 2019]
Task 29	Analysis of Aerodynamic Measurements	Danish DanAero field experiments have been uploaded into a database, released to Task 29 participants
Task 30	Offshore Code Comparison Collaboration Continued, with Correlation, and unCertainty (OC6)	Improvements to industry offshore wind design tools based on findings of Task 30. Release of findings from verification and validation of the full-scale, open-ocean alpha ventus wind farm (see [Popko et al. 2019]
Task 39	Quiet wind turbine technology	Release of factsheet on amplitude modulation in wind turbine noise. Ongoing work focuses on benchmarking wind turbine noise codes [IEA Task 39 2018]
Task 40	Downwind Turbine Technologies	Update of tower shadow simulations for 2MW downwind wind turbine. Completion of experiments on nacelle-rotor interaction and creation of a 10 MW rotor baseline for blade optimization.
WIND INTEGRATION: Energy systems with high amounts of wind		
Task 25	Design and Operation of Power systems with large amounts of wind power	Release of recommendations for 'how to perform integration studies' and final summary report on phase 4 of the task [Holttinen 2019, IEA Task 25 2019].
Task 37	Systems Engineering	Release of technical report and associated data for the two new reference turbines (3.4 MW onshore and 10 MW offshore) [IEA Task 37 2019a, IEA Task 37 2019b, IEA Task 37 2019c]. Ongoing work on publishing of turbine and plant ontology.
Task 41	Enabling wind to contribute to distributed energy future	Task41 performed a revision of existing databases and portals and initiated data collection for the data information catalogue. Review of modelling and simulation tools and review of existing grid codes
SOCIAL, ENVIRONMENTAL and ECONOMIC ISSUES		
Task 26	Cost of Wind Energy	Release of Cost of Wind Energy Phase 3 Final Technical report [IEA Task 26 2019]. Update of data viewer on onshore wind cost indicators.
Task 28	Social Acceptance of Wind Energy Projects	Papers on health concerns (stress, annoyance) and predicting audibility in progress. A proposal for next phase of Task is under development.
Task 34	WREN – Working together to resolve environmental effects of wind energy	Multiple white papers and short science summaries (e.g. on Risk-based Management, European Soaring Birds and Wind Energy Development, Tethys peer review)-close to publication [IEA Task 34 2019].

[13] Light detection and ranging

3.5 R&D focus of other major non-EU players

3.5.1 Wind research focus in the US

Wind energy R&D in the US focuses on the main topics within the sector. The research programme on wind energy technology of the U.S. Department of Energy (DOE) is categorised in the following subtopics [DOE 2020a]:

- Offshore wind
- Land-based wind
- Distributed wind
- Grid system integration
- and Data, Modelling & Analysis.

In general DOE sees key challenges in the costs of both offshore and land-based wind energy and in technical aspects of floating offshore wind. Moreover, integration of large-scale wind farms into the electricity grid and environmental and siting questions are seen as constraints for technology development. In order to tackle these challenges DOE defined the following Top-Line R&D priorities:

- Continue aggressive cost reduction for all technologies (DOE's cost reduction targets for wind energy by 2030: Land-based wind (2 $cent/kWh (1.8 €cent/kWh)); Offshore wind (5 $cent/kWh (4.5 €cent/kWh)); Distributed wind (4-7 $cent/kWh (3.6-6.2 €cent/kWh), depending on turbine size))
- Enable supersized, lightweight wind turbines
- Address key environmental & siting challenges
- Develop electric energy and grid services provided by affordable, transmission-facilitated, cyber-secure, and hybrid-ready wind

Offshore wind R&D priorities address fixed-bottom offshore technology, floating offshore devices and cross-cutting topics. Priorities in fixed-bottom offshore wind address wind resource characterization gaps and the environmental and societal impact of the technology. Floating offshore R&D prioritises simulation and experimental research to reduce the need for extensive demonstration projects. Cross-cutting topics entail the completion of advanced offshore demonstration projects, advanced technology development for ultra-large and ultra-light turbines and blade manufacturing as well as the research on autonomous inspection & maintenance systems. Notably in September 2019, the DOE's of Energy's Advanced Research Projects Agency (ARPA) announced $26m in funding for 13 projects as part of the Aerodynamic Turbines, Lighter and Afloat, with Nautical Technologies and Integrated Servo-control (ATLANTIS) program. It focuses on three technology development areas (1) New Designs, 2) Computer Tools, and 3) Experiments) in order to develop a fully integrated floating offshore wind system [DOE 2019]. ***Table 14*** shows the awarded organisations and projects striving for breakthrough innovations in floating offshore wind.

Table 14 Floating offshore wind projects in the DOE ARPA ATLANTIS programme [DOE 2019]

Project description	Organisation	Funding
ARCUS Vertical-Access Wind Turbine: Design of a vertical-axis wind turbine (VAWT) system replacing the turbine's tower with lighter, tensioned guy wires t reduce the top mass..	Sandia National Laboratories–Albuquerque, NM	$2.5m (€2.2m)
Design and Develop Optimized Controls for a Lightweight 12 MW Wind Turbine on an Actuated Tension Leg Platform (mass reduction of up to 25%)	General Electric Company,GE Research–Niskayuna, NY	$2.8m (€2.5m)
DIGIFLOAT: Development, Experimental Validation and Operation of a DIGItal Twin Model for Full-scale FLOATing Wind Turbines. Digital	Principal Power Inc.–Emeryville, CA	$3.6m (€3.2m)

Project description	Organisation	Funding
twin model will be a real-time, high-fidelity numerical representation of the WindFloat Atlantic (WFA) Project		
A Low-Cost Floating Offshore Vertical Axis Wind System. Development of a system based on a hierarchical control co-design (H-CCD) framework tailored to the floating VAWT system design.	The University of Texas at Dallas–Richardson, TX	$3m (€2.7m)
A Co-Simulation Platform for Off-Shore Wind Turbine Simulations. Development of a software for the coupled simulation and control co-design of floating offshore wind turbines.	The University of Massachusetts–Amherst, MA	$1.2m (€1.1m)
USFLOWT: Ultraflexible Smart FLoating Offshore Wind Turbine. USFLOWT is an advanced wind turbine with ultra-flexible and light blades, advanced aerodynamic control surfaces,and a revolutionary substructure: the SpiderFLOAT (SF). The SF is bioinspired, ultra-compliant, modular, and scalable.	National Renewable Energy Laboratory–Golden, CO	$1.5m (€1.3m)
Wind Energy with Integrated Servo-control (WEIS): A Toolset to Enable Controls Co-Design of Floating Offshore Wind Energy Systems	National Renewable Energy Laboratory–Golden, CO	$2.7m (€2.4m)
The FOCAL Experimental Program: The FOCAL experimental program will generate critical datasets to validate these capabilities from four 1:60-scale, 15-MW (megawatt) FOWT model-scale experimental campaigns in the UMaine Harold Alfond W2 Wind-Wave Ocean Engineering Laboratory.	National Renewable Energy Laboratory–Golden, CO	$1.5m (€1.3m)
AIKIDO -Advanced Inertial and Kinetic energy recovery through Intelligent (co)-Design Optimization.	Otherlab–San Francisco, CA	$2.6m (€2.3m)
Scale Model Experiments for Co-Designed FOWTs Supporting a High-Capacity (15MW) Turbine. Providing experimental data to validate computer programs and new technologies developed for floating offshore wind turbine (FOWT) applications.	WS Atkins–Houston, TX	$1.6m (€1.4m)
Computationally Efficient Atmospheric-Data-Driven Control Co-Design Optimization Framework with Mixed-Fidelity Fluid and Structure Analysis	RutgersUniversity, The State University of New Jersey–Piscataway, NJ	$1.4m (€1.2m)
Model-Based Systems Engineering and Control Co-Design of Floating Offshore Wind Turbines	The University of Central Florida–Orlando, FL	$0.5m (€0.4m)
Development of an ultra-light Concrete Floating Offshore Wind Turbine with NASA-developed Response Mitigation Technology	The University of Maine–Orono, ME	$1.4m (€1.2m)

Since 2017 DOE (2020a) reports 12 funded offshore wind R&D projects totalling to about $65m (see ***Table 15***).

Table 15 DOE R&D investments in offshore wind in the period 2017-2019 [DOE 2020a]

Topics of research projects	Year of funding	# of projects	Funding
Aerodynamic Turbines, Lighter and Afloat, with Nautical Technologies and Integrated Servo-control (ATLANTIS) program	2019	13	$26m (€23.2m)
Offshore wind testing R&D at national level-facilities	2019	6	$7m (€6.2m)
Project development activities for demonstration projects	2019	2	$10m (€8.9m)
Offshore wind environmental monitoring technologies	2018	3	$2.3m (€2.0m)
National Offshore Wind R&D Consortium to address technological barriers and lower costs and risks	2017	1	$20m (€17.8m)

Land-based (onshore) wind R&D focuses on cost reduction, environment and siting. Cost reduction shall be achieved through moving to increased hub heights and the development of larger, lighter and more flexible rotors, meaning a decrease of specific power from about 250 W/m^2 towards 150 W/m^2. Moreover land-based R&D priorities aim for wind plant optimisation through developing a better understanding of the wind resource and the development of controls to minimise losses from wake effects or loads. Environment and siting R&D priorities address all aspects to reduce impacts on wildlife, wind turbine radar interference and communities. Since 2017 DOE (2020a) reports 12 funded land-based wind R&D projects totalling to about $23m

Table 16 DOE R&D investments in land-based wind since 2018 [DOE 2020a]

Topics of research projects	Year of funding	# of projects	Funding
Validation & demonstration of tall tower manufacturing innovations	2019	2	$10m (€8.9m)
Development of next-generation, lightweight generators: (1) WEG Energy Corporation developing a high-efficiency PM direct drive lightweight generator (2) American Superconductor Corporation developing a lightweight generator with high-temperature superconductor (HTS) materials (3) General Electric (GE) Research developing a high-efficiency ultra-light low temperature superconducting (LTS) generator	2018	3	$8m (€7.1m)
Wildlife impact mitigation technologies	2018	7	$5m (€4.5m)

Distributed wind R&D is divided into large scale (MW-scale) and small scale (kW-scale) devices. R&D priorities for large scale devices focus on the integration and control of the technology into microgrids and the interaction with other technologies. In 2019 four projects ($6m) were funded within the WIRED-initiative (Wind Innovations for Rural Economic Development) supporting rural electric utilities and communities by reducing the technical complexity and risks associated with distributed wind and distributed energy resource development and deployment. The small-scale distributed wind R&D aims for an increased deployment of small scale wind turbines in the industrial, commercial and residential area. In order to become more competitive DOE partners with manufacturers of small-scale wind turbines in the Competitiveness Improvement Project (CIP). CIP shows significant progress in cost reduction of small-scale wind as exemplified by the development of the 'Bergey Excel 15' turbine allowing to reduce the technology's LCOE from about 25 $cent/kWh of its predecessor to about 12 $cent/kWh [DOE 2020a].

R&D on grid systems integration of wind energy prioritises energy storage (e.g. incentivised through a new program for American global leadership in energy storage), provision of grid services from wind, enabling technologies for grid integration and resilience towards cyber-attacks. Wind research in this activity can be seen as part of the initiatives performed in the Grid Modernization Consortium Laboratory (GMCL) which was established as a strategic partnership between DOE and the US laboratories to pool strengths in collaborating on the modernization of the national grid. Against this backdrop, the DOE awarded up to $220m to 88 grid related projects to DOE's national labs and partners (a list of awarded projects can be found at DOE (2020b)).

DOE'S R&D on Data, Modelling & Analysis performs technical and economic analysis to find the most promising pathways for federal R&D investment. In this context, the most important target dimensions for wind energy are cost reduction, increased value to the grid, the regulatory framework and to overcome market barriers.

Apart from these main work streams DOE identifies the fast-growing demand for skilled workforce as a major challenge. In 2019 a study on training, hiring and future workforce needs found that the US wind industry is facing a challenging situation with respect to domestic hiring for most wind related occupations. As such, a significant share of companies searches for skilled personnel outside the US. Moreover, the performed survey showed that the majority of graduates from US wind energy educational programmes find employment outside the wind industry [Keyser & Tegen 2019].

3.5.2 Wind research focus in China

As already outlined in the previous version of the LCEO Technology development report [JRC 2019a] information on Chinese wind energy R&I priorities is limited (please see JRC (2019a) for the broader R&I priorities of the generic instruction on wind power development in the 13th Five-Year Plan). However, selected information on current challenges, R&I initiatives and collaborations is obtained from the Chinese Wind Energy Association (CWEA) and the EC funded project "*Improving EU Access to National and Regional Financial Incentives for Innovation in China*" [CIF 2019].

Similar to other markets CWEA (2019) reports that the Chinese market focuses on technology innovations aiming for increasing turbine capacity, extended blade length, increased hub height and intelligent control systems. As such national wind energy R&D tasks released in 2018 focus on:

- *Complicated wind resource characteristics*
- *Extra-long blade test technology and test equipment*
- *Key technology of design, batch production, installation and O&M for large capacity offshore wind turbines*

According to CWEA (2019) the new R&D plan in 2019 targets the following topics:

- *The R&D of large capacity wind turbine and components for development of deep sea wind power*
- *Key technologies on test and verification of large offshore wind turbine's coupling performance under multiple fields [sic].*

R&D of the major Chinese OEMs resulted in the design and commission of new large-scale onshore and offshore turbines. ***Table 17*** summarizes the latest achievements as reported by CWEA (2019).

Table 17 R&D achievements and products released by Chinese wind energy OEMs in 2019 [CWEA 2019]

Chinese OEM	Description of latest R&D achievements/products
Mingyang	ONSHORE: Release of 4.x MW platform with 145m, 156m rotor diameters OFFSHORE: MySE5.5-155 and MySE7.25-158 offshore wind turbines were put into operation
Goldwind	ONSHORE: Release of 4.x MW platform OFFSHORE: Release of 6.x MW platform GW155-4.5MW, GW150-6.7MW were put into operation
Shanghai Electric Group	Assembly of 8MW wind turbine with rotor diameter 167m in August 2019.
Haizhuang Windpower	Release of the H171-6.2MW offshore wind turbine with a rotor diameter of 171m. A 10MW model is under manufacturing.
Dongfang Electric Group	Completed manufacturing of a 10MW wind turbine generator and a 7MW wind turbine (91m rotor blade) in Q3, 2019.

CWEA sees the absence of standards for smart wind turbines as one of the key challenges for wind energy. Moreover, increased size of extra-long blades and weight reduction asks for new design approaches (e.g. airfoil design, low-cost carbon fibre, new materials, etc.) and optimised control technology. Cost reduction is needed along the entire value chain addressing manufacturing, transportation and installation. Furthermore, the increased size of components creates the necessity for appropriate testing and assessment techniques. Finally cost reduction of offshore wind projects and performance measurements at complex terrains are perceived as further key challenges.

China supports public R&D investment in clean energy through its national funding programmes, especially via its National Key R&D Programmes (NKPs). Fifteen out of 64 currently existing NKPs are dedicated (fully or partially) to R&D in clean energy. However, with the 'NKP - Renewable energy and hydrogen technologies' only one NKP could be identified clearly relating to wind energy research (see ***Table 18***). Furthermore, CIF (2019) finds that almost none of the clean energy-related NKPs stimulates Sino-foreign collaboration.

Table 18 Single NKP addressing wind related research (out of the 15 ongoing NKP Chinese funding programmes supporting clean energy R&I) [CIF 2019]

Programme	Policy basis	Objective	Clean energy-related	Past funding projects
NKP - Renewable energy and hydrogen technologies **可再生能源与氢能技术** (2018-2022)	Action Plan for Energy Technology Revolution and Innovation (2016 2030) Medium to Long - term Development Plan for Renewable Energy	Provide significant contribution to the country's efforts in upgrading its energy structure and in tackling climate change	▪ Solar energy ▪ **Wind energy** ▪ Biomass energy ▪ Geothermal energy and ocean energy ▪ Hydrogen energy ▪ Renewable energy coupling and system integration	Around RMB 656m on RMB will be allocated to fund 32 projects in 2018 (tbc)

The Chinese government supports international cooperation in clean energy research through ad hoc topics under "intergovernmental cooperation NKPs" which are open to universities, research institutes and enterprises and joint research partnerships or facilities between Chinese public institutions and foreign governments or institutions. To a limited extent corporate R&I takes place. Two wind energy-related partnerships between European and Chinese partners could be identified. A Sino-Danish joint research partnership to facilitate the roll-out of offshore wind energy in China and a corporate Sino-UK partnership between ORE Catapult/TusPark and Tus-Wind developing an offshore wind farm and providing market access for UK SMEs to the Chinese market (see ***Table 19***).

Table 19 Partnerships between European and Chinese institutions in the area of wind energy [CIF 2019]

Country	Type of partnership	Project name	Foreign partner	Chinese partner	Details
Denmark	Public R&I (Joint research partnership)	Sino-Danish Offshore Wind Cooperation ("Quality Offshore")	Danish Ministry for Energy, Utilities and Climate	National Energy Administration (NEA)	Development of strategies, policies and solutions to improve China's roll-out of offshore wind energy
United Kingdom	Private (corporate) R&I	TUS-ORE Technology Research Centre	Offshore Renewable Energy (ORE) Catapult; TusPark Newcastle	Tus-Wind; Yantai local government (Shandong province)	R&D of innovative clean technologies; development of an offshore wind farm; market access assistance to UK SMEs in China

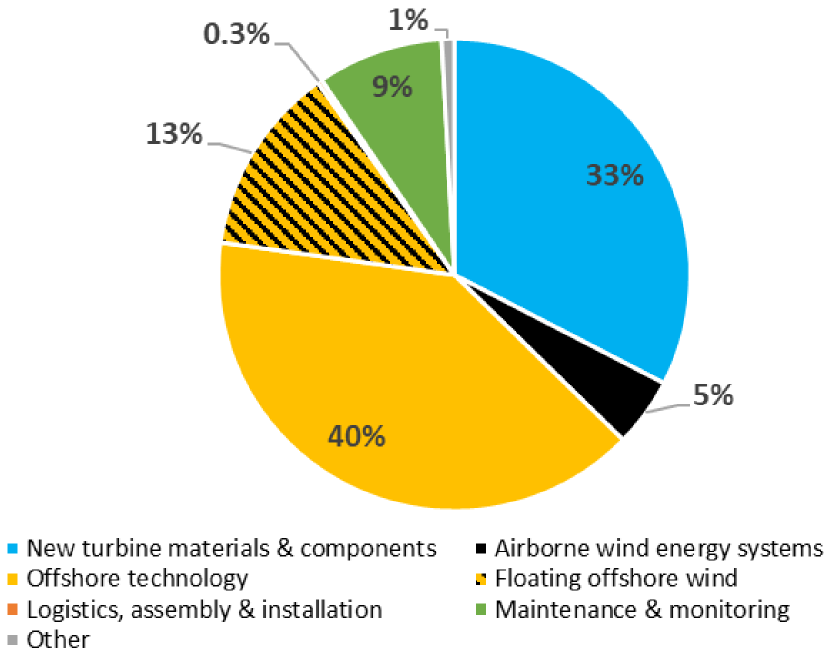
4 Impact assessment of H2020 projects

This chapter analyses the impacts of H2020 projects completed in 2019. The assessment is based on publicly available information as well as on information provided by the projects in their final reports, exploitation and dissemination plans. The information from these sources is mainly evaluated in terms of achieved TRL by the project complemented with the available information on other innovation indicators (e.g. patents, peer-reviewed papers, conference papers).

4.1 H2020 projects completed in 2019

In total 20 wind-related H2020 projects[14] finished in 2019 with a cumulated investment of €57.6m (see Annex 3). With about 40% offshore technology research received the majority of the funds followed by projects on 'New turbine materials and components', 'Floating offshore wind' and 'Maintenance & monitoring' (see ***Figure 31***).

Figure 31 Share of wind energy funding under H2020 granted to projects completed in 2019 categorised by research area for wind energy.



Significant amount of these funds (about 80%) was granted to the leading countries in onshore or offshore wind energy deployment (Spain, Germany, the Netherlands, Denmark, the United Kingdom) mainly in the research area 'New turbine materials and components' and 'Offshore technology' (see ***Figure 32***). Consequently, also eight of the top 10 recipients of these funds stem from these countries and focus on the aforementioned research areas (see ***Figure 33***).

[14] The DEMOGRAVI3 project, which had a planned end date in 2019, is not part of this analysis as the project was terminated beginning of 2018 as one of the key partners left the project consortium and could not be replaced.

Figure 32 Wind energy related EC funding in H2020 projects completed in 2019 by beneficiary country

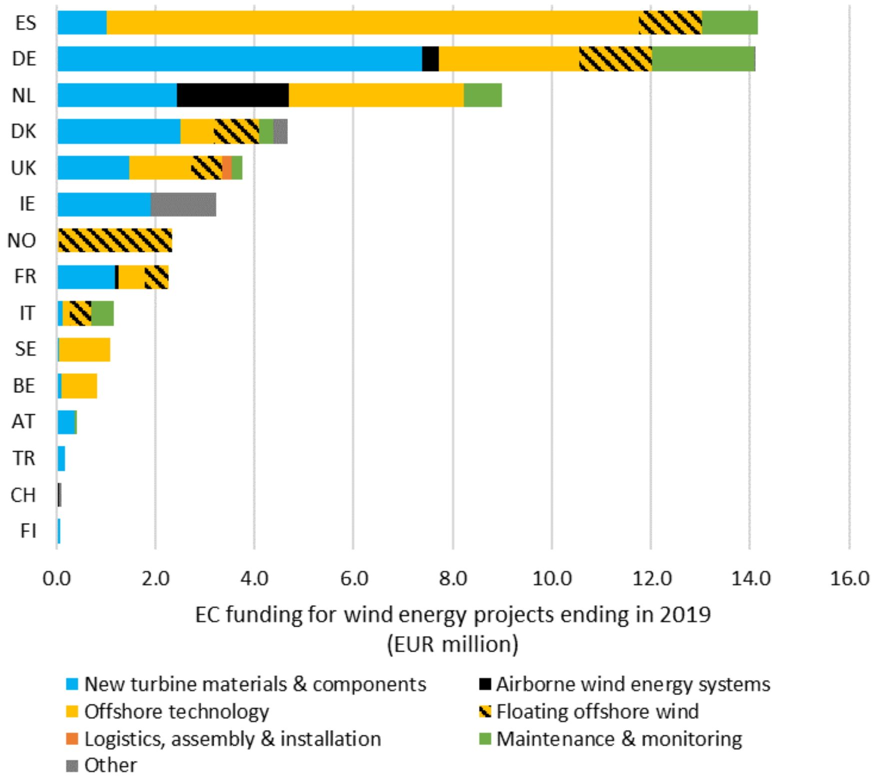
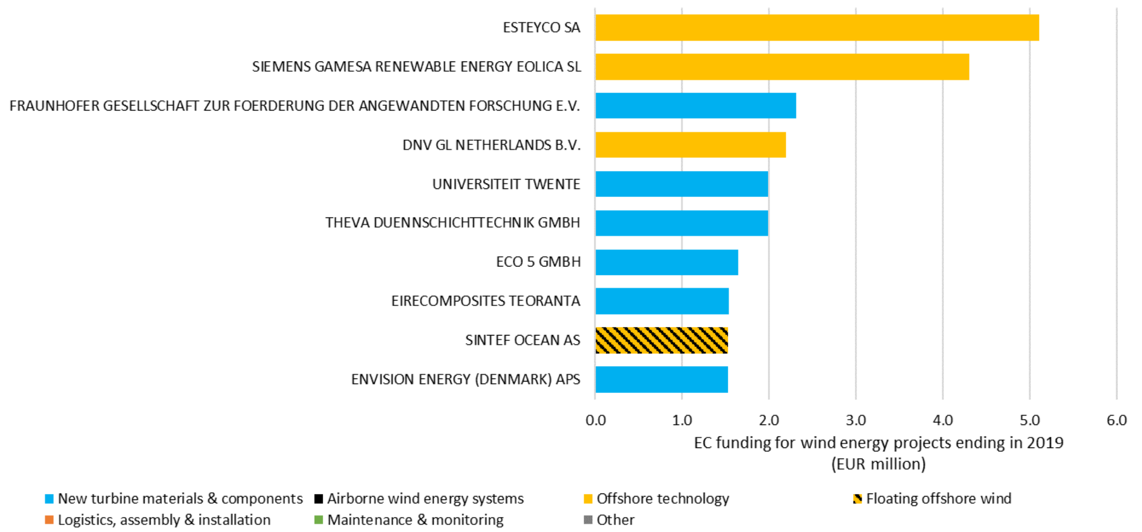


Figure 33 Top10 organisations in terms of received wind energy related EC funding by H2020 projects completed in 2019



The following sections analyse the impact of these projects differentiating by H2020 sub-programmes and type of innovation action instrument (Innovation Action (IA), Research Innovation Action (RIA),…)

4.1.1 H2020 projects – Secure, clean and efficient energy programme

This programme accumulates the majority of the wind-related H2020 funds of projects ending in 2019 (about €49.1m). The following projects ending in 2019 are funded under this programme: LIFES 50plus, EcoSwing, CL-Windcon, PROMOTION, Riblet4Wind and ELICAN. ***Table 20*** shows the TRL target of the project as well as the innovation indicators and the TRL achieved.

Table 20 Overview of impact assessment of H2020 projects completed in 2019 under the 'Secure, clean and efficient energy' sub-programme '

Project Acronym	Research area	TRL target	TRL achieved	# patents	# peer reviewed papers	# conference papers	Type of innovation action / instrument
LIFES 50plus	Floating offshore wind	TRL 5	YES	0 (1*)	5	1	RIA
EcoSwing	New turbine materials & components	Advance from TRL 4-5 to 6-7	YES (now at TRL 7-8)	0	4	5	IA
CL-Windcon	Maintenance & monitoring	TRL 5-6	Unclear (no final report/final assessment of project is ongoing (Feb 2020))	0	19	18	RIA
PROMOTION	Offshore technology	TRL 9	Unclear (no final report/final assessment of project is ongoing (Feb 2020))**	0	8	64	IA
Riblet4Wind	New turbine materials & components	no specific TRL reported (assumed to be TRL7, as objectives mention 'full-scale technology demonstration')	NO***	0	1	0	IA
ELICAN	Offshore technology	TRL 7	YES (TRL7)	3	0	4	IA

* A patent application related to the solution for the connection of the tower and concrete substructure has been filed
** Several subcomponents at TRL 6 according to earlier reporting
*** No access to modern state-of-the-art wind turbines for their demonstration campaign

The objective of the LIFE 50plus project is to install floating wind concepts capable to carry 10 MW turbines at water depths from 50 m to about 200 m. A TRL 5 was achieved through hybrid tests combining wind tunnel and basin tests. Moreover, one of the project partners (DNVGL) produced two floating offshore wind specific service documents providing guidance for the design and analysis of floating wind turbine structures: a standard and a recommended practice. EcoSwing, a project investigating a superconducting low-cost and lightweight drivetrain, demonstrated their concept on a

3.6 MW modern wind turbine. The concept operated more than 650 hours and generated about 660 MWh. Although an even higher TRL (7-8) was achieved, the present system is currently considered as not fully suitable for industrialization as for example the quench protection was reported to be rethought in terms of necessity and design. So far, no indication of patenting out of the project could be observed. For both projects CL-Windcon (advanced control algorithms) and PROMOTION (meshed HVDC offshore grids and technologies) no final project report was available, however several subcomponents (e.g. HVDC grid protection IED, HVDC GIS technology) of the latter were reported to show progress in terms of TRL. Riblet4Wind proposed the application of functional coatings with riblet structure to improve the drag to lift ratio of rotor blades. Unfortunately, the project did not reach the objectives set, as the consortium did not get access to state-of-the-art wind turbines for their demonstrator. Consequently, the demonstrator was applied to an outdated turbine model. ELICAN successfully installed a prototype of a concrete gravity-based foundation together with a self-installing telescopic tower (therefore no heavy-lift vessels are needed). However, the project consortium stressed that further consolidation of the concept is needed towards commercialisation. Within the project three new inventions have been filed as patent applications (PCT/ES2017/070550 (International) "Installation system of anti-scour material in a self floating marine foundation, procedures and uses associated to said system"; ES P201830404 (Spain) "Mobile module for lifting telescopic towers and telescopic tower lifting process"; ES P201731393 (Spain) "Marine construction with concrete boat landing"). So far none of them obtained IPR protection yet.

4.1.2 H2020 projects – Cross-theme: Fast Track to Innovation Pilot

The Fast Track to Innovation Pilot (FTI) is a fully-bottom-up innovation support programme promoting close-to-the-market innovation activities open to industry-driven consortia. FTI is a cross-theme topic of the H2020 priorities 'Societal challenges' and 'Industrial leadership' and aims to reduce the time from an idea to the market, stimulate the participation of first-time applicants to EU research and innovation funding, and increase private sector investment in research and innovation [EC 2020ao].

Table 21 Overview of impact assessment of H2020 projects completed in 2019 under the 'Cross-theme: Fast Track to Innovation Pilot'

Project Acronym	Research area	TRL Target	TRL achieved	# patents	# peer reviewed papers	# conference papers	Type of innovation action / instrument
REACH	Airborne wind energy systems	TRL 9	NO (TRL6)	3	7	3	IA
POWDERBLADE	New turbine materials & components	no specific TRL reported (estimate TRL 8-9)	Unclear (no final report available/final assessment of project is ongoing)	0	1	3	IA

The REACH and the POWDERBLADE projects, both ending in 2019, are funded under this programme. The REACH project aimed for the commercialisation of a 100 kW airborne wind energy system for off-grid areas. The proposed system reached only TRL 6 because of multiple technical challenges preventing to reach full commercialisation. However, the project patented two innovations (General Patent for Airborne Wind Energy System NL 2,020,920; Airborne Wind Energy System, Rigid Wing Patent NL 2,020,673) and recently filed a third patent (Ground Station NL 2,023,519). So far, no final project report was available on the POWDERBLADE project

4.1.3 H2020 projects – EIC Accelerator Pilot - Innovation in Small and Medium Enterprises (SME)

The EIC Accelerator Pilot supports close-to-market activities, with the aim to give a strong boost to breakthrough innovation with a market-creating potential. Highly innovative SMEs with a clear commercial ambition and a potential for high growth and internationalisation are the prime target. The EIC Accelerator Pilot offers small and medium-sized businesses the following [EC 2020ap]:

- Business innovation grants for feasibility assessment purposes (optional phase I): €50 000 (lump sum) per project (70% of total cost of the project)
- Business innovation grants for innovation development & demonstration purposes: an amount in the indicative range of €500 000 and 2.5 million (70% of total cost of the project as a general rule);
- Equity of up to €15 m per company (€100 m total budget for equity in 2019-2020 pilot phase);
- Free-of-charge business coaching in order to support and enhance the firm's innovation capacity and help align the project to strategic business needs;
- Access to a wide range of other business acceleration services and facilitated access to risk finance, to facilitate the commercial exploitation of the innovation.

Projects listed in ***Table 22*** received Phase I business innovation grants for feasibility assessment purposes under this programme and their respective TRL. Descriptions of all projects can be found in chapter 3.1.2.

Table 22 TRL estimate of projects receiving innovation grants under the EIC completed in 2019

Project Acronym	Research area	TRL
eolACC	Maintenance & monitoring	TRL 6
Vertical Sky	Other	TRL 6
MicroCoating	New turbine materials, components	TRL 6-7
Modvion	New turbine materials, components	TRL 6 (foreseen by March 2020)
LEWIATH	New turbine materials, components	TRL 4 (Estimate)
TwingTec	Airborne wind energy systems	TRL5-6
TruePower	Other	TRL 6 (Estimate)
IGP	Other	TRL 6-7 (Estimate)

4.1.4 H2020 projects – Marie-Sklodowska-Curie Actions

The Marie Skłodowska-Curie actions (MSCA) provide grants to researchers and encourage transnational, intersectoral and interdisciplinary mobility. The MSCA enable research-focused organisations (universities, research centres, and companies) to host talented foreign researchers and to create strategic partnerships with leading institutions worldwide [EC 2020aq]. In 2019 three projects were completed of which one (ICONN) provided support to researchers in form of a research network (Support for Innovative Training Networks (ITN)). The remaining two MSCA projects (SAFS and HYPER TOWER) were Individual fellowships (IF).

The European Industrial Doctorate ICONN addresses wind and wave energy harvesting at offshore platforms. Its main aim is to tackle theoretical/technological challenges that still impede the effective and efficient deployment of offshore wind and wave energy infrastructures (e.g. advanced modelling of hydrodynamics and hydraulics of floating platforms and moorings). Within the project three PhD theses were supported which led to publication of eight papers mainly on hydrodynamic numerical modelling and stochastic control of wave energy converters.

The Individual Fellowship SAFS aims for finding an alternative to classical anchoring solutions of new marine renewable energy devices by using screw anchors to connect multiple turbines with each other. The work particularly investigated the fundamental behaviour of screw anchors upon complex loading in sand. So far, eight publications have been published or are under review referring to the design and feasibility of screw anchors. However, more publications are expected focussing on installation methods and design.

The HYPER TOWER project, the second MSCA Individual Fellowship, proposes the elaboration of a new-age tower cross-section and construction methodology. The project delivered two peer reviewed publications specifically on this concept. The first one focusing on advanced numerical calculations and analytical calculations in correlation to wind turbine towers. The overall tower configuration that is robust and economic was proved through the first journal publication. The second publication was related to the life cycle assessment of the proposed wind turbine tower configuration proving that in addition to being robust and economic it is also more environmentally friendly. Moreover, a contribution to a review article on future emerging technologies in the wind power sector was given. Further journal papers are in the process bringing details of the comparison between the numerical and experimental data and main source of discrepancies between them.

Table 23 Overview of impact assessment of H2020 projects completed in 2019 under the 'Marie-Sklodowska-Curie Actions'

Project Acronym	Research area	# peer reviewed papers	# conference papers	Type of innovation action / instrument
ICONN	Other	4	4	European Industrial Doctorates
SAFS	Floating offshore wind	3	5	Standard European Fellowships
HYPER TOWER	Logistics, assembly & installation	3	5	Standard European Fellowships

4.1.5 H2020 projects – Advanced materials

Within the H2020 Industrial Leadership programme, the specific objective of advanced materials research and innovation is to develop materials with new functionalities and improved in-service performance, for more competitive and safe products that minimise the impact on the environment and the consumption of resources [EC 2020ar]. With the EIROS project only one wind-related project under this category ended in 2019.

The EIROS project aims to develop self-renewing, erosion resistant and anti-icing materials for composite aerofoils and composite structures that can be adapted by different industrial applications: wind turbine blades and aerospace wing leading edges, cryogenic tanks and automotive industry. The addition of novel multi-functional additives to the bulk resin of fibre-reinforced composites will allow the achievement of these advanced functionalities. The main objective of the project was the development of a range of composite materials based on a resin system containing nanoparticles that add functionality to components in extreme conditions. Apart from the increased network activity within the project, the SMEs (Polytech, IOM, Sigmatek, Millidyne, Sikema) involved report:

- an increase in expertise in rain erosion testing, gaining insight into potential maintenance scenarios for nanocomposite wind turbine blades,

- an increase in knowledge and expertise on nanosafety of materials and processes.
- creation of new jobs in the companies, enhancing their offering to their customer base and other stakeholders in responsible innovation of advanced materials,
- an increase in modelling expertise and nano-PCM encapsulation techniques,
- development of 3 new types of additives that could be commercialised in future products,
- an increase in offerings and sales of functionalized molecules. Inclusion of new products into the commercial catalogue.

Within the project, no specific TRL target was formulated and no patents have been reported so far. However, the project disseminated several publications among them two peer-reviewed papers elaborating ‘the effects of graphene oxide and chemically reduced graphene oxide on the curing kinetics of epoxy amine composites’ and ‘the thickness effect on the generation of temperature and curing degree gradients in epoxy-amine thermoset systems’.

Table 24 Overview of impact assessment of H2020 projects under the ‘H2020 Industrial Leadership programme – Advanced materials’

Project Acronym	Research area	# patents	# peer reviewed papers	# conference papers	Type of innovation action / instrument
EIROS	New turbine materials & components	0	2	4	RIA

5 Technology development outlook

Building on earlier assessments done in the LCEO project [JRC 2019b], this chapter focuses on the technology outlook for wind energy under the assumption of achieving the SET-Plan targets (80% CO_2 reduction as compared to 1990 levels). However, following the even more ambitious targets of the European Green Deal Investment Plan (striving for carbon neutrality by 2050) [EC 2020a], a more ambitious 'Zero Carbon'-scenario aiming for 100% CO_2 reduction by 2050 is presented. In its first part, this analysis reviews CAPEX and OPEX projections for the most relevant sub-technologies in onshore and offshore wind. This is followed by a comparison of technology outlooks striving for deep carbonisation and results from deep decarbonisation scenarios of the JRC-EU-TIMES model on deployment projections and the associated response of the energy system in terms of sectoral energy related CO2 emissions and electricity consumption. Finally, the most ambitious deep decarbonisation scenario is compared against the technical potential for wind energy in Europe[15].

5.1 Cost trends in wind energy

The costs for both, onshore and offshore wind, have shown a remarkable downwards trend in the last years and are expected to further decrease driven by global market growth (particularly in China), fierce competition and market consolidation. Particularly costs for offshore wind are expected to further decrease as the technological progress towards larger turbines continues and the shift in Europe towards tender-based support schemes resulted in highly competitive price bidding. Consequently, IEA (2017a) estimates its global onshore wind LCOE reference to decrease to about 59 €/MWh by 2022 meaning a decrease by 37% as compared to 2009-levels. For offshore wind IEA (2019) expects the global average LCOE to decline from its 2018 level by nearly 40% until 2030, and nearly 60% by 2040. Depending on the cost of capital (WACC) assumed, this would translate into 38 €/MWh and 51 €/MWh in 2040 for considering low-cost financing (WACC = 4%) and full market risk exposure (WACC = 7-8%), respectively [IEA 2019b]. On European level the downwards trend in onshore wind is confirmed by CAPEX and OPEX figures reported within IEA TCP Task26. Recent projects commissioned in European Task26 member states show CAPEX reductions of up to 20% in the period 2014-2018 (see ***Table 25***).

Table 25 Capacity-weighted average CAPEX and OPEX values for onshore wind projects of selected IEATask26 member states commissioned in the period 2014-2018 [IEA Wind Task26 2020].

Country		2014	2016	2018
Denmark	CAPEX (€/kW)	1377	1174	1210
	OPEX (% CAPEX)	2.8%	2.9%	2.7%
Sweden	CAPEX (€/kW)	1256	1130	1226
	OPEX (% CAPEX)	3.7%	3.6%	3.1%
Norway	CAPEX (€/kW)	1346	1061**	1038
	OPEX (% CAPEX)	3.0%	3.6%	3.7%
Ireland	CAPEX (€/kW)	1776	1677	n.a
	OPEX (% CAPEX)	3.7%	2.0%	n.a
Germany	CAPEX (€/kW)	1577*	1509	1454**
	OPEX (% CAPEX)	n.a	3.5%	n.a

* based on 2015 value, no reporting in the respective year
** based on 2017 value, no reporting in the respective year

[15] Within this chapter EU or EU28 refers to the situation up to 31/1/2020 or to analyses published before that date.

Looking ahead, several studies published by international organisations estimate the future cost developments of onshore and offshore wind presenting comparable CAPEX values as prior JRC analysis on that topic (see [JRC 2018a]). Until 2020, JRC (2018a) shows onshore wind CAPEX values in a range between 1000 €/kW and 1800 €/kW depending on the region. With increasing competition such as for example the introduction of competitive auctions in Europe, a further drop in CAPEX values to about 960 €/kW to 1570 €/kW is expected until 2040 [Greenpeace 2015, IEA 2017a, IEA 2018]. With respect to turbine maintenance, the IEA (2017a) estimates Operational Expenditure (OPEX) costs depending on the lifetime of the turbine. OPEX cost during the first 10 years of a turbine's lifetime range between 18 to 26 €/kW/year and increase to 30-40 €/kW/year for turbines older than 20 years.

An even stronger decrease until 2050 can be observed for the estimated CAPEX for offshore wind. In the long run [Greenpeace 2015, IEA 2018] expect CAPEX to range between 2050 €/kW and 2730 €/kW for an average offshore wind project. Again these values are in line with the JRC assumption for offshore wind, excluding offshore wind floating technology. The CAPEX reduction in the reviewed studies is mainly driven by the increase in average turbine sizes (e.g. from about 4 MW in 2016 and 8 MW in 2022 to about 12-15 MW in 2025) and the increase in offshore wind project size which results in scaling effects. Given this increase in both turbine size and project size until 2025, the IEA (2017a) expects that OPEX will decline from about 4% to below 2.5% of CAPEX.

Table 26 CAPEX and OPEX of onshore wind by sub-technology [JRC 2018a]

System		2020	2030	2040	2050
Low specific capacity, High hub height					
CAPEX ($€_{2015}$/kW)	Min	1 670	1 430	1 310	1 230
	Max	1 830	1 800	1 780	1 760
OPEX (%CAPEX)		3	3	3	3
Medium specific capacity, Medium hub height					
CAPEX ($€_{2015}$/kW)	Min	1 220	1 040	960	900
	Max	1 330	1 320	1 300	1 280
OPEX (%CAPEX)		3	3	3	3
High specific capacity, Low hub height					
CAPEX ($€_{2015}$/kW)	Min	990	840	770	730
	Max	1 080	1 060	1 050	1 040
OPEX (%CAPEX)		3	3	3	3

Table 27 CAPEX and OPEX of offshore wind by sub-technology [JRC 2018a]

System		2020	2030	2040	2050
Monopile, Medium distance to shore					
CAPEX ($€_{2015}$/kW)	Min	2 390	1 550	1 350	1 280
	Max	3 260	3 180	3 140	3 090
OPEX (%CAPEX)		2	2	2	2
Jacket, Medium distance to shore					
CAPEX ($€_{2015}$/kW)	Min	2 460	1 600	1 390	1 320
	Max	3 360	3 280	3 230	3 170
OPEX (%CAPEX)		2	2	2	2
Floating, Long distance to shore					
CAPEX ($€_{2015}$/kW)	Min	3 760	2 440	2 120	2 010
	Max	5 130	5 000	4 930	4 850
OPEX (%CAPEX)		2	2	2	2

5.2 Deployment scenarios

5.2.1 Comparison of scenarios review (TBC with RTD for public version!)

Technology outlooks striving for deep carbonisation (aiming for the 2 ºC temperature increase target) report a wide range of future wind energy deployment depending on the overall transformation of the EU energy system (see ***Figure 34*** and ***Figure 35***). By 2050 these studies show a wind capacity between 465 GW and 1700 GW generating 1200 TWh to 4800 TWh. This would translate into 28% to 68% of the European electricity needs. Scenarios at the higher end of these projections (above 1050 GW in 2050) include the use of renewable energy to produce significant amounts of hydrogen or to directly electrify the energy system (Navigant scenarios, EC LTS scenarios, LCEO Zero Carbon, Eurelectric 95). Scenarios foreseeing around 850 GW of wind energy see generally a lower energy demand (OEKO Vision and IFS 1.5C) but rely exclusively on renewable energy supply, whereas the remaining deep decarbonisation scenarios estimate a more conservative deployment ranging between 500 GW and 850 GW in 2050 [JRC 2019g].

Figure 34 Cumulative installed capacity of wind energy in Europe in deep decarbonisation scenarios [JRC 2019g]

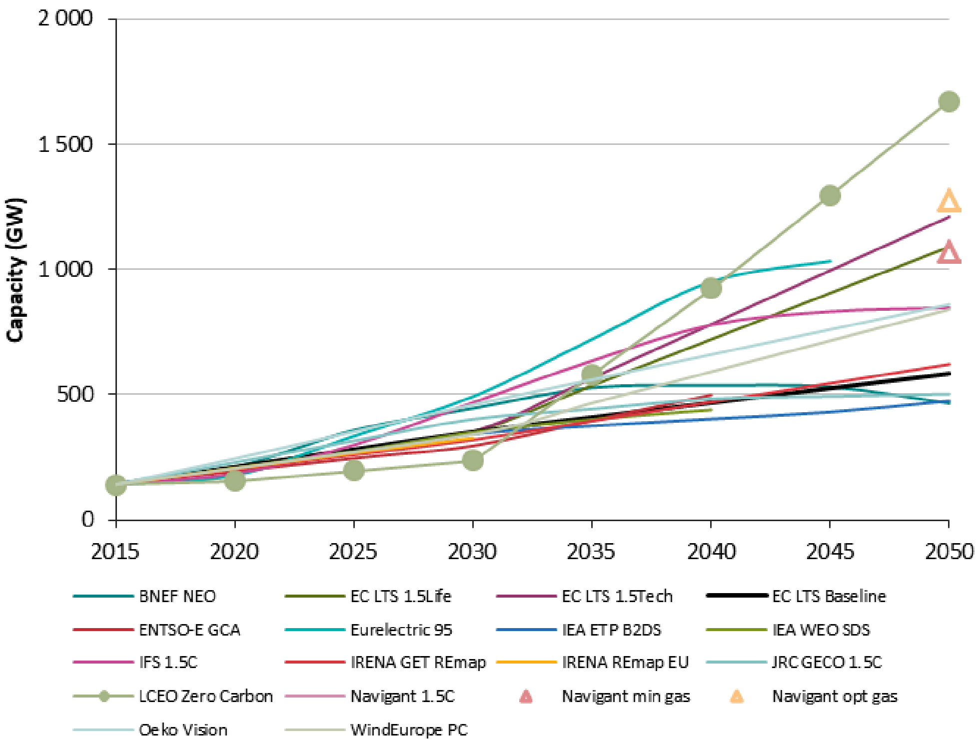
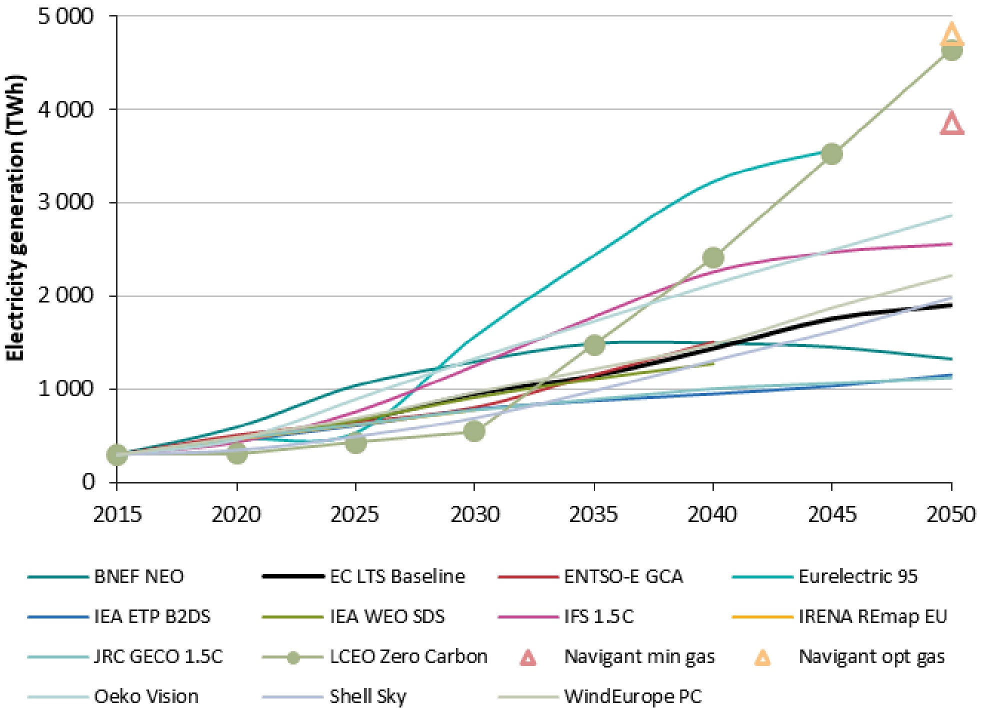


Figure 35 Electricity generation from wind energy in Europe in deep decarbonisation scenarios [JRC 2019g]



5.2.2 Deployment scenarios striving for the SET-plan targets and beyond

The JRC-EU-TIMES model is used to calculate the contribution of wind energy to the overall EU energy system. JRC-EU-TIMES is a linear optimisation model providing cost efficient pathways for the EU to meet its climate targets [JRC 2018b].

Building on the main storylines implemented in the model this analysis outlines two scenarios (Diversified and SET Plan) striving for fulfilling the CO_2 emission reduction target in 2050 (80 % as compared to 1990 levels) and one more ambitious 'Zero Carbon'-scenario aiming for 100% CO_2 reduction by 2050. The following main assumptions are met for each of the three scenarios[16] (see ***Table 28***):

- **Diversified:** this is a mitigation scenario where all known supply, efficiency and mitigation options (including nuclear and Carbon Capture and Storage, CCS) are deployed in order to achieve a long-term temperature increase lower than 2°C. In the EU, this corresponds to an 80%-reduction of CO_2 emissions in 2050 with respect to 1990.
- **SET Plan:** this scenario achieves the same long-term climate targets as the Diversified, but with a stronger focus on renewables, as nuclear is phased out and CCS is not deployed (however, Carbon Utilisation technologies are allowed, the main of which is the production of diesel/kerosene by combining hydrogen and CO_2).
- **ZeroCarbon**: this scenario has the same main technological assumption as Diversified, but the decarbonisation effort is taken to 100%-reduction of CO_2 emissions in 2050 with respect to 1990. In terms of scenario design, this scenario is very comparable to the scenario EC 2050 LTS 1.5TECH [European Commission

[16] Further description about the JRC-EU-TIMES model is available in the dedicated report produced under the LCEO project deliverable 4.7 [JRC 2018b]

2018]. The ZeroCarbon scenario results share the large amounts of RES with the ProRES scenario, as a consequence of the higher reduction of CO_2 and because the underground CO_2 storage is limited to 300 Mt/year.

Table 28 Assumptions of selected LCEO scenarios
Note: for other LCEO scenarios please refer to [JRC 2018]

Scenario	**CO_2 2050**	**Nuclear lifetime extension**	**New nuclear**	**CO_2 storage under the ground**	**CO_2 storage in materials**	**CO_2 reuse**
Diversified	-80%	YES	YES	YES	NO	YES
SET Plan	-80%	YES	NO	NO	NO	YES
Zero Carbon	-100%	YES	YES	YES < 300 Mt/yr	YES < 100 Mt/yr	YES

The contribution of wind energy to emission reduction depends not only on its technological progress as compared to other low carbon technologies but also on the future development of policies in place and resource availability, affecting the demand structure of the entire energy system.

Figure 36 shows that in all scenarios the power and the transport sector experience the strongest emission reductions until 2050. The combined emissions of these sectors decrease from 2400 Mt/year in 2010 to between 800 Mt/year and 330 Mt/year in 2050 in the SET Plan scenario and the Zero Carbon scenario, respectively. The significance of the transport sector becomes apparent by examining the electricity consumption of the decarbonisation scenarios (see ***Figure 36***). Particularly in scenarios excluding or limiting the usage of CCS (SET Plan and Zero Carbon) the transport sector becomes the main consumer of electricity by 2050, as electricity is used for both direct electrification and the production of hydrogen and derived synfuels.

As a consequence, the power sector undergoes a substantial transformation towards low carbon energy technologies and increased installed generation capacity (about 5 800 GW in Zero Carbon in 2050). Besides solar power, most of this increase until 2050 will come from newly installed wind power capacity reaching an installed capacity between 540 GW and 1560 GW in the 80% CO_2 reduction scenarios and more than 1800 GW in the 100% CO_2 reduction scenario (***Figure 37***). For both scenarios aiming for higher wind energy deployment (SET Wind and Zero Carbon) this would mean a ninefold increase in wind electricity generation as compared to current values (EU28 electricity generation from wind in 2018: 362 TWh [GWEC 2019]).

Similarly, the modelling projections within the EC long-term strategy 2050 ('A clean planet for all' communication) find wind energy as a major contributor towards decarbonisation. The installed wind capacity increases from 140 GW in 2015 to values between 700 GW (EE-scenario) and about 1200 GW (1.5TECH scenario) by 2050, leading with 51-56% of the power production in 2050 in all decarbonisation scenarios [EC 2018d].

The more ambitious IEA scenarios, looking even beyond the Paris Agreement (IEA ETP B2DS), foresee wind installations at values up to 475 GW in 2050 [IEA 2017b]. As in the case of the Diversified scenario wind capacities remain at a lower level as both scenarios include CCS as an option.

Figure 36 Sectoral energy related CO2 emissions (top) and electricity consumption - incl. electricity for hydrogen and derived synfuels (bottom)
Source: Based on [JRC 2018b, JRC 2019b]

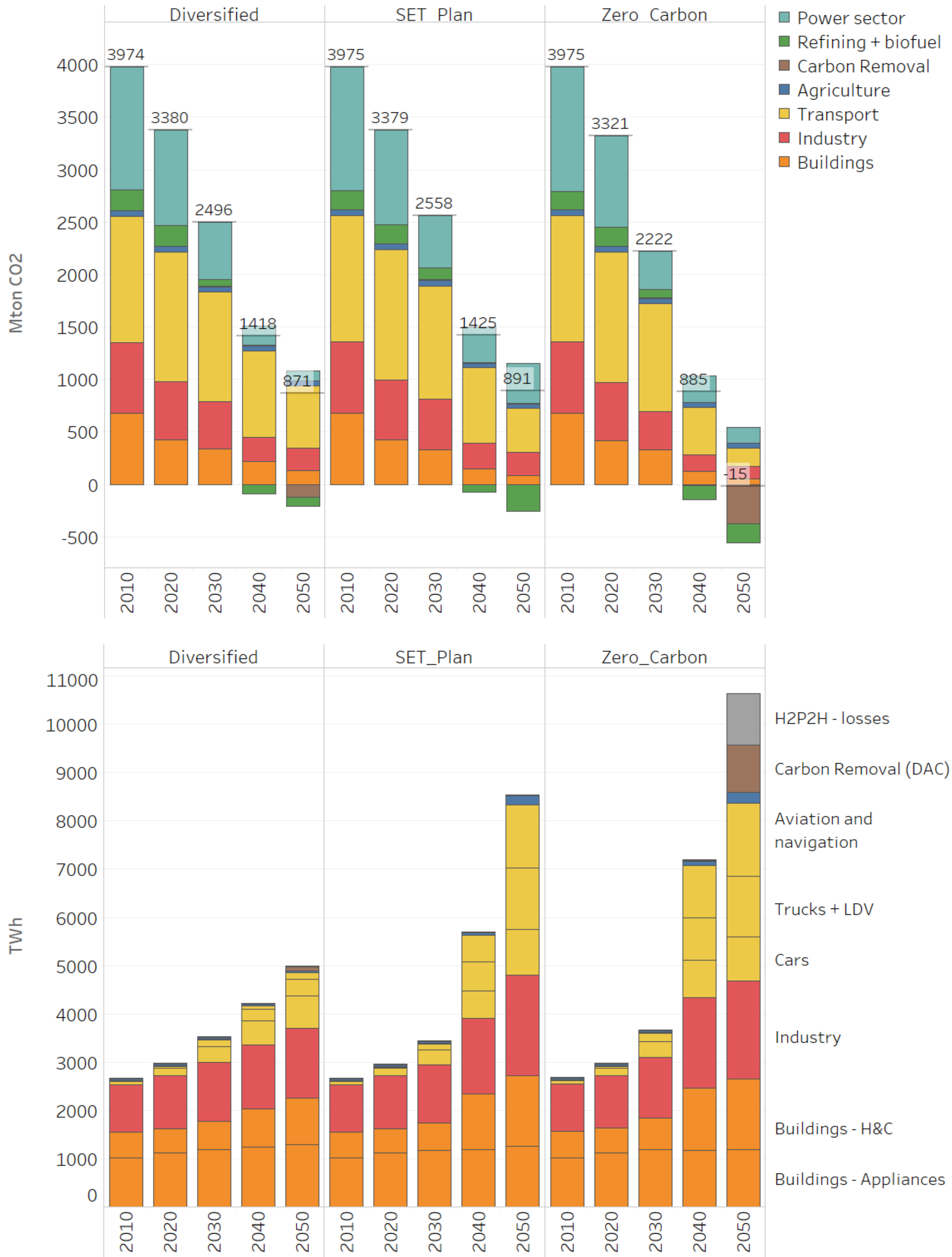
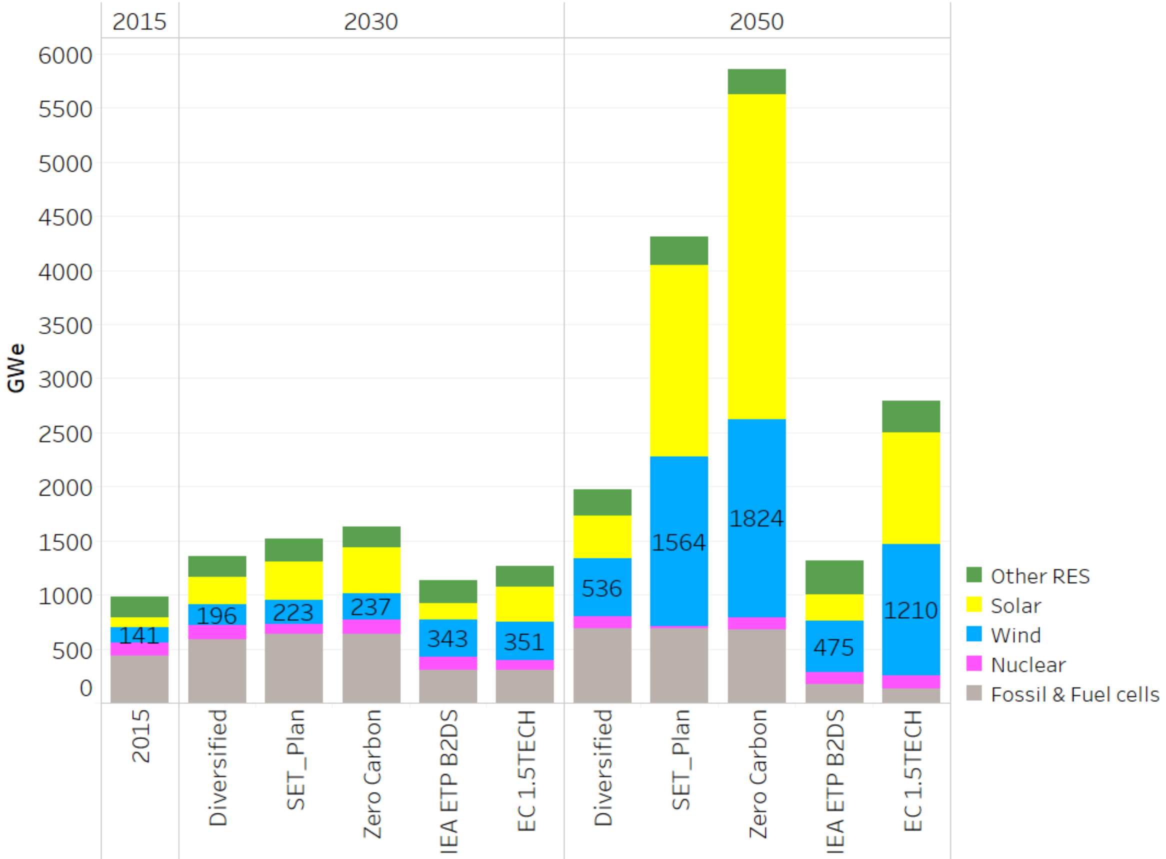


Figure 37 EU installed generation capacities until 2050 within the decarbonisation scenarios of the JRC-EU-TIMES model, the IEA ETP B2DS scenario and the EC 1.5TECH scenario
Source: Based on [IEA 2017b, EC 2018d, JRC 2018b, JRC 2019b]



5.2.3 Technical potentials of wind energy in a deep decarbonisation scenario

In order to determine the limits of wind deployment, the 'Zero Carbon' deep decarbonisation scenario is compared against the technical potential determined by GIS-based land restriction scenarios stemming from the JRC-ENSPRESO[17] database. Within this analysis, the following two JRC-ENSPRESO scenarios defining the land and surface availability for wind energy are used [JRC 2017f, JRC 2019h, Ruiz et al. 2019]:

- EU-wide low restrictions
    - Wind onshore: Exclusion of surfaces for wind converges in 2030 in all countries to a low level: 400 m. Setback remains the same in subsequent years.
    - Wind offshore: Exclusion of surfaces for offshore wind converge in all countries to a low level. Floating offshore wind is included at depths higher than 60 m. Buffer zones to shipping lanes, O&G pipelines, O&G wells and submarine cables are assumed with 2 nm (~3.7 km). Shipping density < 5000 ships/year.
- EU-wide high restrictions
    - Wind onshore: Exclusion of surfaces for wind converges in 2030 in all countries to a high level: 1200 m. Setback remains the same in subsequent years.

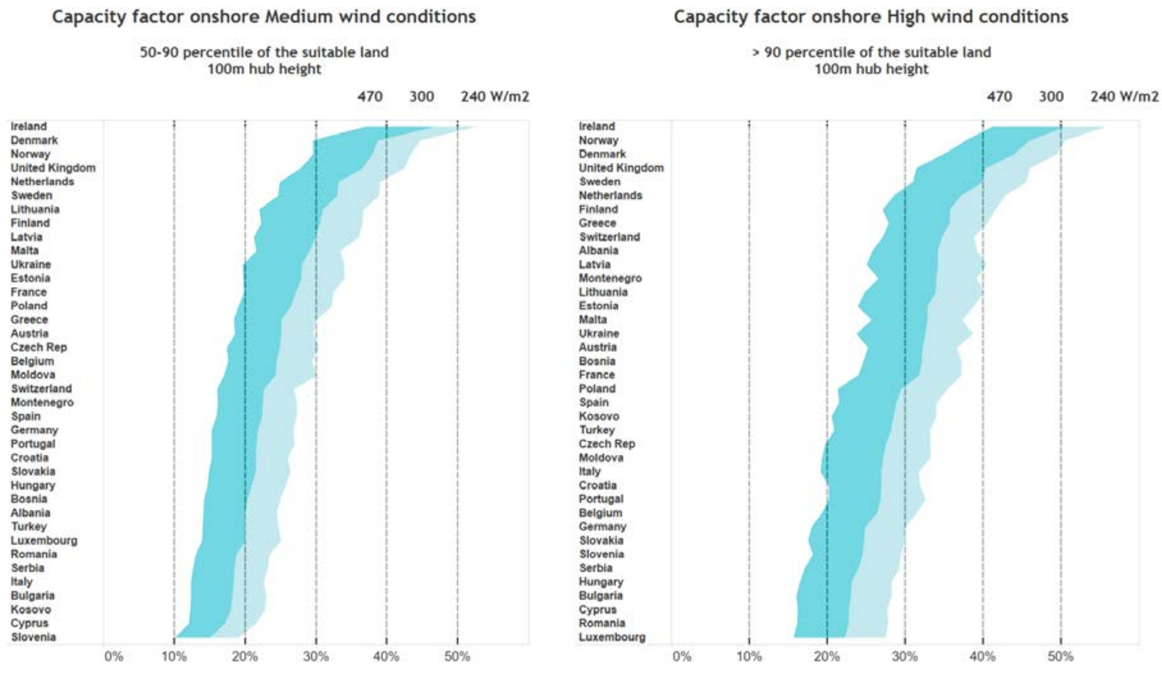
[17] ENSPRESO: ENergy System Potentials for Renewable Energy Sources. The full set of assumptions on the modelled scenarios can be found at [JRC 2019h, Ruiz et al. 2019]

- o Wind offshore: Exclusion of surfaces for offshore wind converge in all countries to a high level. Offshore wind can only be installed in zones that have a sea depth of 60 m or lower (no floating offshore). Buffer zones to shipping lanes, O&G pipelines, O&G wells and submarine cables are assumed with 4 nm (~7.4 km). Shipping density < 500 ships/year.

Results on both scenarios presented here, assume a wind farm power density of 5 MW/km^2 (please refer to [JRC 2019h] for sensitivities of potentials on the power density). Moreover, the conversion from the resulting areas to wind power capacities is based on a turbine with a specific power of 300 W/m^2 (comparable with a Vestas V112-3.0, see also Figure 5). ***Figure 38*** exemplifies the effect of moving towards turbines with higher (470 W/m^2) or lower (240 W/m^2) specific power at onshore wind locations. If the general trend towards lower specific power turbines continues, capacity factors of both high and medium wind resource areas are increasing by about five percentage points.

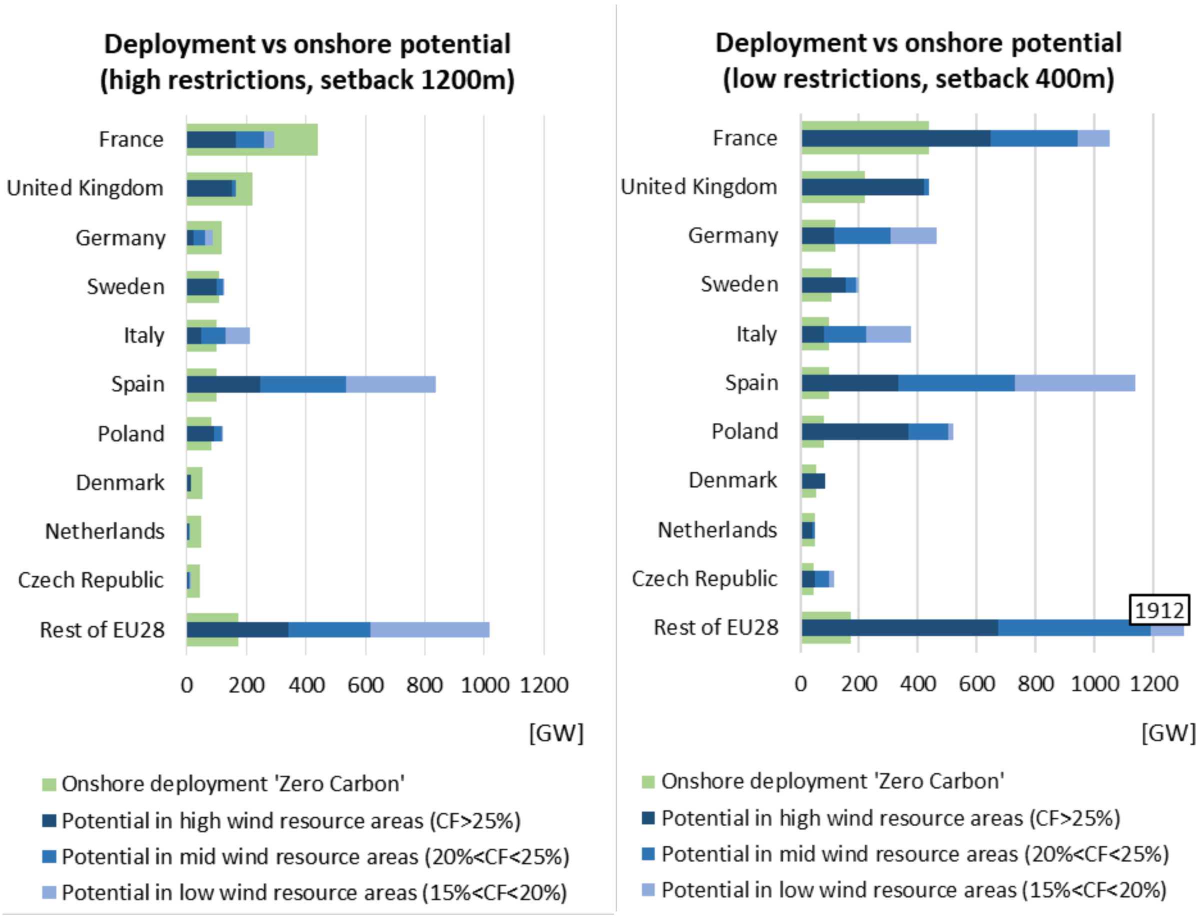
Figure 38 Sensitivity of capacity factors of EU onshore wind under medium (left) and high (right) wind conditions assuming high, medium and low specific power wind turbines at same hub height (100m) [JRC 2017f]

Note: Data is given for three types of new wind turbines. From left to right, the specific power is 470 W/m2, 300 W/m2 and 240 W/m2. The specific power is the wind turbine's power per square meter of rotor swept area. There is a cost optimal level and in most cases with medium to high wind conditions, this level is higher than 300 W/m2 (dark shaded zone). Wind turbines with a specific power less than 300 W/m2 (light shaded) are less economic today, despite the higher capacity factor. Losses are assumed to be 15% (icing, down time, transformer losses and park effects)



Comparing the onshore deployment of the 'Zero Carbon' scenario in 2050 with the lower and upper range of the ENSPRESO technical potentials reveals that strict land restrictions (e.g. increased setback distances) would lead to a significant bottleneck in deployment for some of the leading wind countries (e.g. France, the United Kingdom, Germany, Denmark, the Netherlands). Under this restriction, a cumulated capacity of about 350 GW would not be deployable in the top 10 countries for onshore wind. In contrast decreasing the setback distance would allow installing all the capacity envisaged for 2050 in the ‘Zero Carbon’ scenario leaving an additional onshore potential of 4 862 GW in Europe untapped.

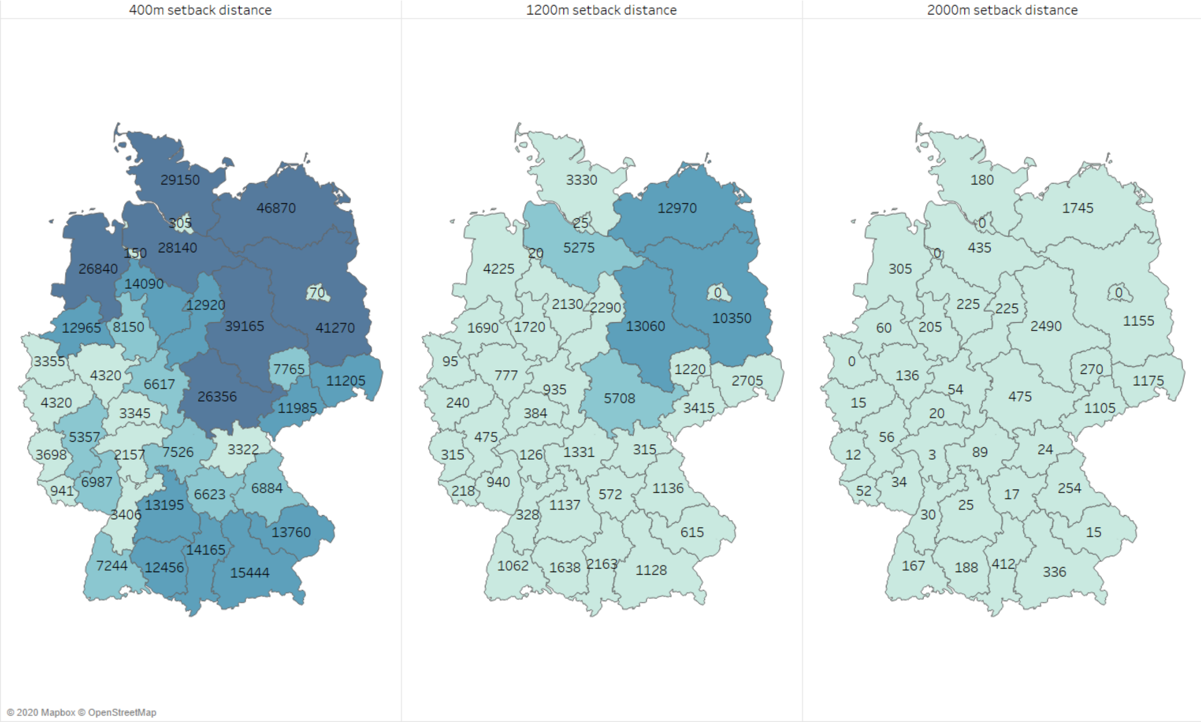
Figure 39 Onshore wind deployment within the ‘Zero Carbon’ scenario in 2050 compared against onshore wind technical potentials under low and high land restrictions



For example,

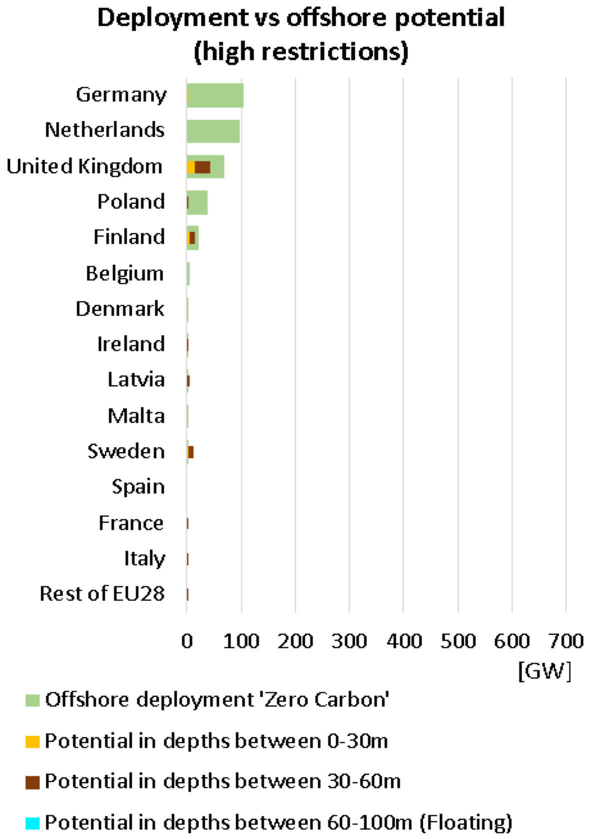
Figure 40 shows the impact of different setback distances on the potential technical potential for the case of Germany. In total about 463 GW and 86 GW of onshore wind potential could be used when restricting the setback distance for wind turbines to 400 m (EU-wide low restrictions scenario) and 1200 m (EU-wide high restrictions scenario), respectively. A further increase in setback distance to 2000 m limits the available surface to an equivalent technical potential of about 12 GW (as compared to Germany’s cumulative installed capacity in 2018 of 53 GW).

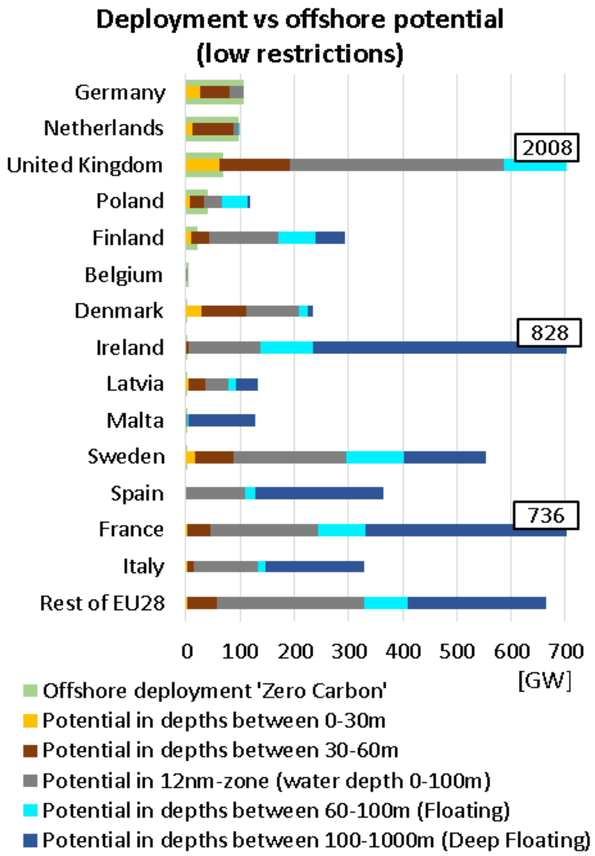
Figure 40 Technical potential (in MW) for onshore wind in Germany (NUTS2 regions) based on land availability restrictions. Wind turbine setback distances from 400 m (ENSPRESO EU-wide low restrictions scenario, left), 1200 m (ENSPRESO EU-wide high restrictions scenario, centre) and 2000 m (right).



For offshore wind, the ‘Zero Carbon’ scenario foresees a capacity of about 340 GW by 2050, mainly deployed in EU MSs of the North Sea and the Baltic Sea. Applying EU-wide high restrictions on offshore wind would limit or exclude offshore deployment in all offshore wind countries with the exception of minor deployment capacities in Sweden and Latvia. In total the gap between EU-wide high restrictions and the deployment in the ‘ZeroCarbon’ scenario in 2050 would account to about 260 GW. Applying the EU-wide low restrictions easily closes the gap between the technical potentials for offshore wind and the ‘Zero Carbon’ deployment, resulting in a total technical offshore wind potential of about 6 600 GW by 2050. However, for Germany and the Netherlands an expansion to areas within the 12 nm-zone (grey areas of map in ***Figure 41***) is a prerequiste to cover the deployment needed in the Zero Carbon scenario. Given the limited area available in Belgium for offshore wind an increase in wind farm power density is needed to deploy the needed capacities in this scenario.

Figure 41 Offshore wind deployment (top) within the 'Zero Carbon' scenario in 2050 compared against offshore wind technical potentials under low and high land restrictions (top and bottom)





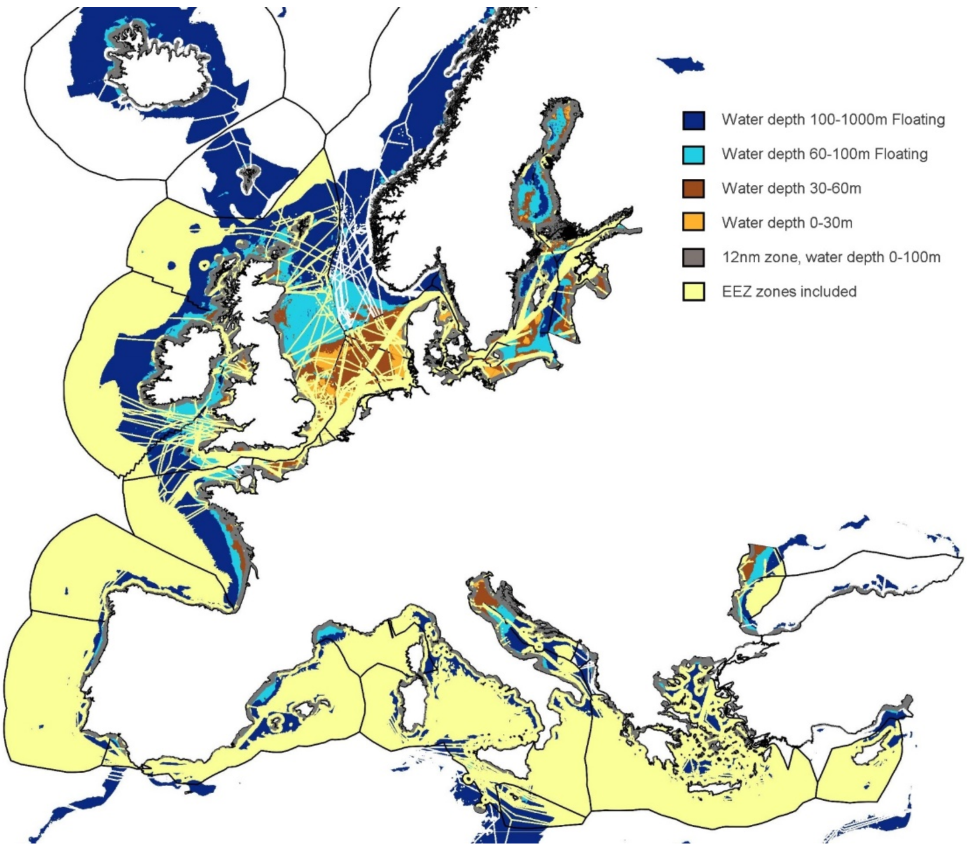
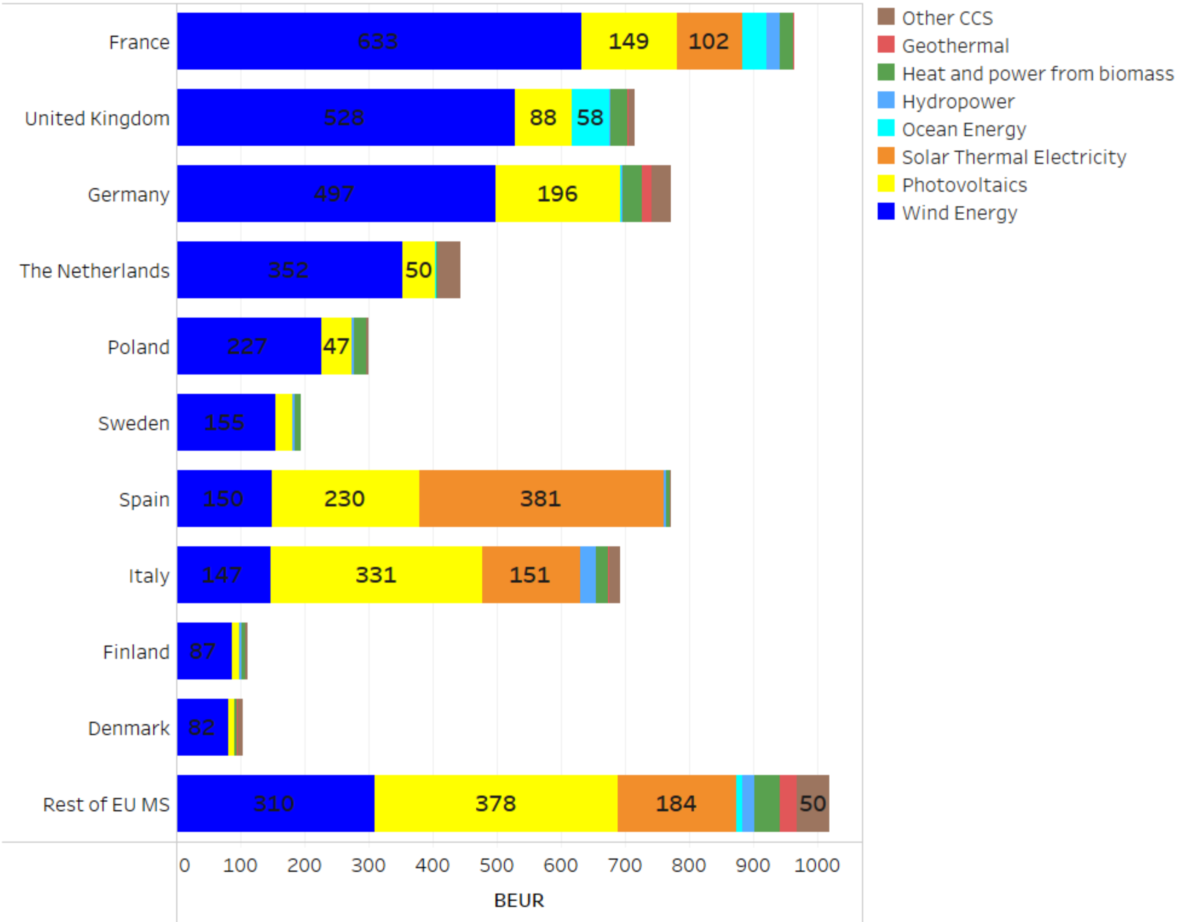


Figure 42 presents the EU MSs with the highest investments in wind energy in low carbon energy technologies up to 2050 according to the 'Zero Carbon' scenario. Until then France, Germany, Spain, the United Kingdom and Italy are the countries with the highest level of investment in new capacity in low carbon energy technologies ranging between about €700 bn and €960 bn. In this scenario investment in wind energy clearly dominates among the different low carbon energy technologies with about €3170 bn until 2050. Apart from the investments in wind energy, this scenario shows significant deployment of solar PV and solar thermal electricity in Italy and Spain.

Figure 42 Top10 member states in terms of investments in capacity additions up to 2050 in the JRC-EU-TIMES 'Zero Carbon' scenario



6 Conclusion

This report presents the state of the art in wind energy technology and analyses R&D development trends focussing particularly on the technology progress made in EU-funded research until end of 2019 in view of the SET-Plan targets. Looking ahead, this work provides a technology outlook which shows that it is possible to reach the targets formulated in the European Green Deal (striving for carbon neutrality by 2050).

In terms of deployment, Europe experienced a decline in onshore capacity additions mainly as a consequence of long permitting procedures, increasing number of legal disputes and citizens protests in Europe’s largest onshore market Germany (2.4 GW in 2018 and only 0.28 GW in the first half of 2019). European offshore wind deployment continues to rise, with most of the new capacity (2.7 GW in 2018) deployed in the North Sea.

Monitoring the main technical indicators of European wind farms deployed (until end of 2018) reveals that the European onshore wind market continues to move towards higher turbine capacities, yet decreasing in specific power. This means that harvesting the wind resource is more efficient in the lower wind speed range before reaching the rated capacity of the turbine. As such, this development has implications on the blade length in use, which increased to an average rotor diameter of 108 m in 2018, and on the type of wind turbine deployed, which shows a trend towards low wind speed classes. Moreover, hybrid drive train arrangements (Type E and F, see Annex 1 for typologies) are gaining ground in Europe, particularly for large onshore turbines and direct drive configurations (Type D), compared to the geared high-speed wind turbines. In light of this, recent industry innovations in onshore wind targeting the low wind speed market include the development of modularised onshore turbine platforms and innovative techniques and materials to improve blade lifetime (e.g. fabric based materials for blades or additive 3D printing processes for moulds and blades).

Project and turbine size in offshore wind continues to rise and so does the average rotor size (149 m in 2018), mostly triggered by the competitive tendering procedures in place, which are expected to lead to the deployment of (currently under test) 10 MW+ turbines in the early 2020s. Together with this increase in size, the industry has recently introduced several innovations to reduce the O&M costs for blade repairs (e.g. leading edge protection through adhesives or the use of Artificial Intelligence (AI) and 3D-printing to develop a more resistant leading-edge protection). Offshore wind projects are targeting the high wind speed class (IEC I) with high specific capacities (300-400 W/m2) and mainly using drive train configurations with permanent magnets (type D-PM and E-PM). The latest innovations for offshore drive trains include alternatives to fault-prone roller bearings by replacing them with flexible conical journal bearings capable to cope with main-shaft deflections. Moreover, the increased masses of future offshore wind turbines (20 MW+) might be addressed by modular two-stage distributed gearbox concepts. This increase in size and mass requires r solutions for turbine installation, such as the ongoing development of new crane concepts for installation vessels. With the first pre-commercial projects for the more advance developed floating typologies, the floating offshore wind sector is gathering pace, with new industry collaborations on the exchange of data to understand operation under real world conditions and the first operating projects to demonstrate the technology's capabilities in a deep water setting.

Airborne wind energy systems (AWES) are at a lower TRL (3-5) still with challenges to overcome with respect to system reliability, duration of autonomous flights, durability of materials, conflicting regulations (interference with air traffic) and the development of autonomous take-off and landing systems.

EU-funded research under the H2020 funding program and its predecessor FP7 granted support to all major R&I priorities in the wind sector (namely: New materials & components; Resource assessment; Grid integration; Offshore technology; Floating offshore wind; Logistics, assembly & installation; Maintenance & monitoring; Airborne wind energy systems). In particular, the development of offshore wind and floating offshore wind concepts received substantial support in the last decade, bringing the latter to pre-commercial technology readiness. This focus is further strengthened through 12 offshore R&I projects addressing the areas of offshore wind or floating offshore wind starting in 2019, accumulating about €25.9m of funds to these topics. H2020 projects on floating offshore wind that started in 2019 target cost reduction, up-scaling and development of concepts for deep water conditions, amongst others. In line with this thematic focus and in order to maintain European leadership in offshore wind, the SET-Plan Implementation Plan for Offshore Wind stresses the need to address cost reduction, development of floating substructures and the system integration. So far, the implementation working group (IWG) reported a significant number of nationally funded projects mainly on its R&I priorities 'Wind Energy Offshore Balance of Plant', 'Floating Offshore Wind' and 'Wind Turbine Technology'.

Other European R&D support instruments include KIC InnoEnergy, which aims to bring innovations at a TRL greater or equal to 5 to the market. In total 14 wind energy-related innovations are supported by KIC InnoEnergy. Moreover, the European Energy Programme for Recovery (EEPR) provided grants of about €565m to nine offshore wind projects of which six are operational as of early 2020. Four of the eight wind energy demonstration projects in the NER300 programme (supporting the demonstration of innovative CCS and renewable energy technologies) have been completed, however there are delays to the remaining projects (all focussing on floating wind technology), mainly because of appeals, permitting or financing issues. Finally, the InnovFin-initiative of the European Investment Bank Group (EIB and EIF) and the EC granted €60m to the 'WindFloat Atlantic' project.

Similar to the European research strategy and the IEA TCP Wind's strategic work plan, national R&D priorities in the US and China concentrate on cost reduction, supersized-lightweight turbines and the system integration aspect of wind energy.

The EU co-funded projects completed in 2019 made progress in terms of the TRL achieved, publication of results and to a lesser extent in patenting innovations. Offshore technology research received most of the funds (40%) followed by projects on 'New turbine materials and components' (33%), 'Floating offshore wind' (13%) and 'Maintenance & monitoring (9%). The assessment of projects under the main sub-programmes that use TRL targets ('Secure, clean and efficient energy' and 'Cross-theme: Fast Track to Innovation Pilot') shows that three out of eight achieved their TRL target and progressed in terms of patenting and publication activity. Two projects in these sub-programmes did not reach their target (due to technical challenges) and the remainder had not provided a final report at time of writing this report.

In order to achieve the original SET-Plan targets (80% CO2 reduction compared to 1990 levels) the European power sector needs to undergo a substantial transformation towards low carbon energy technologies. Depending on the overall restrictions within the JRC-EU-TIMES modelling scenarios performed for the LCEO (e.g. including nuclear and/or CCS) new wind power capacity reaches between 540 GW and 1560 GW by 2050. To fulfil the even more ambitious targets of the European Green Deal (striving for carbon neutrality by 2050) a full decarbonisation LCEO scenario ('Zero Carbon'-scenario) calls an even larger deployment of wind energy of about 1800 GW in 2050 (of which about 340 GW would be located offshore). This means a tenfold increase in installed capacity as compared to 2018-levels and would require a total investment of about €3170 bn until 2050.

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Annexes

Annex 1

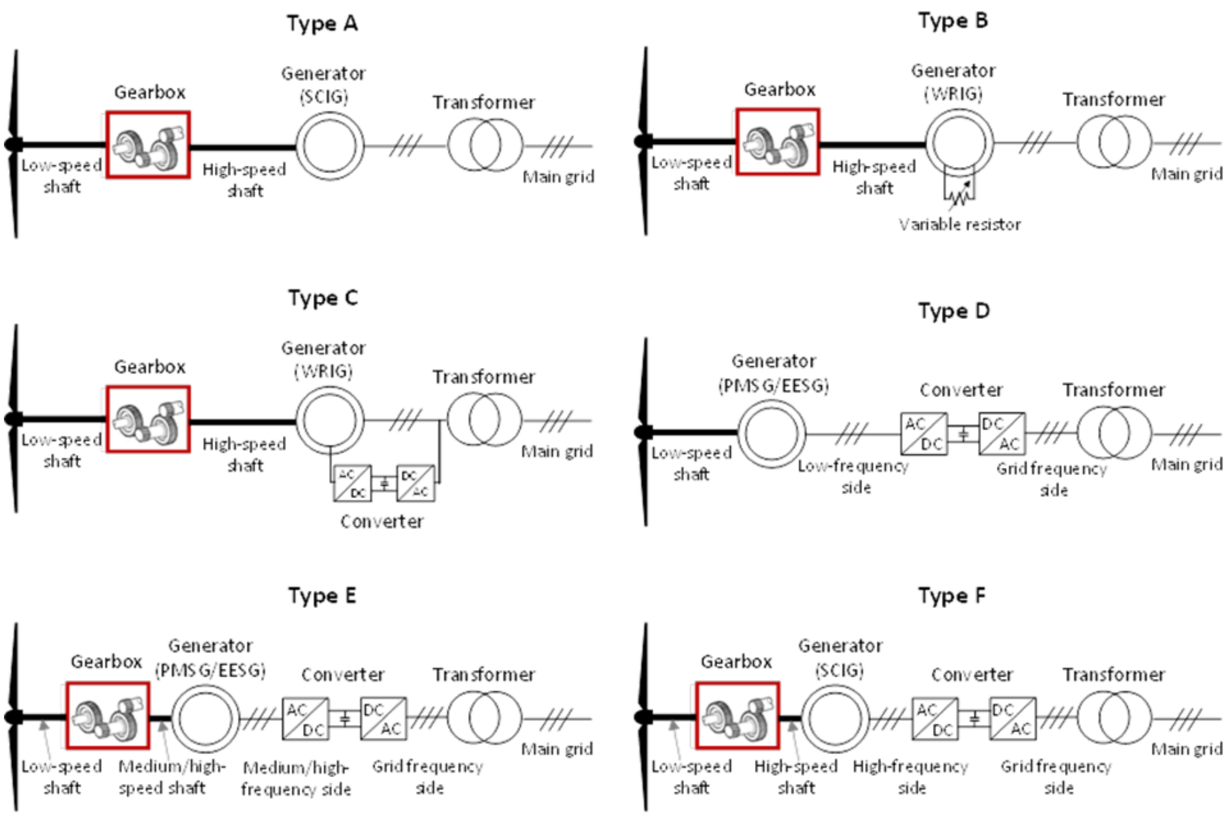

Figure 43. Drive train arrangements usually employed in commercial wind turbines.

Source: Vazquez Hernandez, C., Serrano González, J., & Centeno, G. (2017). A Market-Based Analysis on the Main Characteristics of Gearboxes Used in Onshore Wind Turbines. Energies, 10(11), 1686. http://doi.org/10.3390/en10111686

Annex 2

Table 29 R&I projects considered under JRC methodology to estimate EC funding for wind energy under FP7 and H2020 programs

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
FP7	212825	PROTEST	2008	Maintenance & monitoring	100%	1,980,119	1,980,119
FP7	213740	SAFEWIND	2008	Resource assessment	100%	3,992,400	3,992,400
FP7	218691	KITVES	2008	New turbine materials & components	100%	2,955,738	2,955,738
FP7	212966	RELIAWIND	2008	Logistics, assembly & installation	100%	5,180,767	5,180,767
FP7	219055	7MW-WEC-BY-11	2008	New turbine materials & components	100%	3,270,285	3,270,285
FP7	219048	NORSEWIND	2008	Resource assessment	100%	3,939,517	3,939,517
FP7	224548	AEOLUS	2008	Maintenance & monitoring	100%	2,500,000	2,500,000
FP7	230698	WINDFLOWER	2009	New turbine materials & components	100%	465,495	465,495
FP7	237471	VSABLA	2009	Resource assessment	100%	296,089	296,089
FP7	238576	WAUDIT	2009	Resource assessment	100%	3,984,000	3,984,000
FP7	238325	SYSWIND	2009	Maintenance & monitoring	100%	3,026,568	3,026,568
FP7	239191	PROND	2009	New turbine materials & components	100%	45,000	45,000
FP7	239462	NIMO	2009	Maintenance & monitoring	100%	3,401,900	3,401,900
FP7	239304	WINGY-PRO	2009	New turbine materials & components	100%	2,478,530	2,478,530
FP7	232155	ROOF-CAPTURE	2009	New turbine materials & components	100%	1,049,975	1,049,975
FP7	232190	WINTUR	2009	Maintenance & monitoring	100%	1,103,300	1,103,300
FP7	232362	OSGRAM	2009	Logistics, assembly & installation	100%	958,429	958,429
FP7	230719	METEORES SERVICES	2010	Resource assessment	100%	512,318	512,318
FP7	256714	HAWE	2010	Airborne wind energy systems	100%	1,920,471	1,920,471
FP7	251309	STA-DY-WI-CO	2010	Other	50%	935,868	467,934
FP7	252284	ICIEMSET	2010	Other	50%	247,028	123,514
FP7	241402	MARINA PLATFORM	2010	Floating offshore wind	50%	8,708,660	4,354,330
FP7	249801	LASTBEG	2010	Grid integration	75%	6,187,246	4,640,435
FP7	256769	DEEPWIND	2010	Floating offshore wind	100%	2,992,438	2,992,438
FP7	241421	ORECCA	2010	Offshore technology	50%	1,599,033	799,516
FP7	249812	TWENTIES	2010	Grid integration	30%	31,774,565	9,532,370
FP7	252581	NANOPERMAG	2010	New turbine materials & components	33%	202,319	67,440
FP7	273451	IRWES	2011	Other	100%	179,686	179,686
FP7	268171	TOP WIND	2011	Other	100%	897,050	897,050
FP7	283145	CLUSTERDESIGN	2011	Logistics, assembly & installation	100%	3,582,619	3,582,619
FP7	296050	DEMOWFLOAT	2011	Floating offshore wind	100%	3,563,871	3,563,871
FP7	296043	INFLOW	2011	Floating offshore wind	100%	11,934,953	11,934,953
FP7	262552	MARINET	2011	Offshore technology	50%	8,999,998	4,499,999
FP7	269202	HEMOW	2011	Offshore technology	100%	241,500	241,500

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
FP7	283277	INTELWIND	2011	Maintenance & monitoring	100%	1,087,900	1,087,900
FP7	283533	DASHWIN	2011	Maintenance & monitoring	100%	1,085,100	1,085,100
FP7	286603	RINGMAN	2011	Offshore technology	100%	1,132,700	1,132,700
FP7	259166	HIGHWIND	2011	New turbine materials & components	100%	1,499,800	1,499,800
FP7	272437	ICFLOAT	2011	Other	100%	199,550	199,550
FP7	282797	EERA-DTOC	2012	Offshore technology	100%	2,899,857	2,899,857
FP7	296012	INGRID	2012	Grid integration	50%	13,789,563	6,894,782
FP7	294933	DISKNET	2012	Grid integration	50%	505,700	252,850
FP7	309395	MARE-WINT	2012	Offshore technology	100%	3,822,753	3,822,753
FP7	306471	ACTIVEWINDFARMS	2012	Resource assessment	100%	1,499,241	1,499,241
FP7	320042	ECOWINDS	2012	Maintenance & monitoring	100%	1,757,713	1,757,713
FP7	315207	WINTUR DEMO	2012	Maintenance & monitoring	100%	1,044,000	1,044,000
FP7	312372	WINDSCANNER	2012	Resource assessment	100%	4,350,000	4,350,000
FP7	304760	WIND TURBARS	2012	Maintenance & monitoring	100%	1,066,000	1,066,000
FP7	288145	H2OCEAN	2012	Offshore technology	25%	4,525,934	1,131,484
FP7	308974	INNWIND.EU	2012	Offshore technology	100%	13,799,999	13,799,999
FP7	308793	SUPRAPOWER	2012	New turbine materials & components	100%	3,891,058	3,891,058
FP7	283292	CORETO	2012	New turbine materials & components	100%	917,400	917,400
FP7	286854	CMSWIND	2012	Maintenance & monitoring	100%	1,869,903	1,869,903
FP7	288192	TROPOS	2012	Offshore technology	25%	4,877,911	1,219,478
FP7	288710	MERMAID	2012	Offshore technology	25%	5,483,411	1,370,853
FP7	296164	SOPCAWIND	2012	Resource assessment	100%	1,950,000	1,950,000
FP7	304700	WETMATE	2012	Offshore technology	100%	1,222,000	1,222,000
FP7	315485	WINDRIVE	2012	New turbine materials & components	100%	1,586,998	1,586,998
FP7	315563	OPTIWIND	2012	New turbine materials & components	100%	1,159,875	1,159,875
FP7	318925	EDWTGT	2012	New turbine materials & components	100%	392,700	392,700
FP7	299767	ACRES	2012	Grid integration	50%	116,853	58,426
FP7	287844	COCONET	2012	Other	50%	9,000,000	4,500,000
FP7	297852	RES GRID INTEGRATION	2012	Grid integration	50%	231,547	115,774
FP7	282775	UMBRELLA	2012	Grid integration	50%	3,863,811	1,931,906
FP7	301807	PHASEMASTER	2012	Maintenance & monitoring	100%	209,033	209,033
FP7	295977	FLOATGEN	2013	Offshore technology	100%	10,153,053	10,153,053
FP7	317221	MEDOW	2013	Offshore technology	100%	3,925,537	3,925,537
FP7	618159	NUMIWING	2013	Airborne wind energy systems	100%	100,000	100,000

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
FP7	322430	OPTIMUS	2013	Maintenance & monitoring	100%	3,333,275	3,333,275
FP7	322449	WINDTRUST	2013	New turbine materials & components	100%	6,247,264	6,247,264
FP7	608396	AVATAR	2013	New turbine materials & components	100%	6,680,489	6,680,489
FP7	304753	MONITUR	2013	Maintenance & monitoring	100%	1,062,000	1,062,000
FP7	309985	WALID	2013	New turbine materials & components	100%	3,964,797	3,964,797
FP7	310531	HYDROBOND	2013	New turbine materials & components	100%	2,929,476	2,929,476
FP7	314893	WINDHEAT	2013	New turbine materials & components	100%	1,125,998	1,125,998
FP7	605067	WINDUR	2013	New turbine materials & components	100%	1,158,000	1,158,000
FP7	605138	DEICE-UT	2013	New turbine materials & components	100%	1,066,000	1,066,000
FP7	605420	HEXATERRA	2013	Offshore technology	50%	1,198,998	599,499
FP7	614020	LEANWIND	2013	Logistics, assembly & installation	100%	9,986,231	9,986,231
FP7	308864	iGREENGrid	2013	Grid integration	50%	4,336,217	2,168,109
FP7	334577	CNT-IN-FRPC	2013	New turbine materials & components	100%	100,000	100,000
FP7	315925	MERIKA	2014	Other	50%	3,950,000	1,975,000
FP7	618122	NEWA	2014	Resource assessment	100%	4,335,329	4,335,329
FP7	624562	MESOWAKE	2014	Resource assessment	100%	352,176	352,176
FP7	605013	TOWERPOWER	2014	Maintenance & monitoring	100%	1,469,000	1,469,000
FP7	605451	AUTOWINSPEC	2014	Maintenance & monitoring	100%	1,018,000	1,018,000
FP7	609795	IRPWIND	2014	Other	100%	9,822,218	9,822,218
FP7	604215	CARBOPREC	2014	New turbine materials & components	50%	5,968,027	2,984,014
FP7	612531	MARINCOMP	2014	Offshore technology	50%	2,376,057	1,188,029
FP7	607596	SURFSUP	2014	Other	100%	587,134	587,134
FP7	612581	PLENOSE	2014	Other	50%	281,400	140,700
H2020	651752	SEAMETEC	2014	New turbine materials & components	50%	50,000	25,000
H2020	652138	Briareo	2014	New turbine materials & components	100%	50,000	50,000
H2020	640741	LIFES 50plus	2015	Floating offshore wind	100%	7,274,838	7,274,838
H2020	643167	AEOLUS4FUTURE	2015	Maintenance & monitoring	100%	3,811,805	3,811,805
FP7	627270	OHMWIT	2015	Maintenance & monitoring	100%	273,197	273,197
FP7	632601	LAAME-CROW	2015	New turbine materials & components	100%	710,790	710,790
H2020	654634	TELWIND	2015	Floating offshore wind	100%	3,498,530	3,498,530
H2020	691173	REACH	2015	Airborne wind energy systems	100%	2,675,132	2,675,132
H2020	689772	HPC4E	2015	Resource assessment	33%	1,998,176	666,059
H2020	671868	I-WSN	2015	Maintenance & monitoring	33%	50,000	16,667
H2020	657652	Riblet4Wind	2015	New turbine materials & components	100%	3,307,172	3,307,172

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	642682	AWESCO	2015	Airborne wind energy systems	100%	2,999,015	2,999,015
H2020	675659	ICONN	2015	Other	50%	845,838	422,919
H2020	642108	AWESOME	2015	Maintenance & monitoring	100%	2,862,074	2,862,074
H2020	673976	POSEIDON	2015	Floating offshore wind	50%	1,144,150	572,075
H2020	666624	IRWES	2015	New turbine materials & components	100%	1,696,380	1,696,380
H2020	674741	ELISA	2015	Offshore technology	100%	2,497,863	2,497,863
H2020	666793	AMPYXAP3	2015	Airborne wind energy systems	100%	2,500,000	2,500,000
H2020	698686	SE-NBW	2015	Logistics, assembly & installation	100%	50,000	50,000
H2020	692644	URBAVENTO	2015	New turbine materials & components	100%	50,000	50,000
H2020	698136	WITRO	2015	Resource assessment	100%	50,000	50,000
H2020	698883	LiraTower	2015	New turbine materials & components	100%	50,000	50,000
H2020	683875	MEWi-B	2015	New turbine materials & components	100%	50,000	50,000
H2020	673137	CLOUD DIAGNOSIS	2015	Maintenance & monitoring	100%	50,000	50,000
H2020	672559	AIRCRANE	2015	Logistics, assembly & installation	100%	50,000	50,000
H2020	673202	EeC WITUR	2015	Maintenance & monitoring	100%	50,000	50,000
H2020	663597	MeRIT	2015	Grid integration	50%	50,000	25,000
H2020	672729	Omniflow	2015	New turbine materials & components	50%	50,000	25,000
H2020	646517	DemoWind	2015	Offshore technology	100%	7,783,160	7,783,160
H2020	656024	EcoSwing	2015	New turbine materials & components	100%	10,591,734	10,591,734
H2020	684591	Opti-LPS	2015	New turbine materials & components	100%	50,000	50,000
H2020	673782	FLOATMAST	2015	Offshore technology	100%	50,000	50,000
H2020	666257	Eciwind	2015	New turbine materials & components	100%	1,307,305	1,307,305
H2020	674094	OPTILIFT	2015	Offshore technology	33%	50,000	16,667
H2020	673106	MONOFFSHORE	2015	Offshore technology	33%	50,000	16,667
H2020	663185	ANGELS	2015	Offshore technology	33%	50,000	16,667
H2020	652629	MARIBE	2015	Other	25%	1,977,951	494,488
H2020	691919	ELICAN	2016	Offshore technology	100%	11,181,987	11,181,987
H2020	685842	EIROS	2016	New turbine materials & components	25%	7,993,169	1,998,292
H2020	685445	LORCENIS	2016	New turbine materials & components	25%	7,653,530	1,913,383
H2020	730747	POWDERBLADE	2016	New turbine materials & components	100%	2,731,700	2,731,700
H2020	726776	VORTEX	2016	New turbine materials & components	100%	1,328,688	1,328,688
H2020	718755	CLOUD DIAGNOSIS	2016	Maintenance & monitoring	100%	878,129	878,129
H2020	718125	VOSS	2016	Grid integration	50%	50,000	25,000
H2020	729070	TEES	2016	Grid integration	50%	50,000	25,000

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	727477	CL-Windcon	2016	Maintenance & monitoring	100%	4,931,423	4,931,423
H2020	729363	GW-FortyForty	2016	New turbine materials & components	100%	50,000	50,000
H2020	729183	ECO-TURBINE	2016	New turbine materials & components	100%	50,000	50,000
H2020	744239	NJORD	2016	New turbine materials & components	100%	50,000	50,000
H2020	718016	SWITLER	2016	New turbine materials & components	100%	50,000	50,000
H2020	736224	Triblade	2016	New turbine materials & components	100%	50,000	50,000
H2020	734300	ABLE	2016	New turbine materials & components	100%	50,000	50,000
H2020	691732	DemoWind 2	2016	Offshore technology	100%	8,557,865	8,557,865
H2020	691714	PROMOTION	2016	Offshore technology	30%	39,327,744	11,798,323
H2020	691717	DEMOGRAVI3	2016	Offshore technology	100%	19,037,466	19,037,466
H2020	729107	GroutTube	2016	Offshore technology	100%	50,000	50,000
H2020	729786	Scubacraft	2016	Offshore technology	10%	50,000	5,000
H2020	718838	FLOW	2016	Floating offshore wind	100%	50,000	50,000
H2020	735565	Cable Sentry	2016	Offshore technology	100%	50,000	50,000
H2020	736399	EK200-AWESOME	2016	Airborne wind energy systems	100%	50,000	50,000
H2020	717857	ZephyCloud	2016	Resource assessment	100%	50,000	50,000
H2020	760353	BladeSave	2017	Maintenance & monitoring	100%	1,988,909	1,988,909
H2020	784040	FloatMastBlue	2017	Offshore technology	100%	2,048,568	2,048,568
H2020	775854	AIMS	2017	Maintenance & monitoring	33%	50,000	16,667
H2020	747921	HYPER TOWER	2017	Logistics, assembly & installation	100%	183,455	183,455
H2020	722401	SmartAnswer	2017	Other	25%	3,844,758	961,190
H2020	765585	InnoDC	2017	Grid integration	50%	3,893,200	1,946,600
H2020	761219	3D-COMPETE	2017	New turbine materials & components	33%	50,000	16,667
H2020	768016	WEGOOI	2017	Maintenance & monitoring	100%	773,185	773,185
H2020	774974	NextWind	2017	Other	100%	50,000	50,000
H2020	745625	ROMEO	2017	Maintenance & monitoring	100%	9,999,813	9,999,813
H2020	773657	TRIWIND	2017	Offshore technology	100%	50,000	50,000
H2020	782517	Wind-Drone	2017	Maintenance & monitoring	100%	50,000	50,000
H2020	783913	ZephyCloud-2	2017	Logistics, assembly & installation	100%	1,275,827	1,275,827
H2020	764717	WinWind	2017	Other	100%	2,124,463	2,124,463
H2020	778553	TRIBLADE	2017	New turbine materials & components	100%	2,095,975	2,095,975
H2020	791019	Venturas	2017	New turbine materials & components	100%	50,000	50,000
H2020	720838	NEOHIRE	2017	New turbine materials & components	100%	4,443,889	4,443,889
H2020	744518	FLOWSPA	2017	Floating offshore wind	100%	50,000	50,000
H2020	774253	Space at Sea	2017	Floating offshore wind	100%	6,766,793	6,766,793
H2020	753156	SAFS	2017	Floating offshore wind	100%	195,455	195,455
H2020	761874	SATH	2017	Floating offshore wind	100%	50,000	50,000
H2020	761072	DACOMAT	2018	New turbine materials & components	25%	5,873,915	1,468,479

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	809308	R3FIBER	2018	New turbine materials & components	25%	50,000	12,500
H2020	825833	WINDMIL RT-DT	2018	Maintenance & monitoring	100%	148,890	148,890
H2020	774426	The Blue Growth Farm	2018	Offshore technology	25%	7,602,873	1,900,718
H2020	780662	SheaRIOS	2018	Maintenance & monitoring	100%	2,716,907	2,716,907
H2020	829774	LEADFLOAT	2018	Offshore technology	100%	2,498,563	2,498,563
H2020	829644	NOTUS	2018	Maintenance & monitoring	100%	1,397,229	1,397,229
H2020	811473	LEP4BLADES	2018	New turbine materials & components	100%	1,011,623	1,011,623
H2020	836540	eolACC	2018	Maintenance & monitoring	100%	50,000	50,000
H2020	817421	X1 Wind	2018	Offshore technology	100%	50,000	50,000
H2020	817053	WindiBox	2018	New turbine materials & components	100%	50,000	50,000
H2020	816706	EOLI FPS	2018	New turbine materials & components	100%	50,000	50,000
H2020	817390	INNOWIND	2018	New turbine materials & components	100%	50,000	50,000
H2020	824339	A2MIRO	2018	Maintenance & monitoring	100%	50,000	50,000
H2020	778039	PEARLS	2018	Other	25%	405,000	101,250
H2020	791875	ReaLCoE	2018	Offshore technology	100%	24,838,258	24,838,258
H2020	818153	i4Offshore	2018	Offshore technology	100%	19,877,916	19,877,916
H2020	727680	TotalControl	2018	Maintenance & monitoring	100%	4,876,483	4,876,483
H2020	763990	UPWARDS	2018	Maintenance & monitoring	100%	3,999,918	3,999,918
H2020	817619	AURES II	2018	Other	25%	2,594,058	648,514
H2020	806844	Njord	2018	New turbine materials & components	100%	1,740,260	1,740,260
H2020	804858	AIRCRANE	2018	Logistics, assembly & installation	100%	1,487,588	1,487,588
H2020	808597	Ventura Habitat	2018	Maintenance & monitoring	100%	50,000	50,000
H2020	807460	YURAKAN	2018	New turbine materials & components	100%	50,000	50,000
H2020	808061	HEAF	2018	New turbine materials & components	100%	50,000	50,000
H2020	776559	SecREEts	2018	Other	25%	12,880,032	3,220,008
H2020	857844	FarmConners	2019	Maintenance, condition monitoring systems	100%	1,449,639	1,449,639
H2020	876355	Vertical Sky	2019	Other	100%	50,000	50,000
H2020	875698	SUNCOAT	2019	New turbine materials, components	100%	150,000	150,000
H2020	873403	COOLWIND	2019	Offshore technology	100%	2,499,999	2,499,999
H2020	881193	AWE	2019	Airborne wind energy systems	100%	2,442,116	2,442,116
H2020	860101	zEPHYR	2019	Resource assessment	100%	3,826,416	3,826,416
H2020	873395	Windrone Zenith	2019	Maintenance, condition monitoring systems	100%	1,339,397	1,339,397
H2020	861398	WinGrid	2019	Grid integration	100%	4,290,017	4,290,017
H2020	874042	SeaTwirl	2019	Floating offshore wind	100%	2,482,025	2,482,025

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	874102	EOLOGIX	2019	Maintenance, condition monitoring systems	100%	1,133,878	1,133,878
H2020	860879	FLOAWER	2019	Floating offshore wind	100%	3,500,382	3,500,382
H2020	828799	HPCWE	2019	Grid integration	100%	1,995,651	1,995,651
H2020	868808	MicroCoating	2019	New turbine materials, components	100%	50,000	50,000
H2020	843218	ASSO	2019	Floating offshore wind	100%	184,708	184,708
H2020	867710	Modvion	2019	New turbine materials, components	100%	50,000	50,000
H2020	815159	PivotBuoy	2019	Floating offshore wind	100%	3,960,065	3,960,065
H2020	849307	SATH	2019	Floating offshore wind	100%	1,902,338	1,902,338
H2020	835901	EDOWE	2019	Floating offshore wind	100%	175,572	175,572
H2020	815289	FLOTANT	2019	Floating offshore wind	100%	4,944,958	4,944,958
H2020	836347	LEWIATH	2019	New turbine materials, components	100%	50,000	50,000
H2020	848747	WindTRRo	2019	Maintenance, condition monitoring systems	100%	2,196,023	2,196,023
H2020	850339	AWESOME	2019	Airborne wind energy systems	100%	2,300,000	2,300,000
H2020	855726	TwingTec	2019	Airborne wind energy systems	100%	50,000	50,000
H2020	842231	SETWIND	2019	Other	100%	998,512	998,512
H2020	826042	ETIPWind	2019	Other	100%	726,638	726,638
H2020	798033	HSS-Wind	2019	Offshore technology	100%	195,455	195,455
H2020	793316	OFFSHORE TALL TOWER	2019	Offshore technology	100%	183,455	183,455
H2020	815083	COREWIND	2019	Floating offshore wind	100%	5,031,859	5,031,859
H2020	857631	TWIND	2019	Offshore technology	100%	795,825	795,825
H2020	880041	NBTECH	2019	New turbine materials, components	100%	1,675,538	1,675,538
H2020	885537	SIDEWIND	2019	New turbine materials, components	100%	50,000	50,000
H2020	885916	PAVIMON	2019	Maintenance, condition monitoring systems	100%	50,000	50,000
H2020	876228	TruePower	2019	Other	25%	50,000	12,500
H2020	840461	GiFlex	2019	Other	25%	191,149	47,787
H2020	867602	IGP	2019	Other	25%	50,000	12,500
H2020	821114	SUSMAGPRO	2019	Other	25%	12,977,446	3,244,361
H2020	815301	RE-COGNITION	2019	Grid integration	25%	4,990,000	1,247,500

Table 30 R&I projects considered under JRC methodology to estimate EC funding for wind energy under H2020 projects completed in 2019

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	640741	LIFES 50plus	2015	Floating offshore wind	100%	7,274,838	7,274,838
H2020	691173	REACH	2015	Airborne wind energy systems	100%	2,675,132	2,675,132
H2020	657652	Riblet4Wind	2015	New turbine materials & components	100%	3,307,172	3,307,172
H2020	675659	ICONN	2015	Other	50%	845,838	422,919
H2020	656024	EcoSwing	2015	New turbine materials & components	100%	10,591,734	10,591,734
H2020	691919	ELICAN	2016	Offshore technology	100%	11,181,987	11,181,987
H2020	685842	EIROS	2016	New turbine materials & components	25%	7,993,169	1,998,292
H2020	730747	POWDERBLADE	2016	New turbine materials & components	100%	2,731,700	2,731,700
H2020	727477	CL-Windcon	2016	Maintenance & monitoring	100%	4,931,423	4,931,423
H2020	691714	PROMOTION	2016	Offshore technology	30%	39,327,744	11,798,323
H2020	747921	HYPER TOWER	2017	Logistics, assembly & installation	100%	183,455	183,455
H2020	753156	SAFS	2017	Floating offshore wind	100%	195,455	195,455
H2020	836540	eolACC	2018	Maintenance & monitoring	100%	50,000	50,000
H2020	876355	Vertical Sky	2019	Other	100%	50,000	50,000
H2020	868808	MicroCoating	2019	New turbine materials, components	100%	50,000	50,000
H2020	867710	Modvion	2019	New turbine materials, components	100%	50,000	50,000
H2020	836347	LEWIATH	2019	New turbine materials, components	100%	50,000	50,000
H2020	855726	TwingTec	2019	Airborne wind energy systems	100%	50,000	50,000
H2020	876228	TruePower	2019	Other	25%	50,000	12,500
H2020	867602	IGP	2019	Other	25%	50,000	12,500

Annex 3

Table 31 R&I projects considered under JRC methodology to estimate EC funding for wind energy under H2020 projects completed in 2019

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	640741	LIFES 50plus	2015	Floating offshore wind	100%	7,274,838	7,274,838
H2020	691173	REACH	2015	Airborne wind energy systems	100%	2,675,132	2,675,132
H2020	657652	Riblet4Wind	2015	New turbine materials & components	100%	3,307,172	3,307,172
H2020	675659	ICONN	2015	Other	50%	845,838	422,919
H2020	656024	EcoSwing	2015	New turbine materials & components	100%	10,591,734	10,591,734
H2020	691919	ELICAN	2016	Offshore technology	100%	11,181,987	11,181,987
H2020	685842	EIROS	2016	New turbine materials & components	25%	7,993,169	1,998,292
H2020	730747	POWDERBLADE	2016	New turbine materials & components	100%	2,731,700	2,731,700
H2020	727477	CL-Windcon	2016	Maintenance & monitoring	100%	4,931,423	4,931,423
H2020	691714	PROMOTION	2016	Offshore technology	30%	39,327,744	11,798,323
H2020	747921	HYPER TOWER	2017	Logistics, assembly & installation	100%	183,455	183,455
H2020	753156	SAFS	2017	Floating offshore wind	100%	195,455	195,455
H2020	836540	eolACC	2018	Maintenance & monitoring	100%	50,000	50,000
H2020	876355	Vertical Sky	2019	Other	100%	50,000	50,000
H2020	868808	MicroCoating	2019	New turbine materials, components	100%	50,000	50,000
H2020	867710	Modvion	2019	New turbine materials, components	100%	50,000	50,000
H2020	836347	LEWIATH	2019	New turbine materials, components	100%	50,000	50,000
H2020	855726	TwingTec	2019	Airborne wind energy systems	100%	50,000	50,000
H2020	876228	TruePower	2019	Other	25%	50,000	12,500
H2020	867602	IGP	2019	Other	25%	50,000	12,500

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