International Renewable Energy Agency

TRACKING THE IMPACTS OF INNOVATION

OFFSHORE WIND AS A CASE STUDY

ISBN 978-92-9260-347-2

Citation: IRENA (2021), Tracking the impacts of innovation: Offshore wind as a case study, International Renewable Energy Agency, Abu Dhabi

About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

Acknowledgements

This report was drafted by Martina Lyons, Elisa Asmelash, Karan Kochhar and Mustafa Abunofal under the supervision of Paul Durrant. The report was prepared with the support and guidance of Francisco Boshell, Michael Taylor, Sonia Al-Zoghoul and Pablo Ralon. The report was reviewed by Herib Blanco and Paul Komor (IRENA), Francisco Pasimeni (European Commission) and Karsten Steinfatt (WTO). The report was edited by Jonathan Gorvett and Stephanie Clarke.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 899899 and from the Government of the United Kingdom.

For further information or to provide feedback: **publications@irena.org**

Disclaimer

CONTENTS

FIGURES

TABLES

BOXES

ABBREVIATIONS

CAGR	Compound annual growth rate
CN	China
DE	Germany
DK	Denmark
EU	European Union
GW	Gigawatt
HVDC	High voltage direct current
IID	Innovation Impacts Dashboard
JP	Japan
JRC	Joint Research Centre (European Union)
KR	Republic of Korea
kWh	Kilowatt hour
LCOE	Levelised cost of electricity
MI	Mission Innovation
MW	Megawatt
NO	Norway
O&M	Operation and maintenance
RD&D	Research, development and demonstration
RoW	Rest of the world
TEIIF	Tracking Energy Innovations Impacts Framework
TRL	Technology readiness level
TSO	Transmission system operator
TWh	Terawatt hour
UK	United Kingdom of Great Britain and Northern Ireland
USA	United States of America

EXECUTIVE SUMMARY: CONTEXT AND KEY FINDINGS

Clean energy technology innovation – particularly research, development and demonstration (RD&D) – plays a critical role in accelerating the global energy transition. As this transition progresses and ambitions grow, the need for strong government support for innovation grows alongside it.

Government support mechanisms can include RD&D funding, market instruments, and policies that guide and encourage innovation activities. In this report, these are described as "inputs" into the innovation process. The purpose of these inputs is to lead to outputs (i.e. new or improved technologies, processes and systems) and ultimately outcomes (i.e. positive changes in energy systems). Linking these innovation inputs to the progress of clean energy technology innovation and understanding their impacts can, however, be challenging.

This report is an initial output of two interlinked projects focused on tracking innovation impacts: first, the Innovation Impacts Dashboard (IID) project – funded by the government of the United Kingdom of Great Britain and Northern Ireland – and second, the Tracking Energy Innovation Impacts Framework (TEIIF) project, funded by the Horizon 2020 Programme of the European Union (EU). Both projects have contributed to the work discussed here. Those projects both also contribute to the Mission Innovation Tracking Progress workstream.

Under the TEIIF project, work will continue to build on and refine the approach developed to date. This will be done, in particular, in consultation with – and with feedback from – the EU, the United Kingdom (UK) and other Mission Innovation (MI) members, as well as the MI Secretariat.

The goal of this work is to develop a tool for policy makers. This will enable them to better measure and understand the various factors that impact progress in technology. It will also help better inform innovationsupport related decisions, while also enabling policy makers to better design RD&D activities and innovation policies.

Offshore wind was chosen for a case study to pilot an initial methodology. This methodology looks at a range of indicators that, when considered together, may provide additional qualitative and quantitative insights into ways in which innovative energy technologies are making progress, either fully or in part due to RD&D activities. The methodology analyses 30 indicators across three categories: the innovation ecosystem, technology progress and market formation.

This **main output of the pilot is an online dashboard**, which provides a visual presentation of indicators, showcasing trends and the geographical distribution of activities in offshore wind. This brief accompanies that dashboard. It does so by presenting the results and exploring the insights and perspectives gained from piloting the methodology on offshore wind progress globally, between 2010 and 2019. Offshore wind was chosen due to its significant progress in technology development and deployment, as well as in cost reductions and the rapid maturation of this market over the last decade.

This report does come with caveats. Progress in offshore wind technology is driven by many factors, of which RD&D is only one. Factors that are hard to measure and/or that affect several technologies simultaneously – such as the impacts of wider systemic innovation, dependencies on supply chain and critical materials, and market dynamics – are excluded from this case study. In addition, the approach explored does not currently address RD&D policies or inputs (e.g. RD&D funding), nor does it attempt to prove a causal link between progress made and RD&D inputs (e.g. RD&D funding) or policies. Instead, it highlights where RD&D may have contributed. Lastly, the report's findings are based on the data accessible in the time frame of the project, with its data gathering approach thorough, but not exhaustive. Further work will focus on exploring and refining some of those factors further. The indicators also come with specific limitations addressed in their respective chapters.

Provisional key findings and insights are summarised below. The process behind the selection of the indicators and the overall approach will be documented as an annex to the TEIIF project methodology. Section 7.2, however, briefly discusses the strengths and weaknesses of this initial approach and how the methodology might be refined through further work.

Table 1. Key findings and insights

A HEALTHY AND BROADENING INNOVATION ECOSYSTEM		
Active and broadening research base	**Active private and public sectors seeking commercialisation of their intellectual property**	**Active and growing RD&D collaboration between private and public sector organisations**
• The number of technology related **scientific publications** for offshore wind **increased 2.5 times** between 2010-2019, with **over 88 000 citations** during the same period. • The large global increase was mainly due to a five-fold **increase from China.** Publication rates **plateaued**, but have persisted **in established markets** (the United States of America (USA), the UK, Germany, Denmark, Norway, Japan and the Republic of Korea), while continuing to grow with a **3.5-fold increase in new markets** across countries in Europe, Asia, Latin and North America, **broadening the geographical offshore wind research base.**	• **Patents** for offshore wind **increased by 60%** from 2010 2017. • **China's** inventions (patent families) grew exponentially, **from 2 to 63** during this period. **Japan** and the Republic of **Korea** produced almost **20%** of the inventions in 2017. • Established markets in Asia (China, Japan and the Republic of Korea) and Europe (France and Germany) were **responsible for 90% of patenting activity in 2017.**	• Offshore wind **RD&D collaborations** grew **fourfold** from 2010 to 2019. • **National** collaborations increased between 2015 2019, while **international collaborations** were prevalent between 2010-2015. This suggests **RD&D is moving into higher technology readiness levels (TRLs)** and the market is maturing. • Almost **60 international offshore wind conferences and events** took place between 2010-2019, with over **55% taking place regularly**, either annually or biennially (China, the USA, Poland, Germany, EU level).

TECHNOLOGY DEVELOPMENT IN THE FORM OF DECLINING COSTS, IMPROVED TECHNOLOGY PERFORMANCE AND A WIDENING RANGE OF SOLUTIONS.

Costs continued to decline	Technological performance improved	Innovative solutions brought diversity and continued to reach different geological conditions
• Overall **installed costs declined by 28%** between 2015 and 2019, but cost volatility is still present due to immaturity of the market. • **Levelised cost of electricity (LCOE) dropped by 32%**, from USD 0.169/kilowatt hour (kWh) in 2010 to **USD 0.115/kWh** in 2019. • Cost declines were **driven by learning-by-RD&D, learning-by-doing and economies of scale.**	• The **capacity factor** increased by 18%, **reaching 44%** in 2019. • Capacity factor improvements were in large part **driven by RD&D activities** contributing to **technology improvements**, including the hub height of offshore wind turbines – which grew by 30% – the rotor diameter of offshore wind turbines – which grew by 40% – and by turbines doubling in size.	• Offshore wind projects reached deeper and more **distant waters, with distance from the shore growing almost threefold.** • Over 80% of all offshore wind foundations were monopile, due to their price and ease of use. To address various seabed conditions, water depths, and differences in manufacturing, installations and operation, a wide range **of foundation types were deployed, enabled by RD&D activities.** • Improvements in the efficiency of offshore wind logistics contributed to increased and faster deployment. RD&D activities contributed to this by, for example, enabling more efficient and specialised **installation vessels** for offshore wind. • To tap potential in **water depths beyond 50 metres**, an **increase in RD&D activities** is needed to improve existing solutions and further explore the suitability of foundations, including **floating foundations.**

RAPIDLY GROWING MARKETS MOVING TOWARDS MATURITY			
Deployment continued to increase	**Base of international standards for offshore wind continued to grow**	**Differentiated products and services led to commercialisation**	**Strong growth of wind energy exports trade flows**
• **Installed capacity** for offshore wind grew more than **ninefold** between 2010-2019, when it reached 28 gigawatts (GW). • **Electricity** generated grew exponentially, from 7.3 terawatt hours (TWh) in 2010 to **68 TWh in 2018.** • In 2018, the share of offshore wind power was **1% of the global renewable energy mix,** up from 0.2% in 2010.	• Countries involved in developing international standards for offshore wind grew from **24** in 2010 to **31** in 2019. • The number of international standards increased from **zero to nine** in the same period.	• The number of registered trademarks for offshore wind grew from **73** in 2010 to **193** in 2015 and then **fell by 55%, to 86,** in 2019 – indicating a shift from the development phase to **commercialisation**.	• Global trade flows in wind energy technology as measured by wind energy exports **doubled** between 2005-2019. • China, Germany and the USA were the largest exporters, while countries like Italy also emerged. In the case of Italy – an onshore wind leader – **RD&D activities and innovation** may have allowed an adaptation of onshore wind technology and an increase in manufacturing capacities.

1. ASSESSING THE IMPACT OF TECHNOLOGY INNOVATION SUPPORT

Clean energy technology innovation – particularly research, development and demonstration (RD&D) – plays a critical role in accelerating the global energy transition. As this transition progresses and ambitions grow, the need for strong support for innovation grows with it.

Innovation support is a combination of multiple measures, including RD&D funding (from the public and private sectors), market instruments and policies. Together, these guide and encourage innovation activities. In this report, those support mechanisms are described as "inputs" into the innovation process. The purpose of these inputs is to lead to outputs (i.e. new or improved technologies, processes and systems) and ultimately outcomes (i.e. positive changes in energy systems).

Innovation, however, involves uncertainty and timelags between generating and codifying knowledge and reducing costs and increasing deployment (Jamasb, 2007). Linking the impact of innovation inputs to the progress of clean energy technology innovation and understanding that impact can therefore be challenging. Yet, understanding those impacts is important in assessing past support mechanisms and informing decision making on future funding and support (Vidican-Sgouridis, Lee Woon and Madnick, 2009).

To date, the principal focus has been on the gathering of data on inputs into the innovation process. There has been substantially less activity trying to define meaningful metrics to track the outputs and outcomes from clean energy technology innovation. Such metrics would allow for a more rigorous comparative analysis of the relative performance of innovation support for different technologies (Hu, Skea & Hannon, 2017).

This report summarises the early findings from a pilot study on offshore wind technology, which is an output of two interlinked projects seeking to address that challenge. Both projects are focused on tracking the outputs and outcomes of innovation and are intended to contribute to the Mission Innovation Tracking Progress workstream. Given the sometimes complex interconnections between outputs and outcomes, these projects group them as particular "impacts".

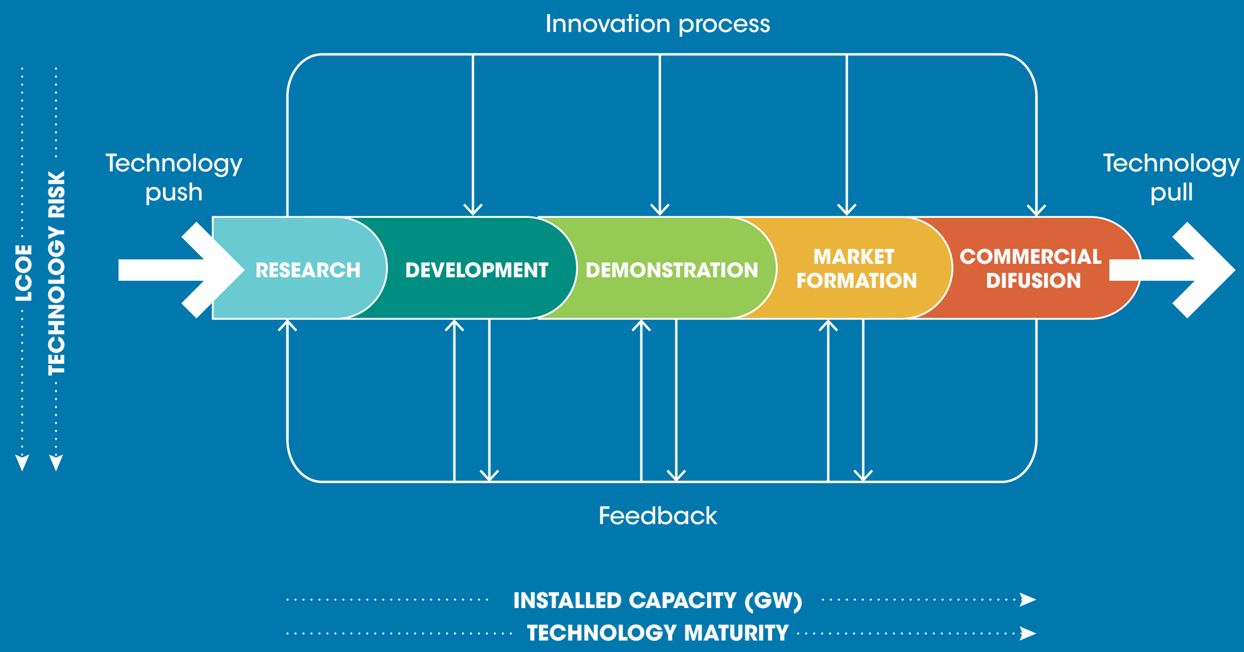
The Innovation Impacts Dashboard (IID) project is funded by the government of the United Kingdom of Great Britain and Northern Ireland. It aims to explore the value of using a range of indicators that, when assessed in combination, may shed new light on trends in – and the role of – innovation in the progress of selected energy technologies. The second project, the TEIIF (Tracking Energy Innovation Impacts Framework) project, is funded by the Horizon 2020 Programme of the European Union (EU). This project aims to expand the energy technology knowledge base by broadening and deepening existing datasets on costs, performance, and project characteristics, as well as on patents and standards (i.e. outputs and outcomes from the innovation process). It also seeks to explore what insights can be gained from that data on the impact of innovation support.

Both projects have contributed to the work discussed here. The IID project concludes with this report, but the TEIIF project will continue to build on and refine the approach developed to date – in particular in consultation with and with feedback from the EU, the UK and other Mission Innovation (MI) members, as well as the MI Secretariat.

BOX 1. DEFINITIONS

The innovation life cycle depicts the maturity of a particular technology and can be divided into five broad stages (Figure 1): basic science and research and development (R&D); applied R&D; demonstration; market development; and commercial diffusion (IRENA, 2017). This helps to contextualise the types of innovation activities advancing a given technology at a given time. Innovation processes encompass feedback loops between different stages, providing information on gaps and opportunities.

Figure 1. Innovation life cycle



Source: IRENA (2017)

Technology RD&Ds are the components of the innovation lifecycle that take place at the early stages of technical development. While these stages normally precede the commercial use of technology, commercial use may never follow.

Market formation follows the RD&D stages and includes policies and tools, including standards to address specific market failures or issues of technology lockin.

Commercial diffusion closely follows the market formation phase and focuses on building industrial capacities around proven technologies across the value chain of technology.

Innovation is one of the key factors driving the energy transition. Technological innovation lays at its core, but other innovations are equally important in advancing solutions. These include innovation in business models to engage new actors, market design and system operation, as well as new types of financing.

Innovation inputs indicators describe public and private financial resources (Table 2) that help to accumulate knowledge, strengthen collaboration, reduce costs and improve technological performance at different stages of the innovation lifecycle. These input indicators tend to be biased towards the early stages of the innovation cycle (RD&D), due to more easily available data.

Table 2. Input indicators and their applicability/use in different stages of innovation

Indicators	Research	Development	Demonstration	Market formation	Commercial diffusion
R&D expenditures	✓	✓			
Demonstration expenditure & instruments			✓		
Subsidies				✓	✓
Asset finance				✓	✓
R&D workforce	✓	✓	✓		

Source: Hu, Skea & Hannon (2017)

The innovation outputs indicators present immediate results of RD&D activities and include scientific publications, patents, technology cost reduction and technology performance improvements. They can also include collaboration and exchanges of knowledge between actors, such as RD&D joint projects or scientific conferences.

The innovation outcomes indicators present the results of the adoption and use of energy technologies in terms of economics, social and environmental benefits. This can include jobs, installed capacity, trademarks or trade flows.

In work to date, an initial methodology has been developed that aims to provide qualitative and quantitative insights into ways in which innovative energy technologies are making progress, either fully or in part due to RD&D activities. This methodology seeks to provide a tool for policy makers to better measure and understand the various factors that impact progress in technology, to better inform innovationrelated decisions, and to better design RD&D activities and innovation policies. The rationale behind the methodology is that technology development occurs in multiple ways, so no one indicator can provide a reliable insight into the progress the technology is making. Therefore, the case study looks at a range of indicators that when considered together may provide useful insights.

To explore the value of that approach, the methodology has been piloted on offshore wind, looking at progress globally, between 2010 and 2019. The **main output of the pilot is an online** [dashboard,] which provides a visual presentation of indicators, showcasing trends and the geographical distribution of activities in offshore wind.

This report accompanies that dashboard by presenting the results and discussing the insights and perspectives gained from piloting the methodology on offshore wind globally, between 2010 and 2019. Offshore wind was chosen due to its significant progress in technology development and deployment, cost decline and the rapid maturity of the market. The report presents the results and offers the enhanced insights and perspectives gained from piloting the methodology on offshore wind technology.

There are, however, some caveats to what follows. Firstly, progress in technology is driven by many factors, of which RD&D is only one. Factors that are hard to measure and/or affect several technologies simultaneously – such as systemic innovation, dependencies on supply chain and critical materials, as well as market dynamics – are excluded from this case study. Secondly, the approach explored does not currently address policies or RD&D inputs (e.g. RD&D funding), nor does it attempt to prove a causal link between progress made and RD&D inputs (e.g. RD&D funding). Instead, it highlights where RD&D may have contributed.

Lastly, the report's findings are based on the data accessible within the time frame of the project, with the data gathering approach thorough, but not exhaustive. The indicators also come with limitations, with these addressed in their respective chapters.

Follow on work will focus on exploring and refining some of those factors further, including exploring the interlinkages between indicators.

2. INDICATORS AND INNOVATION IMPACTS

A set of impact indicators have been identified and used to map the progress of offshore wind between 2010 and 2019 at the global level. Studying the indicators in combination aims to bring new perspectives, help stimulate policy debates and uncover new dynamics.

Thirty indicators are mapped across seven categories grouped under three impact categories of outputs and outcomes that innovation support mechanisms seek to deliver.[1,2]

The categories are:

- **Innovation ecosystem:** An active, growing and broadening innovation ecosystem.
- **Technology progress:** Continual improvements in technology in the form of declining costs, improving technology performance and a widening range of solutions.
- **Market formation:** A growing and broadening market moving towards maturity.

2.1 Innovation ecosystem: An active, growing and broadening innovation ecosystem

Table 3 below encompasses indicators of the state of knowledge development, codification and dissemination, and an increase in awareness and collaboration among various actors.

A healthy innovation ecosystem allows innovations to develop and be adopted. It is enabled by public and private innovation support mechanisms. It is also an essential precondition for stimulating further innovation. The growth of the indicators in this category and their broadening to involve more organisations and countries is a positive sign of progress in technology. Stagnation or consistent falls in these indicators would call for a re-evaluation of policy, including innovation support mechanisms.

Table 3. Indicators mapping the innovation ecosystem

KNOWLEDGE	AWARENESS & COLLABORATION
• Scientific publications	• RD&D collaboration
• Joint scientific publications	• Membership in industry associations
• Citation of scientific publications	• International conference & events
• Citation of joint publications	• Co-inventions between countries
• Web 2.0 citation of publications	• Data mining on awareness on technology across web
• Web 2.0 citation of joint publications	
• Patents filed	
• Patents filed internationally	
• Patents of high value	
• Patents specialisation index	
• Filing patents by companies per country	
• Citation of patents	

1 For more information on the categories, please see an annex to the TEIIF project (forthcoming).

2 Data for the blue/green/orange indicators were collected as part of the TEIIF project funded by the EU's Horizon 2020 Programme. White indicators were not utilised in this study, but could be considered for the future work.

2.2 Technology progress: Continual improvements in technology in the form of declining costs, improving technology performance and a widening range of solutions

Improvements in technology are the most direct impact of innovation support. They are enabled by a healthy innovation ecosystem, but also require a functioning market. Indicators in this category (Table 4) map cost reduction and technology performance improvements, including efficiency, incremental improvements and breakthroughs, as well as diversity in project characteristics.

2.3 Market formation: A growing and broadening market moving towards maturity

Innovations only have an impact if they can be deployed. The formation and maturation of a market and the associated enabling conditions for the technology are indirect signs of progress and are influenced by innovation support mechanisms. The indicators in this category (Table 5) provide some insights into the scaleup of offshore wind deployment and its broad commercialisation.

Table 4. Indicators mapping technology progress

COST	PROJECT CHARACTERISTICS	PERFORMANCE

• Total installed costs
• O&M
• LCOE
• Cost competitiveness ratio
	• Water depth
	• Distance from the shore
	• Average turbine size
	• Foundation type
	• Installation time of foundations
	• Number of installations vessels
	• Number of HVDC projects
		• Capacity factor:
		  • Nameplate capacity
		  • Hub height
		  • Rotor diameter
		  • Turbine rating
		• Average downtime per turbine per year

Table 5. Indicators mapping market formation

DEPLOYMENT	COMMERCIAL
• Total installed capacity • Total electricity generated • Start-ups • Share of electricity generated by technology in the energy mix • Number of international standards • Countries developing international standards • Countries adopting international standards • New international standards under development	• Certification • Jobs • Trade flows • Licenses applications submitted • Registered trademarks

3. OFFSHORE WIND

Offshore wind energy is an emerging renewable technology that has developed rapidly in the past ten years. It has seen significant technology cost reductions, technology advancements and breakthroughs, increased supply chain efficiencies and substantial uptake in different markets, which in turn has unlocked further investments.

Offshore wind allows countries to exploit the generally higher and more consistent wind resources offshore, while achieving gigawatt-scale projects close to the densely populated coastal areas that are prevalent in many parts of the world. This makes offshore wind an important addition to the portfolio of low carbon technologies available to decarbonise many countries' energy sectors (IRENA, 2019).

In 2019, 28 GW of offshore wind capacity was installed worldwide, of which 90% was commissioned and operated in the North Sea and the North Atlantic Ocean. Denmark (DK), Germany (DE), and the UK are pioneers, but deployment is moving beyond the front runners and is broadening to China (CN), Japan (JP), North America and the Republic of Korea (KR) (IRENA, 2019).

Offshore wind is a rapidly maturing technology. It has undergone significant developments in the past decade and is poised to play an important role in future energy systems. These characteristics made offshore wind an attractive technology for this case study.

4. PROGRESS IN THE OFFSHORE INNOVATION ECOSYSTEM

This group of indicators provides insights into the degree and breadth of activity in the innovation ecosystem. It particularly looks at publications (and their citations), patents, RD&D collaboration and international events focused on offshore wind technology. The text also explores which other indicators could bring additional insights into the growth and health of the innovation ecosystem.

4.1 Scientific publications

While innovation goes beyond technology and includes systemic innovation in business models, market design and system operation, it is technological RD&D that often lies at its core, forming the building block from which new products and services are further developed.

Capturing and disseminating knowledge from offshore wind technology RD&D has been building momentum over the past ten years, as indicated by the steady growth in **scientific publications** related to this technology. Between 2010 and 2019, more than 12 300 technology related papers[3] were published, with the annual tally rising steadily from 756 in 2010 to 1 777 in 2019 (representing an almost 2.5-fold increase), with only a slight dip in 2017.

The breadth of topics was also wide and included engineering, energy, and material science. This case study, however, does not analyse the topics of these publications further. Nonetheless, a growing publication base and an advancing interest in diverse topics for offshore wind indicate a flourishing innovation ecosystem that can support scaleup.

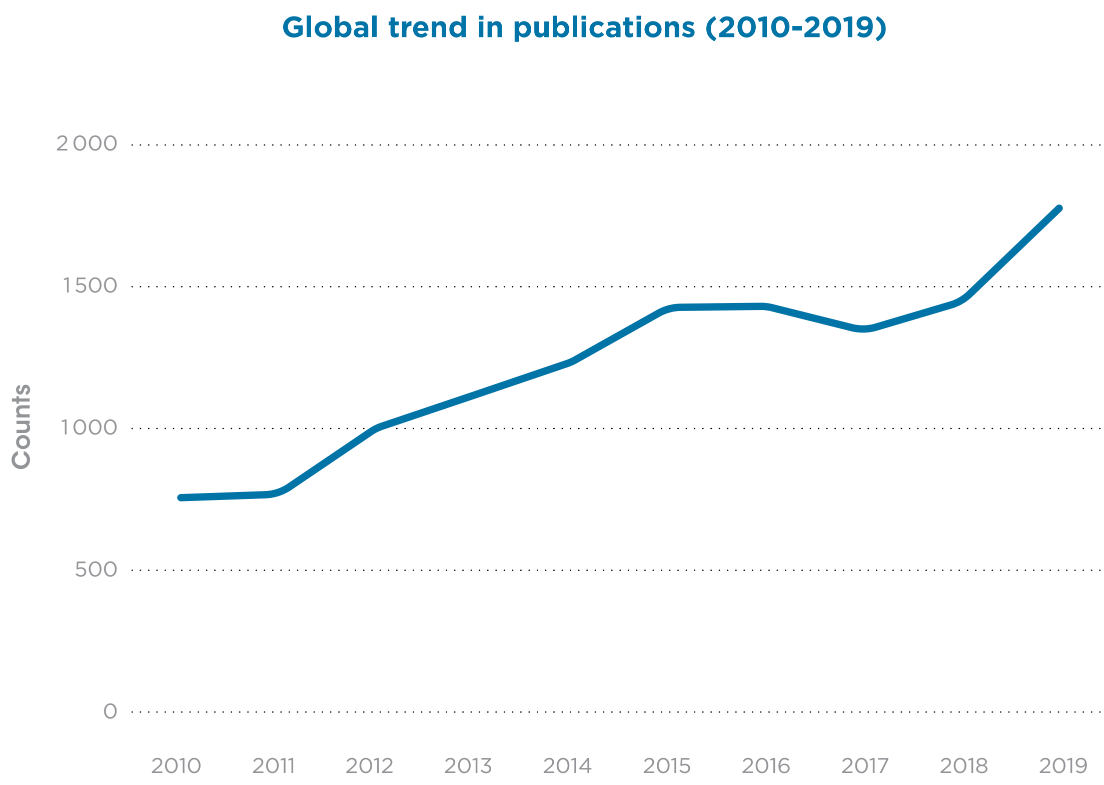
Certain countries continued to lead the development of expertise in this field, publishing[4] more research outcomes from their activities than other countries. The share of publications from the **top eight countries – China**, **Norway (NO), Germany, Denmark, the UK, the USA**, **Japan, and the Republic of Korea –** grew from 71% in 2010 to 79% by 2019. Figure 2 shows the changes in countries' global shares over the years. Starting in 2011 and then in 2013 and 2014 and every year since 2016, the USA, the UK and Germany have been overtaken by China, whose global share more than doubled, from 12% in 2010 to 27% in 2019. China's contribution in absolute numbers also increased more than five times over the period, from 90 to 482 per year. The US global share decreased in this period, from 14% to 11%, although, in absolute terms, the number of publications more than doubled. The largest drop in global share in publications was documented in Germany, which decreased from 12% to 7%, while in absolute numbers, their publishing activity remained constant. While the remainder of the established market's publishing activity grew modestly and rather plateaued, China was the largest contributor responsible for the global increase in publications.

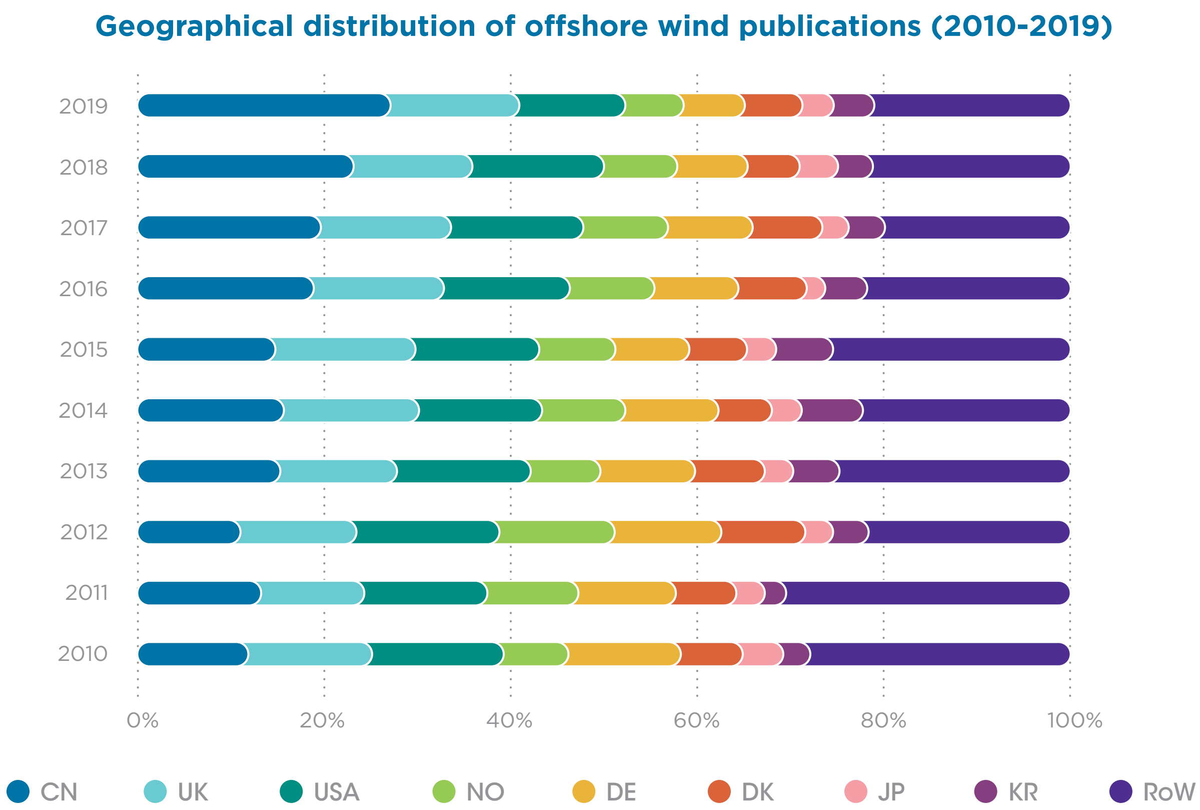
In addition to the top publishing countries, the research base also broadened over the period, with publications from **India, Canada, Australia, and the European countries of Ireland, Italy, France, Portugal and Belgium** growing 3.5 times between 2010 and 2019.

3 The Scopus database includes conference papers, articles, books and book chapters, reviews, business articles, etc.

4 The Scopus database contains predominantly English language publications, with over 20% of publications in other languages.

Figure 2. Global publications trends, countries leading in publications and global shares (2010-2019)





Source: Scopus database (2019)

The number of times publications were **cited** in subsequent years can help measure their quality and impact by showing how research outcomes are being carried forward to support innovation and deployment. Papers published between 2010 and 2019 were cited over the same period **more than 88 000 times**. Measuring the impact factor of citations, the US and European publications showed the largest impact, with the Chinese papers showing an increasing impact over time.

The growing number and the breadth of technologyrelated topics, along with the geographical coverage, positively indicates that knowledge is growing and proliferating. This is a sign of a generally healthy innovation ecosystem. A declining number would be of concern for a technology at this stage of development. The rise suggests there is still scope for further development, too.

Whilst this broadening of the number of countries publishing is encouraging, it is still relatively narrow, and ideally would be expanded further.[5] Publications[6] almost entirely came from academia and research institutes. These same organisations often partner in many of the publicprivate RD&D collaborations and many publications stem from these projects (see RD&D collaboration below).

4.2 Patents

The patent analysis is based on the patent dataset of the TEIIF project funded by the European Union's Horizon 2020 programme. The patent dataset has been produced by the Joint Research Centre (JRC) of the European Commission, following the JRC patentbased methodology (Fiorini et al., 2017; Pasimeni, 2020, 2019; Pasimeni, Fiorini and Georgakaki, 2019).

The development of offshore wind technology can be explored and evaluated through the analysis of the **patenting activity.** Patents play a crucial role throughout the whole technology lifecycle – from early R&D phases up to successful commercialisation – and can be used as a metric for informing technology trends.

For this report, patent data (patent families) have been analysed for one component of the offshore wind installation: towers.[7] Other patent categories (nacelle, rotors, blades, etc.) cover both onshore and offshore wind, while the towers category gives us a view which is unique to offshore wind.

Between 2010 to 2017, **overall patent activity** (patent families) in offshore wind towers generally increased.[8] This denoted an increased interest in offshore wind technology. Between 2010 and 2017, the countries with the highest number of inventions – in total, as well as on an annual basis – were China, followed by the EU28[9] (top countries: Germany, France and the Netherlands), the Republic of Korea and Japan. This shows a growing interest from other countries besides the front runners in innovation in offshore wind technologies.

The number of filed **patents of high value** is also a useful metric in assessing global trends in technology transfer. It refers to patent families that include patent applications filed in more than one patent office. Results show that patents of high value have been following a similar trend to patent activity, showing the interest of countries in filing patents in more than one patent office.

5 The database may underrepresent publications in languages other than English. This could be investigated further.

6 As recorded in the Scopus database.

7 In August 2020, the European Patent Office introduced a change in categorisation of wind technology by eliminating and aggregating several categories. These changes, however, do not impact our analysis.

8 An important consideration when analysing patent data on an annual basis is the reporting timeframe. The filing process for patents normally takes around two years and sometimes longer, so data in the last three years is not as reliable, because a patent filed in 2017 may be reflected in the data two years later. As such, for the purpose of this exercise, patents data is being presented up until 2017. Data for 2017 is still incomplete, however, as the gathering process is still ongoing. As such, the results presented in this report are only preliminary for 2017, but have still been taken into consideration, as they still provide a good overview of the trends in patenting activity.

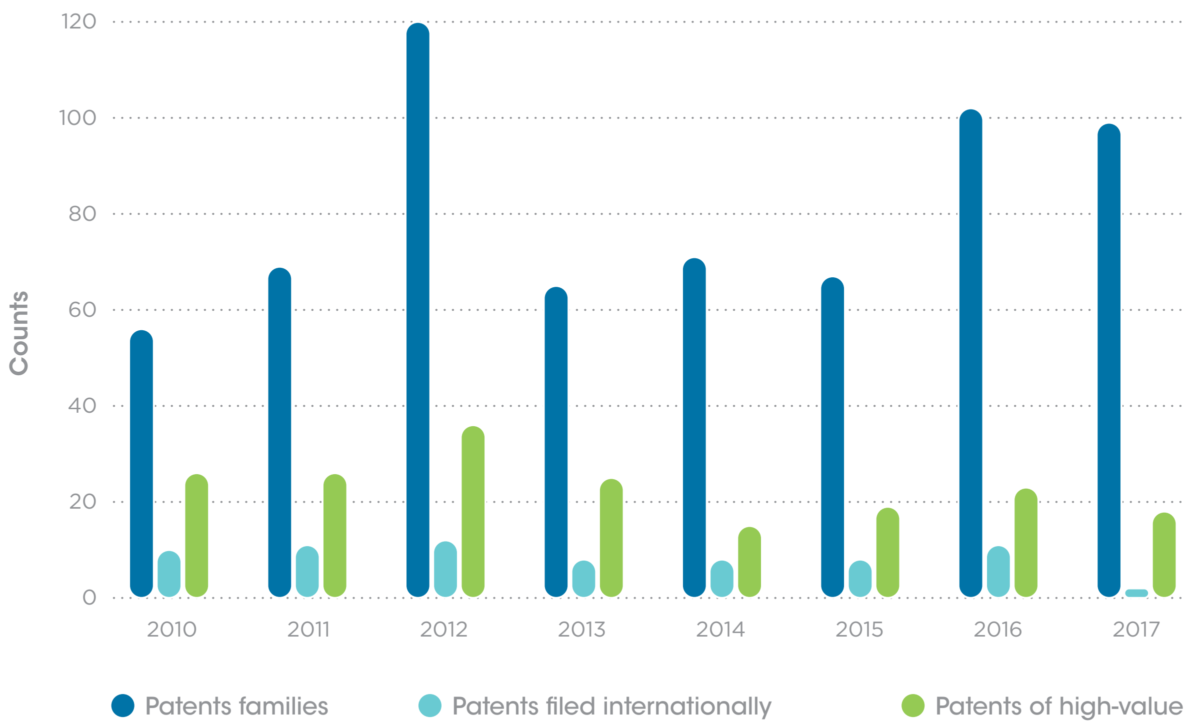
9 The 28 member states of the EU, which included the UK at that time, were: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the UK.

Additional insights can also be gained by looking at patents on a country level. The top countries filing patents of high value are European ones, namely France, Germany and Spain, along with the USA. Out of these, France and Spain have low deployment levels, but possess knowledge gained from their development of onshore wind farms. China and the Republic of Korea, on the other hand, have in general a high level of inventions in their overall patent activity, but tend to file their applications in only one patent office (in most cases, a domestic one) and not at multiple locations. This insight can be subject to different possible interpretations. One, for example, could be the size of the country/market. The Chinese market by itself is large compared to the European one, which could explain the interest of European countries in filing patents in multiple offices and suggesting interest in a wide applicability of the technology. Other explanations are related to the strategic decision of patenting in order to block imitation, as well as to the quality level of the patents (i.e. low quality patents do not easily flow internationally).

Besides filing patents in multiple offices, there is also an interest in filing patents internationally (i.e. patent applications filed by an applicant resident in a country which is different from the jurisdiction where this patent is filed).

For offshore wind, **patents filed internationally** were relatively stable between 2010 and 2016 with a slight dip in 2017, denoting the interest in establishing an international flow of inventions. At a country level, the highest cumulative numbers of patents filed internationally were from the USA, the Republic of

Figure 3. Offshore wind patent families, patents filed internationally and of high value (2010- 2017)



Source: Joint Research Centre (JRC) based on data from the European Patent Office (EPO)

Korea, the European countries (namely Germany, Spain and France) and Japan. Interestingly, China is not among the countries interested in filing patents internationally. One possible explanation could be attributed to filing procedures, which are generally easier when filing in national offices compared to other countries' offices. Another possibility could be the size of the patents components that are being filed (i.e. large or small).

When looking at patenting activity on a country-level, another insightful indicator is the **specialisation index**, which represents patenting intensity in a technology for a given country compared to global activity. In this regard, it is interesting to see how the specialisation index of the top countries in offshore wind towers compares with the global specialisation.

China is now at the forefront of offshore wind deployment. It does not have a high patenting intensity in offshore wind towers, as its specialisation index over all the years considered (2010-2016) is lower than the global one. A similar situation can be seen with Germany, except for 2010, when its specialisation index was higher than the global one. Finally, the UK's specialisation index for 2010 was significantly higher than the global one, suggesting a high patenting intensity, but became lower from 2014 onwards. If we compare the three EU countries with the specialisation index for Europe overall, we can see that for all years, they all score lower (with the exception of the UK in 2010).

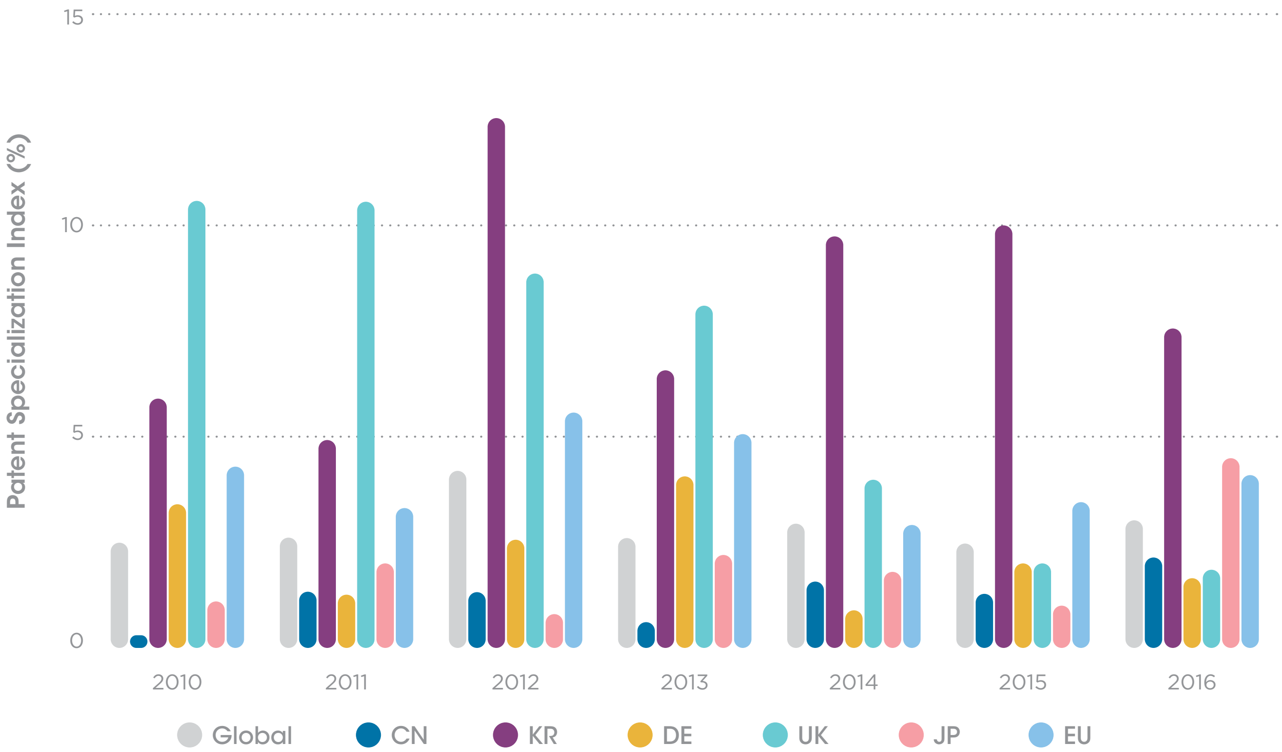
It is also worth looking at emerging countries deploying offshore wind – namely Japan and the Republic of Korea. Japan's patenting intensity was higher than the global level in 2016, while it was lower between 2010 and 2015. The Republic of Korea's patenting intensity was always higher than global levels for all years considered.

Table 6. Specialisation index for offshore wind technology (2010-2016): Global and regional level, selected countries

	SPECIALISATION INDEX						
	2010	2011	2012	2013	2014	2015	2016
World	2.49%	2.61%	4.19%	2.60%	2.94%	2.47%	3.02%
Europe	4.29%	3.31%	5.57%	5.06%	2.91%	3.45%	4.09%
Germany	3.4%	1.26%	2.56%	4.06%	0.89%	2.25%	1.65%
UK	10.58%	10.56%	8.86%	8.10%	3.98%	2.00%	1.85%
China	0.3%	1.33%	1.32%	0.61%	1.57%	1.28%	2.14%
Japan	1.10%	2.00%	0.80%	2.20%	1.80%	1.33%	4.49%
Republic of Korea	5.90%	4.92%	12.54%	6.57%	9.74%	9.58%	7.56%

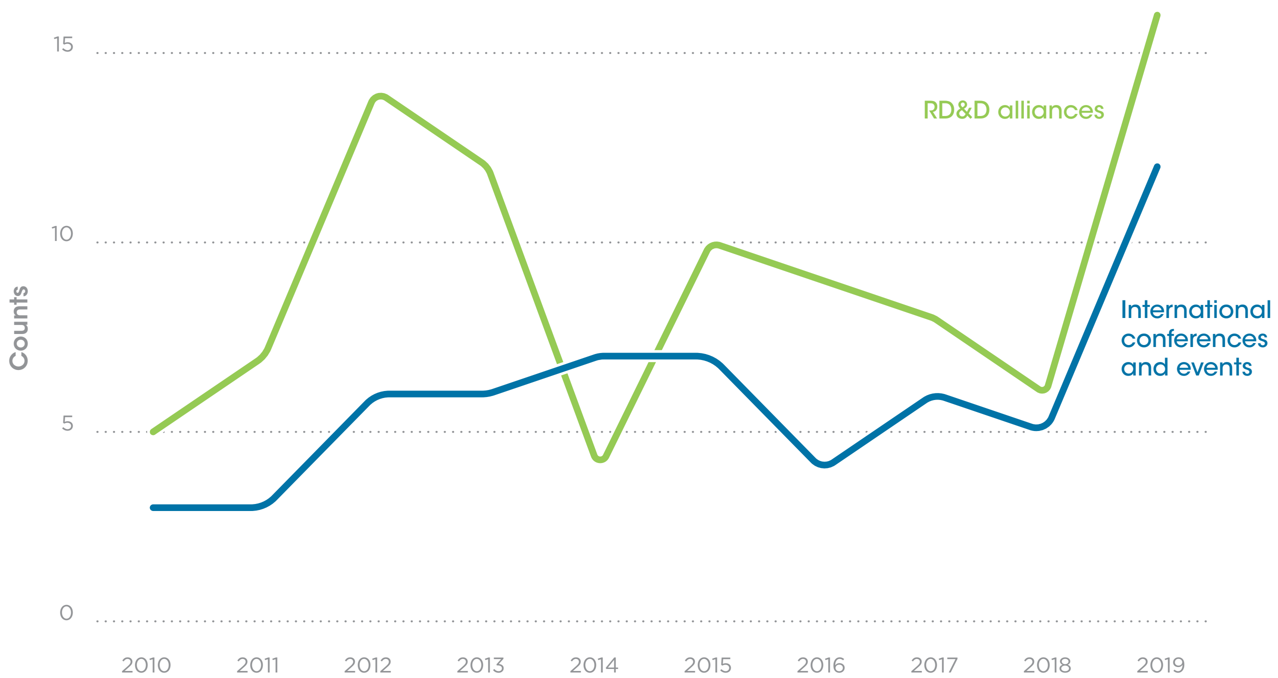
Source: Joint Research Centre (JRC) based on data from the European Patent Office (EPO)

Figure 4. Patent specialisation index (2010-2016)



Source: Joint Research Centre (JRC) based on data from the European Patent Office (EPO)

Figure 5. Offshore wind RD&D alliances and international conferences (2010-2019)



4.3 RD&D collaboration

RD&D collaboration has become an important vehicle to share knowledge, jointly advance innovation, understand barriers in different contexts, and help to cross the valley of death to bring research to the market. RD&D collaboration can be formed: between public institutions (public-public); between public institutions and the private sector (public-private); and between national or international entities.

Between 2010 and 2019, over 90 **national and international RD&D collaborations** were formed that focused exclusively on offshore wind technology. The overall trend was positive, but annual additions experienced a slight decline between 2015 and 2018, which was followed by a steep surge in 2019, which saw 14 newly formed RD&D collaborations in offshore wind.

Overall, there was a 50% increase in collaborations between the 2010-2014 period and the 2015-2019 period. Most collaborations were publicprivate. They occurred mostly amongst **European** partners and were funded by the European Framework for Research and Development or by European national programmes.

The beginning of the 2010s saw several collaborative efforts at the national levels in **Japan and India**, while 20152019 saw a surge of national collaborations in the **USA, China and the Republic of Korea**.

The ten years from 2010 to 2019 saw almost 20 public-public collaborations between international partners. These included collaborations between research organisations and universities in Europe and **Brazil, North America (the USA, Canada), Asia (China, Malaysia, Thailand), and the Middle East and North Africa region (Morocco, Tunisia, Israel, the Kingdom of Saudi Arabia and the United Arab Emirates)**. Almost 75% of these collaborations took place between 2010 and 2015, while since then, international collaboration has decreased substantially. One explanation for this could be that the initial collaboration happened at lower technology readiness levels (TRLs), but with technology moving towards maturity and the market becoming more competitive, interest in collaborating declined.

We also looked at the **international events and conferences** specifically focused on offshore wind. While there were other events and conferences focused on the wind industry, which also included offshore wind, the growing number of events focused specifically on offshore wind indicated both the growing interest of the market and its heading towards maturity.

Between 2010 and 2019, approximately 60 international offshore wind events or conferences took place. **Over 55%** of these events took place either **annually or biennially**. Annual conferences took place in China, the USA, Poland and Germany, while biennial conferences were held at the EU level. The remainder of the events took place in other **European offshore pioneers, such as the UK**, and in countries new to the conference scene, such as **Viet Nam,** which started organising annual offshore wind conferences as they sought domestic opportunities along their coastlines.

4.4 Relevance to innovation

The indicators offer insights into the strength and breadth of the innovation ecosystem. Scientific publications, patents and RD&D collaborations are considered core outputs of RD&D activities, forming part of knowledge creation and dissemination. International events and conferences are less direct indicators, but are included because they offer some insights into how the innovation ecosystem is changing. A growth and broadening of each of these indicators is an essential condition for a healthy innovation ecosystem.

The analysis showed an increase in technologyrelated research in offshore wind over the 10-year period and presented **a strong and consistent innovation ecosystem.** This was characterised by **a large and broadening research base –** as indicated by scientific publications **– active private and public sectors** seeking to commercialise their intellectual property – as shown by patents – and **active and growing RD&D collaboration** between the private and public sectors. The analysis also suggested that offshore wind technology innovation is no longer niche and instead, is becoming globally significant. Between 2010 and 2019, global research – as measured by the number of **scientific publications** – grew almost 2.5-fold, from 756 to 1777. This research also broadened beyond a few frontrunners in Europe (Denmark, Germany, Norway and the UK), Asia (China, Japan and the Republic of Korea), and the USA. Publications coming from other European countries (Belgium, France, Ireland, Italy and Portugal) and from India, Canada and Australia grew 3.5-fold during this period.

The increasing interest in offshore wind technology is also demonstrated by the increasing number of inventions in overall **patenting activities,** as well as in patents of highvalue. At a country level, while China and the Republic of Korea have a high level of inventions in overall patent activity, they tend to file patents in only one patent office; while European ones, namely France, Germany and Spain, are among the top countries with the highest number of inventions, as well as filing patents in different offices. Patents filed internationally have been relatively stable between 2015 and 2016 denoting a general interest in establishing an international flow of inventions, with the top countries being the USA, the Republic of Korea, European countries (namely Germany, Spain and France) and Japan.

The indicators on **RD&D collaboration** and **international events and conferences** provide some insight into the health of the innovation ecosystem.

Whilst a rise in events is not necessarily linked to RD&D support, collaborations are mainly on aspects of technology development. The small numbers of cases captured by these two indicators make it difficult to draw strong conclusions, however. A moderate uptick in collaborations and events in the last five years, including a broadening of countries involved (beyond those few European countries that pioneered offshore wind in the first half of the decade) is an encouraging sign of a maturing technology that is spreading beyond its original niche.

4.5 Potential for further insights

Several other indicators could have further improved the analysis, but were not added to the study due to difficulties in gathering data, or a lack in its availability.

More analysis on the topics within offshore wind covered by scientific papers would help to identify areas and gaps in technology focus. More enhanced insights might be gained through a more indepth analysis of jointly published papers by the public and private sectors. With increased activity on the internet, additional insights might also be gained by analysing the impact of scientific publications through mentions in blogs, posts on Twitter, LinkedIn and other social media, as well as saves in reference management systems (as Web 2.0 citations). Insights into the impact of RD&D support might be gained by linking this data to trends in RD&D funding.

Patents are a useful metric to track progress in innovation, as well as identify RD&D trends and forecast innovation and market development. Expanding an analysis beyond offshore wind towers to include other parts could give a more comprehensive picture of the technology's innovative trends. Citation of patents in the patent application – either as an examiner citation, or as an applicant citation – is considered a proxy to measure the impact of the invention. It can also represent an indicator of the technological and commercial value of a patent and help identify 'key' patents.

Measuring collaboration is an important practice in understanding how synergies can lead to technological advancements and greater deployment. Further analysis of RD&D collaboration and events could enhance the insights gained so far.

More nuanced insights could be gained by understanding the number and diversity of members in industrial associations around the world over the period. Mapping coinventions between countries can provide additional insights into the geographical distribution of collaboration. With increased activity on the internet, data mining on the web can help to gain a better understanding of its role in disseminating knowledge, raising awareness and gaining support among the general and the more specialised public, when it comes to offshore wind technology and its market.

5. PROGRESS IN OFFSHORE WIND TECHNOLOGY

This group of indicators offers insights into the ways clean energy technology innovation works to reduce installed and operation and maintenance (O&M) costs, improve performance, generate higher energy yields and in turn, reduce electricity prices generated from offshore wind.

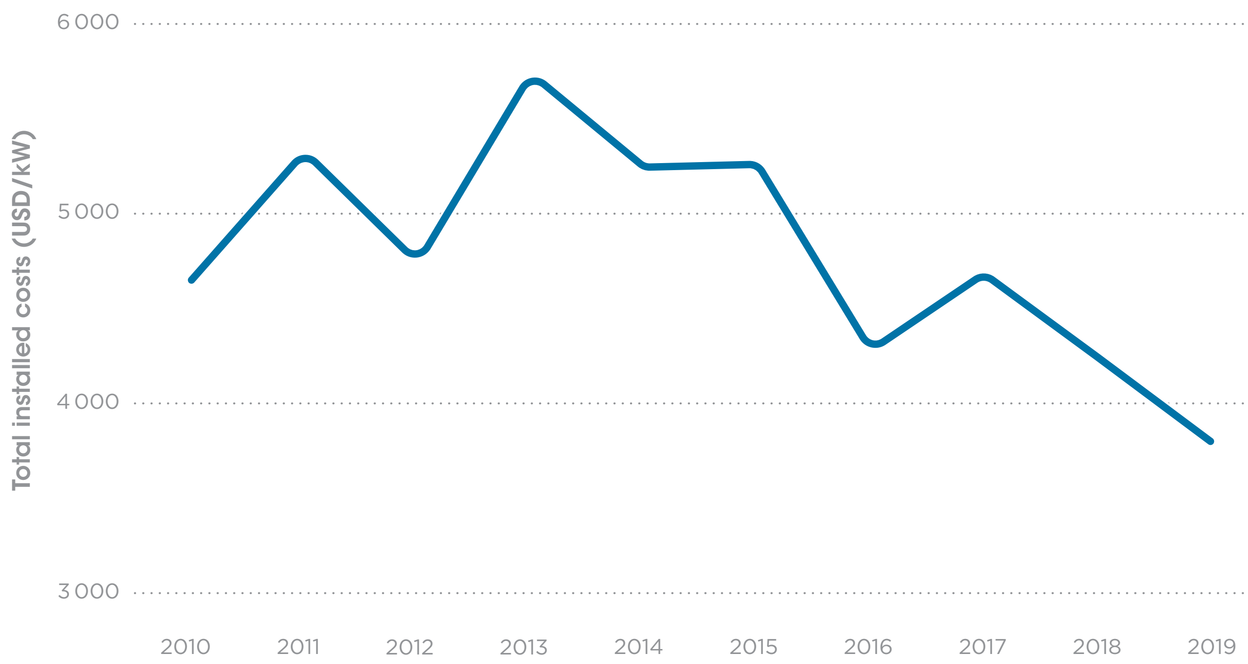
The offshore wind market was a relatively new one back in 2010 and since then it has been maturing rapidly. Further cost reduction has been seen in the past five years, along with an increased performance of wind farms, which have been reaching deeper water, further from the shore.

5.1 Costs

Installed offshore wind costs are higher than onshore. This is due to: the complexity of the technology and project management; the far greater logistical costs; and the harsher marine environment they operate in, which impacts total installation costs (Lacal-Arántegui, Yusta, Domínguez-Navarro, 2018). These installation costs are also significant. Generally speaking, nearshore wind farms in shallower water have lower installed costs than those farther from the shore in deeper water, due to the latter's greater logistical costs for installation and the increased foundation costs.

Figure 6 shows that after an overall increase in global weightedaverage **installed costs** between 2010 and 2015, these then declined by 28% between 2015 and 2019, from USD 5 260/kW to USD 3 800/kW. Costs fell by 20% between 2015 and 2016, rose again, and then dropped by an average 10% between 2017 and 2019. This volatility is in part due to the sitespecific costs of offshore wind, but is also due to the relatively thin market. In this, shifts in the share of markets with different cost structures in annual new deployment can affect the global weighted-average.

Figure 6. Total installed costs (2010-2019)



Source: IRENA (2019b)

In 2019, the lowest installed costs were reported in **Denmark**, followed by **China, Germany, the UK and Japan.**[10] The largest drop between 2015 and 2019 was in the UK, where costs fell 23%.

When comparing installed costs with 2010 figures, there was a slight increase in Japan and the UK, a small decrease in Denmark and a significant decrease in China and Germany. These same countries are also leaders in publishing scientific papers, standards development and adoption, as well as patents filing and technology deployment.

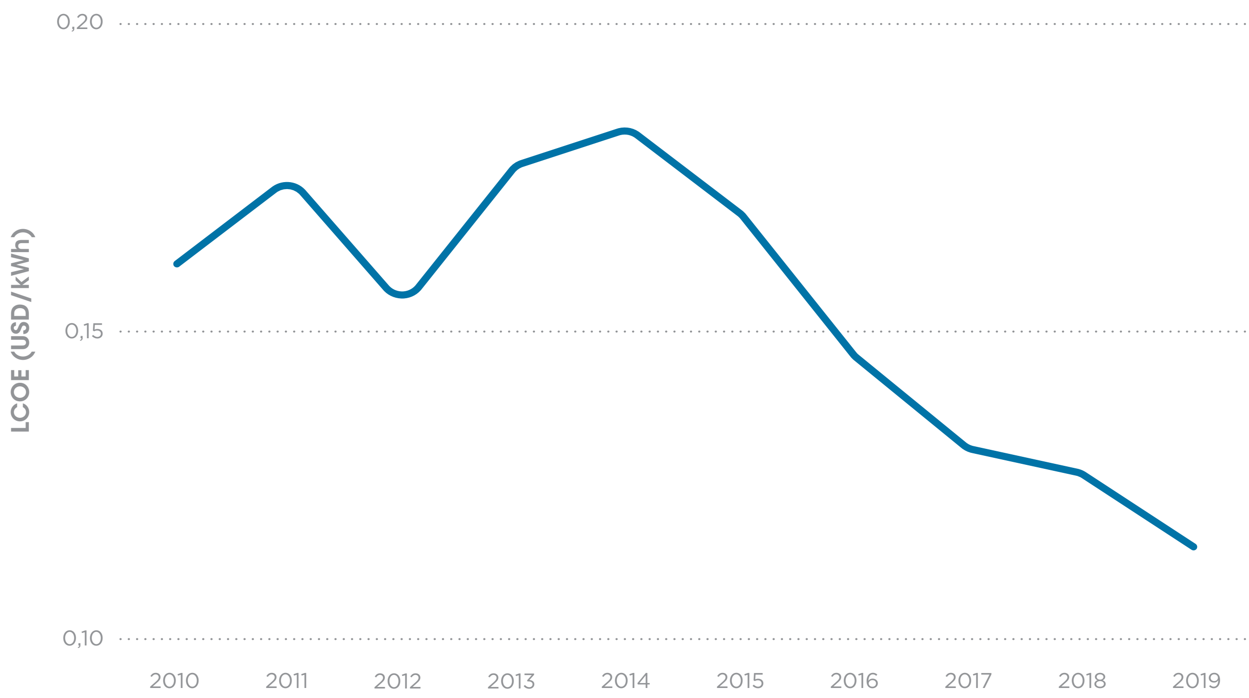
Given the thinness of the market, installed costs showed volatility. Factors were various and included: project site characteristics – including ownership of transmission assets by transmission system operators (TSOs) or at the project level; the market's progress towards maturity; and dependencies within the supply chain across regions. There is still a large potential in learning-by-RD&D through technology improvements. This includes: the use of specialised installation vessels (see more below); the spreading of offshore wind farm clusters; improvements in construction time; learning-by-doing through industrial manufacturing; in the supply chain and in relation to the materials used in turbines, foundations, cabling, etc.; and through economies of scale.

Table 7. Installed costs in selected countries

USD/KW	2010	2015	2019
DENMARK	3 264	NA	2 927
CHINA	4 423	3 039	3 011
GERMANY	6 427	5 350	4 076
JAPAN	4 876	5 153	4 900
UK	4 533	5 934	4 579

Source: IRENA (2019b)

Figure 7. LCOE (2010-2019)



Source: IRENA (2019b)

10 It should be noted that costs in Japan are not directly comparable to the other markets discussed here, as they are yet to deploy commercialscale offshore wind farms.

The global weightedaverage **levelised costs of electricity** (**LCOE**)[11] of offshore wind increased between 2010 and 2014, as projects shifted further offshore, into deeper waters and started using the latest multi-megawatt (MW) designs. They then reached a peak before declining, with the LCOE down 33% between 2014 and 2019, from USD 0.183/kWh to USD 0.115/kWh.

As already discussed, annual volatility in market growth by country results in varying shares of markets with different capital costs and capacity factors, meaning there is some volatility in LCOE as well. The largest decline was between 2015 and 2016 – 14% – and then between 2018 and 2019, by 10%. The factors driving this trend were identical to those driving installed costs and capacity factors and were driven by learning-by-doing, supply chain dynamics and – indirectly – by learning-by-RD&D.

An increase in capacity factors was driven by technology improvements in turbine design and manufacturing and diversity in the design of turbines for different operating conditions. This was followed by the development and adoption of international standards. The latter factor also enabled more competitive global supply chains.

Falling LCOEs occurred against the background of a ninefold increase in installed capacity between 2010 and 2019 – from 3 GW to 28 GW – and a ninefold increase in electricity generation between 2010 and 2018, from 7.4 TWh to 68 TWh (see more in Chapter 7.1).

Over the 2010 to 2019 period, the LCOE of offshore wind among frontrunning countries saw a declining trend, with 2019 seeing Denmark, followed by China, Germany, the UK and Japan report the lowest LCOEs. Offshore wind projects in the UK, Denmark and Germany do not receive any subsidies, so their prices are or are becoming competitive with other conventional power sources.

The geographical distribution of offshore wind projects in the past ten years remained constant, with Europe (the UK, Denmark, and Germany) and Asia (China and Japan) seen as frontrunners.

Table 8. LCOE in selected countries

(USD/kWh)	2010	2015	2019
DENMARK	0.111	NA	0.086
CHINA	0.176	0.130	0.112
GERMANY	0.179	0.168	0.120
JAPAN	0.213	0.223	0.197
UK	0.162	0.185	0.121

Source: IRENA (2019b)

11 Assuming a real weighted average cost of capital of 7.5%.

5.2 Technology performance and project characteristics

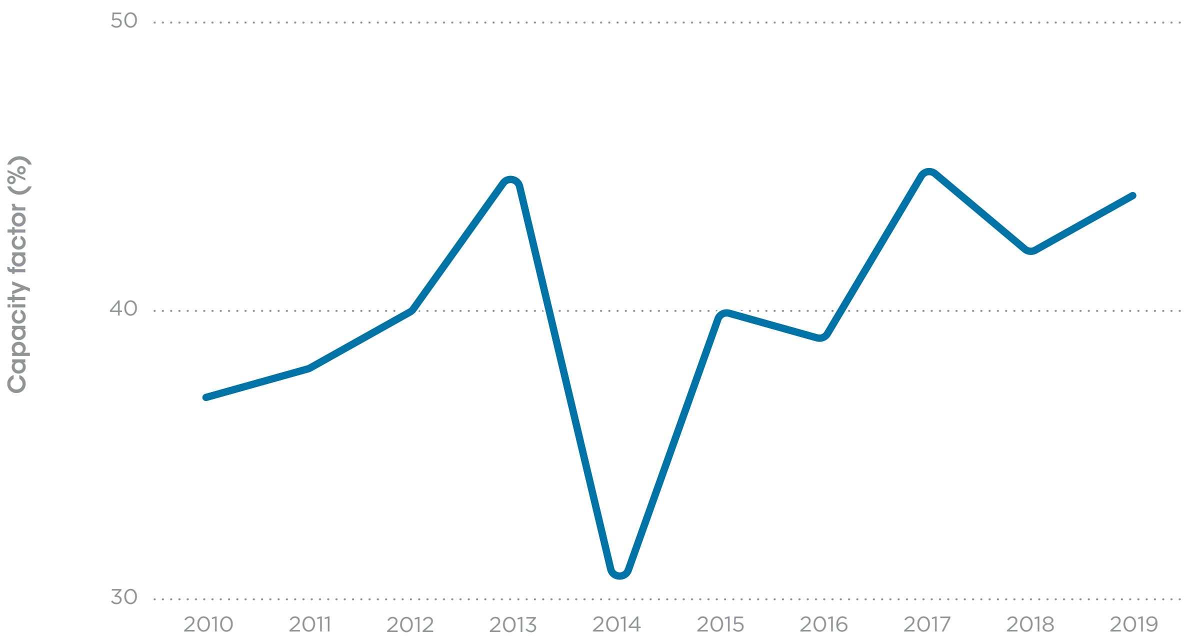
Offshore wind has benefitted from innovations across the supply chain and in operations and maintenance (O&M). These have been driven by industry innovation, R&D and the feedback of greater experience in designing, installing and operating offshore wind turbines.

Offshore wind turbine components and foundations also significantly benefit from RD&D activities and contribute to an increase in capacity factors, lower costs, and higher energy yields. Offshore wind turbines have benefitted from significant technological improvements over the past ten years, resulting in **larger-capacity** turbines, increased rotor diameters and hub heights, which increase energy yields and have decreased installation costs.

The main outcome of these improvements, however, has been to increase capacity factors and help drive down the LCOE, making offshore wind cost-competitive with conventional power sources. RD&D efforts have also managed to decrease costs and eventually reverse the additional costs of moving wind farms farther from shore and into deeper waters. This deployment brings the additional benefit of farms being sited in locations with stronger and more consistent wind speed. With the cost-competitiveness of fixed-bottom foundations and increasing diversity in foundations, there has been significant interest in and progress made on the RD&D of floating foundations for deep waters. This is an opportunity to greatly increase the number of areas where offshore wind can provide competitive power.

The global **weighted-average offshore wind capacity factor** increased by 19% between 2010 and 2019 from 37% to 44%, with the highest global weightedaverage recorded in 2017, at 45% (Figure 8). In 2019, the range of capacity factors of newly installed projects was between 30% and 54%, while in 2010 it was between 29% and 41%. This wide range reflected a myriad of factors. These included the wind farm's location (water depth, distance from the shore) and the wind speed, as well as the technology used (the turbine size, hub heights and rotor diameter, etc.). Other factors included the configuration of the wind farm (turbine spacing within clusters along the coast). In addition, the optimisation of the O&M strategy was a factor, including improved data collection and analysis over the life of the project, with great potential to further increase the capacity factor partly through RD&D activities.

Figure 8. Capacity factors (2010-2019)



Source: IRENA (2019b)

Table 9 shows the changes in capacity factors in countries leading offshore wind deployment between 2010, 2015 and 2019.

Major increases in the capacity factor were reported in the UK between 2010 and 2019, where it rose by 46%. Between 2015 and 2019, the UK saw an increase of 22%. Denmark's capacity factor surge between 2010 and 2019 was 12% (comparison with 2015 was not possible due to the lack of reported projects). While there were no changes in capacity factors of China and Japan between 2010 and 2015, their capacity factors increased by 10% and 7%, respectively, between 2015 and 2019. Germany's capacity factor decreased by 3% between 2010 and 2019, but increased by almost 5% between 2015 and 2019. Germany's capacity factor was, however, already higher than the global weightedaverage in 2010.

A lower range of capacity factors in China can be explained by Chinese projects being located closer to shore, in shallow waters and with lower wind speeds, using smaller turbines. This resulted in a 33% capacity factor in China, compared to 44%, 50% and 52% capacity factors in Germany, Denmark and the UK, respectively.

Ongoing RD&D activities drove the improvements in **turbine ratings,** hub heights and rotor diameters that directly helped to increase capacity factors through energy output. In 2019, the global weightedaverage of a deployed turbine was around 6.0 MW, which doubled from 3.1 MW in 2010. An increase in wind turbine size increases their cost competitiveness, resulting in fewer (and more efficient) turbines, which in turn would require fewer maintenance visits and improvements in health and safety, reduced installed and O&M costs, and have a positive impact on the environment.

Turbines deployed in 2019 had sizes between 3.0 MW and 8.4 MW,[12] while turbines deployed in 2010 had sizes between 2.0 MW and 5.0 MW[13]. In 2019, the smallest wind turbine, at 3.0 MW, was built 1.5 km from the shore in water 18 metres deep, while the largest turbine, at 8.4 MW, was built 98 km from the shore in water 40 metres deep. Compared to that, in 2010, the smallest wind turbine, at 2.0 MW, was built 8.5 km from shore in water 4 metres deep, while the largest turbine, at 5.0 MW, was built 56 km from shore in water 30 metres deep.

Table 9. Capacity factors in selected countries

	2010	2015	2019
DENMARK	44%	NA	50%
CHINA	30%	30%	33%
GERMANY	46%	42%	44%
JAPAN	28%	28%	30%
UK	36%	41%	52%

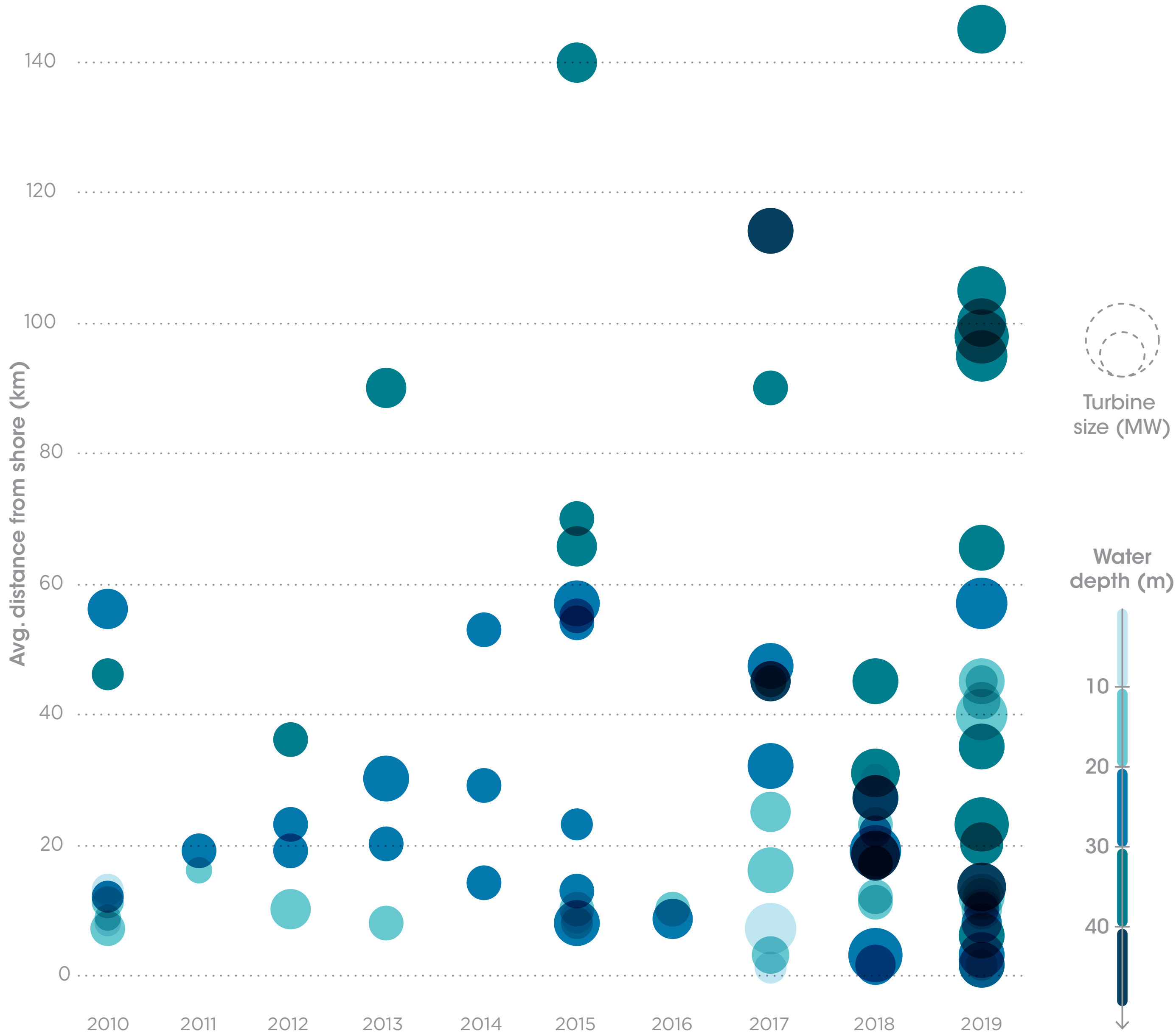
Source: IRENA (2019b)

12 Based on the 5th and 95th percentile of wind turbine size projects deployed in 2019

13 Based on the 5th and 95th percentile of wind turbine size projects deployed in 2015

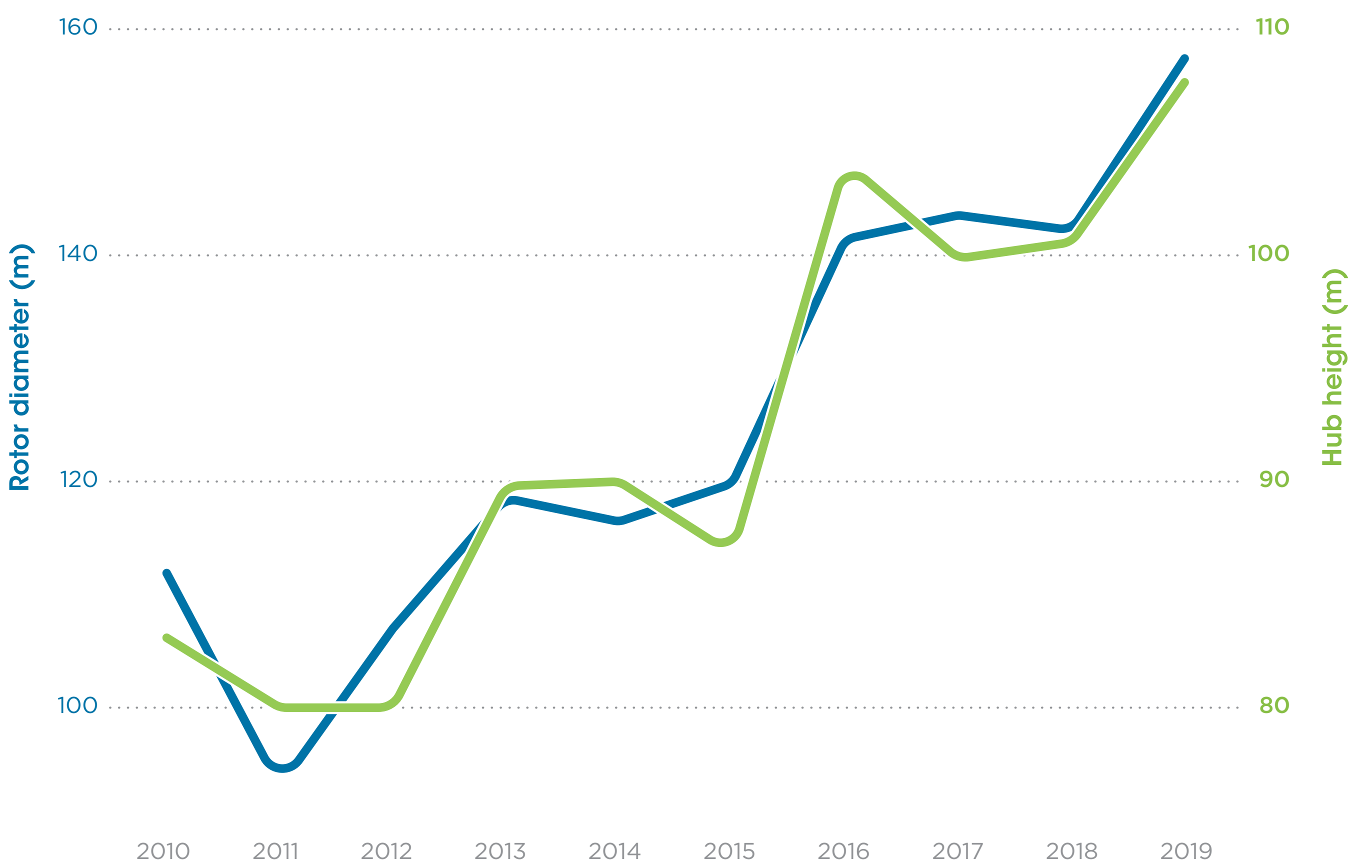
To reach the strongest and most consistent wind, RD&D activities have driven wind farms **farther from shore and into deep waters**. The first offshore wind farms were built in the late 1990s and early 2000s, mostly for demonstration purposes at relatively short distances of between 1 km and 12 km from shore, in shallow waters of around 6 metres. Most new offshore wind farms after that were built in waters between 11 metres and 40 metres deep, with the number of farms growing from six in 2010 to 24 in 2019. In the latter year, offshore wind farms were built as far as 145 km from shore and in water as deep as 40 metres. In 2010, offshore wind farms were built much closer to shore, at a maximum of 56 km out, but in water as deep as 37 metres, which is almost the same water depth as in 2019. A technical potential of over 13 terawatts (TW) can be reached in waters beyond 50 metres, with an economically attractive option being floating offshore wind (ESMAP, 2019; IRENA, 2019) (Box 2). This can unlock potential in countries with large seabed drops, allowing farms to be located at a greatly increased distance from shore (e.g. in Japan, China, the USA and Europe).

Figure 9. Water depth and distance from shore (2010-2019)



Source: IRENA (2019b)

Figure 10. Rotor diameter and hub height (2010-2019)

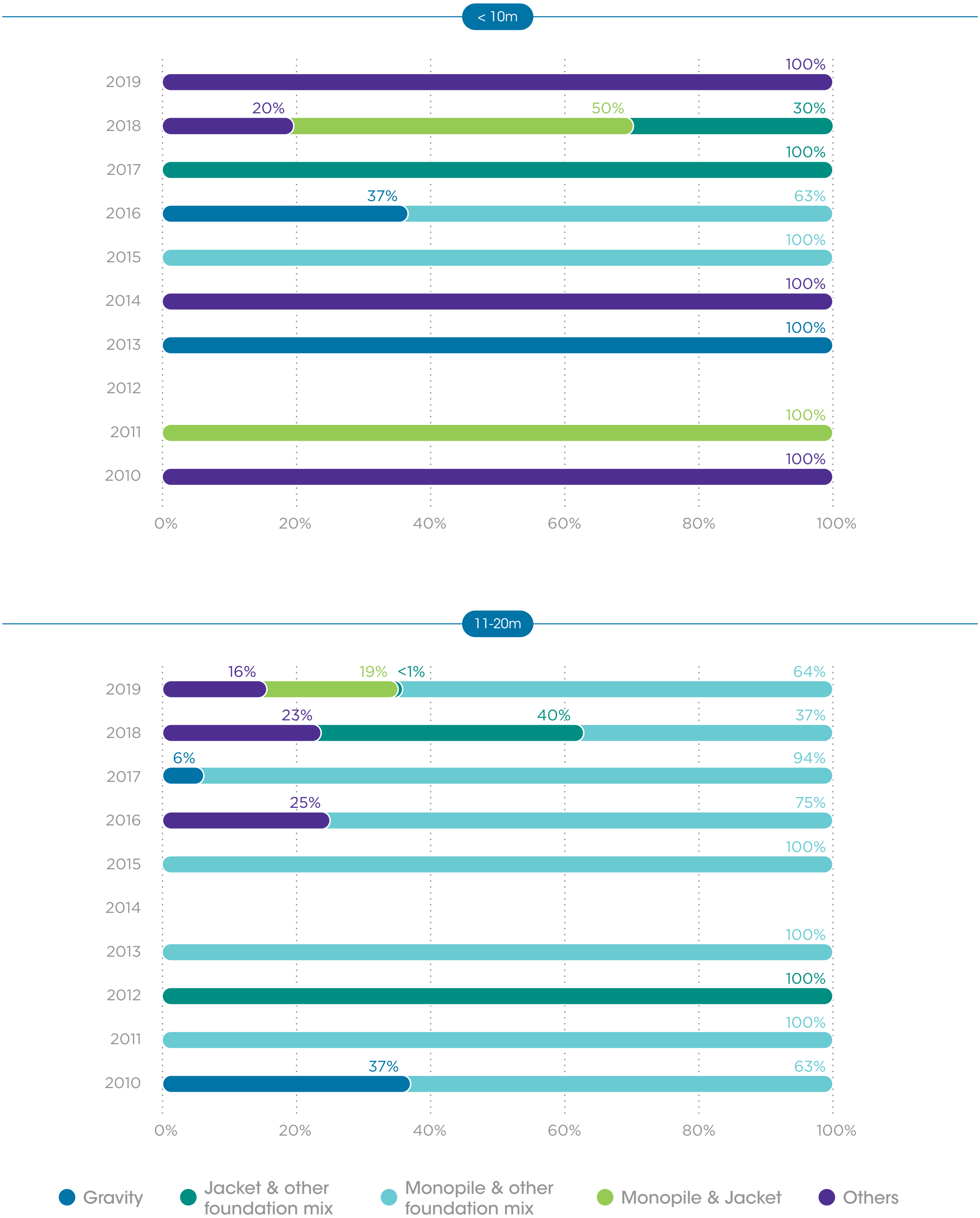


Source: IRENA (2019b)

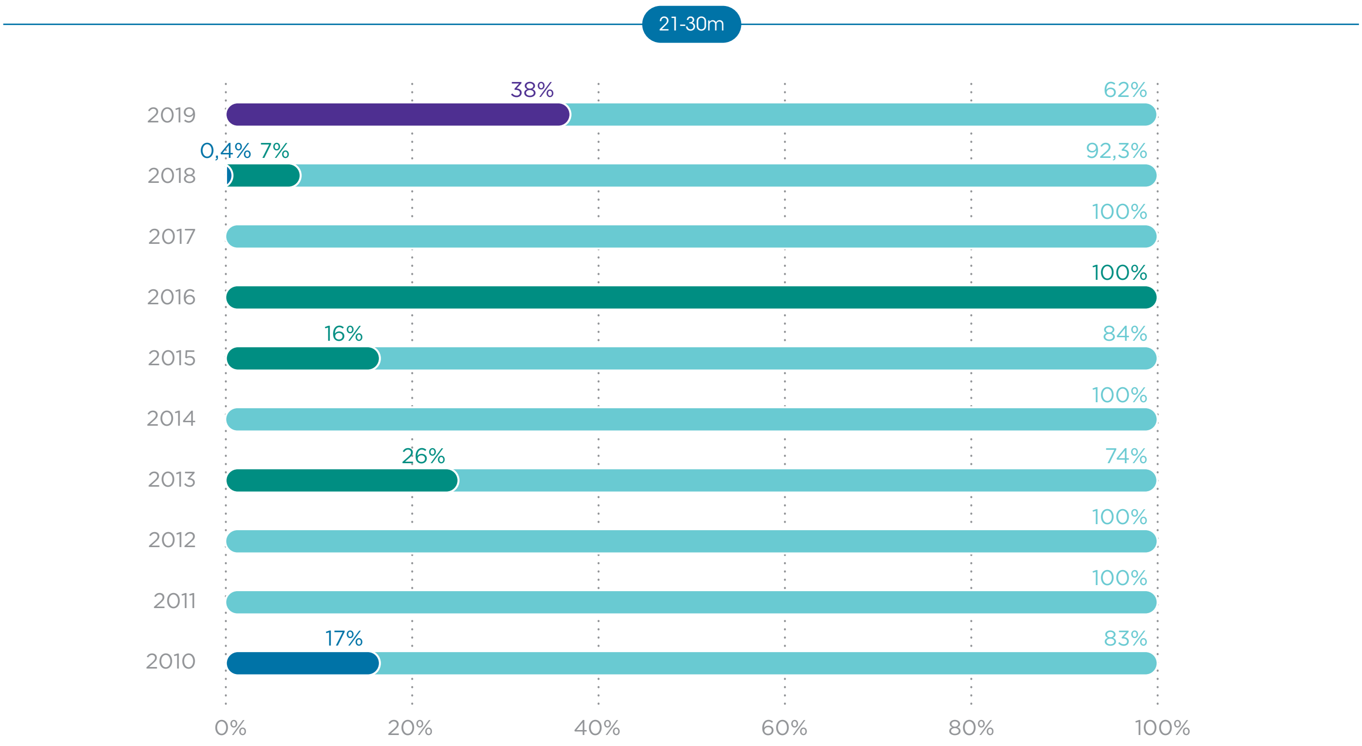
Capacity factor improvements have in large part been driven by RD&D activities contributing to improvements in technology. Examples of this are in the **hub height** and **rotor diameter** of offshore wind turbines. Rotor diameters experienced a 40% increase in the ten years from 2010 to 2019, growing from 112 metres to 157 metres in size, while hub height grew by 30%, from 83 metres in height in 2010 to 108 metres in 2019. In line with growing turbine dimensions, wind farms also kept growing, with an increase from 83 MW recorded in 2011 to 254.5 MW in 2017.

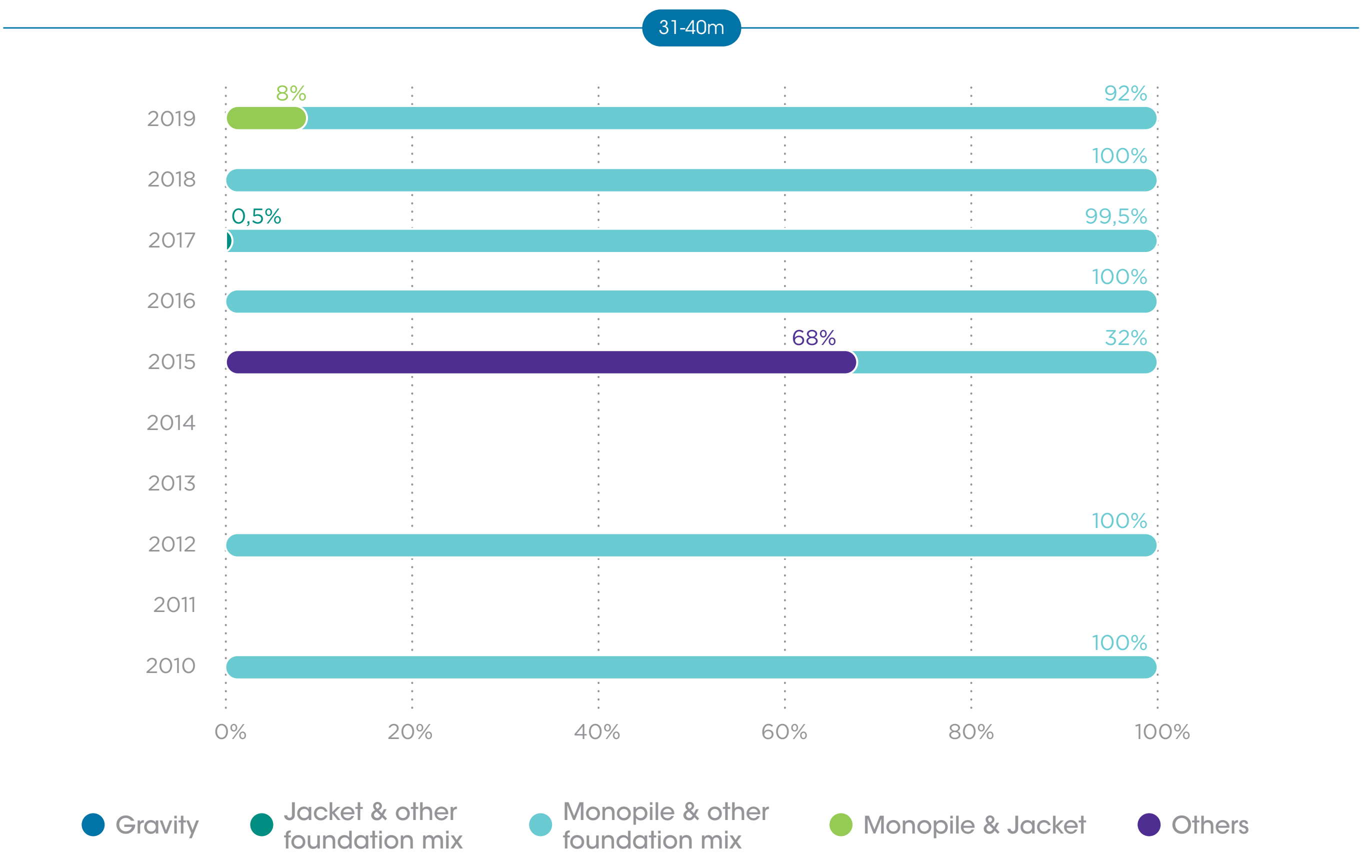
The past 10 years also saw an increase in RD&D activities in the design of the **foundations** deployed at different depths of water. The designs used the most were: monopile; jacket; a combination of monopile and jacket; gravity; and an emergence of new foundation designs, such as multiple, suction bucket, tripile/tripod (referred to in Figure 11 as 'others', as there were fewer projects of these types). Monopile foundations are simple, well proven and dominated installed capacity in waters between 20 metres and 40 metres, for which they are most suited. Jacket foundations dominated water depths beyond 40 metres, as they are particularly suited for deep water and/or high waves. Gravity foundations saw a boom in shallow water in 2010, 2013 and again 2016. In 2017, their deployment was seen in water 10 metres to 20 metres deep, while in 2018, it was seen in water 20 metres to 30 metres deep. Other foundation types, such as suction buckets, multiple or tripile/tripod started emerging in shallow water.

Figure 11. Share of installed capacity and water depth by foundation type (2010-2019)

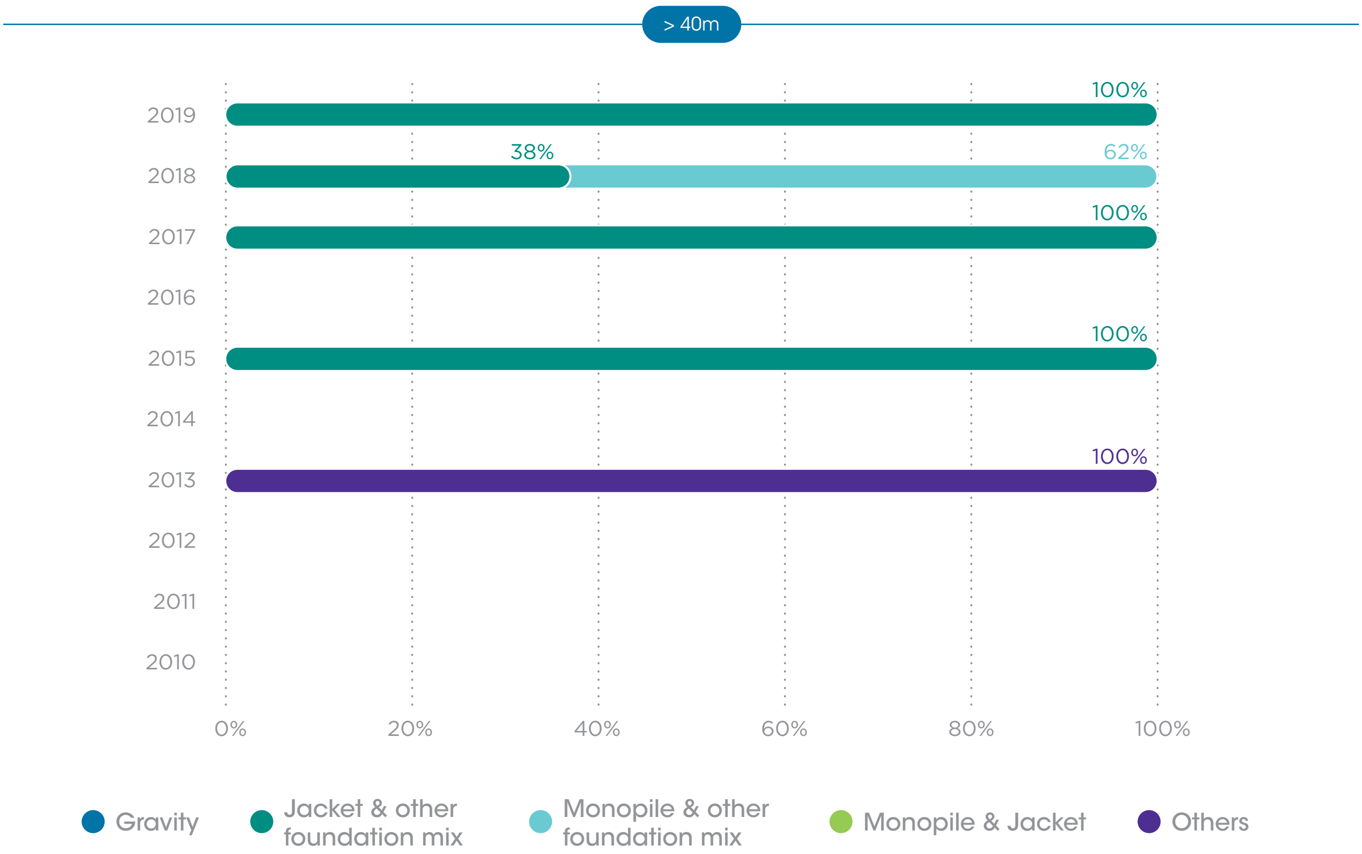


Source: IRENA (2019b)





Source: IRENA (2019b)



Source: IRENA (2019b)

Offshore wind has benefitted from innovations across the supply chain and in O&M. These have been driven by industry innovation, RD&D and the feedback of greater experience in designing, installing and operating offshore wind turbines.

BOX 2. FLOATING OFFSHORE WIND

For waters deeper than 50 metres – where the seabed drops rapidly with increased distance from shore – floating foundations represent a technically and economically attractive option for harnessing wind potential. Floating foundations are currently at a less advanced state of development than other options. But given the technical potential capacity is over 13 TW in deep waters around the world– and also large in some countries in particular (Table 10) – RD&D activities will play a critical role in bringing solutions to the market, while also reducing their price.

Table 10. Technical potential for floating offshore wind in selected countries/regions

COUNTRY[11]	TECHNICAL POTENTIAL (GW)	COUNTRY[11]	TECHNICAL POTENTIAL (GW)
Europe	**4 000**	**Morocco**	**178**
USA	**2 450**	Philippines	160
China	**2 240**	Viet Nam	214
Chile	**1 340**	**India**	**83**
Brazil	**750**	Turkey	57
Japan	**500**	Sri Lanka	37
South Africa	590		

Source : ESMAP (2019); IRENA (2019b)

According to IRENA's projections, which are consistent with the goals of the Paris Agreement, floating offshore wind installed capacity might grow to between 5 GW and 30 GW by 2030 and 50 GW and 150 GW by 2050 (IRENA, 2019).

RD&D activities have been driving the installation of demonstration projects. In 2019, up to 19 of these were installed, with a total capacity of 56 MW (with 43 MW operational). Of this, 54% of capacity was in the UK, and 30% in Japan (Wood Mackenzie, 2019). Commercialisation is expected to pick up pace from 2021 onwards, but continuous RD&D activities are needed to further unlock technological potential and test multiple solutions to fit various site characteristics and conditions. Depending on those site characteristics, floating foundations would bring various benefits, including: eliminating disturbances to the seabed for installation purposes; reducing installation time (and therefore costs), with assembly carried out in ports and turbines then towed to the final location; and the possibility of carrying out O&M in ports, amongst other factors.

11 MI member countries are highlighted in bold.

Technological improvement through RD&D activity in the construction of **installation vessels** has also contributed to increasing the ease of installation of offshore foundations and turbines. In the first years of deployment of offshore wind (i.e. 2000 and 2001), the lack of availability of specialised vessels caused bottlenecks and delays in construction. This was primarily because the vessels being used were the same as those being used in the oil and gas sector. These ships were oversized and not suited for offshore wind operations, while competition was also created between the two industry sectors (Paterson et al., 2018). Since then, RD&D activities have been focused on the development of offshore windspecific vessels. These constitute a critical part of the offshore industry, as the installation of the technology (i.e. turbines, cables and foundations) plays a key role in the timely completion of offshore wind projects and is a significant element in reducing installation costs.

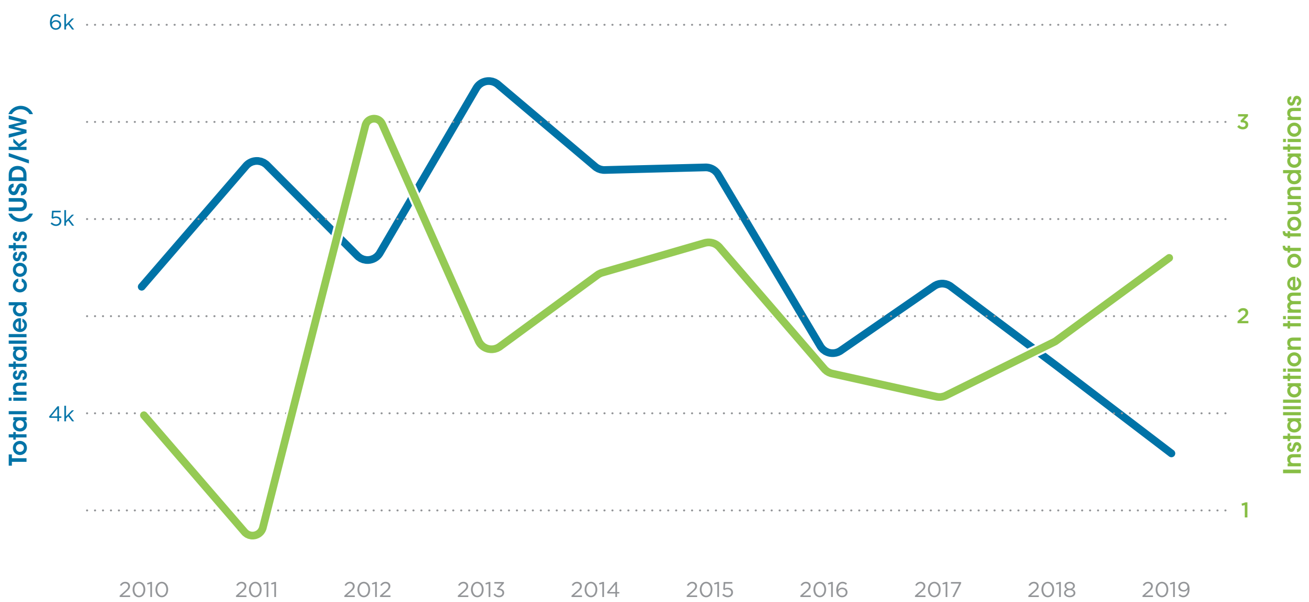
Globally, the number of vessels for offshore wind turbine installation increased by 17% between 2015 and 2020,[14] from 119 to 137. Of these, 61% are located in Europe and the remaining 39% in China, which also represent the two largest offshore wind markets for capacity installed (GWEC, 2020).

The design of foundations, together with the provision of installation vessels and installation methods, have a direct impact on **the installation time of foundations**, which in turn significantly impacts installation costs.

Installation time varied considerably over the years, with the highest being in 2012 (3.1 years). However, the high-level trend is the reduction of installation time from its peak value of 3.1 years in 2012 to 2.34 years in 2019. Different foundation designs require different installation times. Monopiles dominated total installed capacity, as they were the fastest foundations to be installed compared to all other types. Installation time for gravity foundations decreased, while jacket and tripile/tripods took the longest to install. In addition to foundation types, distances from shore (or from the installation port), and water depths, installation vessels and installation methods played an equal – or even more critical – role in impacting installation time (Lacal-Arántegui, Yusta, Domínguez-Navarro, 2018). A further decrease in installation time and thus installed costs will therefore require continued RD&D efforts to improve installation vessels and installation methods.

Table 11 summarises various indicators and provides an overview of typical offshore wind farms in 2010, 2015 and 2019, using global weighted averages.

Figure 12. Installation time of foundations and total installed costs (2010-2019)



Source: IRENA (2019b)

14 Data for vessels is only available from GWEC for the years 2015 and 2020.

Table 11. Typical offshore wind farms in 2010, 2015 and 2019

	TYPICAL WIND FARM 2010	TYPICAL WIND FARM 2015	TYPICAL WIND FARM 2019
WATER DEPTH (m)	19	28	32
DISTANCE FROM THE SHORE (km)	17	47	53
WIND FARM CAPACITY (MW)	136	231	226
HUB HEIGHT (m)	83	87	108
ROTOR DIAMETER (m)	112	120	157
TURBINE SIZE/RATING (MW)	3.0	4.20	6.50
FOUNDATION	Monopile/Gravity	Monopile/Jacket	Monopile

Source: IRENA (2019b)

5.3 Relevance to innovation

Innovation is sometimes perceived of as only consisting of breakthroughs. Yet, incremental changes also help increase the diversity of solutions, enable these to spread to different geographical conditions and thus scale-up the global deployment of a technology. Over the past decade, both breakthroughs and incremental innovations have been observed in offshore wind technology.

The decline in costing metrics is the result of a combination of learning-by-RD&D, learning-by-doing, and economies of scale, although their relative weight of these factors is harder to calculate.

RD&D activities have contributed to an increase in capacity factors and brought a diversity of projects. These have included widening the diversity of foundation designs and increasing the ability to go further from shore and into deeper waters. They have also included boosting the ability to tap higher wind speeds at greater heights, generating more power by using larger rotor diameters. The hub height of offshore wind turbines grew by 30% between 2010 and 2019, while the rotor diameter of offshore wind turbines grew by 40%. Over the same period, the maximum distance from shore grew almost threefold. The majority of new projects, post 2010, were in water depths of between 11 metres and 40 metres, with the number of projects growing from six in 2010 to 24 in 2019.

These projects predominantly used monopile foundations. In general, over 80% of all offshore wind foundations in the 2010 to 2019 period were monopile, due to their price and ease of installation (Esteban, López-Gutiérrez and Negro, 2019). To address a wide variety of seabed conditions, however, such as the loadbearing capacity of soils, climatic loads (e.g. tides, wind, currents) and water depths – as well as factors in manufacturing, installation, operation and dismantling – recent years have seen a lot of RD&D efforts go into different foundation designs. This needs to continue, to ensure broad global deployment.

5.4 Potential for further insights

Several additional indicators could have further improved this analysis, but were omitted from this case study due to the lack of availability of data, or difficulties in gathering data.

Insights into O&M costs could improve our understanding of the role of continuous improvements in experience, along with competition in O&M optimisation. They could also improve our understanding of incremental innovations in O&M technologies in areas such as monitoring and the robotic maintenance used in extreme wind conditions, as well as in automation for servicing, surveying and repairing, and regarding vessels.

The LCOE is the indicator most frequently used by policy makers to measure and compare alternative sources of energy. Comparing the LCOEs of offshore wind projects with conventional sources (e.g. gas, coal or nuclear) at the global and country level could provide a useful reference tool for policy makers.

Significant improvements in the performance of offshore wind technologies and in the diversity of project characteristics were reflected in their scaled up deployment over the period examined. Additional, more nuanced, insights into how innovation is improving component designs to reduce failure rates could be gained by measuring the average downtime of wind farms. With increased deployment further from shore, mapping high voltage direct current (HVDC) technology could offer insights into the progress made in the transmission of power over long distances.

6. PROGRESS IN OFFSHORE WIND MARKET FORMATION

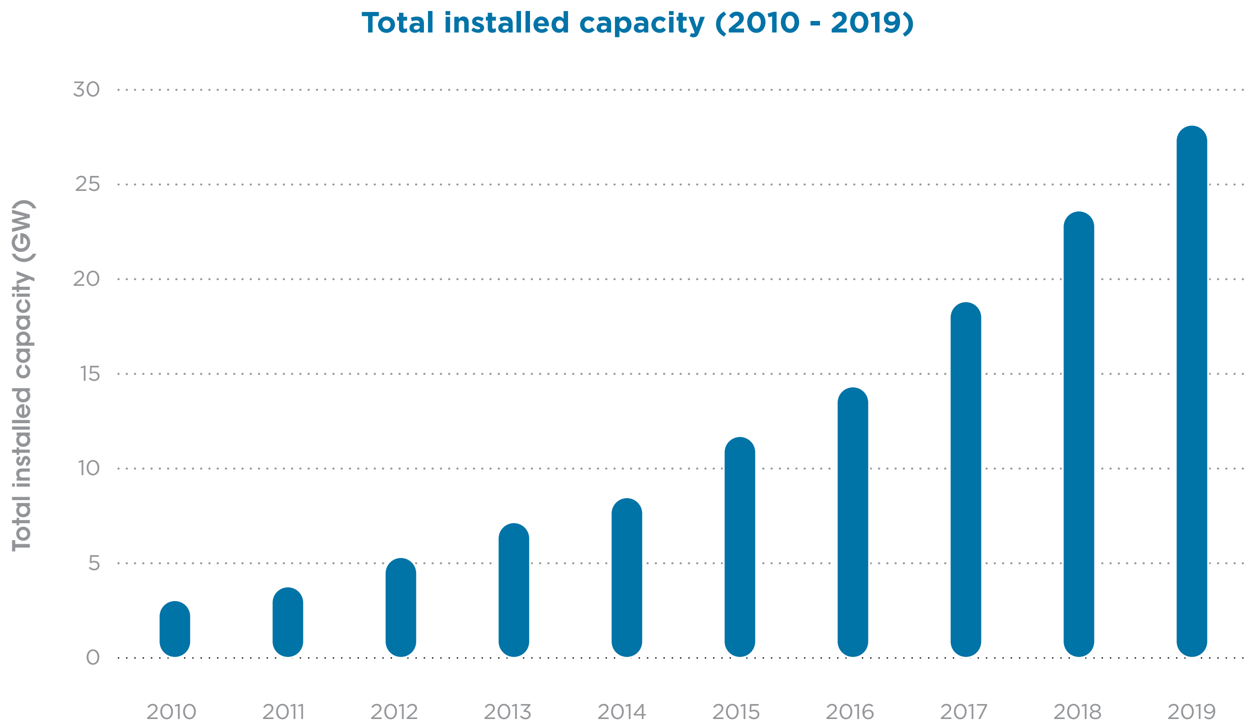
This group of indicators provides insights into progress in market formation. It looks at installed capacity and generation, the share of electricity taken by offshore wind in the overall energy mix, international standards, start-ups, trademarks and trade flows in offshore wind.

6.1 Installed capacity and generation

The offshore wind market grew significantly from 2010 to 2019, from almost 3 GW of **installed capacity** in 2010 to 28 GW in 2019. This reflected an average compound annual growth rate (CAGR) of 25%, implying the feasibility and easy of scaling up offshore wind installations. In 2019, Europe and China were the front runners in capacity installed, with almost 22 GW installed in the former (top countries: the UK, with almost 10 GW, and Germany, with 7.5 GW) and the latter with almost 6 GW installed.

Total offshore wind generation experienced a ninefold increase from 2010 to 2018,[15] rising from 7.3 TWh to 68 TWh, yet only provided 1% of global renewable power generation. Although offshore wind has not come close to tapping its full potential, improvements in technology – partly due to RD&D investment and activity, learning-by-doing and economies of scale – all translated into continuous costs decreases. This is a prerequisite for increasing deployment, so that offshore wind plays a more visible role in the global renewable energy mix.

Figure 13. Total installed capacity (2010-2019) and electricity generation (2010-2018)

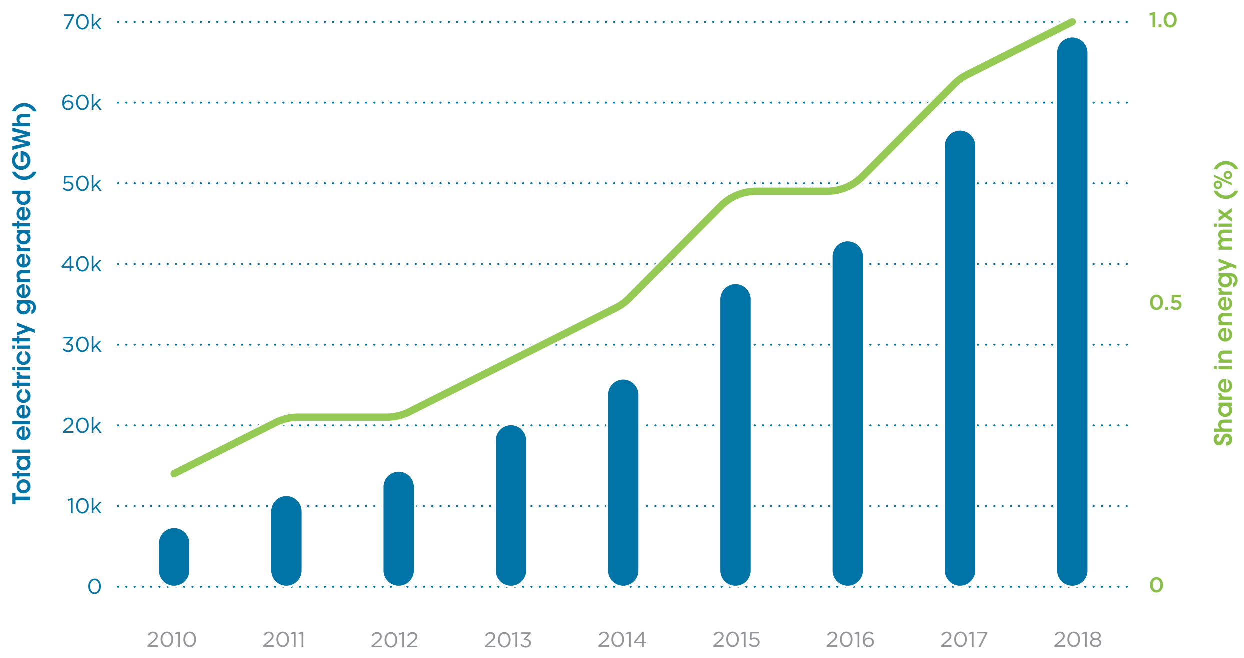


Source: IRENA (2020)

15 Data for 2019 not yet available

Figure 13. Continued

Electricity generation (2010 - 2018), share of electricity in the mix



Source: IRENA (2020)

6.2 International standardisation

The **standardisation** of installation vessels, offshore wind equipment (including its design, production, safety, performance, operation and testing), and improvements in electrical interconnection equipment also contributes to optimised operations.

The number of international standards in offshore wind increased from only four in 2010 to nine in 2019.

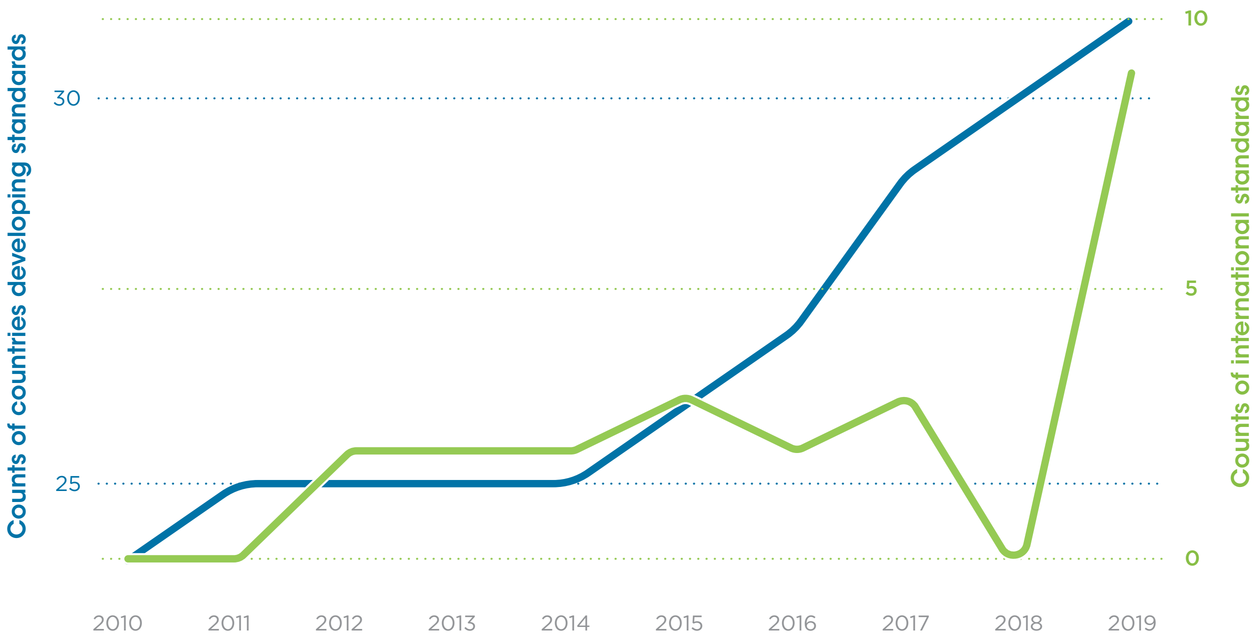
Technical committees can serve as a platform for discussion between experts, fostering more innovation. They help to document and disseminate information on state-of-the-art technologies and allow RD&D efforts to build upon best practices in technology, facilitating transition to the commercialisation stage.

Offshore wind technology has also attracted interest in many countries, with the number of these developing international standards in wind technology (both onshore and offshore) increasing steadily from 2010 to 2019. There has also been a more varied geographical distribution amongst interested countries, with these now including Japan, the Republic of Korea, and South Africa. These add up to the historical frontrunners – Europe and China – which currently have the highest capacity installed and are also active in standards development. The growing interest in standards development from a wider group of countries denotes a growing interest in the technology and thus its likely expansion to other markets, in future.

6.3 Start-ups

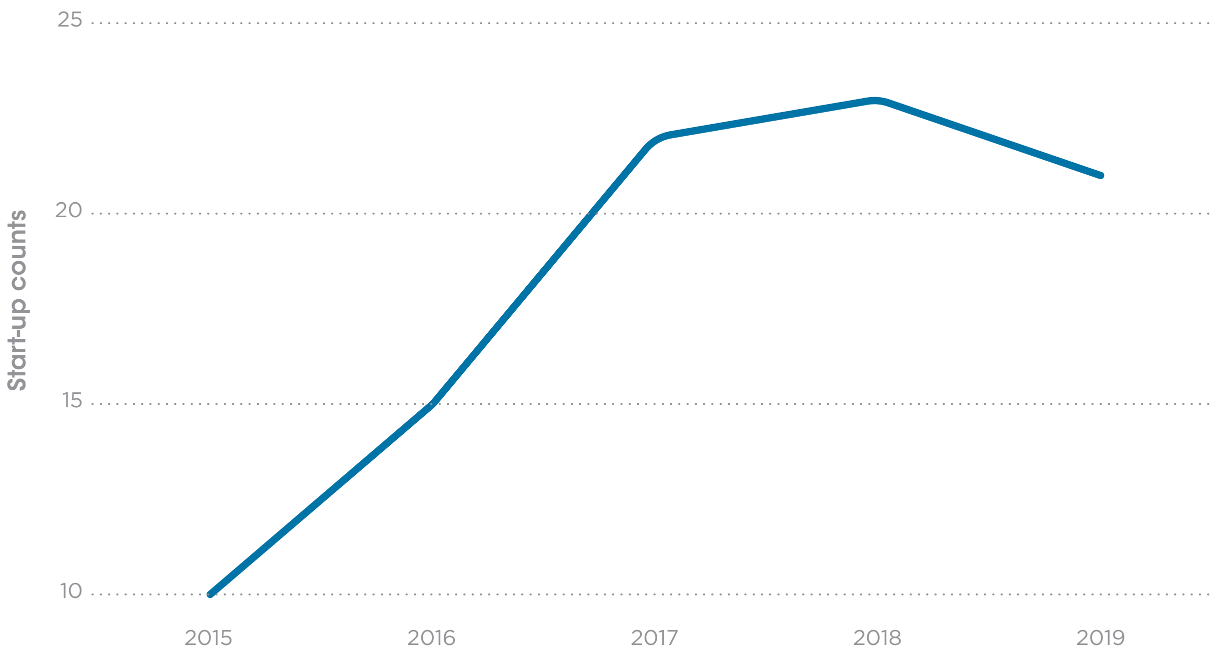
The emergence of **start-ups** could also be seen as a factor contributing to the acceleration of market and product advances in offshore wind. According to data provided by GlobalData, the technology registered a twofold increase in start-up creation between 2015, when there were 10 start-ups, and to 2019, when there were 21. This can be seen as one of the catalysers of faster technological development and market penetration.

Figure 14. Number of international standards and countries participating in standards development (2010-2019)



Source: IRENA Inspire

Figure 15. Start-ups for offshore wind (2015-2019)



Source: GlobalData database

6.4 Trade flows

The deployment and development of offshore wind technology also has positive effects on countries' economies, including on their **trade flows**. The technological development of offshore wind has increased the trade in parts and equipment over the years.

This case study considers two of these components, which have been deemed the most representative of trade in the wind turbine sector. These are: gears and gearing (including gearboxes, speed chargers and converters) and blades (hubs, electric motors, generators and engine parts).

While trade flows offer valuable insights, they come with limitations. In particular, these categories do not distinguish between onshore and offshore wind. This issue is not linked to the data itself, but to the way national trade offices collect and report this data.

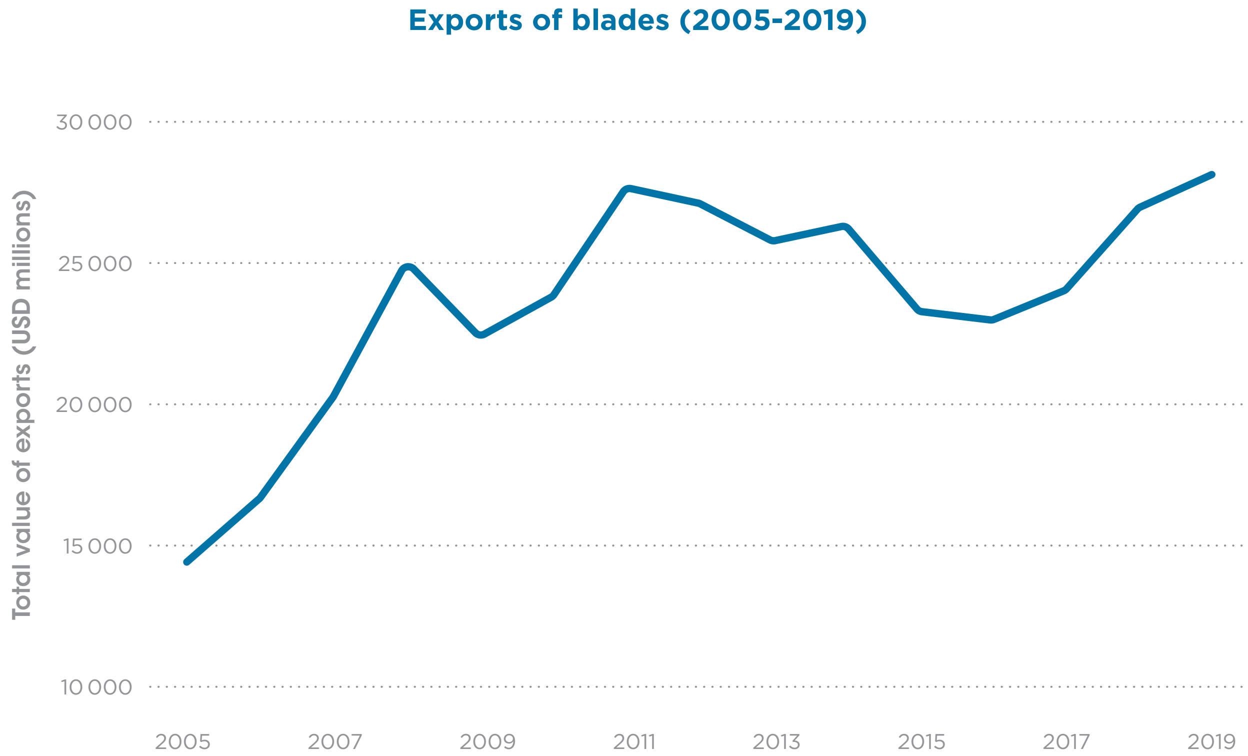
Trade values of exports for these two components remained stable in the period between 2015 and 2019. To get a better overview of changes in the trade values of exports, however, it is worth expanding the timeframe of the analysis. Looking at data from 2005 as well allows a longerterm comparison.

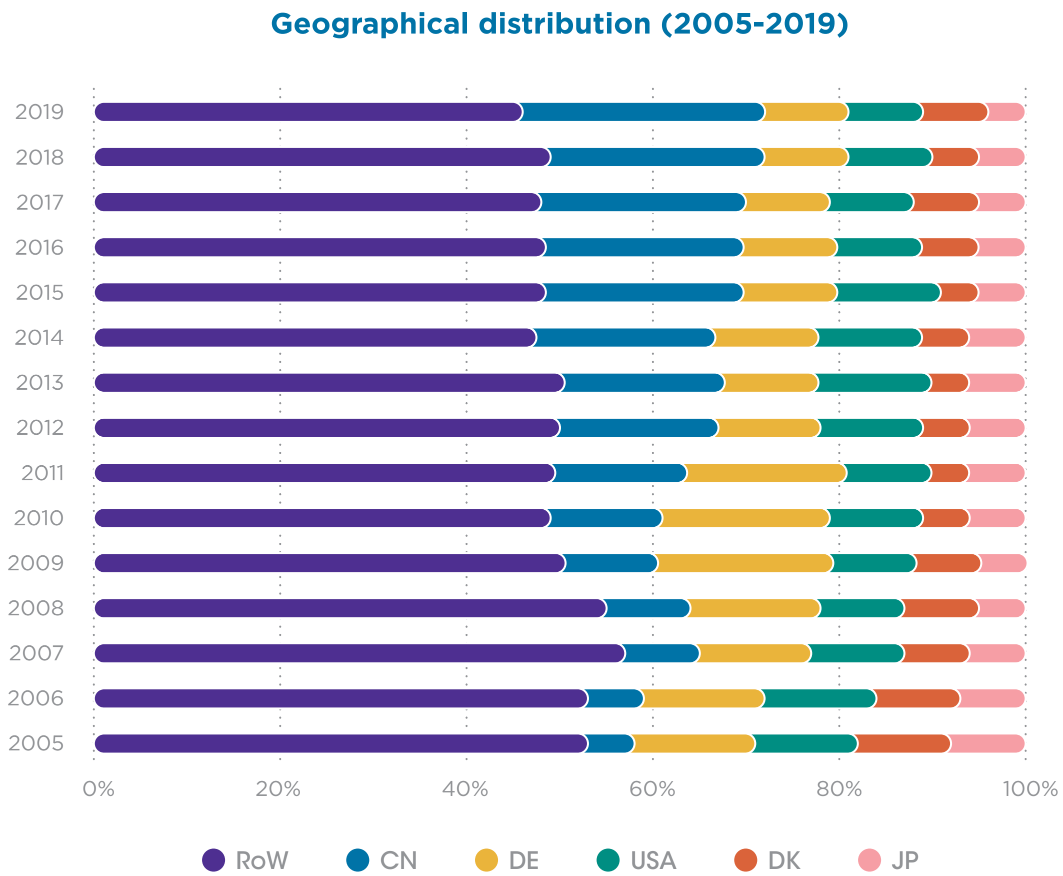
Trade values from 2005 to 2015 have increased for both component categories, especially for gears and gearing, which has almost doubled (Figure 17). When comparing 2010 and 2019 though, while there is an increase in trade values for gears and gearing and for blades, it is less remarkable than the change between 2005 and 2015 (Figures 16 and 17).

When looking at country-level results, an interesting finding is that the top exporters in both categories have not changed between 2005 and 2019. They remain China, Germany, the USA, Denmark and Japan for 'blades', and China, Germany, the USA and Japan for 'gears and gearing'. Some of these exporters are offshore wind trailblazers, but many are frontrunners for onshore wind only where RD&D activities and innovation may have allowed them to adapt onshore wind technology, as well as increase manufacturing capacity.

International standards help to document and disseminate information on state-of-the-art technologies and allow RD&D to build on best practices in technology standards and facilitate the transition to commercialisation.

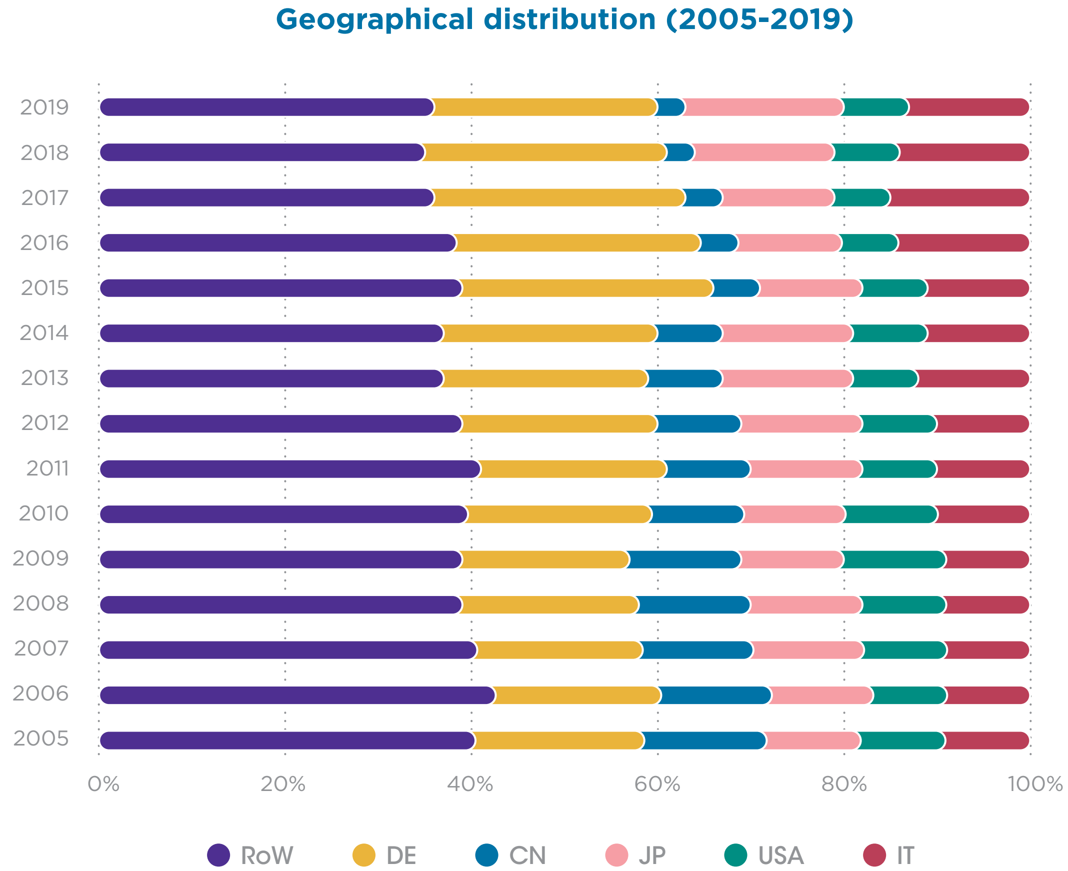
Figure 16. Blades exports and geographical distribution (2005-2019)





Source: WTO database

Figure 17. Gears and gearing exports and geographical distribution (2005-2019)



Source: WTO database

6.5 Trademarks

Increasing recognition of offshore wind's potential has had a positive impact on its deployment. An externality of this is the competition fostered between companies in developing solutions suited to different conditions and geographies. These solutions range from energy generation, transmission and distribution to cloudbased monitoring, among others. Companies then **trademark** these products to diversify the solutions offered by them.

From 2010 to 2015, the number of trademarks registered for offshore wind increased from 73 to 193, then decreased, reaching 86 in 2019. Furthermore, a majority of these trademarks were held by a few players in Germany. The fall in trademark registration indicates an industry moving quickly towards maturity and commercialisation, while the high number of trademarks held by just a few companies also denotes market consolidation.

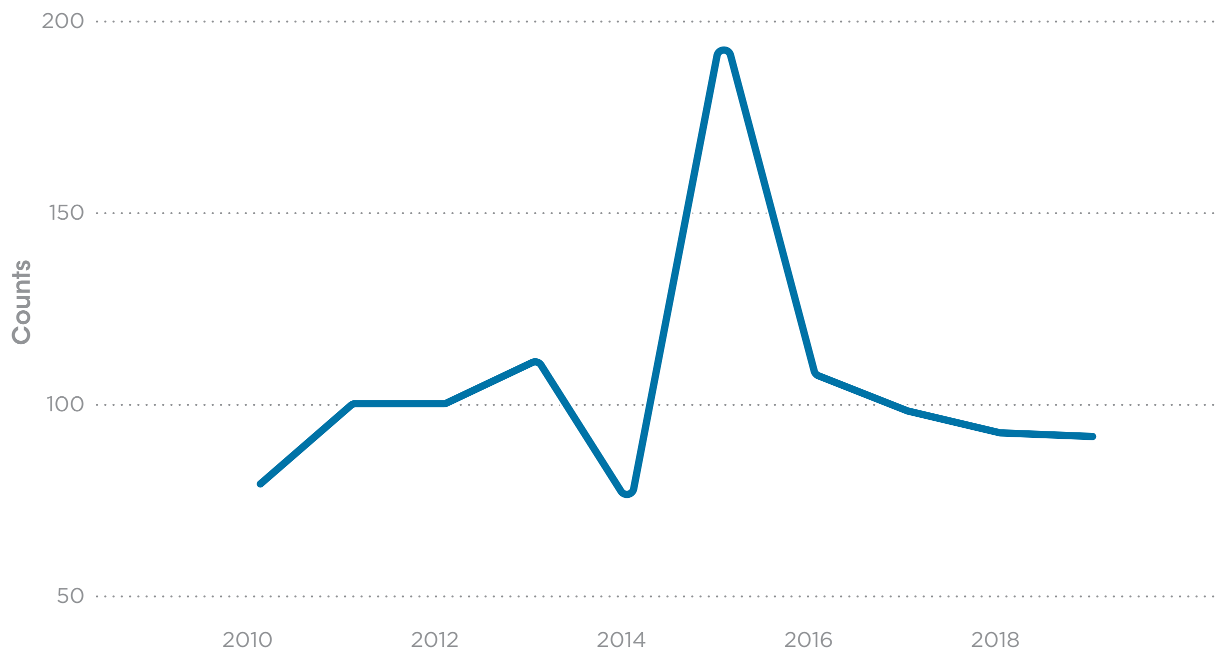
6.6 Relevance to innovation

The final section of this report provides an overview of offshore wind market formation by tracking the development of a range of indicators. Metrics such as offshore deployment, the number of start-ups, international standards, trademarks and exports all track the progress of the offshore wind market from different perspectives.

Analysis of these metrics shows a rapidly growing market with capacity increasing annually. Following this, every year the electricity generated by the offshore wind has also been rising. Yet, offshore wind's share of the global, electricity generation energy mix has remained low, representing only 1% in 2018.

While these deployment metrics belong to the final step in the innovation chain, they are also crucially linked to both RD&D and learning-by-doing. This involves testing technologies in new topographies with higher generation potentials, which can have a multiplying effect on deployment levels.

Figure 18. Registered trademarks for offshore wind (2010-2019)



Source: WIPO database

One indicator suggesting the level of global interest in deploying offshore wind is the number of countries developing international standards. This metric increased steadily from 2010 to 2019, rising from 24 to 31 and facilitating deployment in different regions. Additionally, the presence of international standards leads to innovation by documenting and disseminating information about state-of-the-art technology. The number of such international standards increased from zero in 2010 to nine in 2019.

Another important metric is the number of registered trademarks, which indicates commercialisation of different products and services by offshore wind suppliers and developers. The analysis shows that the number of trademarks increased roughly twofold from 2010 to 2015. The number of trademarks then fell rapidly, from 193 in 2015 to 86 in 2019. This trend indicates innovation in product differentiation among customers and a market that is swiftly moving towards commercialisation.

This case study also analyses the role of different countries in offshore, windrelated trade flows. It tracks exports of two components: blades, and gears and gearings. Cumulative exports of these increased annually. The geographical distribution of exports also yields insights into potential RD&D activities in developing new, or adapting existing, technologies. For instance, China's share of global wind energyrelated exports grew from just 4% in 2005 to 20% in 2019, driven by exports of blades for wind turbines, which increased roughly 10-fold over the same period.

6.7 Potential for further insights

The indicators used above to track market formation provide a useful overview of the evolution of the offshore wind industry in the past ten years.

Several other indicators could have further improved the analysis, however, but were not added to the study due to lack of availability, or difficulties in gathering data.

Such indicators include licenses, which provide information on the extent to which companies transform RD&D investment into innovative outputs and protect it. Licensing creates new business opportunities, facilitates easier entry into foreign markets and offers the freedom to develop a unique marketing approach.

The number of jobs in the offshore wind sector also provides insights into the contribution of the industry to economic activities. Due to industrial and manufacturing overlaps, however, data on jobs is often collected for the wind sector as a whole (onshore and offshore), as it is difficult to differentiate and show numbers of manufacturing jobs created in offshore wind only. On the other hand, this can be mitigated by collecting and presenting data on jobs specific to the offshore industry, such as installation, or O&M.

Finally, increasing or decreasing dependency on critical materials can offer nuanced insights into sustainability and geopolitical interdependencies and could improve the analysis further. As mentioned in Chapter 1, though, this indicator is hard to measure, as it affects more technologies at the same time and it is difficult to attribute and quantify its influence.

7. CONCLUSIONS AND NEXT STEPS

7.1 Implications of innovation

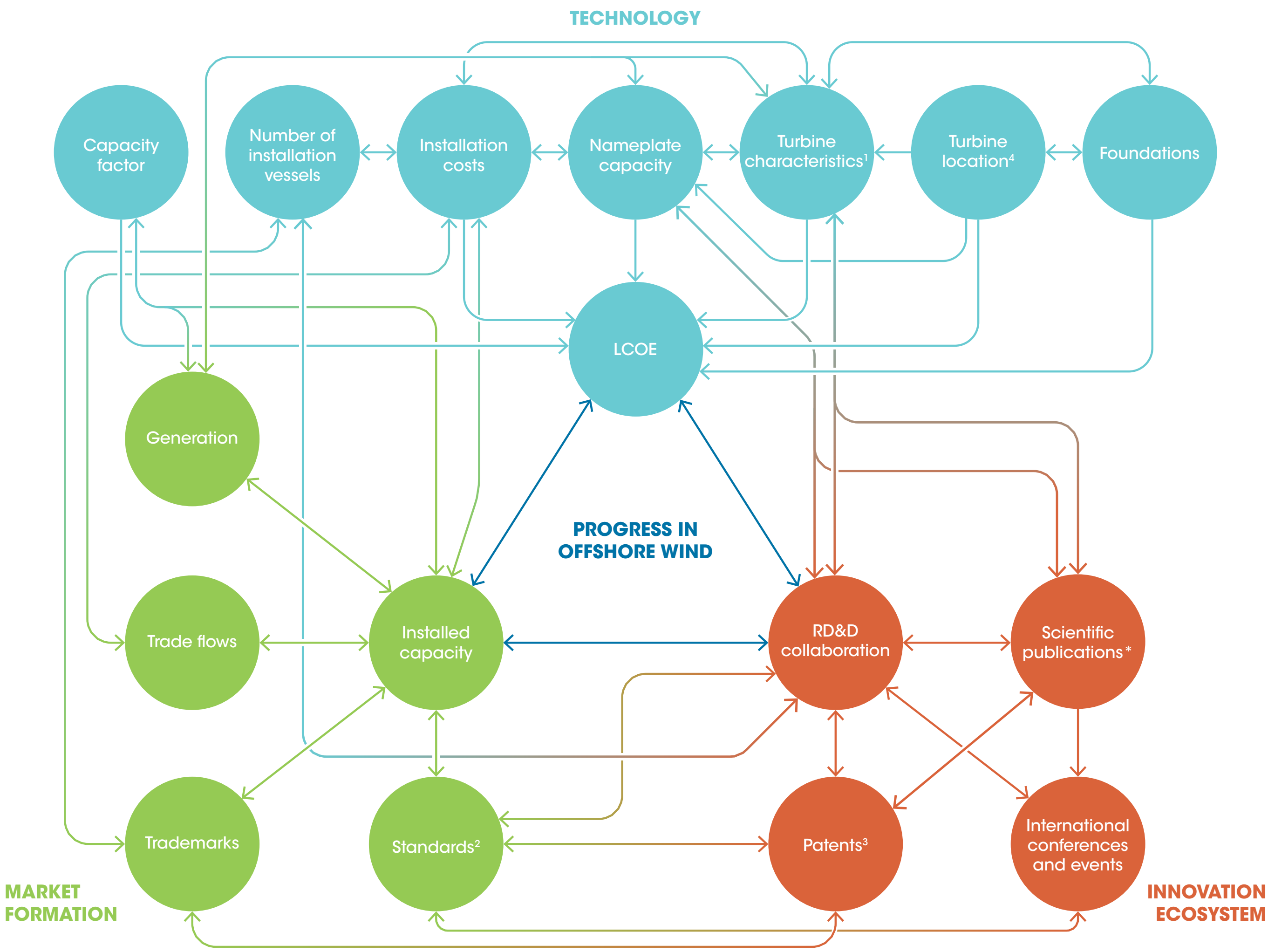
Offshore wind is one of the fastest-growing renewable power markets. It made significant progress between 2010 and 2019 in multiple aspects of the innovation chain. These included: rapid cost reductions; advances and breakthroughs in technology; supply chain efficiencies; and a scaled up deployment in new markets; along with other factors key to forming an enabling market. This has increased confidence in that market and unlocked further investments.

Despite the progress made, the sector **needs to continue to innovate, collaborate and harmonise** in order to broaden use, harness wind potential in deeper waters and further reduce costs.

The 30 indicators discussed above provide insights into the progress made in the offshore wind sector over the past 10 years. Some indicators are specifically linked to RD&D, while others connect to broader innovations.

Understanding the overall impact of innovation, however, is a difficult task. To gather further insights, indicators were considered together, with many linked in multiple ways – as illustrated in Figure 19.

Figure 19. Indicators and their interlinkages



1 Turbine size, hub height, rotar diameter
2 Countries developing and counties adopting standards
3 Patents filed, patents filed internationally, patents of high-value and patents specialization index
4 Distance from shore, water depth

Sector characteristics identified in this report include the following:

I. A HEALTHY AND BROADENING INNOVATION ECOSYSTEM

The analysis shows an increase in technologyrelated activities in offshore wind over the 2010 to 2019 period. It also shows a **strong and persisting innovation ecosystem**, which has been **driven by individual and joint RD&D investments and activities.** It is suggested that offshore wind technology innovation is not a niche area and is instead attaining global significance. It can also support scaled up deployment of the technology.

Characteristics supporting this include:

An active and broadening research base:

- The number of technologyrelated **scientific publications** for offshore wind **increased 2.5 times** between 2010 and 2019, with **over 88 000 citations** during this same period.

- The large global increase was mainly due to a fivefold **increase from China**. Publications rates have **plateaued,** but have persisted **in established markets** (the USA, the UK, Germany, Denmark, Norway, Japan and the Republic of Korea), while continuing to grow with a **3.5-fold increase in new markets** across countries in Europe, Asia, Latin and North America, **broadening the geographical offshore wind research base.**

Active private and public sectors seeking commercialisation of their intellectual property:

- **Patents** for offshore wind **increased by 60%** between 2010 and 2017.

- **China's** inventions (patent families) grew exponentially, from **2-63** during this period. **Japan** and the Republic of **Korea** produced almost **20%** of all inventions in 2017.

- Established markets in Asia (China, Japan and the Republic of Korea) and Europe (France and Germany) were **responsible for 90% of patenting activity in 2017**.

Active and growing RD&D collaboration between the private and public sector organisations:

- Offshore wind **RD&D collaborations** grew **fourfold** from 2010 to 2019.

- **National** collaborations increased between 2015-2019, while **international collaborations** were prevalent between 2010-2015. This suggests **RD&D is moving into higher TRLs** and the market is maturing.

- **Almost 60 international offshore wind conferences and events** took place between 2010-2019, with **over 55% taking place regularly** either annually or biennially (China, the USA, Poland, Germany, the EU level).

II. TECHNOLOGY DEVELOPMENT IN THE FORM OF DECLINING COSTS, IMPROVING TECHNOLOGY PERFORMANCE AND A WIDENING RANGE OF SOLUTIONS.

Breakthroughs and incremental innovations contributed, albeit with a time lag, to cost declines and improved technology performance, while also offering a diversity of solutions. **Cost** declines were **driven by a combination of** learning-by-doing, economies of scale, and by proxy through technology performance and by learning-by-RD&D. **RD&D activities drove improvements in technology performance and the development of diverse solutions** to address different geographical conditions. This should **continue**.

Characteristics supporting this include:

Costs continued to decline:

- Overall **installed costs declined by 28%** between 2015 and 2019**,** but cost volatility is still present due to the immaturity of the market.

- **LCOE by 32%,** from **USD 0.169/kWh** in 2010 **to USD 0.115/kWh** in 2019**.**

- Costs declines were **driven by learning-by-RD&D, learning-by-doing and economies of scale.**

Technology performance improved:

- The **capacity factor** increased by 18%, **reaching 44%** in 2019.

- Capacity factor improvements were in large part **driven by RD&D activities** contributing to **technology improvements**, including the hub heights of offshore wind turbines – which grew by 30% - the rotor diameter of offshore wind turbines - which grew by 40 % - and by turbines doubling in size.

Innovative solutions brought diversity and broadened geological and geographical conditions:

- Offshore wind projects reached deeper and more distant waters during the 2010 to 2019 period, with **distance** from the shore **growing almost threefold**.

- Over 80% of all offshore wind foundations were monopile, due to their price and ease of use. To address various seabed conditions, water depths, differences in manufacturing, installation and operation, a wide range of **foundation types** were **deployed, enabled by RD&D activities.**

- Improvements in the efficiency of offshore wind logistics contributed to increased and faster deployment. RD&D activities contributed to this, for example, enabling more efficient and **specialised installation vessels** for offshore wind sector, which contributed to shorter installation times and lower installation costs.

- To tap potential in **water depths beyond 50 metres**, an **increase in RD&D activities** is needed to improve existing solutions and further explor the suitability of foundations, including **floating foundations**.

III. RAPIDLY GROWING MARKETS MOVING TOWARDS MATURITY

There is a considerable **timelag between the RD&D activities and** their translation into large scale **deployment and market formation**, and therefore any interpretation of the links between activities under the innovation ecosystem (such as scientific publications) and scaled up deployment in offshore wind should be done with caution.

Deployment and market formation are also largely driven by learning-by-doing and economies of scale, but the scale of each driver is harder to measure.

Characteristics supporting this include:

Deployment continued to increase:

- **Installed capacity** for offshore wind **grew** more than **ninefold** between 2010-2019, when it reached 28 GW in 2019.

- **Electricity** generated grew exponentially, from 7.3 TWh in 2010 to **68 TWh in 2018**.

- In 2018, the share of offshore wind power was **1% in the global renewable energy mix** up from 0.2% in 2010.

Base of international standards for offshore wind continued to grow:

- Countries involved in developing international standards for offshore wind grew from **24 in 2010 to 31 in 2019.**

- The number of international standards increased from **zero to nine** in the same period.

Differentiated products and services led to commercialisation:

- The number of registered trademarks for offshore wind grew from **73** to **193** between 2010 and 2015 and then **fell by 55%** to 86 in 2019 - indicating a swift from the development phase to **commercialisation**.

Strong growth of wind energy exports:

- Global wind energy exports **doubled** between 2005 and 2019.

- China, Germany and the USA were the largest exporters, while countries like Italy also emerged. In the case of Italy – an onshore wind leader - **RD&D activities and innovation** may have allowed an adaptation of onshore wind technology and an increase in their manufacturing capacity.

7.2 Next steps for the methodological approach

This report is an output of the Innovation Impacts Dashboard (IID) project and the Tracking Energy Innovation Impacts Framework (TEIIF). These aim to provide additional qualitative and quantitative insights in the exploration of ways in which technology is making progress fully or in part due to RD&D activities. It thus aims to help policy makers design targeted RD&D policies and programmes.

The two projects mentioned above have developed a methodology to track the progress of RD&D activities. This uses a systemic approach that maps innovation by using 30 indicators across three categories. The methodology was then piloted on offshore wind technology.

The majority of data from that pilot was collected as part of the TEIIF project. The remainder of the data were then either collected specifically for this project, were readily available in IRENA databases, or were provided by external data providers free of charge. By employing a systemic approach, the analysis seeks to show how interrelated and mutually reinforcing various RD&D activities are in reducing costs and increasing technology deployment.

This pilot study shows that the approach can provide some valuable additional insights into the impact of RD&D activities on the progress of technology. It also enables some provisional conclusions to be drawn. This study should, however, be viewed as an initial work to be built upon. The methodology would benefit from further investigation and refinement. There is scope to add some additional indicators, while some of the analysis would benefit from greater data granularity. Additional data could also be included to bring additional insights and reflect the broadening base of engaged stakeholders, knowledge sharing and awareness building. This could be done, for example, by exploring the web, or job creation.

Further work will focus on exploring the readacross to other technologies, refining the indicators, developing more nuanced insights and, in particular, exploring in more depth the linkages between innovation support and the impacts observed. These points and others will be the focus of the followup work currently underway under the linked TEIIF project, which will provide further refinement of the approach and recommendations on how to develop a collaborative international process for tracking the impacts of innovation support.

REFERENCES

ESMAP (2019), Going Global: Expanding Offshore Wind to Emerging Markets. World Bank, Washington, DC.

Esteban, M.D., J.S. López-Gutiérrez and V. Negro (2019), Gravity-Based Foundations in the Offshore Wind Sector. Journal of Marine Science and Engineering, Vol. 7, No. 3, p. 63. https://doi.org/10.3390/jmse7030064

Fiorini, A. (2017), Monitoring R&I in Low-Carbon Energy Technologies. EUR 28446 EN / JRC105642. https://publications.jrc.ec.europa.eu/repository/handle/JRC105642https://doi.org/10.2760/447418

GWEC (2020), GWEC Market Intelligence releases Global Offshore Wind Turbine Installation Vessel Database. Global Wind Energy Council. https://gwec.net/gwec-market-intelligence-releases-global-offshore-wind-turbine-installation-database/

Hu, R., J. Skea and M.J. Hannon (2017), Measuring the energy innovation process: An indicator framework and a case study of wind energy in China. Technological Forecasting and Social Change, Vol. 127, pp. 227-244. https://doi.org/10.1016/j.techfore.2017.09.025

IRENA (2019), Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper). International Renewable Energy Agency, Abu Dhabi, United Arab Emirates.

IRENA (2017), Accelerating the Energy Transition through Innovation. International Renewable Energy Agency (IRENA), Abu Dhabi. www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Jun/IRENA_Energy_Transition_Innovation_2017.pdf

IRENA (2019b), Renewable Power Generation Costs in 2019, Abu Dhabi, www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019.

IRENA (2020), Renewable energy statistics 2020, Abu Dhabi: IRENA, www.irena.org/publications/2020/Jul/Renewable-energy-statistics-2020.

Jamasb, T. (2007), Technical Change Theory and Learning Curves: Patterns of Progress in Electricity Generation Technologies. The Energy Journal, Vol. 28, pp. 51–72. doi.org/10.2307/41323109

Lacal-Arántegui, R., J.M. Yusta and J.A. Domínguez-Navarro (2018), Offshore wind installation: Analysing the evidence behind improvements in installation time. Renewable and Sustainable Energy Reviews, Vol. 92, pp. 133–145. https://doi.org/10.1016/j.rser.2018.04.044

Pasimeni, F., A. Fiorini and A. Georgakaki (2019), Assessing private R&D spending in Europe for climae change mitigation technologies via patent data. World Patent Information, Vol. 59, 101927. https://doi.org/10.1016/j.wpi.2019.101927

Pasimeni, F. (2020), Patent-Based Indicators: Main Concepts and Data Availability. European Commission. https://doi.org/10.13140/RG.2.2.17379.58402

Pasimeni, F. (2019), SQL query to increase data accuracy and completeness in PATSTAT. World Patent Information, Vol. 57, pp. 1–7. https://doi.org/10.1016/j.wpi.2019.02.001

Paterson, et al. (2018), Offshore wind installation vessels – A comparative assessment for UK offshore rounds 1 and 2, Vol. 148, pp. 637–649. https://doi.org/10.1016/j.oceaneng.2017.08.008

Vidican-Sgouridis, G., W. Lee Woon and S. Madnick (2009), Measuring Innovation Using Bibliometric Techniques: The Case of Solar Photovoltaic Industry. http://dx.doi.org/10.2139/ssrn.1388222

Wood Mackenzie (2019), The momentum of floating wind and its outlook implications. www.woodmac.com/reports/power-markets-the-momentum-of-floating-wind-and-its-outlook-implications-368914

IRENA

International Renewable Energy Agency

www.irena.org