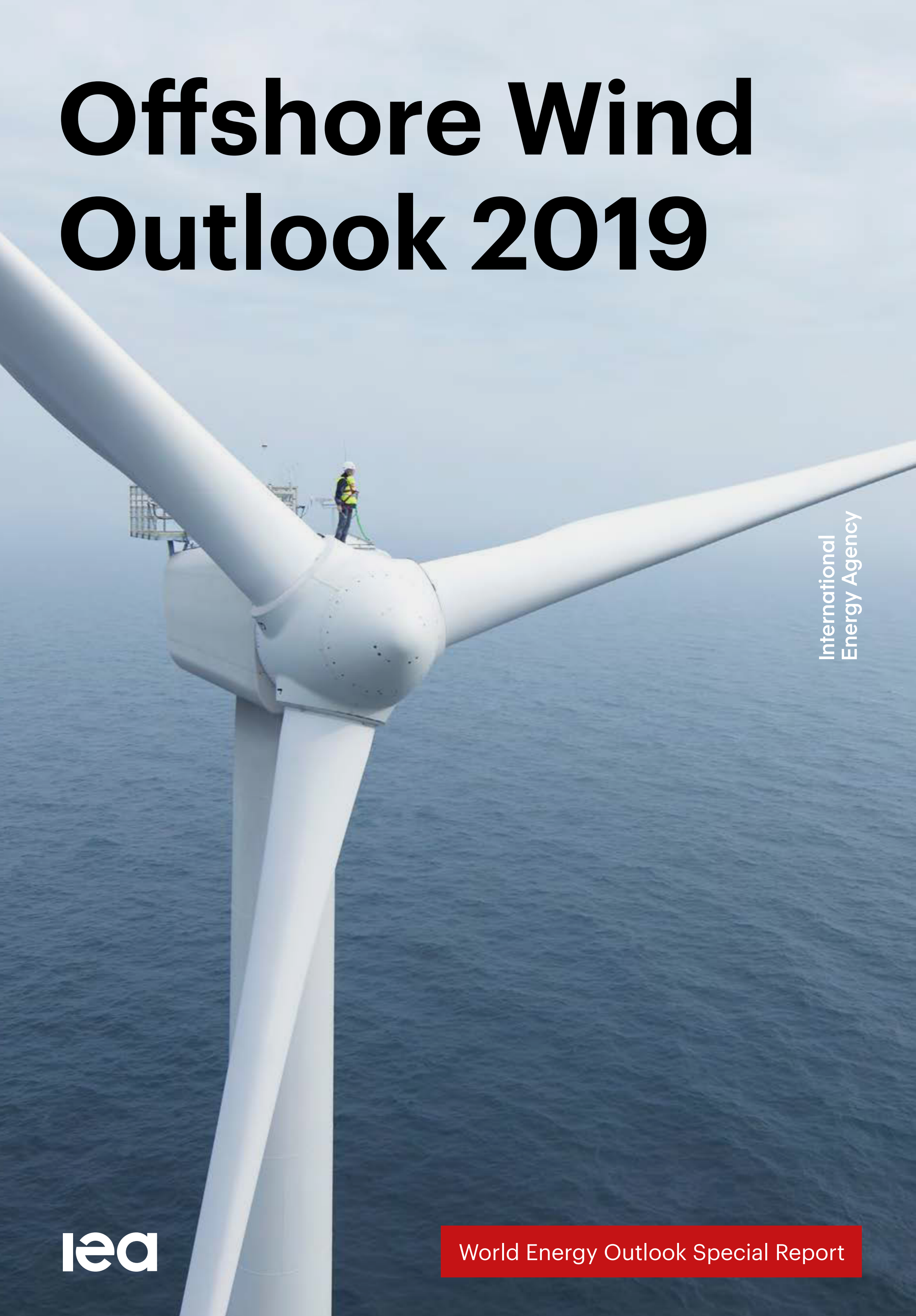
Offshore Wind Outlook 2019



International Energy Agency

World Energy Outlook Special Report

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INTERNATIONAL ENERGY AGENCY

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As the challenge of meeting global sustainable energy goals increases, it becomes ever more crucial to expand the range of available and affordable low-carbon technologies. Pioneered in Europe, offshore wind is a compelling example of a rapidly maturing technology that is poised to make a major difference in future energy systems. Working with governments, industry and research bodies, the International Energy Agency (IEA) has produced the most comprehensive global study on offshore wind to date.

Based on current and proposed policies, our analysis shows that global offshore wind power capacity is set to increase 15-fold over the next two decades, turning it into a $1 trillion business. Its potential is far greater than that, however, as made clear by the IEA Sustainable Development Scenario, which outlines a path to meeting global climate, air quality and universal energy access goals. In this scenario, offshore wind not only helps to put the global power sector on track for full decarbonisation, it also becomes the leading source of electricity in Europe and enables hydrogen to dramatically cut emissions from sectors such as iron, steel and shipping.

This report lays out where offshore wind stands today, how it could develop and which challenges still need to be overcome. To properly assess offshore wind's global potential, the IEA collaborated with Imperial College London to undertake a special geospatial analysis. Using the latest satellite data, the project mapped out in detail the speed and quality of wind along hundreds of thousands of kilometres of coastline around the world.

This new study complements IEA coverage of the renewables sector and its increasingly in-depth work on electricity security. Those efforts include co-organising with the German Federal Ministry for Economic Affairs and Energy the first Global Ministerial Conference on System Integration of Renewables in October 2019 to share ideas for fully grasping the opportunities of wind and solar power. We are also carrying out a major new study on global electricity security in the 21st century. The report, to be published in September 2020, will look at how to manage the integration of more variable renewables into power grids, how to protect energy infrastructure from cybersecurity threats and how to improve resilience to natural events.

Some may question why I decided to devote so much of the IEA's time and effort to this report on offshore wind, a technology that today supplies just 0.3% of global power generation. The reason is that its potential is near limitless. Improved technology and steep cost reductions are putting more and more of that potential within our reach. But much work remains to be done for offshore wind to help decarbonise electricity and, through the production of hydrogen, possibly other sectors as well. That work includes putting in place policies to promote investment and spur innovation. I hope this report helps governments make those smart policy choices for the future development of this powerful emerging technology.

Dr. Fatih Birol
Executive Director
International Energy Agency

This study was prepared by the World Energy Outlook (WEO) team in the Directorate of Sustainability, Technology and Outlooks (STO) in co-operation with other directorates and offices of the International Energy Agency. The study was designed and directed by **Laura Cozzi**, Chief Energy Modeller, and **Brent Wanner**, *WEO* lead on power sector modelling and analysis. The other main authors were **Connor Donovan**, **Alberto Toril** and **Wilfred Yu**. The study relied on support from across the entire WEO team, in particular from **Yasmine Arsalane**, **Davide D'Ambrosio**, **Jianguo Liu**, **Sebastian Papapanagiotou**, **Claudia Pavarini**, **Daniele Perugia**, **Leonie Staas**, and **Michael Waldron**, as well as valuable guidance from **Tim Gould,** Head of the WEO Energy Supply and Investment Outlook Division.

Edmund Hosker carried editorial responsibility. **Debra Justus** was the copy-editor.

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Further details on these events are at www.iea.org/weo/events.

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Offshore Wind Outlook 2019

Annexes

The need for affordable low-carbon technologies is greater than ever

Global energy-related CO_2 emissions reached a historic high in 2018, driven by an increase in coal use in the power sector. Despite impressive gains for renewables, fossil fuels still account for nearly two-thirds of electricity generation, the same share as 20 years ago. There are signs of a shift, with increasing pledges to decarbonise economies and tackle air pollution, but action needs to accelerate to meet sustainable energy goals. As electrification of the global energy system continues, the need for clean and affordable low-carbon technologies to produce this electricity is more pressing than ever. This *World Energy Outlook* special report offers a deep dive on a technology that today has a total capacity of 23 GW (80% of it in Europe) and accounts for only 0.3% of global electricity generation, but has the potential to become a mainstay of the world's power supply. The report provides the most comprehensive analysis to date of the global outlook for offshore wind, its contributions to electricity systems and its role in clean energy transitions.

The offshore wind market has been gaining momentum

The global offshore wind market grew nearly 30% per year between 2010 and 2018, benefitting from rapid technology improvements. Over the next five years, about 150 new offshore wind projects are scheduled to be completed around the world, pointing to an increasing role for offshore wind in power supplies. Europe has fostered the technology's development, led by the United Kingdom, Germany and Denmark. The United Kingdom and Germany currently have the largest offshore wind capacity in operation, while Denmark produced 15% of its electricity from offshore wind in 2018. China added more capacity than any other country in 2018.

The untapped potential of offshore wind is vast

The best offshore wind sites could supply more than the total amount of electricity consumed worldwide today. And that would involve tapping only the sites close to shores. The IEA initiated a new geospatial analysis for this report to assess offshore wind technical potential country by country. The analysis was based on the latest global weather data on wind speed and quality while factoring in the newest turbine designs. Offshore wind's technical potential is 36 000 TWh per year for installations in water less than 60 metres deep and within 60 km from shore. Global electricity demand is currently 23 000 TWh. Moving further from shore and into deeper waters, floating turbines could unlock enough potential to meet the world's total electricity demand 11 times over in 2040. Our new geospatial analysis indicates that offshore wind alone could meet several times electricity demand in a number of countries, including in Europe, the United States and Japan. The industry is adapting various floating foundation technologies that have already been proven in the oil and gas sector. The first projects are under development and look to prove the feasibility and cost-effectiveness of floating offshore wind technologies.

Offshore wind's attributes are very promising for power systems

New offshore wind projects have capacity factors of 40-50%, as larger turbines and other technology improvements are helping to make the most of available wind resources. At these levels, offshore wind matches the capacity factors of gas- and coal-fired power plants in some regions – though offshore wind is not available at all times. Its capacity factors exceed those of onshore wind and are about double those of solar PV. Offshore wind output varies according to the strength of the wind, but its hourly variability is lower than that of solar PV. Offshore wind typically fluctuates within a narrower band, up to 20% from hour to hour, than solar PV, which varies up to 40%.

Offshore wind's high capacity factors and lower variability make its system value comparable to baseload technologies, placing it in a category of its own – a variable baseload technology. Offshore wind can generate electricity during all hours of the day and tends to produce more electricity in winter months in Europe, the United States and China, as well as during the monsoon season in India. These characteristics mean that offshore wind's system value is generally higher than that of its onshore counterpart and more stable over time than that of solar PV. Offshore wind also contributes to electricity security, with its high availability and seasonality patterns it is able to make a stronger contribution to system needs than other variable renewables. In doing so, offshore wind contributes to reducing CO_2 and air pollutant emissions while also lowering the need for investment in dispatchable power plants. Offshore wind also has the advantage of avoiding many land use and social acceptance issues that other variable renewables are facing.

Offshore wind is on track to be a competitive source of electricity

Offshore wind is set to be competitive with fossil fuels within the next decade, as well as with other renewables including solar PV. The cost of offshore wind is declining and is set to fall further. Financing costs account for 35% to 50% of overall generation cost, and supportive policy frameworks are now enabling projects to secure low cost financing in Europe, with zero-subsidy tenders being awarded. Technology costs are also falling. The levelised cost of electricity produced by offshore wind is projected to decline by nearly 60% by 2040. Combined with its relatively high value to the system, this will make offshore wind one of the most competitive sources of electricity. In Europe, recent auctions indicate that offshore wind will soon beat new natural gas-fired capacity on cost and be on a par with solar PV and onshore wind. In China, offshore wind is set to become competitive with new coal-fired capacity around 2030 and be on par with solar PV and onshore wind. In the United States, recent project proposals indicate that offshore wind will soon be an affordable option, with potential to serve demand centres along the country's east coast.

Innovation is delivering deep cost reductions in offshore wind, and transmission costs will become increasingly important. The average upfront cost to build a 1 gigawatt offshore wind project, including transmission, was over $4 billion in 2018, but the cost is set to drop by more than 40% over the next decade. This overall decline is driven by a 60% reduction in the costs of turbines, foundations and their installation. Transmission accounts for around one-quarter of total offshore wind costs today, but its share in total costs is set to increase to about one-half as new projects move further from shore. Innovation in transmission, for example through work to expand the limits of direct current technologies, will be essential to support new projects without raising their overall costs.

Offshore wind is set to become a $1 trillion business

Offshore wind power capacity is set to increase by at least 15-fold worldwide by 2040, becoming a $1 trillion business. Under current investment plans and policies, the global offshore wind market is set to expand by 13% per year, passing 20 GW of additions per year by 2030. This will require capital spending of $840 billion over the next two decades, almost matching that for natural gas-fired or coal-fired capacity. Achieving global climate and sustainability goals would require faster growth: capacity additions would need to approach 40 GW per year in the 2030s, pushing cumulative investment to over $1.2 trillion.

The promising outlook for offshore wind is underpinned by policy support in an increasing number of regions. Several European North Seas countries – including the United Kingdom, Germany, the Netherlands and Denmark – have policy targets supporting offshore wind. Although a relative newcomer to the technology, China is quickly building up its offshore wind industry, aiming to develop a project pipeline of 10 GW by 2020. In the United States, state-level targets and federal incentives are set to kick-start the offshore wind market. Additionally, policy targets are in place and projects under development in Korea, Japan, Chinese Taipei and Viet Nam.

The synergies between offshore wind and offshore oil and gas activities provide new market opportunities. Since offshore energy operations share technologies and elements of their supply chains, oil and gas companies started investing in offshore wind projects many years ago. We estimate that about 40% of the full lifetime costs of an offshore wind project, including construction and maintenance, have significant synergies with the offshore oil and gas sector. That translates into a market opportunity of $400 billion or more in Europe and China over the next two decades. The construction of foundations and subsea structures offers potential crossover business, as do practices related to the maintenance and inspection of platforms. In addition to these opportunities, offshore oil and gas platforms require electricity that is often supplied by gas turbines or diesel engines, but that could be provided by nearby wind farms, thereby reducing CO_2 emissions, air pollutants and costs.

Offshore wind can accelerate clean energy transitions

Offshore wind can help drive energy transitions by decarbonising electricity and by producing low-carbon fuels. Over the next two decades, its expansion could avoid between 5 billion and 7 billion tonnes of CO_2 emissions from the power sector globally, while also reducing air pollution and enhancing energy security by reducing reliance on imported fuels. The European Union is poised to continue leading the offshore wind industry in support of its climate goals: its offshore wind capacity is set to increase by at least fourfold by 2030. This growth puts offshore wind on track to become the European Union's largest source of electricity in the 2040s. Beyond electricity, offshore wind's high capacity factors and falling costs makes it a good match to produce low-carbon hydrogen, a versatile product that could help decarbonise the buildings sector and some of the hardest to abate activities in industry and transport. For example, a 1 gigawatt offshore wind project could produce enough low-carbon hydrogen to heat about 250 000 homes. Rising demand for low-carbon hydrogen could also dramatically increase the market potential for offshore wind. Europe is looking to develop offshore "hubs" for producing electricity and clean hydrogen from offshore wind.

It's not all smooth sailing

Offshore wind faces several challenges that could slow its growth in established and emerging markets, but policy makers and regulators can clear the path ahead. Developing efficient supply chains is crucial for the offshore wind industry to deliver low-cost projects. Doing so is likely to call for multibillion-dollar investments in ever-larger support vessels and construction equipment. Such investment is especially difficult in the face of uncertainty. Governments can facilitate investment of this kind by establishing a long-term vision for offshore wind and precisely defining the measures to be taken to help make that vision a reality. Long-term clarity would also enable effective system integration of offshore wind, including system planning to ensure reliability during periods of low wind availability.

The success of offshore wind depends on developing onshore grid infrastructure. Whether the responsibility for developing offshore transmission lies with project developers or transmission system operators, regulations should encourage efficient planning and design practices that support the long-term vision for offshore wind. Those regulations should recognise that the development of onshore grid infrastructure is essential to the efficient integration of power production from offshore wind. Without appropriate grid reinforcements and expansion, there is a risk of large amounts of offshore wind power going unused, and opportunities for further expansion could be stifled. Development could also be slowed by marine planning practices, regulations for awarding development rights and public acceptance issues.

The future of offshore wind looks bright but hinges on the right policies

The outlook for offshore wind is very positive as efforts to decarbonise and reduce local pollution accelerate. While offshore wind provides just 0.3% of global electricity supply today, it has vast potential around the world and an important role to play in the broader energy system. Offshore wind can drive down CO_2 emissions and air pollutants from electricity generation. It can also do so in other sectors through the production of clean hydrogen and related fuels. The high system value of offshore wind offers advantages that make a strong case for its role alongside other renewables and low-carbon technologies. Government policies will continue to play a critical role in the future of offshore wind and the overall pace of clean energy transitions around the world.

Offshore Wind Outlook 2019

Offshore wind is a rapidly maturing renewable energy technology. In 2018, it provided just 0.3% of global electricity supply, nevertheless its future prospects look bright. Individual offshore wind turbines have been enlarging in physical size and rated power capacity, bringing performance gains for offshore wind installations. Further technology improvements are promising steep cost reductions in the near term.

New analysis of offshore wind was performed for this *WEO* special report, with an emphasis on three areas: its technical potential; continued evolution of the technology; and its role in energy systems now and in the future. We undertook a detailed geospatial analysis of the regional and global technical potential for offshore wind, considering areas available for development on the basis of the latest wind resource data, and taking account of wind turbine technology advances. This includes an assessment of the future evolution of the relevant technology in close consultation with major industry market leaders, manufacturers, developers and other key stakeholders. The systems analysis considered the role of offshore wind with scenario-based quantifications, using our World Energy Model to provide contextual data on the wider evolution of global energy systems.

This report provides a deep dive into offshore wind power. It gives a snapshot of where the market and technology stand today and the outlook to 2040, in light of the policy environment and the evolving competitiveness of offshore wind. It explores the key uncertainties for the outlook, looking at both the potential for faster growth and the main challenges that could slow development. It concludes with a look at the implications of the growth of offshore wind for environmental goals, energy security and affordability.

Offshore wind power today

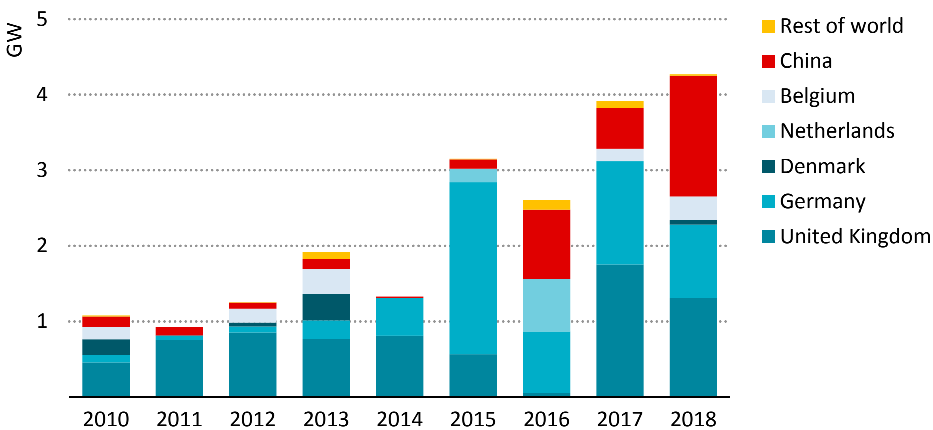
Current status

Offshore wind has emerged as one of the most dynamic technologies in the energy system. For the first time in 2010 global capacity additions of offshore wind surpassed 1 gigawatt (GW). In 2018, a total of 4.3 GW of new offshore wind capacity was completed (Figure 1). From 3 GW of offshore wind in operation in 2010, installed capacity expanded to 23 GW in 2018. Annual deployment has increased by nearly 30% per year, higher than any other source of electricity except solar photovoltaics (PV). By mid-2019, there were over 5 500 offshore turbines connected to a grid in 17 countries. Policy support has been fundamental to this expansion, including through technology-specific capacity tenders, progress on including offshore wind in marine planning, financial support and regulatory efforts to support grid development.

The growth of the offshore wind industry has been fostered in European countries bordering the North Seas, where high quality wind resources and relatively shallow water have provided exceptionally good conditions in which to develop offshore wind technologies and bring them to market. Stable policies supported nearly 17 GW of offshore wind capacity additions in Europe between 2010 and 2018. The United Kingdom, Germany, Belgium, Netherlands and Denmark together added 2.7 GW of capacity in 2018 alone.

China has recently taken strides forward on offshore wind and now stands among the market leaders. In 2018, China added 1.6 GW of offshore wind capacity, the most of any country. This rapid growth has been driven by the government's 13th Five-Year Plan, which called for 5 GW of offshore wind capacity to be completed by 2020, and for the establishment of supply chains to support further expansion thereafter.

Figure 1 ▷ Annual offshore wind capacity additions by region, 2010-2018



Deployment of offshore wind has increased by nearly 30% per year since 2010, second only to solar PV, as the technology and industry have matured

Note: Figure reflects date of connection to grid and power output, which may be before final commissioning.

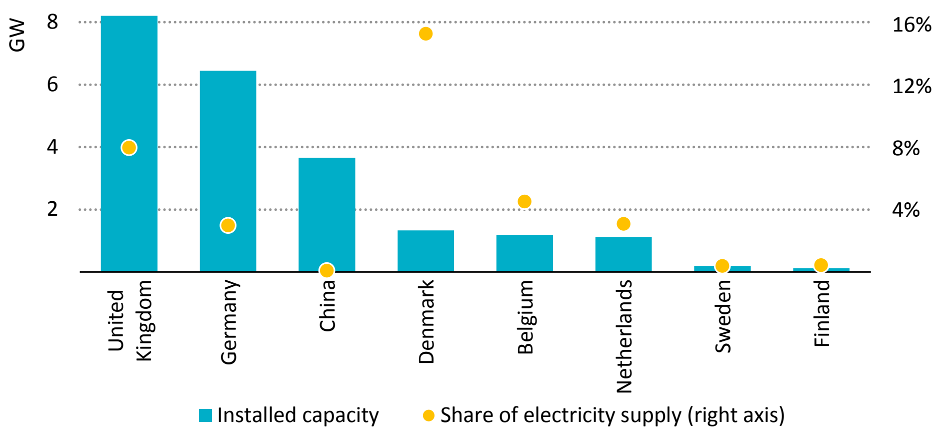
Offshore wind is set to gain a foothold in new markets in the next five years. The current pipeline includes about 150 new offshore wind projects spread across 19 countries. Over 100 projects are scheduled to be completed by 2021, pointing to further acceleration in the rate of annual capacity additions. In the United States, there are 25 GW of offshore wind projects in the longer-term pipeline (US DOE, 2019). There are also large-scale projects in Australia, Chinese Taipei, India, Japan, Korea, New Zealand, Turkey and Viet Nam.

In 2018, more than 80% of global installed offshore wind capacity was located in Europe. Around 8 GW, one-third of the total, was in the United Kingdom and 6.5 GW in Germany, with Denmark, Netherlands and Belgium providing a further 3.6 GW between them. Even as a relative newcomer, China already has 3.6 GW of offshore wind capacity (Figure 2).

Offshore wind power accounted for just 0.3% of global electricity supply in 2018, but played a larger role in the leading countries. It provided 15% of electricity generation in Denmark in 2018, where onshore and offshore wind together accounted for almost 50% of electricity generation. Offshore wind provided 8% of electricity generation in the United

Kingdom, more than twice as much as from solar PV generation, and for 3-5% of electricity generation in Belgium, Netherlands and Germany. Despite recent growth, output from China's offshore wind fleet in 2018 represented just 0.1% of its overall power output.

Figure 2 ▷ Offshore wind installed capacity and share of electricity supply by country, 2018



Most leading countries in offshore wind are in Europe, led by the United Kingdom, though China has quickly joined the top-three and is gaining momentum

Market size and key players

Today, offshore wind is a multi-billion dollar business, with developed supply chains in leading markets that span development, project construction and installation, operation and maintenance, and decommissioning activities. The offshore wind industry attracted a growing share of investment in wind and renewable energy in recent years, nearing $20 billion in 2018, up from less than $8 billion in 2010. Investment in offshore wind in 2018 accounted for nearly one-quarter of global investment in the wind sector and 6% of all investment in renewable energy. Investment was particularly pronounced in the European Union, where offshore wind accounted for about half of total investment in wind power in 2018 and one-quarter of total investment in renewable energy (IEA, 2019a).

Investment in offshore wind projects is mainly by large utilities and investment funds because the projects have relatively high upfront capital costs: a 250 megawatt (MW) project costs around $1 billion. Solar PV and onshore wind by contrast have lower upfront costs and present fewer barriers to entry for smaller players.

European companies develop and own the majority of offshore wind assets (Table 1). Denmark-based Ørsted owns the largest share, and is actively expanding into other markets in the United States and Asia. Germany-based RWE consolidated its share of the offshore wind market after acquiring E.ON and Innogy renewable energy assets in the North Sea and Baltic Sea, and is now the second-largest offshore wind operator in the world.

Chinese companies account for a growing share of the market. Two Chinese state-owned enterprises rank among the top-ten developers in the industry, with around 7% market share in terms of ownership. China Longyuan Power Group ranks as the largest producer of wind power across Asia, while the China Three Gorges Corporation (CTG) – previously known for its hydroelectric projects – is one of the world's largest energy companies and has become actively involved in the offshore wind industry. CTG set itself the goal of becoming the leader in offshore wind power development in China, and owns five wind installations with combined capacity of 1.2 GW, although some is under construction.

Table 1 ▷ Leading market players in the offshore wind industry, 2018

Organisation	Main activities	Assets (GW)			Market share	Headquarters	Ownership
		In operation	Under construction	In development			
Ørsted	DOO	2.97	2.79	5.23	12.86%	Denmark	Private
RWE	DOO	2.41	0.51	1.83	10.44%	Germany	Private
China Longyuan	DOO	1.23	0.40	1.00	5.34%	China	Public
Vattenfall	DOO	0.88	1.01	4.92	3.82%	Sweden	Public
Macquarie Capital	Investor	0.87	0.07	0.10	3.78%	Australia	Private
Northland Power	DOO	0.64	0.27	0.63	2.78%	Canada	Public
Global Infrastructure Partners	Investor	0.63	0.61	-	2.73%	United States	Private
Iberdrola	DOO	0.55	0.97	0.81	2.36%	Spain	Private
Equinor	DOO	0.48	-	2.17	2.10%	Norway	Public
Siemens Financial Services	Investor	0.46	-	-	1.98%	Germany	Private
Public Pension, Denmark	Investor	0.45	-	-	1.97%	Denmark	Public
Électricité de France	DOO	0.43	-	1.67	1.85%	France	Public
Stadtwerke München	Investor	0.41	-	-	1.79%	Germany	Public
China Three Gorges	DOO	0.40	0.88	6.87	1.74%	China	Public
Scottish and Southern Energy	DOO	0.34	0.24	0.52	1.49%	United Kingdom	Public

Notes: DOO = developer, owner and operator. Market shares are adjusted to reflect each company's equity stake across all of its projects.

Source: IEA analysis based on BNEF (2019).

Manufacturers of offshore wind turbines are mostly based in Europe, and the market is concentrated among a small number of companies (Table 2). Spanish-headquartered Siemens Gamesa and MHI Vestas, a joint venture between Vestas and Mitsubishi Heavy Industries, dominated the offshore wind industry, accounting for over two-thirds of the offshore wind capacity installed in 2018. Together, these two manufacturers account for over 80% of all offshore capacity commissioned from 1995 through the end of 2018. The share of turbines produced by Chinese manufacturers is expanding with its focus on the market in Asia, accounting for close to 30% of offshore wind capacity additions in 2018.

Table 2 ▹ Leading manufacturers of offshore wind turbines, 2018

Rank	Company	Offshore wind market share, 2018	Offshore wind market share, 1995-2018	Offshore wind capacity sold, 1995-2018 (MW)
1	Siemens Gamesa	41%	63%	13 881
2	MHI Vestas	30%	18%	3 882
3	Envision	15%	4%	804
4	Goldwind	8%	3%	574
5	Ming Yang	2%	1%	113
6	Sewind	2%	1%	306
7	GE Renewable Energy	0.4%	1%	177
8	Taiyuan	0.2%	0%	10
9	Senvion	-	6%	1 253
10	Bard	-	2%	405

Source: IEA analysis based on BNEF (2019).

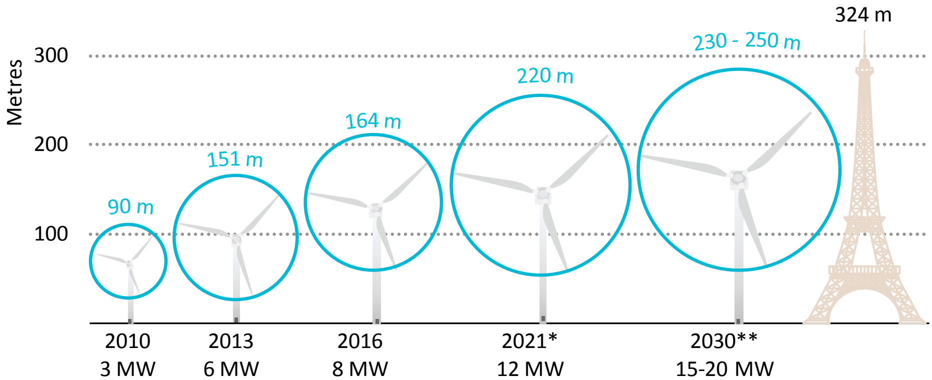
Another important component in the value chain is the construction and servicing of offshore wind turbines. Between 2010 and 2018 nearly $4 billion per year was invested in the construction of offshore wind installations across Europe and China, while over $1 billion was spent annually on operations and maintenance. As the offshore wind sector expands, the opportunities to exploit synergies with oil and gas contractors and servicing companies will increase (see section "Synergies with oil and gas activities").

Offshore wind technology and performance

Offshore wind technology has made impressive advances since the first turbines were installed near the shore in Denmark in 1991. Since then, equipment suppliers have focused research and development spending on developing bigger and better performing offshore wind turbines. The technology has grown dramatically in physical size and rated power output.

Technology innovation has led to an increase in turbine size in terms of tip height and swept area, and this has raised their maximum output. The tip height of commercially available turbines increased from just over 100 metres (m) in 2010 (3 MW turbine) to more than 200 m in 2016 (8 MW turbine) while the swept area increased by 230%. The larger swept area allows for more wind to be captured per turbine. A 12 MW turbine now under development is expected to reach 260 m, or 80% of the height of the Eiffel Tower (Figure 3). The industry is targeting even larger 15-20 MW turbines for 2030. This increase in turbine size and rating has put upward pressure on capital costs as larger turbines pose construction challenges and require larger foundations, but it has also reduced operation and maintenance costs, ultimately leading to lower levelised costs of electricity.

Figure 3 ▹ **Evolution of the largest commercially available wind turbines**



Technology advances enabled offshore wind turbines to become much bigger in just a few years and are supporting ongoing increases in scale

* Announced expected year of commercial deployments. ** Further technology improvements through to 2030 could see bigger turbines sizes of 15-20 MW.

Notes: Illustration is drawn to scale. Figures in blue indicate the diameter of the swept area.

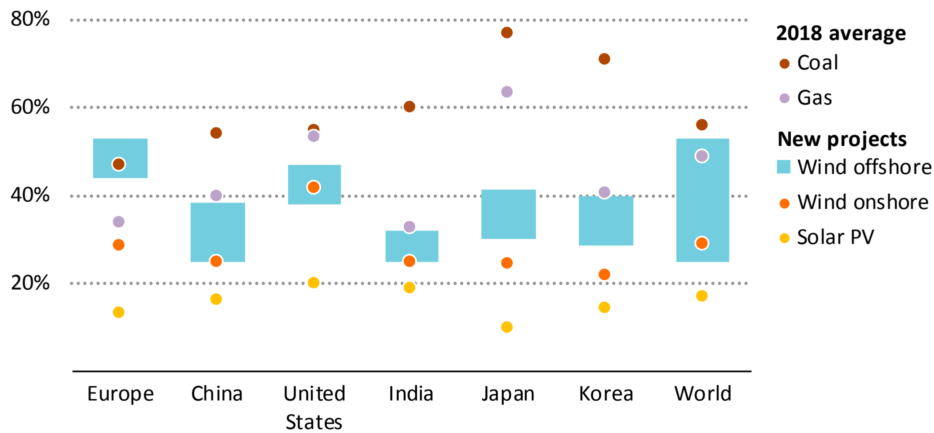
The average turbine size used in offshore wind farms increased from 3 MW in 2010 to 5.5 MW for projects completed in 2018 (IRENA, 2019). In the same period, annual capacity factors for new projects increased from 38% to 43%.[1] New turbines of 10-12 MW promise to achieve capacity factors well over 50% (before wake losses).[2] Compared to smaller units, a bigger turbine can achieve a capacity factor improvement of two to seven percentage points given the same site conditions. However, not all projects will necessarily see a significant increase in performance as a result of using larger turbines. Capacity factors remain dependent on the quality of the wind speeds of individual sites, which may not be suitable for larger turbines. There may also be a trade-off for developers between incremental performance gains and higher costs of larger turbines.

Offshore wind provides higher capacity factors than other variable renewables. In 2018, the average global capacity factor for offshore wind turbines was 33% compared with 25% for onshore wind turbines and 14% for solar PV. Looking forward, new offshore wind projects are expected to have capacity factors of over 40% in moderate wind conditions and over 50% in areas with high quality wind resources. Other variable renewable energy technologies are also likely to see improvements, but not to match the expected capacity factors of new offshore wind projects. For example, technology improvements are raising expected capacity factors for onshore wind to between 30% and 40% in most regions (Figure 4).

[1] Capacity factor describes the average output over the year relative to the maximum rated power capacity.

[2] Wake loss refers to the effect on the space behind a turbine that is marked by decreased wind speed on a downstream wind turbine due to the fact that the turbine itself used the energy in turning the blades.

Figure 4 ▷ Indicative annual capacity factors by technology and region



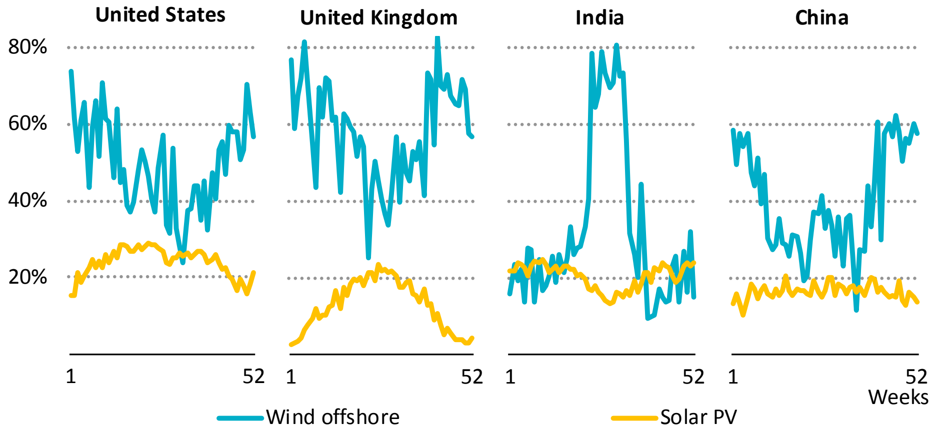
Offshore wind offers similar capacity factors to efficient gas-fired power plants in several regions, with levels well above those for other variable renewables

Simulations indicate that new offshore wind projects will produce as much electricity per unit of capacity each year as some forms of dispatchable generation, and will have capacity factors on a level with or higher than those of conventional gas-fired power plants in several regions, including Europe, China, India and Korea.[3] In Europe, new offshore wind projects are set to have an average capacity factor of over 45%, exceeding the 2018 average for Europe's coal-fired power plants. This development has implications for how offshore wind is integrated into electricity supply and its impact on grid infrastructure, as well as for its suitability for producing hydrogen, an application that could greatly expand the offshore wind market (see section "Increased demand for renewable hydrogen").

The electricity produced from offshore wind projects depends on the available wind resources at a given time, leading to variable output. High average capacity factors and variable production put offshore wind power into a category of their own as a "variable baseload" technology. Over the course of a year, offshore wind exhibits substantial variability from week-to-week. It tends to produce more electricity during the winter and less during the summer in Europe, United States and China, as indicated by the simulated output for new offshore wind projects (Figure 5). In India, the simulations indicate that the monsoon season from June to September would see higher output from offshore wind projects compared with other parts of the year. In all cases, the seasonal profile of offshore wind is complementary to that of solar PV, which tends to produce more electricity in the summer and less in the winter in Europe, United States and China, and less in the monsoon season in India than at other times of the year.

[3] Gas-fired capacity and other dispatchable power plants can readily adjust their output up to their maximum rated capacity according to market conditions and system needs.

Figure 5 ▹ Simulated average weekly capacity factors for new offshore wind and solar PV projects by region



Seasonality of offshore wind can complement that of solar PV

Note: Based on weather data for 2018, 2013 and 2008.

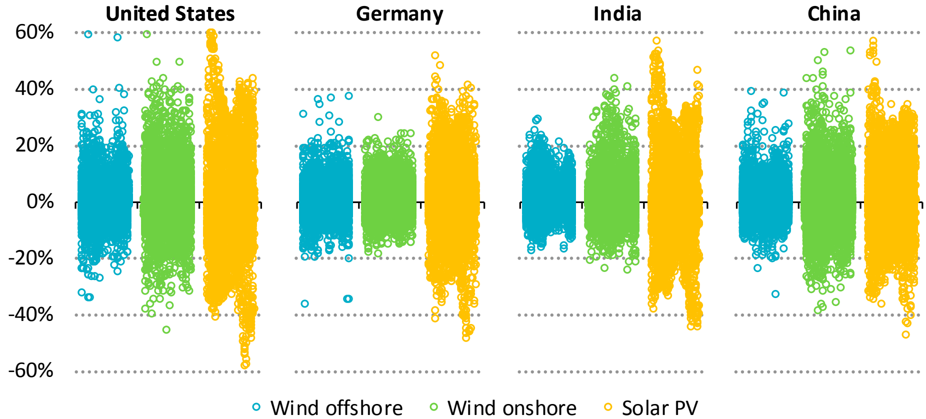
Source: IEA analysis based on Renewables.ninja.[4]

Hour-to-hour variations in offshore wind power output tend to be comparable with those for onshore wind and lower than those for solar PV. Offshore wind typically fluctuates within a narrower band, up to 20% from hour-to-hour, than is the case for solar PV, up to 40% from hour-to-hour (Figure 6). Lower hourly variability offers a potential advantage for offshore wind over other variable renewables, though its impact on system flexibility needs depends on a number of factors, including the correlation of its output with electricity demand and the output from other variable renewables. At the system level, regional diversity can also moderate the impact of the variability at the project level.

Offshore wind installations are also moving further from shore and into deeper water where better quality wind resources are available. Most projects commissioned to date have been within 50 km of shore. However, several large projects in the pipeline are 100 km or more from shore. This is becoming more common as developers look to install turbines in deeper water with improved construction techniques that reflect learning from earlier projects and from the offshore oil and gas industry. The use of relatively low-cost monopile foundations has been the offshore wind industry standard for the majority of the projects installed in water depths of less than 50 m. Projects located in slightly deeper depths are also seeking to find ways to use monopile foundations rather than to have to adopt higher cost jacket and floating foundations. In order to deploy offshore wind in yet deeper waters, the industry has been deploying pilots and pre-commercial scale projects to improve the designs of floating foundations and to establish their costs (Box 1).

[4] Renewables.ninja is a publicly available tool that is validated and calibrated against real-world output in 70 countries (Staffell and Pfenninger, 2016), accessible at www.renewables.ninja.

Figure 6 ▻ Range of simulated hour-to-hour variations in output for new projects by technology



Offshore wind has similar hourly variability as onshore wind, but far less than solar PV

Note: Based on weather data for 2018.

Source: IEA analysis based on Renewables.ninja.

Box 1 ▻ Floating foundations – the next frontier for offshore wind

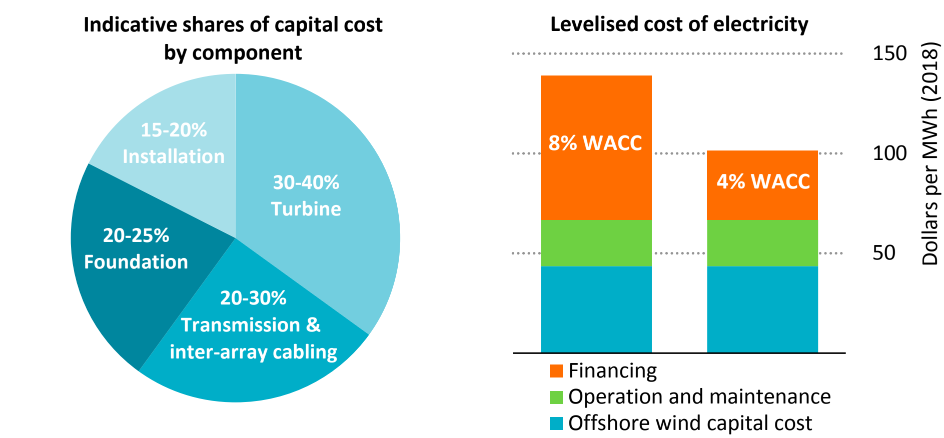
Floating offshore wind is a fast maturing technology that could harness untapped wind resources located in regions with water depths exceeding 50-60 m where traditional fixed-bottom offshore wind installations are not economically attractive. The industry is adapting various floating foundation technologies that have already been proven in the oil and gas sector, though design modifications are still required. Broadly, there are three main concepts for floating foundations: spar-buoy, semi-submersible and tension leg platforms. Other variants exist, including multiple turbines on one platform and hybrid wind/wave floating devices (IRENA, 2016; Carbon Trust, 2015).

In recent years, there have been significant developments in floating offshore wind projects including the commissioning of the world's first multi-unit installation in 2017 (30 MW Hywind in Scotland). A number of smaller demonstration projects were installed in 2018, including Floatgen in France (2 MW) and Hibiki in Japan (3 MW). In addition, at least ten new pre-commercial scale projects in Europe are in the pipeline (WindEurope, 2017), including the 30 MW WindFloat Atlantic in Portugal and the 48 MW Kincardine in Scotland. Equinor also received approval in 2019 to build a 200 MW project off the coast of the Canary Islands which is expected to be the world's largest when it begins operations in the mid-2020s. These pre-commercial and commercial-scale projects should help to establish more firmly the costs of floating foundations. Similar undertakings are under assessment for offshore substations. Both will be critical to the success and deployment of offshore wind projects in deep waters.

Offshore wind costs for projects commissioned in 2018

For offshore wind projects completed in 2018, the global average capital cost was $4 353 per kilowatt (kW), and the average expected capacity factor was 43% (IRENA, 2019). Applying an 8% weighted average cost of capital (WACC) in advanced economies and 7% WACC in developing economies, the global average LCOE for offshore wind in 2018 fell below $140 per megawatt-hour (MWh) (Figure 7).[5] Recent auction results point to rapidly falling costs for offshore wind (Box 2). Nearly half of the LCOE for completed projects is directly attributable to the capital investment needed for offshore wind projects, including the costs of the turbine, foundation, internal cabling, substation and offshore transmission assets. The remaining half is attributable to the project financing cost, reflecting the high capital-intensity of offshore wind projects.

Figure 7 ▹ Offshore wind indicative shares of capital costs by component and levelised cost of electricity for projects completed in 2018



Offshore wind generation costs are heavily influenced by the cost of capital and were about $100/MWh for projects completed in 2018 based on low financing costs

Notes: WACC = weighted average cost of capital; Transmission includes offshore substations.

Source: IEA analysis based on IRENA (2019), IJGlobal (2019) and BNEF (2019).

Improved financing terms would significantly reduce the LCOE of offshore wind, as it would the cost of other capital-intensive technologies. For example, applying a 4% WACC to 2018 costs and performance parameters yields an offshore wind LCOE of about $100/MWh, which is 30% less than the LCOE derived from the standard WACC. The sensitivity of the calculated LCOE to the cost of capital is also shown for projected costs in the section "Offshore wind costs, value and competitiveness".

[5] Standard assumptions are applied to all power generation technologies in the *World Energy Outlook* to represent the required return in the face of market conditions and investment risk. Operation and maintenance (O&M) costs below $100/kW per year and a 25-year economic lifespan are also assumed.

Offshore wind turbines constitute around 30-40% of total upfront capital costs. In an effort to improve the economics of this critical component, projects are getting larger, increasing the numbers of wind turbines to be delivered and enabling economies of scale, while at the same time equipment suppliers are using lighter and more resilient materials such as glass and carbon fibres for blade and nacelles[6] manufacturing, as well as improving aerodynamics. Increasing the size of turbines is also having the effect of reducing the number of foundation positions and inter-array cabling, which is reducing installation and operation and maintenance costs.

Offshore transmission, array cabling (internal wiring at a wind farm) and the offshore substation make up some 20-30% of total upfront capital costs. The costs for offshore transmission assets, in particular, are closely tied to the regional regulations for connecting the project to the onshore grid (see section "Onshore grid development").

Foundations account for nearly a quarter of total project costs. Monopile structures are currently the preferred technology, underpinning around 80% of deployment (WindEurope, 2019). It is becoming possible to use this type of foundation in increasingly deep water – up to 55-60 m in some cases – thus reducing the need for more expensive jacket foundations, which are suited to deeper water and are the second most used technology globally.

Box 2 ▹ Rapid cost reductions are on the horizon for offshore wind

Recent strike prices in Europe for offshore wind indicate significant cost reductions on the horizon (Figure 8). Some strike prices are at the level of wholesale electricity prices, though these are often underpinned by power purchase agreements. Exposure to wholesale prices increases market risks that can lead to higher financing costs, but competition can help drive down project costs.

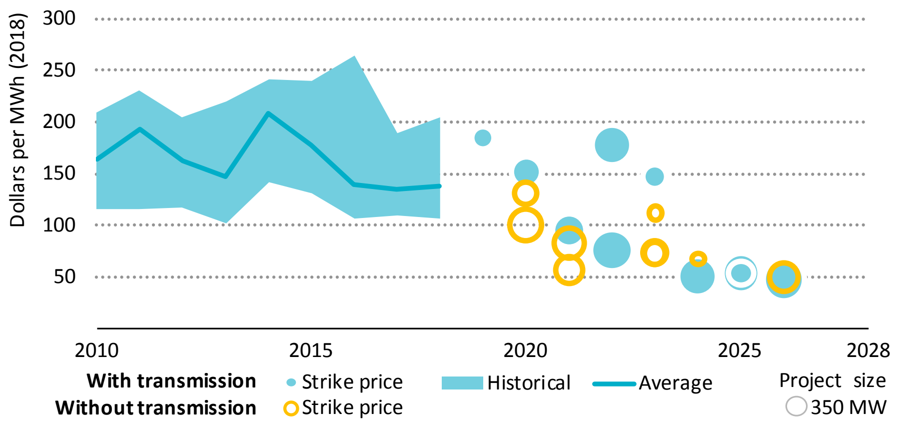
The allocation of transmission costs between developer and system operator is a key factor in auction awards. Strike prices where the developer does not need to bear the cost of the grid connection to shore have generally been lower. For example, the Dunkirk project in France was awarded to EDF at $50/MWh (EUR 44/MWh) but excluded the offshore transmission asset. Some recent auctions which exclude the cost of the offshore transmission assets have not involved subsidies, including Hollandse Kust Zuid I and II and Hollandse Kust Zuid III and IV in the Netherlands, and He Dreiht, Borkum Riffgrund West 1 and 2, and OWP West in Germany.

Including the offshore transmission assets within the scope of the auctions does, however, bring competitive pressure to reduce the cost of the transmission asset and therefore could lead to lower overall prices in the future. This has been reflected in the recently awarded auctions in United Kingdom's Dogger Bank wind farm, where Scottish and Southern Energy and Equinor have joint efforts to develop 3.6 GW of total capacity. The inclusion of transmission assets under the scope of developers, but also moving

[6] Nacelle is the cover that houses all generating components of a wind turbine.

into deeper waters and consequently tapping into better resources, have been major drivers in bringing strike prices down to almost $50/MWh, on average. Ultimately, the responsibility to deliver these projects rest in the hands of offshore wind developers, and recent market signals indicate growing confidence from investors. This sets the stage for low-cost financing and for an increasing pipeline of future projects.

Figure 8 ▹ Historical LCOE of offshore wind and strike prices in recent auctions in Europe



With transmission		
Project	**Strike price ($/MWh)**	**Expected COD**
United Kingdom		
Beatrice	185	2019
East Anglia 1	152	2020
Triton Knoll	95	2021
Moray East	73	2022
Hornsea 1	178	2022
Hornsea 2	76	2022
Neart na Gaoithe	148	2023
Cr. Beck A Dogger Bank	51	2024
Cr. Beck B Dogger Bank	54	2025
Dogger Bank Teeside A	54	2025
Seagreen	54	2025
Sofia	47	2026

Without transmission		
Project	**Strike price ($/MWh)**	**Expected COD**
Germany		
Baltic Eagle	74	2023
Gode wind 3	68	2024
Gode wind 4	112	2023
Netherlands		
Borssele I/II	83	2020
Borssele III/IV	62	2021
Denmark		
Horns Rev 3	118	2020
Kriegers Flak	57	2021
Vesterhav Nord/Syd	73	2023
France		
Dunkirk	50	2026

Recent auctions in Europe set the stage for a fall in costs for new projects as the industry moves to deploy higher capacity turbines

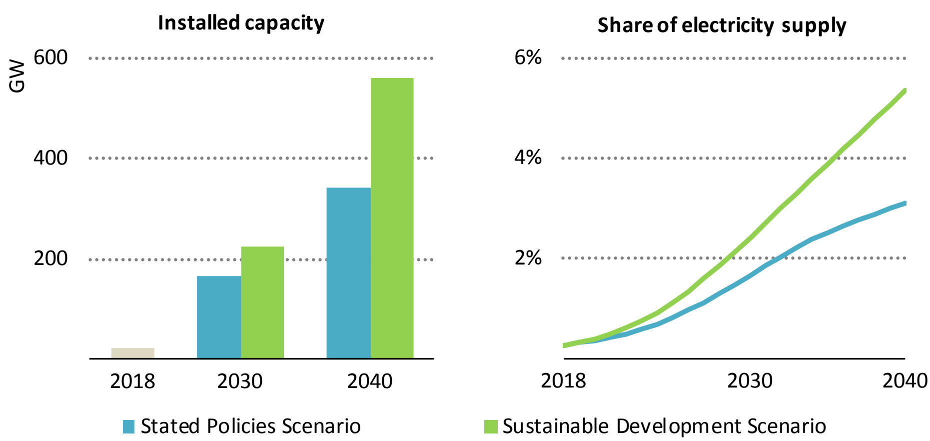
Notes: COD = commercial operation date; LCOE = levelised cost of electricity. Historical values correspond to LCOEs including transmission. Strike prices are included for projects of over 100 MW.
Source: IEA analysis based on IRENA (2019).

Offshore wind outlook to 2040

Global outlook

The global offshore wind market is set to expand significantly over the next two decades, growing by 13% per year in the Stated Policies Scenario and faster still in the Sustainable Development Scenario. Bolstered by policy targets and falling technology costs in the Stated Policies Scenario, global offshore wind capacity is set to increase fifteen-fold from 2018 to 2040 (Figure 9). Annual offshore wind capacity additions are set to double over the next five years and increase almost fivefold by 2030 to over 20 GW per year. Beyond 2030 the cost competitiveness of offshore wind helps to maintain the pace of growth. Additional supportive policy frameworks, including designated auction schemes, drive further growth in the Sustainable Development Scenario. In this scenario, global offshore wind capacity rises to about 560 GW by 2040, a 65% increase over the Stated Policies Scenario, as part of accelerated efforts to decarbonise electricity supply. Annual capacity additions approach 30 GW by 2030 and reach 40 GW in 2040.

Figure 9 ▻ Projected global offshore wind capacity and share of electricity supply by scenario

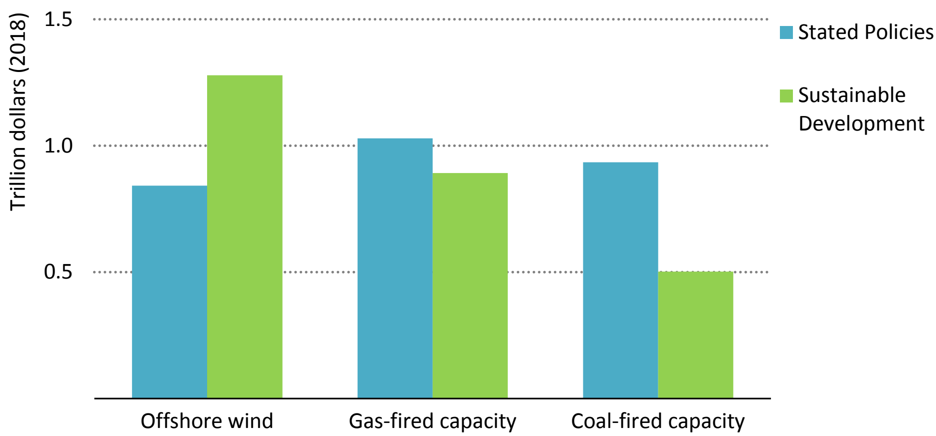


Global offshore wind installed capacity increases by fifteen-fold in the Stated Policies Scenario, raising its share of electricity supply to 3% in 2040

As the global offshore wind market expands, so does its role in supplying electricity around the world. In the Stated Policies Scenario, offshore wind accounts for 3% of global electricity supply by 2040. In the Sustainable Development Scenario, its share of global electricity supply rises to 5%.

In the Stated Policies Scenario, cumulative investment in offshore wind is about $840 billion from 2019 to 2040. Annual investment in the offshore wind power sector averages $38 billion, double the level in 2018 (Figure 10). This level of investment means that offshore wind accounts for 10% of investment in renewables-based power plants globally over the next two decades, roughly the same share as the total of bioenergy, concentrating solar power, geothermal and marine energy. Across the power sector more broadly, offshore wind captures almost 8% of all power plant investment, rivalling the share that goes to natural gas or to nuclear power over the period.

Figure 10 ▷ Cumulative capital spending on offshore wind, gas- and coal-fired capacity worldwide by scenario, 2019-2040



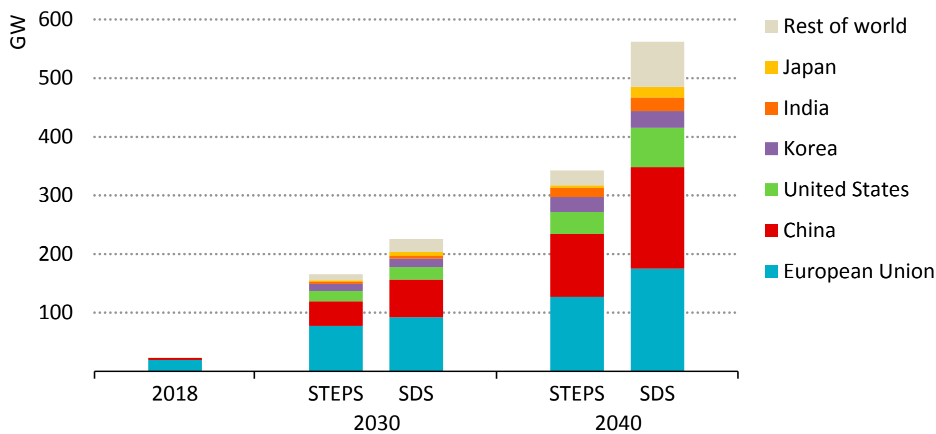
Offshore wind is set to become a $1 trillion industry over the next two decades, matching capital spending on gas- and coal-fired capacity to 2040

In the Sustainable Development Scenario, cumulative spending in the offshore wind sector rises by half to $1.3 trillion between 2019 and 2040 relative to the Stated Policies Scenario. This equates to roughly $60 billion of annual investment per year on average. This means more investment goes to offshore wind than to coal, gas or new nuclear power to 2040. Higher aggregate spending on other renewables during this period means that offshore wind attracts a similar share of total investment in renewables as in the Stated Policies Scenario (about 10%).

Regional outlook

In the Stated Policies Scenario, offshore wind growth is concentrated in six regions, reflecting policy ambitions, available wind resources and the improving economics of offshore wind. Europe and China lead the offshore wind market with over 70% by 2040 of installed capacity, while there is significant expansion in the United States, Korea, India and Japan, which between them capture about one-quarter of the global market (Figure 11).

Figure 11 ▷ Installed capacity of offshore wind by region and scenario



European Union and China account for 70% of the global offshore wind market to 2040, but a number of countries enter the market and increase their capacity

As of mid-2019, many regions have adopted policy targets for offshore wind to 2030 (Table 3). The European Union has the strongest ambitions to 2030, with targets in individual member states totalling 65-85 GW by 2030. China's Five-Year plans are encouraging provinces to expand their construction capacities for offshore wind to 2020, while state-level targets set the course for rapid growth in the United States. India, Korea and Chinese Taipei also have ambitious targets, while other countries, including Japan and Canada, are laying the groundwork for future offshore wind development.

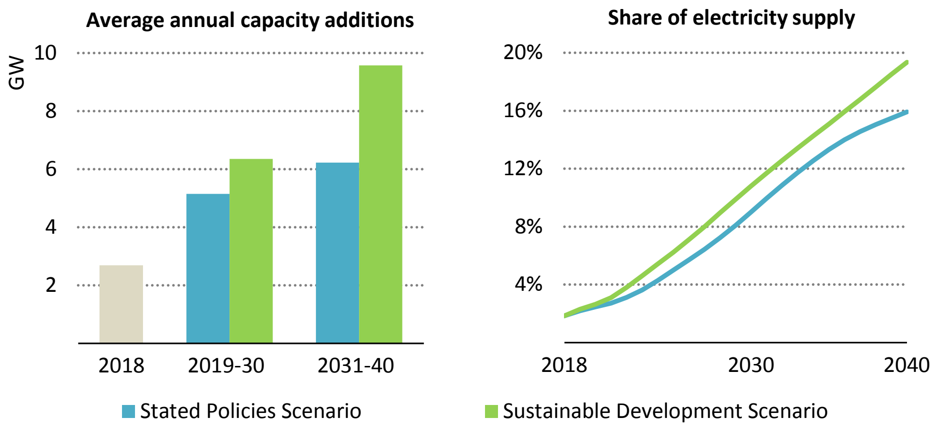
Table 3 ▷ Policies targeting at least 10 GW of offshore wind by 2030

Region/country	Policy target
European Union	65-85 GW by 2030
China	5 GW by 2020 (10 GW construction capacity)
United States	22 GW by 2030
India	5 GW by 2022 and 30 GW by 2030
Chinese Taipei	5.5 GW by 2025 and 10 GW by 2030
Korea	12 GW by 2030

European Union continues to be the leader in offshore wind

Offshore wind is set for robust growth in the European Union (EU) over the next two decades. In the Stated Policies Scenario, the European Union accounts for nearly 40% of the global offshore market by 2040, increasing installed capacity to almost 130 GW by 2040. Annual investment in the offshore power sector increases from $11 billion in 2018 to an average of $17 billion per year over the outlook period. Offshore wind also plays an important role in meeting new electricity demand: output from new offshore wind projects far outpaces overall electricity demand growth to 2040, and offshore wind provides more than one-in-six kilowatt-hours generated within the European Union in 2040 (Figure 12).

Figure 12 ▹ Outlook for offshore wind in the European Union, 2018-2040



In the European Union, offshore wind is set to play a central role and has the potential to become the largest source of electricity supply, matching onshore wind

In the Sustainable Development Scenario, the European Union's offshore installed capacity increases by almost 40% relative to the Stated Policies Scenario, reaching 175 GW by 2040. Cumulative investment in offshore wind reaches $500 billion over the projection period, or $23 billion per year. Together with other renewables, nuclear power and carbon capture, utilisation and storage, offshore wind lifts the low-carbon share of generation above 90% in the European Union in 2040. Offshore wind accounts for one-fifth of electricity supply in 2040 and rivals onshore wind as the largest source of electricity in the European Union, exceeding nuclear power.

Member states have made various commitments that underpin the future development of offshore wind in the European Union (Table 4).[7] These targets are under regular review as offshore wind technology matures. The United Kingdom is set to be the leading EU offshore wind market to 2030, followed by Germany and the Netherlands. France, Poland and Ireland are also committed to develop offshore wind capacity.

The offshore wind industry is looking to develop 180 GW of offshore wind in the North Sea by 2050 (NSWPH, 2019). The 2016 North Seas Energy Cooperation agreement brought together a number of European countries with the aim of improving conditions for the development of offshore wind in the North Sea. It prioritises four main work areas:

[7] This includes countries such as Estonia, Belgium, Denmark, United Kingdom, Germany, Netherlands, France, Finland, Greece, Ireland, Latvia, and Poland, which have made technology-specific targets or permitting timelines for offshore wind technology.

maritime spatial planning; development and regulation of offshore grids; finance for offshore wind projects; and standards, technical rules and regulations for offshore wind. Alternative pathways to achieving a net-zero emissions economy may include significantly higher electricity demand due to demand for hydrogen or other fuels (see section "Increased demand for renewable hydrogen") and expanded opportunities for offshore wind development, as seen in scenarios developed in support of the European Union's long-term strategy that include 240-450 GW of offshore wind in 2050 (European Commission, 2018).

Table 4 ▹ Policy targets for offshore wind in the European Union

Country	Policy	Capacity target	Year set
United Kingdom	UK Offshore Sector Deal	Up to 30 GW by 2030	2019
Germany	The Renewable Energies Act	15-20 GW by 2030	2017
Netherlands	The Offshore Wind Energy Roadmap	11.5 GW by 2030	2017
Denmark	Energy Agreement	5.3 GW by 2030	2019
Poland	Draft National Energy and Climate Plan	Up to 5 GW by 2030	2018
France	Multi-Annual Energy Plan	4.7-5.2 GW by 2028	2019
Belgium	Draft National Energy and Climate Plan	4 GW by 2030	2019
Ireland	Climate Action Plan 2019	3.5 GW by 2030	2019
Italy	Draft National Energy and Climate Plan	0.9 GW by 2030	2018

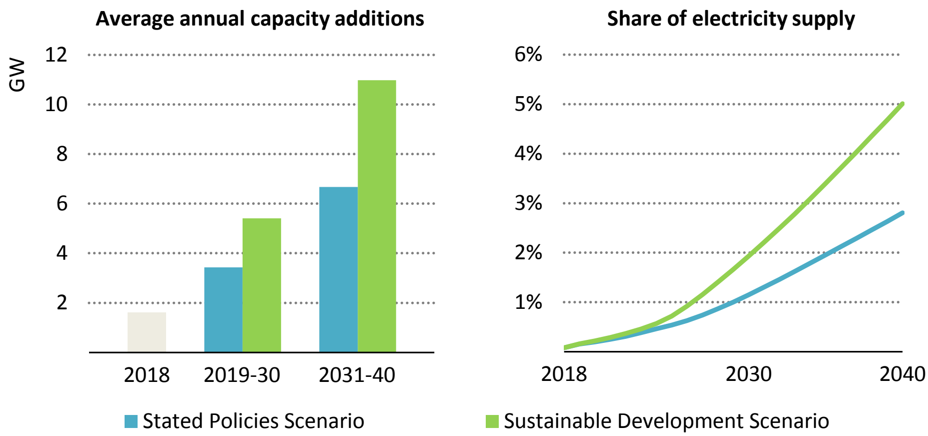
China moves strongly ahead with offshore wind

China has already undertaken a number of offshore wind projects and is set to play a central role in the long-term growth of offshore wind, alongside the European Union. In the Stated Policies Scenario, China has the largest offshore wind fleet of any country around 2025, surpassing the United Kingdom. Offshore wind capacity additions steadily increase throughout the period of the outlook, averaging more than 6 GW per year after 2030 (Figure 13). Average annual investment in the offshore wind likewise rises from $6 billion in 2018 to $9 billion per year from 2019 to 2040, accounting for nearly one-quarter of global investment in offshore wind over the period.

In the Sustainable Development Scenario, China reaches almost 175 GW of installed capacity by 2040, matching the size of the offshore wind fleet in the European Union. Annual investment increases to $13 billion on average between 2019 and 2040, meaning that 8% of total power plant investment in China is allocated to offshore wind.

Improving economics and firm policy support guide China's ambitions for the offshore wind sector. The country's 13th Five-Year Plan calls for 5 GW of capacity to be installed by 2020 and for 10 GW more to be in the construction pipeline, split among the coastal provinces so as to help develop local supply chains (Table 5). The National Development and Reform Commission (NDRC) recently adopted a competitive bidding scheme for offshore wind capacity in an effort to drive down costs (NDRC, 2019). Around 2030, offshore wind reaches cost parity with coal-fired generation in LCOE terms, a critical milestone that supports continued long-term growth in China. In the Sustainable Development Scenario, CO_2 pricing helps offshore wind reach cost parity with coal-fired power plants in the mid-2020s, and this leads to accelerating average capacity additions of over 10 GW per year after 2030.

Figure 13 ▷ Outlook for offshore wind in China, 2018-2040



China builds as much offshore wind capacity as the European Union over the next two decades, with its growth complementing other low-carbon sources

Table 5 ▷ Offshore wind targets by province in China's 13th Five-Year Plan

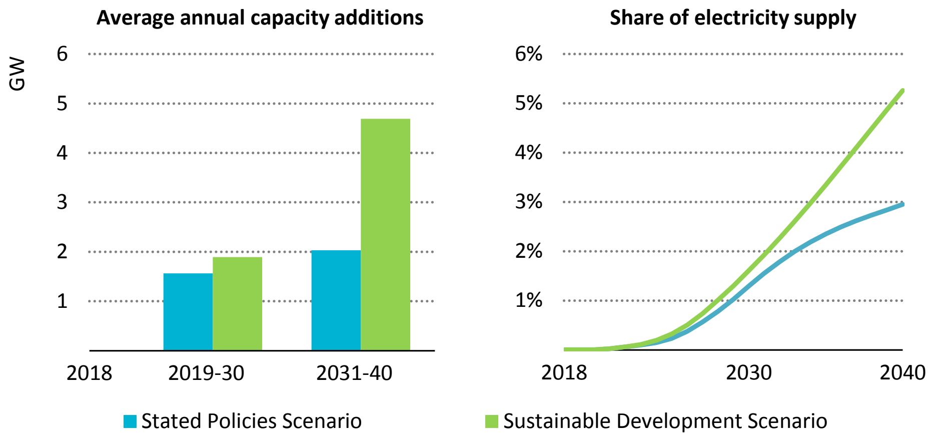
Province	Grid-connected by 2020 (MW)	Total construction pipeline by 2020 (MW)
Tianjin	100	200
Liaoning	-	100
Hebei	-	500
Jiangsu	3 000	4 500
Zhejiang	300	1 000
Shanghai	300	400
Fujian	900	2000
Guangdong	300	1 000

Source: China National Development and Reform Commission (2016).

United States

Offshore wind gains significant ground in the United States over the next two decades. In the Stated Policies Scenario, the United States adds nearly 40 GW of offshore wind capacity by 2040, with related investment totalling $100 billion over the period. In the Sustainable Development Scenario, the United States increases its offshore wind capacity by 80%, reaching nearly 70 GW by 2040. This pace of growth calls for average investment of over $7 billion per year. Offshore wind provides over 5% of the US electricity supply in 2040, compared with the 3% level reached in the Stated Policies Scenario (Figure 14).

Figure 14 ▷ Outlook for offshore wind in the United States, 2018-2040



Offshore wind is set to gain traction in the United States after more than a decade of false starts, reaching 3% of generation in the Stated Policies Scenario

Note: No offshore wind capacity was completed in 2018 in the United States.

Table 6 ▷ Offshore wind targets and support policies in the United States

State/Jurisdiction	Policy	Target, awards or incentives	Year
New York	Climate Leadership and Protection Act	9 GW installed by 2035	2019
Massachusetts	Act to Advance Clean Energy, Act to Promote Energy Diversity	3.2 GW installed by 2035	2016
New Jersey	Offshore Wind Economic Development Act	3.5 GW installed by 2030	2018
Connecticut	Act Concerning the Procurement of Energy Derived from Offshore Wind	2 GW installed by 2030	2019
Virginia	Virginia Energy Plan	2 GW installed by 2028	2018
Maryland	Clean Energy Jobs Act	1.2 GW installed by 2030	2019
Rhode Island	’20 Clean Energy Goal	1 GW by 2025	2019
US Federal	Production tax credit (PTC)	$0.009-0.023/kWh*	1992
US Federal	Investment tax credit (ITC)	12-18%**	2002

* The exact value of the PTC for wind facilities depends on the year of construction. ** The ITC applies to projects starting construction before 2020.

A combination of federal incentives and state-level targets support the strong growth of offshore wind in the United States. The US Bureau of Ocean and Energy Management has tendered over 15 licences for offshore wind development along the east coast that are capable of supporting 21 GW of offshore capacity.[8] There have also been proposals in the US Congress to extend the tax credits available to offshore wind developers. Individual states are also setting offshore wind capacity targets totalling over 20 GW by 2035 (Table 6). In a nod to the important role of offshore wind in achieving its ambitious decarbonisation targets, New York revised its offshore wind target upwards from 2.4 GW to 9 GW by 2030. The technology could also play an important role in California's decarbonisation plan, but the state has not specified a capacity target for offshore wind.

Emerging markets

Offshore wind is set to establish itself in a number of new markets in the Asia Pacific region, outside of China. In the Stated Policies Scenario, countries including Korea, India and Japan account for close to 60 GW of offshore wind capacity by 2040. They account for one-sixth of cumulative global investment in offshore wind, equating to over $6 billion in average annual investment over the outlook period. In the Sustainable Development Scenario, markets in the Asia Pacific region excluding China have average annual investment of close to $10 billion over the period to 2040.

Korea becomes the largest market for offshore wind outside the European Union, China and the United States, reaching 25 GW of capacity by 2040 in the Stated Policies Scenario. Ambitious policy targets in Korea set under its Renewable Energy Plan 3020 mean that offshore wind provides more than 10% of the country's electricity by 2040, complementing 16% of electricity generation from solar PV and onshore wind. In terms of generation costs, the LCOE of offshore wind reaches parity with onshore wind and solar PV in the 2030s.

Offshore wind development also makes notable progress in India, but faces stiff competition from low-cost solar PV and onshore wind. India has set ambitious targets for offshore wind by 2030 and is expected to tender its first 1 GW wind farm in late 2019. Installed capacity reaches 16 GW by 2040 in the Stated Policies Scenario, generating more electricity than solar PV in India does today. This installed capacity increases by an additional 40% in the Sustainable Development Scenario to 23 GW by 2040, requiring approximately $2 billion in average annual investment.

Although Japan has not yet set a firm target for offshore wind by 2030, recent legislation established eleven promotion zones in five prefectures, with competitive auctions to support offshore wind deployment. In the Stated Policies Scenario, Japan has 4 GW of installed capacity by 2040. In the Sustainable Development Scenario, the total reaches 18 GW, providing nearly 7% of the country's electricity in 2040. While most of Japan's current project pipeline uses fixed-bottom type turbines, there are relatively few shallow areas available offshore, and this means that more ambitious deployment of offshore wind is likely to be tied to the successful development of floating turbines. Japan has a series of experimental floating wind farms in place.

[8] Number of licenses as of mid-2019.

A number of other countries outside Asia are now actively appraising their offshore wind resources. Much of this development hinges upon sustained political support and the development of local supply chains. Chinese Taipei has set offshore wind targets for 2025, while a number of countries with significant offshore potential, including Brazil, South Africa, Sri Lanka and Viet Nam, have expressed interest in the World Bank's offshore wind emerging markets fund. This programme provides upwards of $5 million in funding for offshore wind research and supply chain development (World Bank, 2019).

Offshore wind costs, value and competitiveness

The long-term prospects for offshore wind depend to a large extent on how competitive it is with other sources of electricity. This section considers the evolution of the cost components of offshore wind, ultimately expressed through the LCOE, the system value of offshore wind, and its competitiveness based on the value-adjusted LCOE metric.

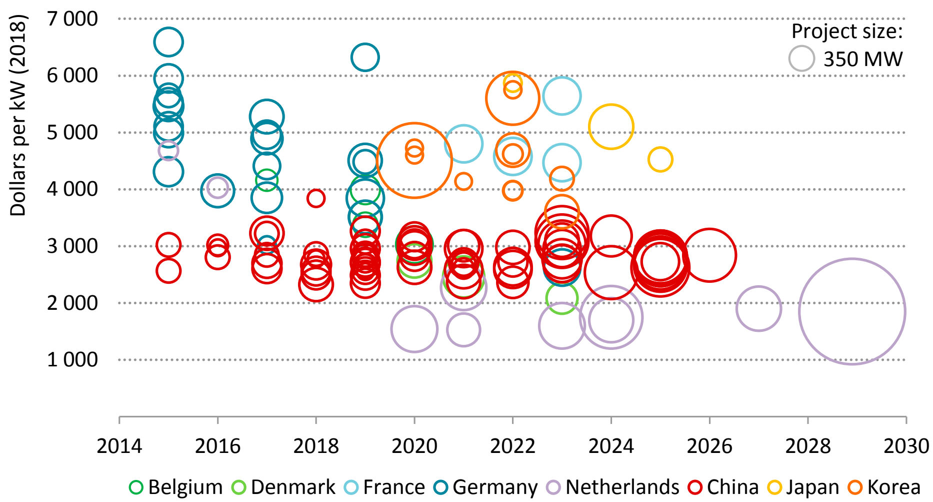
Capital costs

The development of offshore wind is gathering momentum. The technology is in a dynamic stage, and developers are working to bring down costs in established and new markets with support from governments and regulators. Project-level upfront capital costs will continue to depend on the choice of site, and on the inevitable trade-offs between distance from shore, water depth and quality of the resource.

The evolution of capital costs for power generation technologies is heavily influenced by whether there is a sufficient pipeline of projects to create the necessary momentum for a technology to develop. Global average upfront capital costs for offshore wind (including transmission) are projected to decline to below $2 500/kW by 2030, more than 40% below today's average. This is based on the assumed learning rate that sees capital costs decline by 15% each time global capacity doubles. By 2040, global average offshore wind costs are projected to fall to $1 900/kW. Increased deployment enables industry learning about offshore wind project development and management, as well as providing opportunities to establish efficient supply chains. Wind farm operators are learning how to push costs down, and equipment manufacturers are learning how to bring bigger and more efficient components to the market.

Excluding transmission costs, the global upfront capital costs of offshore wind projects averaged some $3 300/kW in 2018 and are projected to decline to $1 500/kW in 2030 and under $1 000/kW in 2040 with the level of deployment in the Stated Policies Scenario. This would mean that in 2040, transmission capital costs would be on a similar level as the offshore wind farm. However, individual project costs varied widely reflecting project specifics and regional particularities (Figure 15). The availability of sites in relatively shallow waters is a critical determinant of project costs, as it is the case of the Netherlands, where projects to be commissioned in the first-half of the next decade are at the lower end of the global cost range (PBL, 2019). Capital costs are also likely to be lower in places where there are enough projects of sufficient size to achieve economies of scale, as in China.

Figure 15 ▹ Capital costs of offshore wind projects excluding transmission, historical and projects in development



Continued industry learning propels offshore wind down the cost curve, and cost reductions can be enhanced through policy frameworks that support a healthy project pipeline

Note: Capital costs refer to the year of commissioning.

Sources: IEA analysis based on IJGlobal (2019), BNEF (2019) and company reports.

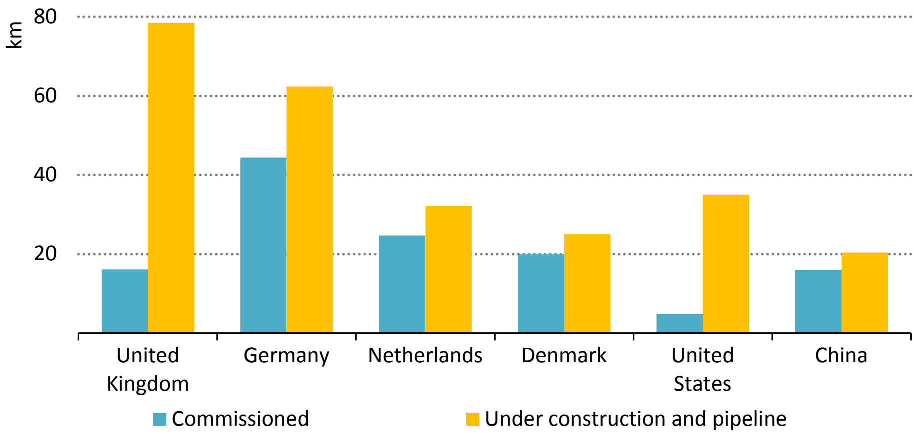
In Europe, the largest offshore wind market in terms of installed capacity, measures that harness competitive forces such as auctions are putting downward pressure on costs and generally making cost information more transparent. Continued policy support and long-term design improvements in the clustering of offshore wind farms are also helping with cost reductions. Excluding transmission costs, upfront capital costs for offshore wind farms in Europe were around $4 000/kW in 2018, though the project pipeline points to rapidly falling costs in the near term. Average offshore wind costs are projected to decline to below $2 000/kW in 2030 without transmission costs, and to about $1 500/kW in 2040.

In China, the first commissioned offshore wind projects were relatively close to shore – the average distance was less than 20 km (The Wind Power, 2019). This helped to keep total upfront capital costs (including transmission) below $2 800/kW in 2018. China is likely to see a range of project-level costs for some time as new projects adapt to specific site conditions. In the Stated Policies Scenario, capacity additions of 100 GW in China over the period to 2040 help drive down total upfront capital costs of offshore wind by nearly half.

Offshore transmission costs

There is a trend towards locating offshore wind farms further from shore. This highlights the importance of developing more advanced connection technologies and establishing appropriate regulations to govern the connection arrangements (Figure 16).

Figure 16 ⊳ Offshore wind: average distance from shore by country



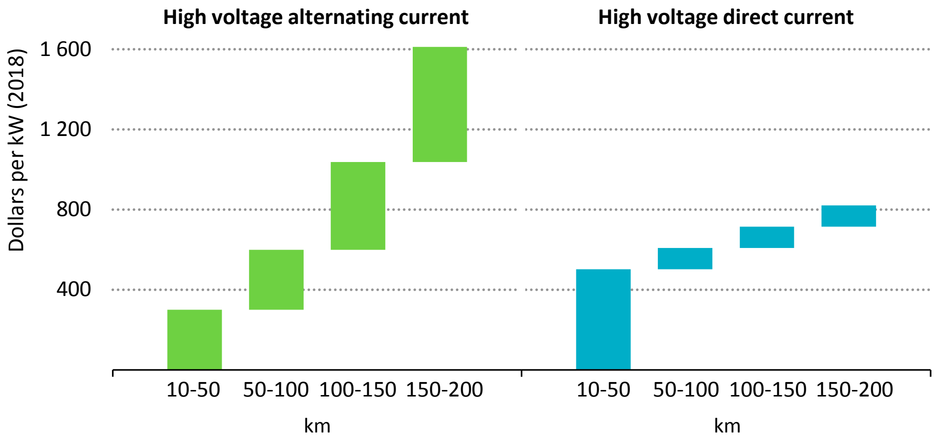
Offshore wind farms have been moving into deeper waters, amid a trend of increasing project sizes, that have impacted offshore transmission design as well as foundations

Sources: IEA analysis based on The Wind Power (2019) and BNEF (2019).

Large offshore wind farms that are more than 10 km from shore are usually attached to an offshore substation that is connected to an onshore substation. There are two main technologies behind offshore connections: alternating current (AC) systems that transport electricity directly through AC cables; and direct current (DC) systems where the current is converted from AC to DC in converter stations and back to AC in the onshore substation before the electricity is supplied to a grid. Even without considering the cost of substations, AC transmission has a cost advantage over short distances, but over longer distances high-voltage DC (HVDC) transmission can offer significant cost savings (Figure 17).

To date, offshore wind farms have been mostly connected to shore by radial offshore transmission assets, which imply one transmission line connecting one offshore wind farm, and the offshore transmission assets being viewed as part of the wind farm. However, where there are conflicts of use or spatial planning requirements, offshore wind farms can be designed as clusters in which several projects are connected to what is defined as an offshore "hub-and-spoke" with the aim of avoiding the impact that building several offshore transmission assets would have, while also reducing costs. That is the case with the North Sea Wind Power Hub, where Tennet together with Energinet.dk, Gasunie and the Port of Rotterdam are shaping a power hub in the North Sea. Tennet, the national transmission system operator in the Netherlands, has been playing a leading role since the installation of Borwin1. This was the first HVDC connection commissioned in Germany in 2010, with a capacity of 400 MW and 125 km offshore. Today, the longest offshore cable is located in Germany and spans 160 km, while the largest capacity of an offshore cable supports 916 MW.

Figure 17 ▹ Indicative upfront capital cost for high-voltage transmission cables by type and distance from shore



With increased distances from shore, offshore wind farms require new transmission connection technologies and regulation models to bring project costs down

Note: Installation costs for transmission cables vary based on site conditions.

Sources: IEA analysis; Xiang et al. (2016); DIW ECON (2019).

The responsibility for designing, installing and maintaining offshore transmission assets is defined by regulation, and can rest with the transmission system operator (TSO), government or project developer. This differs from arrangements for onshore wind, where transmission line liabilities are nearly always the responsibility of TSOs.

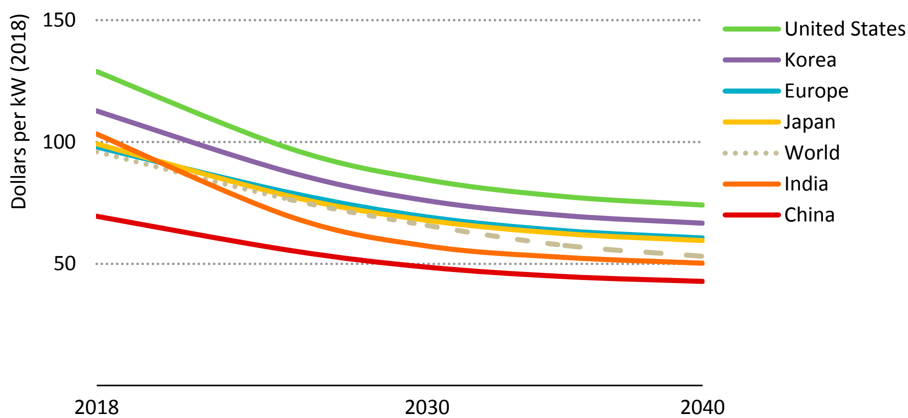
There are several models for developing offshore wind transmission in Europe. In the United Kingdom, licences for offshore transmission assets are granted through competitive auctions where offshore wind farm developers can also be in charge of building the transmission asset and then transfer it to the TSO or to a competitively appointed offshore transmission owner for operation. In other European markets such as Germany, Netherlands, France and Denmark, it is currently the system operator that provides the offshore grid connection (and in some cases the offshore substation), although Denmark has announced its intention to bring responsibility for developing offshore transmission assets into its competitive bidding framework.

There is not a one-size-fits-all solution that could guarantee the perfect regulatory framework to manage offshore transmission assets. TSOs may be able to achieve better co-ordination and standardisation of projects when the transmission connections fall under their scope. Equally it could be argued that including offshore transmission assets in auction schemes harnesses competitive market forces and could lower infrastructure costs (DIW ECON, 2019). Market transparency and long-term planning should be at the heart of whatever approach is taken, together with the need to support the development of offshore wind (Box 4).

Operation and maintenance costs

In much the same way as capital costs, operation and maintenance (O&M) costs are going through a phase of major development and improvement that is leading to cost reductions. Global average O&M costs for offshore wind stood at about $90/kW in 2018, and are projected to go down by one-third by 2030, before declining towards $50/kW in 2040. Regions, such as China, where offshore wind markets are more developed show lower costs for O&M than others (Figure 18).

Figure 18 ▹ Regional average annual O&M costs for new projects



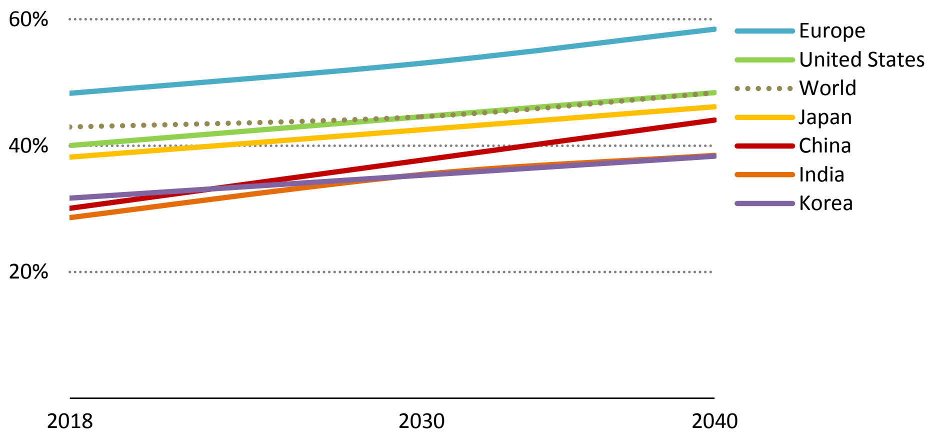
Economies of scale and industry synergies, along with digitalisation and technology development will bring current costs for O&M down by 40% in 2040

Digitalisation is bringing new techniques for monitoring that proactively identify failures not only in the turbines but also in structures and connections, helping to reduce costs. For example, the use of drones for visual inspections can enable preventative maintenance and cuts down on the need for labour-intensive inspections, along with speeding up maintenance work. In addition, synergies with the oil and gas industry have allowed offshore wind projects to draw on that industry's expertise in offshore structures in planning and carrying out maintenance activities (see section "Synergies with oil and gas activities"). The result of these improvements can help prolong the expected lifetime of projects, improving their economics and reducing the LCOE for offshore wind.

Capacity factors

As set out in the section "Offshore wind technology and performance", offshore wind technology advancements are helping to improve performance. The size of turbines has increased and most current projects under construction in Europe involve the installation of 8-10 MW models (WindEurope, 2019). Larger turbines are able to raise wind farm electricity production by reaching a wider range of wind speeds, ultimately generating more electricity. Offshore wind farms are moving further from shore, where wind speeds tend to be higher – the maximum distance reached 90 km in recent years while distances rarely exceeded 20 km before 2006 (IRENA, 2019).

Figure 19 ▷ Regional average annual capacity factors for new projects



Technology advances including bigger turbine sizes and operation in areas with high quality wind resources will boost offshore wind performance in the years ahead

Sources: IEA analysis based on IRENA (2019).

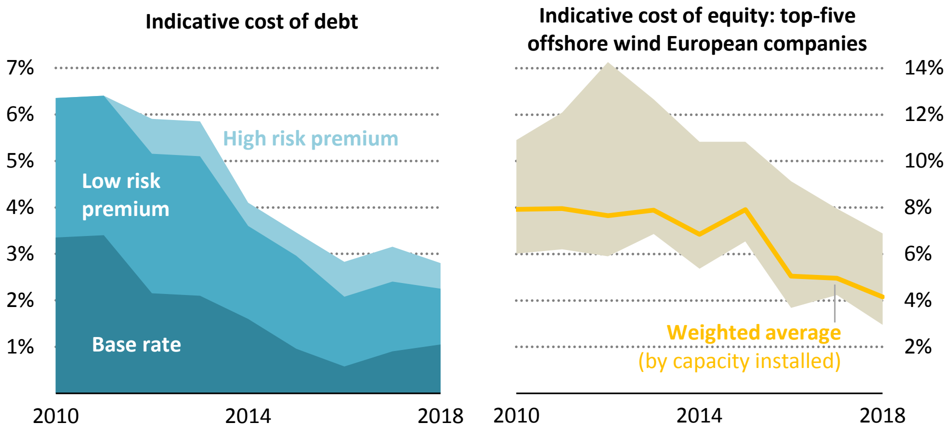
The ability to make use of higher quality wind resources by moving into deeper waters further from the shore has helped capacity factors reach 43% (after wake losses) for projects commissioned in 2018. Global average capacity factors are expected to increase by five percentage points by 2040 (Figure 19). Capacity factors move towards 60% in Europe by 2040 as a consequence of high quality resources and technology development. In China, new projects reach 45% annual capacity factors in 2040. Korea and India have lower quality wind resources overall, but new offshore wind projects are still expected to see capacity factors near 40%.

Cost of financing

Global investment in offshore wind totalled around $20 billion in 2018. Improved market maturity, underpinned by policies, regulations and the early involvement of public finance players, has facilitated lower cost financing over time from a diverse set of actors. Project finance – a financing model that requires a high degree of co-ordination and risk allocation among developers, banks and other actors – now represents the largest source of new asset financing. This suggests improved investor confidence in offshore wind developments and a greater degree of project standardisation than a few years ago, when most finance came from the balance sheets of developers and government-backed sources.

Commercial banks have increased their financing of offshore wind projects, a reflection of both the stable policy frameworks put in place in a number of countries and the successful track record of well-known investors involved in providing backing for early projects. The participation of public finance institutions such as the European Investment Bank, EKF in Denmark and KfW development bank in Germany has been instrumental in helping to manage risk and attract private capital, but their involvement has declined as the market achieved higher degrees of scale and as an array of private sector investors entered the market (IEA, 2018a). At the same time, there is a growing market for refinancing, whether by banks or through the capital markets, as well as for asset acquisitions on the part of institutional investors and pension funds.

Figure 20 ▷ Offshore wind: indicative nominal cost of debt in Europe (left) **and LCOE sensitivity analysis to cost component changes** (right)



Offshore wind in Europe has benefited from low interest rates and debt risk premiums, allowing developers to decrease project WACCs, the largest component of LCOE

Note: WACC = weighted average cost of capital; LCOE = levelised cost of electricity.

Sources: IEA analysis based on Bloomberg (2019) and company reports.

Debt financing terms continue to improve for projects in Europe. Project leverage has increased – the debt-to-equity ratios for projects achieving financial close averaged 75% in 2018, compared with 60% a decade earlier – which indicates that commercial banks are now more comfortable with offshore wind projects. Borrowing has been eased by low interest rates and lower debt risk premiums: loans are currently priced at 120 to 175 basis points above base rates (Figure 20) and maturities have typically increased to around 15-18 years (Green Giraffe, 2019). Nevertheless, these terms are most common for projects benefiting from long-term power purchase agreements awarded via government schemes or through contracting with a corporate off-taker: the bankability of projects relying on a high degree of revenue from wholesale markets remains less certain.

On the other side of the equation, the cost of equity has evolved in the same kind of way, with lower perceived risks from investing in offshore wind assets being underpinned by supportive policies. This has led to the cost of equity nearly halving over the last decade for companies operating in the most mature markets. The combination of lower financing costs and higher debt-to-equity ratios has directly shaped the potential WACCs that offshore wind farms have been able to achieve in recent auctions, and has led to some recent auctions being able to take place without any government subsidies.

Levelised cost of electricity

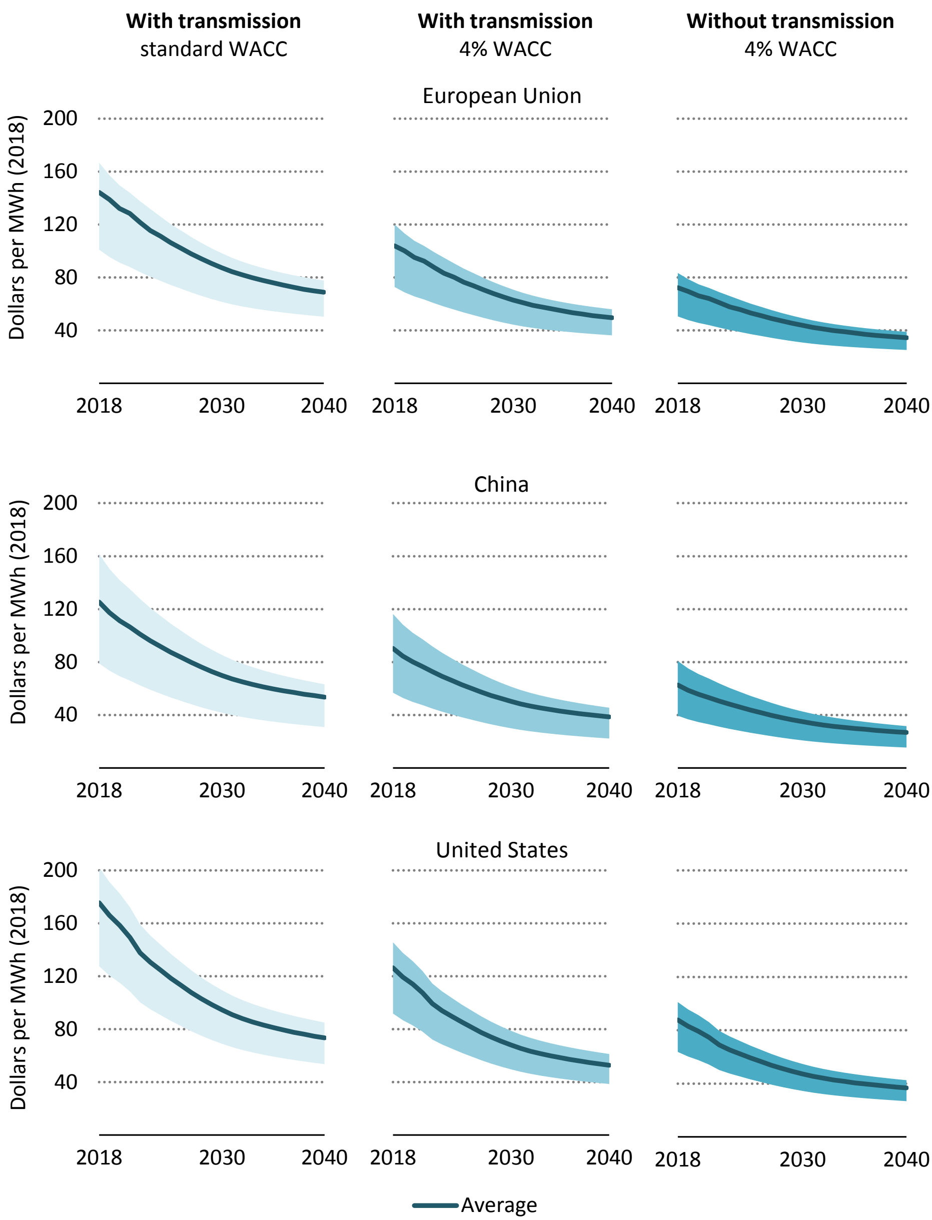
The levelised cost of electricity (LCOE) combines all the previously described elements into a single number representing the average generation cost for a technology. The cost trends described in this section taken together mean that the global average LCOE of offshore wind is set to decline from the 2018 level by nearly 40% to 2030, and nearly 60% to 2040. Applying a standard WACC representing full market risk (7% in developing economies and 8% in advanced economies), the global LCOE falls from $140/MWh in 2018 to less than $90/MWh in 2030 and close to $60/MWh in 2040. Based on the same underlying technology costs and performance parameters but applying low-cost financing (WACC of 4%), the global LCOE of offshore wind declines from $100/MWh in 2018 to $60/MWh in 2030 and less than $45/MWh in 2040.

Offshore wind costs are set to decline in all regions. Improvements in wind turbine and foundation designs, construction processes and O&M procedures tend to have spill over effects, driving down costs in all markets as global deployment increases. Individual markets can accelerate those cost reductions further by using the development of a healthy project pipeline to help establish efficient supply chains for both equipment manufacturing and technical expertise. The LCOE of offshore wind is also influenced by the quality of wind resources and water depths in areas available for energy development.

Applying a 4% WACC on the basis of the prevailing costs of debt and equity in the region, the average LCOE of offshore wind in the European Union declines from $104/MWh in 2018 to just over $60/MWh in 2030 in the Stated Policies Scenario (Figure 21). Excluding transmission assets, the LCOE of European Union offshore wind farms is just $44/MWh in 2030. This is the relevant point of comparison for strike prices in markets such as Germany or the Netherlands where transmission costs are socialised by transmission system operators, paid through levies to consumers. It is also a relevant benchmark when considering dedicated projects for hydrogen and other electro-fuels. In China, where capital costs are lower but current capacity factors are lower as well, the LCOE averaged around $125/MWh in 2018 (applying a 7% WACC). Based on global and local deployment, offshore wind costs in China are projected to fall to $70/MWh in 2030 and $55/MWh by 2040, reaching cost parity with coal-fired power generation around 2030. The costs of offshore wind in nascent markets, including the United States, are linked to technology development elsewhere, but are relatively uncertain until the markets evolve.

A number of factors influence the LCOE for offshore wind, but financing costs are among the most important. As noted, a four point decline in the cost of capital – as a result of improved debt terms, but also a lower cost of equity from developers (IEA, 2019a) – translates into nearly a 30% reduction in LCOE. Improved capacity factors are another critical element for project costs, as are associated technology developments that benefit from economies of scale and standardisation. A 20% reduction in total project capital costs could reduce LCOE by about a further 17%. The LCOE benefits across the board from the economies of scale and the standardisation of processes and manufacturing supply chains that are examined more in depth in the next section.

Figure 21 ▷ LCOEs for new offshore wind projects in the European Union, China and the United States, 2018-2040



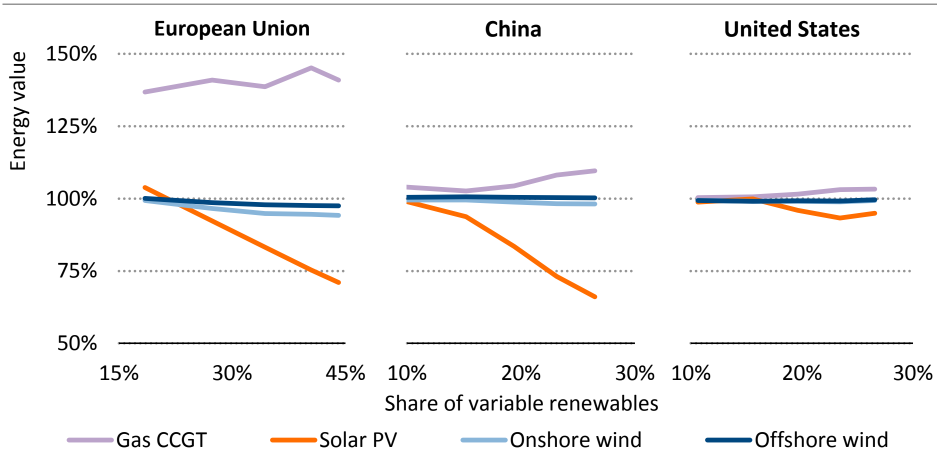
Offshore wind LCOEs are set to decline by 40% to 2030 and by over 50% to 2040, with the development of efficient local supply chains boosting global technology learning

Notes: WACC= weighted average cost of capital; LCOE = levelised cost of electricity. Standard WACC applied is 8% (real) for the European Union and United States, and 7% for China.

System value of offshore wind

Offshore wind is characterised by high capacity factors and widespread availability, making its value proposition potentially comparable to that of baseload technologies such as nuclear power and coal-fired generators. Offshore wind's value is generally higher than that of its onshore counterpart and more stable over time than that of solar PV, which has a concentrated output during daylight hours. Its energy value (equivalent to the average price received for energy sold to the market) depends on the pattern of demand and the power mix, but in most cases remains close to the average wholesale electricity price over the year (Figure 22), which means that in general its energy value is similar to that of baseload technologies. Even as the share of offshore wind increases, its energy value remains relatively stable, because offshore wind produces energy across all hours. Offshore wind can provide flexibility services, though incentives in most markets are insufficient to warrant the trade-off with lower energy output.

Figure 22 ▹ Energy value by technology and region relative to average wholesale electricity price in the Stated Policies Scenario

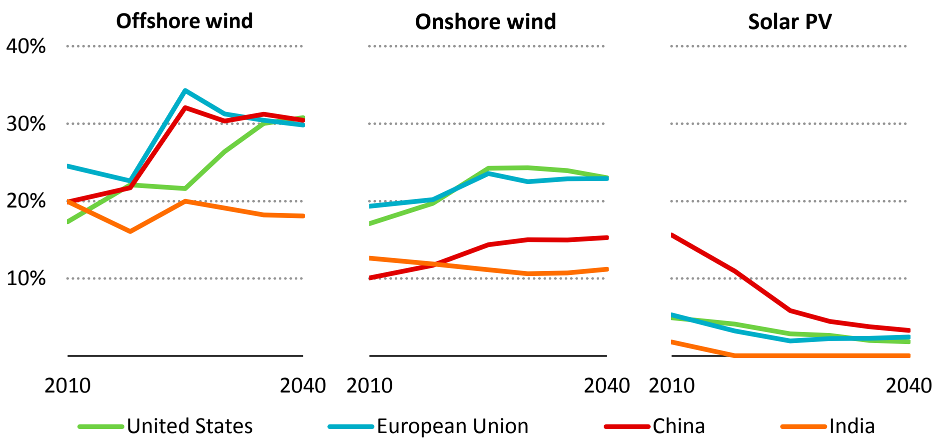


Offshore wind maintains its energy value through to 2040, even as the share of variable renewables increases compared with onshore wind and solar PV

Offshore wind can also contribute to the adequacy of electricity supply (the ability of the system to meet demand at all times from a planning perspective). The high capacity factors and seasonality of offshore wind means that 30% or more of its capacity can be counted towards reliability requirements, which is a higher percentage than for onshore wind and solar PV (Figure 23). This reduces the need for investment in other dispatchable capacity, including investment in combined-cycle gas turbines (CCGTs).

Pairing energy storage systems with an offshore wind project, an option which is currently being considered in connection with the North Sea Wind Power Hub, could significantly increase the capacity credit of the output from an offshore wind project. Energy storage could take a variety of forms, including batteries or thermal storage, both of which are currently being explored. The addition of energy storage to offshore wind (and other renewables) is particularly important for the Sustainable Development Scenario, where the share of variable renewables reaches 40% worldwide by 2040, and more than that in some regions.

Figure 23 ▹ Average capacity credit by technology and region in the Stated Policies Scenario



Offshore wind makes a larger contribution to system adequacy in key markets than onshore wind and solar PV

Note: In addition to fluctuating hourly profile for variable resources, other factors influence the capacity credit for a given year such as increasing capacity factors for the new unit of generation through to the total existing installed variable renewable generation in the power system.

Offshore wind could also provide flexibility services to power systems where the proper incentives are in place, as its high capacity factors mean that it could provide both upward and downward ramping. Some onshore wind projects already provide flexibility, largely in the form of downward regulation (i.e. reduced output on call). With sufficient economic incentives, onshore and offshore wind could also include upward regulation (i.e. curtailing output prior to the need to ramp upwards). To date, flexibility services have had limited attraction for most wind projects because revenues for such projects are often tied exclusively to electricity generation, but technological advances enabled by digitalisation could increase the value of flexibility for such projects in the future so as to make them economically attractive.

Offshore wind could also be used to produce low-carbon hydrogen, providing a zero-carbon fuel that could be used to provide power system flexibility, or be put to use in sectors that are hard to decarbonise, including industry, refining and transport (IEA, 2019b).

Box 3 ▹ Calculating the capacity credit of variable renewables

In order to quantify the expected contribution to power system adequacy (capacity credit)[9] of rising shares of variable renewables (such as offshore wind, onshore wind and solar PV), a new capacity credit tool has been developed. The tool incorporates both the annual projections generated in the IEA's World Energy Model (WEM) and the load and renewable resource profiles utilised in its hourly power module.[10]

The method employed in the capacity credit tool builds upon the approach that is currently used in the WEM and that has also been adopted by the US National Renewables Energy Laboratory (NREL) in their Regional Energy Deployment System model (NREL, 2017). It determines the contribution that a new unit of variable generation may provide to the power system during peak hours (sorted from highest to lowest) relative to a residual demand profile (actual demand less electricity production from variable renewables sorted from highest to lowest). These peak hours may be considered as a proxy for the hours with the highest risk for loss of load.

Two sorted residual demand profile are computed: one with the new unit and the other with existing variable generation. Over the peak hours, the difference between the sorted actual demand (often termed a load duration curve) and the residual demand profile without the new unit gives the capacity credit for the existing variable generation. Similarly, if we take the difference over the same period between the two sorted residual demand curves (with and without the new unit) this provides the capacity credit of the new unit of variable generation in the power system.

Value-adjusted LCOE of offshore wind

The competitiveness of power generation technologies calls for consideration of both the technology costs and the value provided to the system. The LCOE captures all the direct costs of a technology and is a commonly used metric of competitiveness. However, power generation technologies provide a number of services to the system that should be included in a comprehensive assessment of competitiveness. The services provided include contributions to the bulk energy supply, to the adequacy of the system, and to the flexibility of the system (enabling supply to match demand very closely in real-time operations).

The value-adjusted LCOE, first presented in the *World Energy Outlook-2018*, assesses the value of each of these services to the system and combines them with the LCOE to provide a single metric of competitiveness (IEA, 2018b). The metric can be applied to a wide range of power generation technologies, from variable renewables to dispatchable fossil fuels,

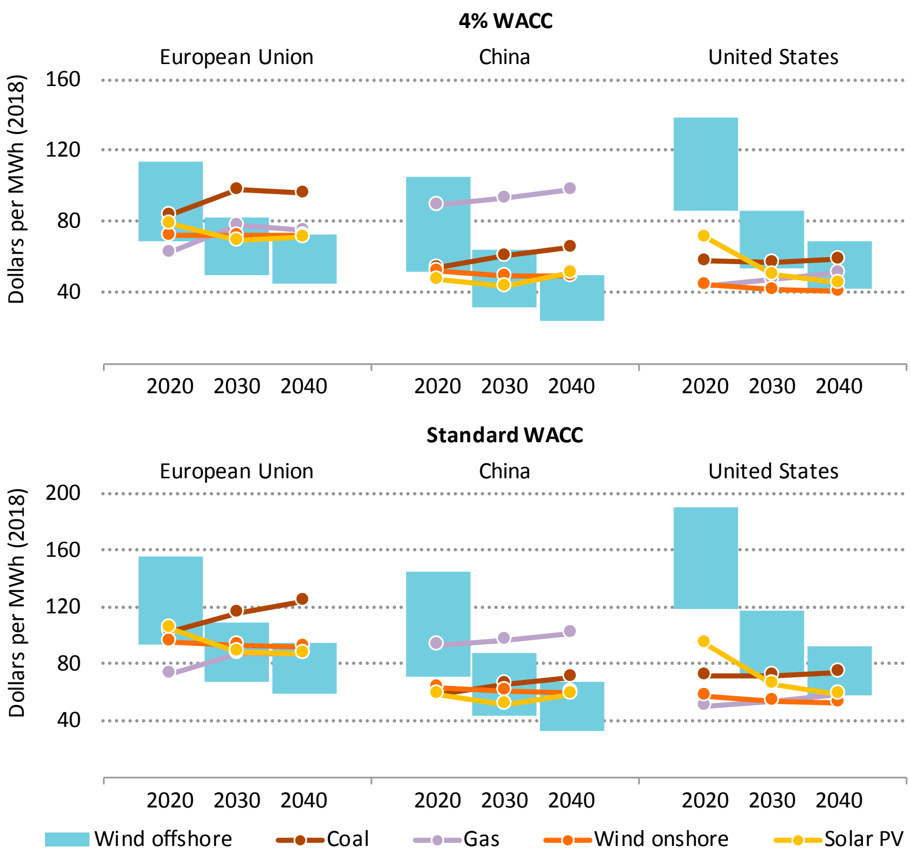
[9] Proportion of the capacity that can be reliably expected to generate electricity during times of peak demand in the network to which it is connected.

[10] For the full WEM methodology, see www.worldenergyoutlook.org/weomodel/. Wind and solar PV resource data used in the hourly modelling and capacity credit tool are sourced from Renewables.ninja, Open Power System Data (2019) and Ueckerdt et al. (2016).

and to both existing and new projects. It is applicable in a wide range of system conditions, including the share of variable renewables and available dispatchable technologies. It has similarities to other metrics applied in long-term energy modelling that combine cost and value, including the system LCOE (Ueckerdt et al., 2013) and the value-to-cost ratio applied by the US Energy Information Administration.

The value-adjusted LCOE has a basis in emerging electricity market designs around the world, incorporating and combining elements of competitive energy-only markets, ancillary service markets and capacity mechanisms (IEA, 2016; IEA, 2018c). However, the metric is applicable in all regions, though one or more value streams or the full technology costs may not be relevant to investors. The value-adjusted LCOE does not include site-specific network integration costs or externality costs that are not directly priced in the market.

Figure 24 ▹ Evolution of offshore wind competitiveness: value-adjusted LCOEs by technology and region in the Stated Policies Scenario



Offshore wind is competitive with gas, solar PV and onshore wind in several markets by 2030

Offshore wind closes the competitiveness gap with other low-carbon technologies in different regions over the next decade and in some cases moves ahead of fossil fuels (Figure 24). In the European Union, offshore wind is competitive with onshore wind, solar PV alone and solar PV paired with storage. With a rapidly rising share of variable renewables, however, the importance of flexibility in the European Union gives gas-fired power a competitive edge despite higher costs. In China, offshore wind moves within striking distance of other low-carbon technologies and coal-fired power by 2030, on the assumption of a modest carbon dioxide (CO_2) price. Offshore wind power is an attractive option in China because it can be built near population centres in the east and south of the country, complementing the extensive build-out of cross-province ultra-high transmission systems (IEA, 2017). In overall terms, the United States appears to be a challenging place for offshore wind to compete on a pure cost basis with onshore wind, solar PV and efficient gas-fired power. However, the availability of offshore wind resources in the northeast of the country and along the densely populated east coast means that it could have a role in diversifying the power mix.

Opportunities for faster growth of offshore wind

There are many factors that have a bearing on how fast the offshore wind market will expand, and some of the most important are highlighted in this section. Changes to technology, market conditions and policy decisions could accelerate offshore wind deployment in the decades to come and cause it to grow faster than projected in the Stated Policies Scenario. The upside potential is limited by the technical potential for offshore wind, not only in terms of the quality of wind resources and available turbine technologies, but also in terms of other factors that might limit its deployment including the suitability of seabed conditions for offshore wind and the nature of regulations concerning competing uses and environmental protection.

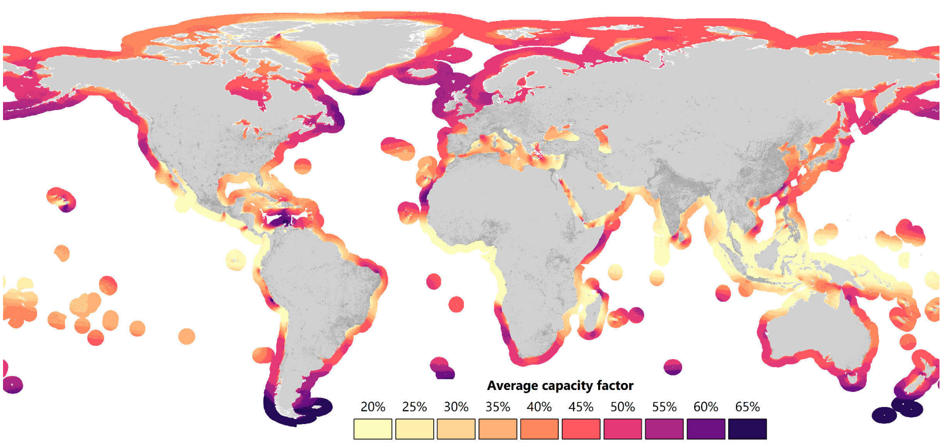
Global technical potential for offshore wind

A detailed assessment of the technical potential for offshore wind development was undertaken in collaboration with Imperial College London specifically for this report. Geospatial analysis was performed globally using the "Renewables.ninja" modelling tool based on the latest reanalysis of satellite data by the European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA-5). Power curves corresponding to specific power output at different wind speeds were implemented for the latest turbine designs (up to 10 MW) and synthesised for designs up to 20 MW for which data are not yet available (Saint-Drenan et al., 2019). Areas available for offshore wind development excluded areas that are specified for competing uses (i.e. fishing, shipping, defence, and oil and gas exploration and production) and environmental protection (excluding Marine Projection Areas classified by the International Union for Conservation of Nature [IUCN]).[11] Areas close to submarine cables and earthquake fault lines were also excluded.[12]

Potential offshore wind performance

The quality of wind resources for energy production is best represented by the average capacity factor for new wind projects, which translates the wind speeds in a given area into the average performance over the course of a year. Based on the global assessment performed for this analysis, wind resources are generally of higher quality for energy production nearer to the poles (Figure 25). In Europe, the North Sea, Baltic Sea, Bay of Biscay, Irish Sea and Norwegian Sea, offshore wind has average annual capacity factors of around 45-65%, which is higher than the comparable figures for the United States (40-55%), China (35-45%), and Japan (35-45%). The capacity factor is also high in regions off the coast of South America and New Zealand (50-65%). Moderate wind speeds resources in India translate to a 30-40% average capacity factor. The average capacity factor in general is relatively low in regions nearer to the equator for example in Southeast Asia and parts of western Africa. The detailed geospatial analysis captures varying conditions within regions, bringing out for example capacity factors in the Palk Strait between India and Sri Lanka that are well above average for the region and comparable to those found in Europe.

Figure 25 ▹ Average simulated capacity factors for offshore wind worldwide



Average capacity factors reflect the quality of the wind resources available offshore around the world

Notes: Inland dots depict population density of more than 500, 2 000 and 8 000 people per km^2 with darker shades of grey.

Source: IEA analysis developed in collaboration with Imperial College London based on Renewables.ninja.

[11] Classification areas Ia, Ib, II and III were excluded from the technical potential assessment (IUCN, 2013).

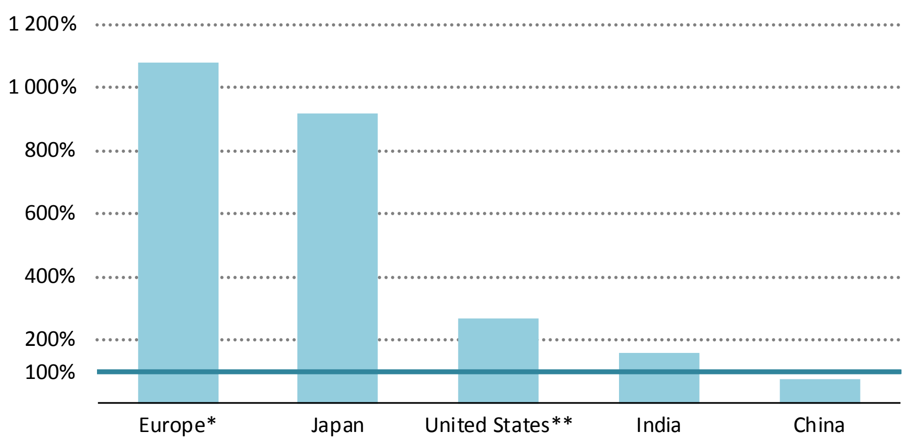
[12] For more information on the methodology, please refer to *Global Offshore Wind Outlook* (IEA, 2019c).

The assessed capacity factors provided the foundation of the technical potential assessment for offshore wind. Once exclusion areas and offshore wind farm designs have been factored in, the potential power capacity and annual electricity generation from each 5x5 km^2 site can be estimated and aggregated regionally and globally. Adding in estimated costs for offshore wind farms and transmission assets enables calculations to be made of the LCOE for each site, which are aggregated to provide supply curves by region.

Technical potential for offshore wind by region

Based on the assessment, we estimate that the technical potential for offshore wind worldwide is more than 120 000 GW, with the potential to generate more than 420 000 terawatt-hours (TWh) of electricity per year. This is enough to meet 11-times global electricity demand in 2040. Our study, however, does not consider other constraints such as the availability of transmission and distribution infrastructure to bring electricity generated to shore and other market related issues (see section "Onshore grid development"). Because of their long coastlines, Russia (80 000 TWh per year, or 20% of the total), Canada (50 000 TWh per year, or 12% of the total) and the United States (over 45 000 TWh per year, or 11% of the total) together account for more than 40% of the global technical potential. Excess resources could be harnessed for export to other countries given favourable market conditions.

Figure 26 ▷ Ratio of technical potential to domestic electricity demand by region in the Stated Policies Scenario, 2040



Based on technical potential, many regions could cover more than or nearly all of their domestic electricity demand from offshore wind alone

* Potential excluding Greenland and overseas territories. ** Potential available excluding Alaska and Hawaii.

Source: IEA analysis developed in collaboration with Imperial College London.

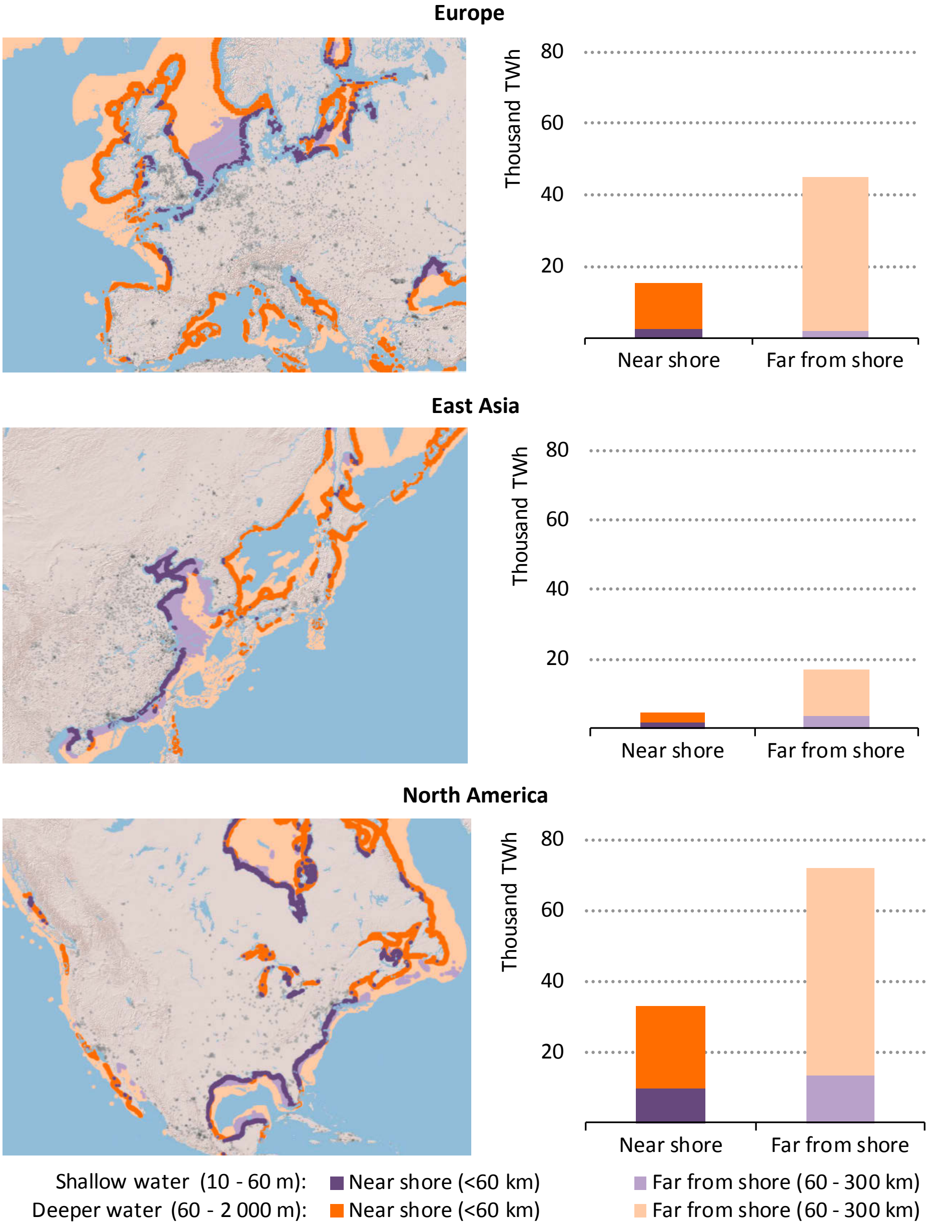
A comparison of technical potential with domestic electricity demand indicates that many countries would be able to meet their local electricity demand from offshore wind in 2040 in the Stated Policies Scenarios. For example, in Europe (excluding Greenland and overseas territories), the technical potential of offshore wind is more than ten-times demand (Figure 26). In the United States, excluding the offshore wind potential in Alaska and Hawaii, offshore wind could provide twice the level of total electricity demand in 2040. India and China would be able to meet the majority of electricity demand in 2040, with technical potential close to 6 000 TWh per year and 8 300 TWh per year respectively. Japan would be able to meet more than nine-times its demand based on its technical potential.

Technical potential can be divided between what is available in shallow water (i.e. < 60 m), and in deep water (i.e. 60-2 000 m). Broadly speaking, shallow water sites are suitable for established fixed-bottom foundations and are easier to access, while those for deeper water sites require floating platforms and are harder to access. The technical potential in shallow water is more than 87 000 TWh per year, which is enough to meet global electricity demand in 2040 under the Stated Policies Scenario more than twice over. The technical potential of sites located in deeper waters is more than 330 000 TWh per year. Deployment in deep water is currently costly, but the development of floating platforms technologies could bring down costs and open up enormous potential.

Within these two broad categories, the technical potential can be further subdivided: sites that are near to shore (i.e. 20-60 km) and within 50 km of existing commissioned projects; other potential sites that are close to shore; sites far from shore (i.e. 60-300 km); and sites with existing restrictions or competing uses such as oil and gas installations. Tapping just the most attractive potential in near shore shallow waters could provide close to 36 000 TWh globally per year, which is nearly equal to global electricity demand in 2040. Other near shore projects could generate a further 76 000 TWh per year. Around 70% of overall potential is in deep water and floating platform technology would be needed to develop this potential. Beyond the accessible technical potential, sites with existing competing uses and restrictions could provide around 17 000 TWh per year which could be made use of if policies and regulations made this both practicable and economic.

In Europe (excluding Greenland and overseas territories), the technical potential is close to 50 000 TWh per year, with countries bordering the North Sea and Baltic Sea such as Norway, Iceland, United Kingdom, France, Denmark, Netherlands and Germany accounting for two-thirds of this potential. Greenland adds another 14 000 TWh of potential, though its distance from large demand centres makes it less accessible. European countries are actively trying to expand their offshore wind markets to harness this potential and there are plans to develop a North Sea Wind Power Hub, to connect multiple wind farms in a hub-and-spoke configuration, with the first electricity due to come on shore in the 2030s (NSWPH, 2019). More than 1 300 TWh of Europe's technical potential is in shallow waters and close to shore, with a particularly large number of good sites located in the North Sea (Figure 27).

Figure 27 ▷ Regional technical potentials for offshore wind



There is enormous potential for offshore wind development around the world, though the quality of wind resources varies widely

Notes: Inland dots depict population density of more than 500, 2 000 and 8 000 people per km^2 with darker shades of grey. Offshore regions far from shore shown in lighter shades of orange and purple respectively.

Source: IEA analysis developed in collaboration with Imperial College London.

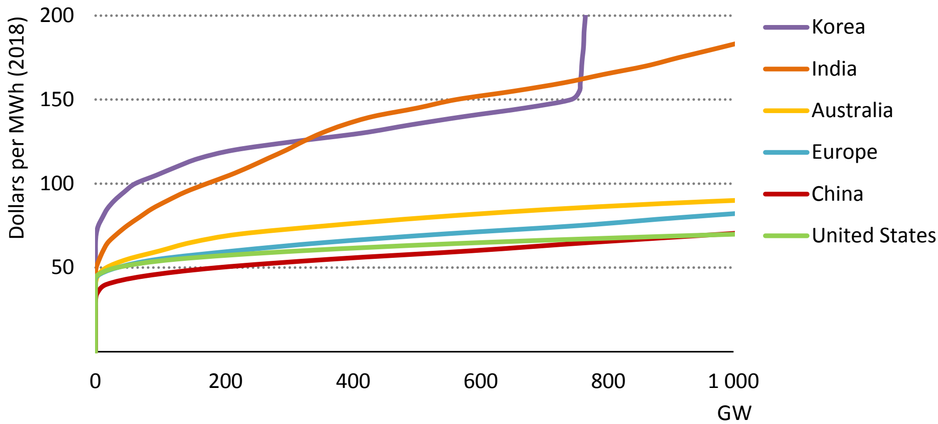
In East Asia, where a wave of deployment is expected in the upcoming years, the technical potential for offshore wind is over 22 000 TWh per year. In China, shallow coastal waters near major cities have the technical potential to produce close to 4 700 TWh per year, of which more than 1 800 TWh is available at sites close to the shore. This means that a good deal of the technical potential in China could be tapped at relatively low cost. In Japan, most of the technical potential of more than 9 000 TWh per year is located in deep water and would require floating platform technology in order to harness most of this potential. Even so, shallow waters could provide some 40 TWh per year, which would be enough to meet 4% of Japan's electricity demand in 2040 in the Stated Policies Scenario.

In North America, strong winds in places like Hudson Bay, Labrador Sea, Gulf of Alaska and the Atlantic seaboard together yield offshore wind potential of more than 100 000 TWh per year. The United States has technical potential of more than 46 000 TWh per year. Only around a quarter of this is in the contiguous United States, but this is still three-times more than enough to meet the total electricity demand of United States today and to meet its demand through to 2040 in the Stated Policies Scenario. Within the contiguous United States, shallow waters have the potential to provide more than 3 300 TWh per year and deep waters more than 8 700 TWh per year. Some of this potential is located off the Atlantic coast near major cities such as Washington D.C., Boston and New York. There is also technical potential of more than 900 TWh per year within the Great Lakes region.

The geospatial analysis undertaken also assessed the technical potential available at a given generation cost level, and it indicates that several hundred gigawatts of offshore wind could be deployed in leading markets at costs at or below that of coal- and gas-fired generation in 2030 (Figure 28). For each 5x5 km^2 site, the LCOE of a potential offshore wind project was calculated based on the estimated capacity factor combined with the project cost. The total cost of the offshore wind installation varied according to the distance from shore and the sea bed depth for each site. Deeper waters and farther distances from shore served to increase the total cost above a standard assumed cost of $2 000/kW. Based on this assessment, several regions have very large potential to develop offshore wind at low to moderate costs:

- China starts to have significant potential at about $50/MWh, despite only moderate wind conditions (shallow and close to shore).
- At around $60/MWh, an attractive cost in most cases, potential starts to become available in the United States, Europe and Australia.
- At $80/MWh, a moderate cost for a new source of electricity, China, United States and Europe each have around 1 000 GW of potential or more.
- Potential remains limited in Korea due to deep waters and middling wind conditions, while India also remains limited at these cost levels due to poor wind conditions.
- Japan also has limited potential at these costs, although this could potentially change once the costs of floating turbines are better known.

Figure 28 ▹ **Offshore wind potential supply curves by region**



Based on near-term costs, at least 1 000 GW of offshore wind potential is available for less than $80/MWh in China, Europe and United States

Notes: LCOEs were calculated based on a standard wind farm cost of $2 000/kW, with additional costs related to greater distances from shore and deeper water.

Source: IEA analysis developed in collaboration with Imperial College London.

Improved economics for offshore wind

The economic attractiveness of offshore wind to investors depends on a host of factors including technology and project costs, prevailing market conditions, the extent of government support and the evolution of other power generation technologies.

Available information for the offshore wind projects under development indicate a step change in project costs in the near term and industry expectations are for further robust cost improvements in the longer term as supply chains mature. Standardisation of project components and installation procedures could also help to reduce costs. More accurate meteorological information would help developers to choose the best sites for projects and could help make offshore wind technology more competitive with other sources of electricity. Where reductions in costs outpace those detailed in section "Offshore wind costs, value and competitiveness", the growth of offshore wind could be accelerated further without increasing the delivered cost of electricity to consumers. Lower costs would also boost the prospects for production of renewable hydrogen.

Market conditions will play a critical role in the long-term future for offshore wind. Wholesale electricity prices seem likely to continue to experience downward pressure on the back of rising shares of variable renewables with zero or near-zero marginal costs and natural gas prices that are projected to remain at relatively low levels in several markets. Low wholesale electricity prices make it difficult to make a market-based case for investment in any power generation technology, including renewables. There are some notable exceptions for offshore wind projects in Europe, though it has yet to be seen whether this business model can be replicated for many projects. Without reforms there is a risk of inadequate signals for efficient and timely investment in new sources of power and in the power system flexibility that will be needed in the future.

Market reforms that promote such investment would improve the opportunities for market-based deployment of offshore wind. For example, capacity mechanisms are in operation or under consideration in several markets with the aim of remunerating contributions to system adequacy. Given that the characteristics of offshore wind lead to relatively high capacity credits (see section "Offshore wind costs, value and competitiveness"), capacity mechanisms seem likely to boost the competitiveness of offshore wind compared with solar PV and onshore wind. Further reforms that recognise the value of low-emission sources of electricity would also help to reinforce the business case for offshore wind and indeed other clean energy sources.

The economics of offshore wind would also be enhanced if transmissions network costs can be further reduced through innovation, economies of scale and supportive action on the part of electricity transmission grid operators. Planning that enables further expansion of the most competitive sources of electricity from a system perspective would make a significant difference to the prospects for offshore wind power in all regions.

Increased demand for renewable hydrogen

Demand for low-carbon hydrogen has an important role in the transition to a sustainable future (IEA, 2019b). Its versatility means that it has the potential to contribute to the decarbonisation of several sectors, as well as providing a low-carbon source of flexibility in power systems. The high capacity factors and improving cost competitiveness of offshore wind mean that it could play an important part in the production of low-carbon hydrogen.

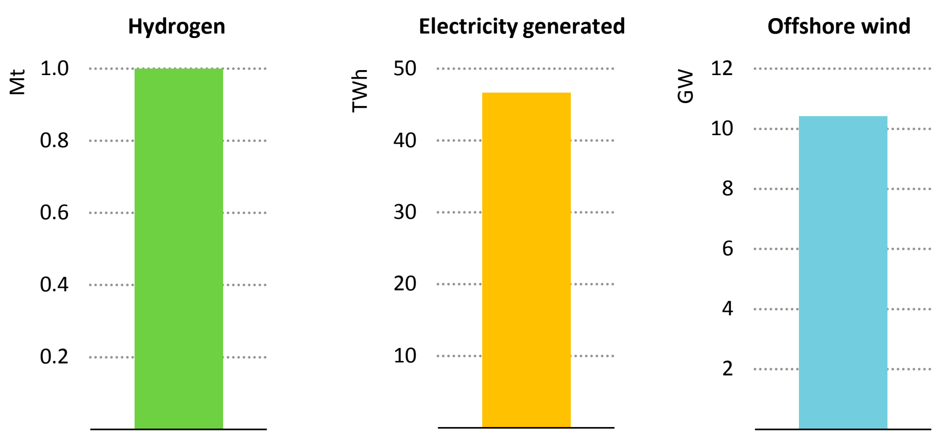
Around 70 million tonnes (Mt) per year of hydrogen is used today, mainly in oil refining and chemical production, but it is almost all produced from fossil fuels. Using low-carbon sources of electricity to produce hydrogen could help to support a clean energy transition through sector coupling. For example, low-carbon hydrogen could be used to reduce CO_2 emissions in hard-to-abate sectors of industry such as iron, steel and chemicals. It could also be used in transport, where fuel cell electric vehicles powered by hydrogen would be well suited to heavy trucks, and where there could be other uses for low-carbon hydrogen in aviation and shipping.

Offshore wind projects dedicated to produce local, renewable-based hydrogen could offer significant cost advantages over projects using electricity direct from the grid. In part this is because dedicated offshore wind farms would benefit from cost reductions by avoiding the need for transmission. For example, the LCOE of offshore wind in the European Union in 2030 is projected to be in the range of $40-70/MWh including transmission (with a 4% WACC), but just $30-50/MWh without transmission. With average EU retail industry electricity prices projected to be around $130/MWh, offshore wind could offer 60-80%

savings on the costs of electricity input. The high upfront capital costs of electrolysers mean they need to run as often as possible to be economic, and the high annual capacity factors offered by offshore wind would fit well with this need (see section "Offshore wind costs, value and competitiveness").

The cost of producing hydrogen is declining. Hydrogen could be produced today at a dedicated offshore wind farm without transmission costs to shore at about $9 per kilogramme (kg) of hydrogen before transportation, with 87% of this cost related to the cost of offshore wind production and 11% related to electrolyser costs. Transportation costs would add to this, but could potentially be relatively low if it were to be possible to repurpose existing oil and gas pipelines. Production costs are projected to fall below $4/kg by 2040 as a result of falling costs for offshore wind and electrolysers. In the Sustainable Development Scenario, close to 4.5 Mt of low-carbon hydrogen are used in Europe in 2040, and offshore wind accounts for a significant share of this, with 10 GW of offshore wind capacity able to produce about 1 Mt of hydrogen per year (Figure 29).

Figure 29 ▻ Offshore wind capacity needed to produce 1 Mt of hydrogen



Additional demand for hydrogen offers significant upside potential for offshore wind, as 10 GW of offshore wind capacity can produce about 1 Mt of renewable hydrogen

Public acceptance

Offshore wind is not subject to some of the challenges faced by other technologies in terms of public acceptance precisely because of its offshore nature. Concerns about noise, visual impact and use of land do not arise in the same way that they do for onshore wind and solar PV, for example. Offshore wind does face public acceptance challenges of its own, exemplified by the decade-long challenges to the Cape Wind project in the eastern United States, and these should not be glossed over. However the challenges so far appear to be generally less widespread and intractable than for onshore wind developments.

Uncertainties that could slow offshore wind growth

As a technology poised for rapid growth, offshore wind faces a number of challenges. Developers must establish efficient supply chains, address environmental concerns, and demonstrate that the impressive cost reductions promised by recent auction bids are replicable in other markets and under a range of marine conditions. Offshore wind developers must also deal successfully with a unique set of technical and regulatory challenges, in particular in terms of marine planning and the development of supporting grid infrastructure on land to deliver electricity produced offshore to consumers. Strong growth may also bring new challenges, such as gaining access to adequate quantities of the rare earth elements that are critical to large offshore wind turbines. These various challenges will have to be overcome if offshore wind is to fulfil its potential and make a strong contribution to a clean energy future.

Developing efficient supply chains in new markets

One key challenge is the need to establish clear plans that enable efficient supply chains to be developed, limiting project risk and supporting low costs. In a perfect scenario for offshore wind, we would see improved turbine models and lighter and resilient foundations being delivered on time to projects, transparent planning and regulations providing clear long-term market visibility for project developers and investors, healthy competition among players to reduce costs, a good balance of international and national industry partnerships, and creating a well-trained work force.

For all these things to happen, however, markets need connections in place between all the various offshore wind supply chain links. Governments have an important part to play at the outset in demonstrating a clear commitment to national renewable energy goals that provides sufficient security to industry to procure a healthy pipeline of projects, and in backing this up by setting clear rules, for example on the handling of grid connections and the conducting auctions. This should engender the confidence in industry to develop supply chains, where the standardisation of equipment and operations help to reduce costs, and to pursue further efficiencies by making the most of synergies with the oil and gas industry (see section "Synergies with oil and gas activities").

Environmental concerns

To reduce the impact on the environment, offshore wind projects are increasingly being examined carefully by government agencies at the planning stage to ensure that developers complete a detailed environmental impact assessment and if approved, put in place measures to comply with marine protection standards throughout the life of the project. For example, the Crown Estate in the United Kingdom recently blocked the expansion of Race Bank Offshore wind farm citing environmental concerns after a Habitats Regulations Assessment was conducted.

Offshore wind projects could potentially have negative impacts on fish, marine mammals and birds related to habitat change, displacement or injury during construction and operational noise, risk of collisions as well as avoidance or attraction to electromagnetic fields (WWF, 2014). On the other hand, several studies have pointed to potential benefits including enhanced biological productivity and improved ecological connectivity. Based on a long-term environmental study on the Horns Rev project in Denmark, fish species may be attracted to foundations, providing a refuge and potentially increasing the number of species in a project area (Danish Energy Agency, 2019).

While there are uncertainties about overall impact, it is important that measures are taken to protect biodiversity throughout the lifetime of the offshore wind farm. The IUCN has a set of guidelines on maritime protection areas which the industry can consult (IUCN, 2013).

Onshore grid development

The development of supporting onshore grid infrastructure is essential to the efficient integration of power production from offshore wind projects. Without appropriate reinforcements and perhaps some expansion of the grid, electricity from offshore wind may be curtailed. The risk posed by taking separate approaches to renewables and to grid development is larger in systems where the share of variable renewables is rising, especially where onshore wind plays a significant role and is exposed to the same kind of weather patterns as offshore wind.

Europe has set significant ambitions for the development of wind offshore, with member states together aiming for 65-85 GW of capacity by 2030. With strong and reliable wind speeds, additional development in the North Sea is of great interest. Analysis was carried out to explore the impacts of onshore grid development on integration of a wind hub in the North Sea in 2030 (Box 4).

Box 4 ▻ Tapping offshore wind potential in Europe calls for onshore transmission expansion

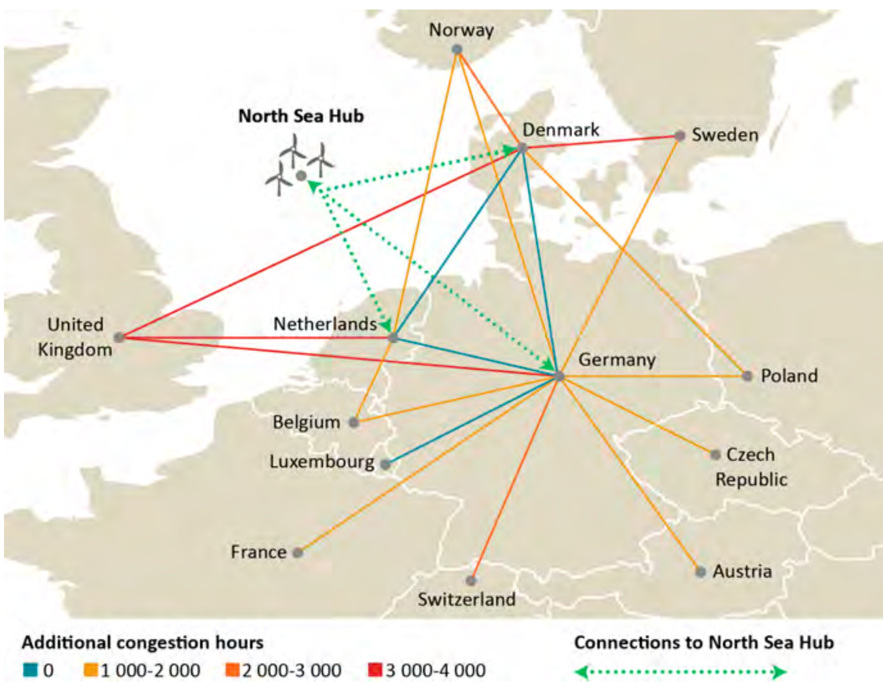
Along with actively deploying individual offshore wind farms, Europe is also exploring offshore "hubs" to facilitate further deployment of offshore wind. The North Sea Wind Power Hub project represents a step towards a possible 180 GW of offshore wind by 2050 (NSWPH, 2019). At that scale, offshore wind would offer the opportunity to decarbonise not only electricity supply but also other sectors through the dedicated production of hydrogen.

To illustrate the interplay between transmission network and offshore wind developments, analysis was conducted of the integration of an offshore wind hub in the North Sea. The impacts of two different grid configurations for 2030 have been simulated and analysed, based on a country-by-country representation of the European power system, and using an hourly time resolution across the whole year based on the

Stated Policies Scenario. One case includes network infrastructure that is economically optimal (from a societal point of view). It has been obtained by allowing the model to invest in the interconnection projects submitted to the ENTSO-E Ten-Year Network Development Plan 2018 as long as they are found to generate benefits that outweigh their costs. A second case includes an additional 12 GW of offshore wind power capacity, as well as including expanded interconnections with Germany (6 GW), Netherlands (4 GW) and Denmark (2 GW).

The comparison between the two cases shows that adding the offshore wind hub would trigger around 10 TWh of additional curtailment in Europe, mostly in the areas directly connected to the hub, and would increase congestion in the network (Figure 30). There would be significant additional congestion between the countries connected to the hub and their neighbours, notably with the Scandinavian countries, United Kingdom and Switzerland. Some interconnections would see additional congestion in 30% to 40% of the hours in the year.

Figure 30 ▹ Rise in the number of hours of cross-border grid congestion with the addition of a 12 GW hub in the North Sea



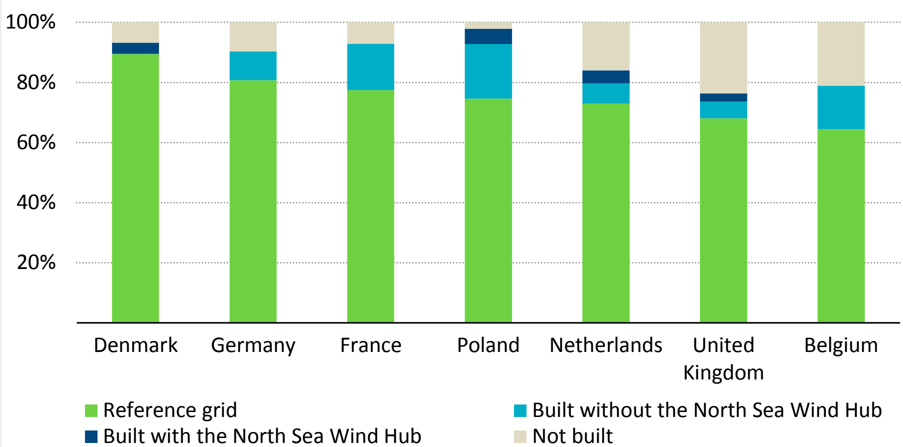
Expanding offshore wind capacity would increase congestion on the grid without additional network investment

Note: Other interconnections with zero additional congestion hours were not included in the figure.

To resolve these issues, an alternative case was developed by allowing the network to adapt when adding the North Sea offshore hub. The results show that an investment of EUR 750 million in 1.1 GW of interconnections from Denmark, Netherlands and Germany to their neighbours could help reduce the curtailment by around 1 TWh per year, and save EUR 130 million per year of operational costs. Furthermore, the integrated renewable energy reduces the use of thermal-based generation by the same amount (1 TWh) and the CO_2 emissions by around 0.5 Mt per year.

This comparison also shows that all onshore interconnection projects connecting Denmark, Netherlands and Germany to their neighbours and included in the ENTSO-E Ten-Year Network Development Plan 2018 are found to be cost effective (the benefits they bring outweigh their investment costs) (Figure 31). These new transmission capacities would relieve grid congestion, reduce overall generation costs and decrease CO_2 emissions in Europe. Additional interconnection projects might well increase the cost effectiveness of the integration of this project.

Figure 31 ▻ Share of potential cross-border connection projects developed by case in Europe to 2030



Additional investment in onshore transmission is key to making the most of offshore wind

An alternative to fully utilise production from offshore wind farms would be to produce hydrogen via electrolysis, part of the long-term vision for hubs in the North Sea. At offshore wind costs of $30-40/MWh, hydrogen could be produced for $18-22 per million British thermal units in 2040 (or $2-2.5/kg of hydrogen), before transportation costs. The production of hydrogen could unlock more of the offshore wind potential.

The analysis was developed in collaboration with Artelys and carried out using Artelys Crystal Super Grid, a multi-energy systems modelling platform. A model of the European electricity system based on the IEA's Stated Policies Scenario was developed.

The model allows for joint optimisation of investments and operations (cost-minimising criterion) for a given year using an hourly time resolution and country-level spatial granularity. The costs considered include investment and operational costs, i.e. fuel and CO_2 costs, variable O&M costs and loss of load penalties (if any) in order to ensure that electricity demand can be met at all times in the considered areas (all member states of the European Union, Norway, Switzerland, Republic of Macedonia, Montenegro, Serbia and Bosnia-Herzegovina). The model is able to simultaneously optimise investment in and the operation of all categories of assets, including different generation technologies, flexible consumption technologies, storage assets and interconnections between areas.

With offshore wind potential spread around the world, significant infrastructure development is likely to be necessary to ensure the cost-effective integration of renewable energy. This will be most effective if it is forward looking. Planning practices favouring the emergence of synergies between renewable energy deployment, onshore and offshore grids and cross-sectoral flexibility solutions are likely to result in the most cost-effective systems. It would make sense as part of this to consider hubs connected to several countries or regions and to assess the scope for synergies, in particular the possible use of offshore hubs to exchange electricity between the interconnected areas. This could reduce the overall costs across the connected countries even when the wind generation is low and increase the level of security of supply.

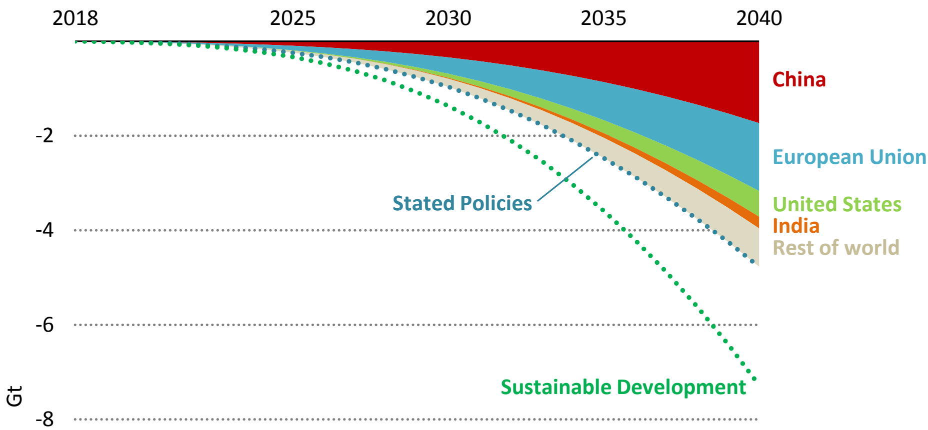
Implications

Offshore wind is a maturing technology that can help to achieve environmental goals while contributing to the security and affordability of electricity. The growth of offshore wind in the Stated Policies Scenario sees expansion well beyond the North Sea to markets around the world. In the Sustainable Development Scenario, offshore wind grows faster still. The falling costs of offshore wind support expansion in all scenarios, though policy makers have an important role to play in creating the necessary conditions for this to happen.

Achieving environmental goals

In the Stated Policies Scenario, the fifteen-fold growth of global offshore wind generation helps to decarbonise electricity supply in several key markets. Over the next two decades, the average CO_2 intensity of electricity generation declines by more than one-third. This keeps related CO_2 emissions flat in the face of demand growth of 2.1% per year. Without the growing contribution of offshore wind, cumulative global CO_2 emissions would be about 5 gigatonnes (Gt) higher over the next two decades on the assumption that its lost output was replaced by the average of the existing power generation mix. In the European Union, the central role of offshore would be particularly difficult to replace. Scaling up generation based on the current power mix in the absence of offshore wind would lead to an additional 1.4 Gt of CO_2 emissions from 2019 to 2040 in the European Union, 0.5 Gt in the United States and 1.7 Gt in China (Figure 32).

Figure 32 ▹ Avoided CO_2 emissions due to the deployment of offshore wind in the Stated Policies and Sustainable Development scenarios



Offshore wind complements the growth of other clean energy sources, avoiding more than 7 Gt of CO_2 emissions to 2040 in the Sustainable Development Scenario

In the Sustainable Development Scenario, an additional 790 TWh of offshore wind helps avoid 2.5 Gt CO2 emissions from 2019 to 2040. These CO2 emissions reductions occur mainly in China, United States and India as a result of an accelerated deployment of offshore wind. They are equal to half the avoided emissions attributable to nuclear power in the transition to a more sustainable energy pathway.

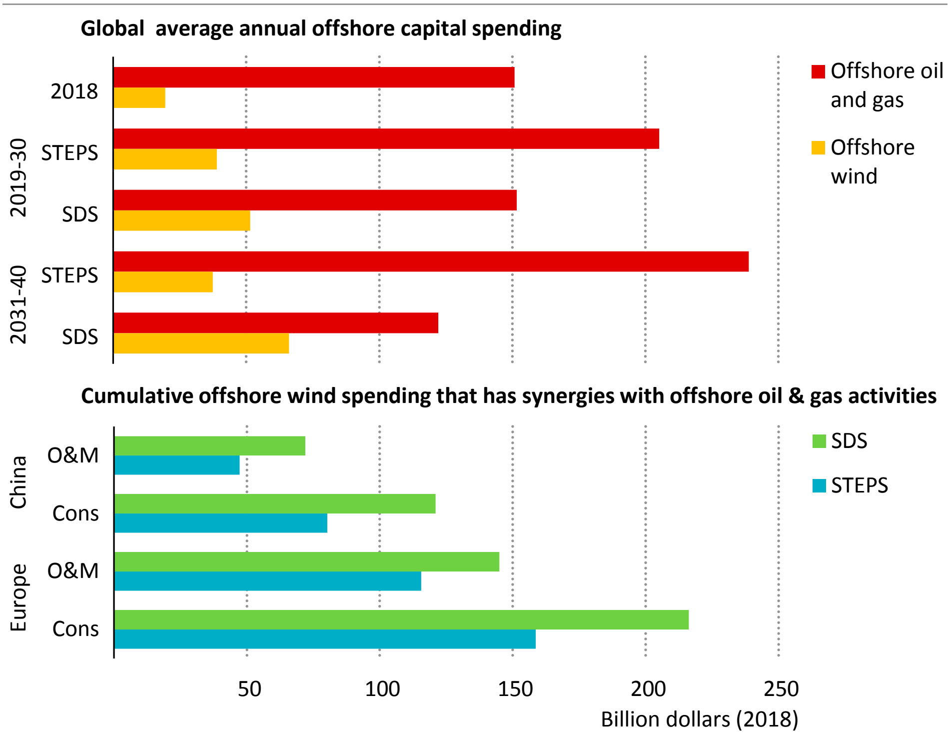
The rise of offshore wind also leads to reductions of air pollutant emissions. In China, offshore wind development helps to limit the use of coal-fired power generation near large population centres in the eastern and southern parts of the country. In India and countries in Southeast Asia, offshore wind contributes to the decline in reliance on coal-fired power generation. In the United States and Europe, offshore wind displaces some gas-fired power generation and the related pollutants.

Synergies with oil and gas activities

The offshore wind power and oil and gas sectors share both technologies and elements of their respective supply chains, and there is scope to exploit the linkages further. Overall spending in offshore wind power reached $20 billion in 2018. Under the Stated Policies Scenario, the projected global annual spending for the next decade doubles and is two-and-a-half times higher in the Sustainable Development Scenario. This growth in offshore wind offers opportunities to those involved in providing a range of relevant offshore oil and gas services, whose skills could be very valuable to offshore wind developers in the light of the synergies between the two sectors.

In this context, it is not a surprise that oil and gas companies started investing in offshore wind projects many years ago, against the background of a trend of increasingly large projects requiring significant amounts of capital. For instance, Shell made its first entry into the offshore wind business with the Vattenfall offshore wind farm Egmond aan Zee in 2007, and is currently developing two more projects in the Netherlands that will be commissioned in the first-half of the next decade: it is also participating in the offshore market in the United Kingdom, France and United States. Equinor, a Norwegian company, has an active pipeline of projects of more than 2 GW, including 0.8 GW recently won in the first large-scale auction in New York in the United States. However, the largest portfolio of offshore wind capacity built belongs to the Danish company Ørsted (formerly DONG Energy), which recently sold its oil and gas assets to focus on renewable energy: it has an active pipeline of more than 8 GW.

Figure 33 ▷ Global offshore wind capital spending and potential synergies with offshore oil and gas activities



A growing pipeline of offshore wind projects opens new opportunities for traditional oil and gas companies, and these increase in the Sustainable Development Scenario

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Con = construction and includes activities considered as potential synergies, e.g. foundations, installation and logistics. O&M includes potential synergies in operation and maintenance of offshore wind installations.

We estimate that about 40% of the full lifetime costs of a standard offshore wind project have significant synergies with the offshore oil and gas sector. That translates into a $400 billion market opportunity in Europe and China in the Stated Policies Scenario, and about a $550 billion opportunity in the Sustainable Development Scenario (Figure 33). While turbine manufacturing is specific to wind power, the construction of the foundations and subsea structures provides scope for significant learning from the oil and gas industry, especially in terms of how best to utilise vessels during installation and operation. There is likely to be much to learn from the oil and gas industry in developing floating platforms for offshore wind. Last but not least, work on the offshore substations required for large offshore wind projects and internal wiring in turbines could benefit from collaboration with the oil and gas industry.

In addition, there are a variety of equipment and support services with cross-over potential after the installation phase. Maintenance and inspection of oil and gas platforms is one area where oil and gas practices and safety standards are highly transferable.

On the other side, many processes in the offshore oil and gas platforms require electricity that is often supplied by (not very efficient) gas turbines or diesel engines that emit CO_2 and air pollutants. Nearby wind farms could supply oil and gas platforms with low-carbon electricity, reducing emissions and costs. Variable output from offshore wind could be a challenge, but batteries could help match patterns of electricity demand and supply, and limit the use of fossil fuel combustion engines.

Linkage with carbon capture, utilisation and storage would involve depleted oil and gas fields being used to store CO_2, which could be brought to the platforms using existing pipeline infrastructure. If the platforms are already electrified, they could house compression facilities that could be powered by nearby offshore wind farms.

Enhanced energy security and affordability

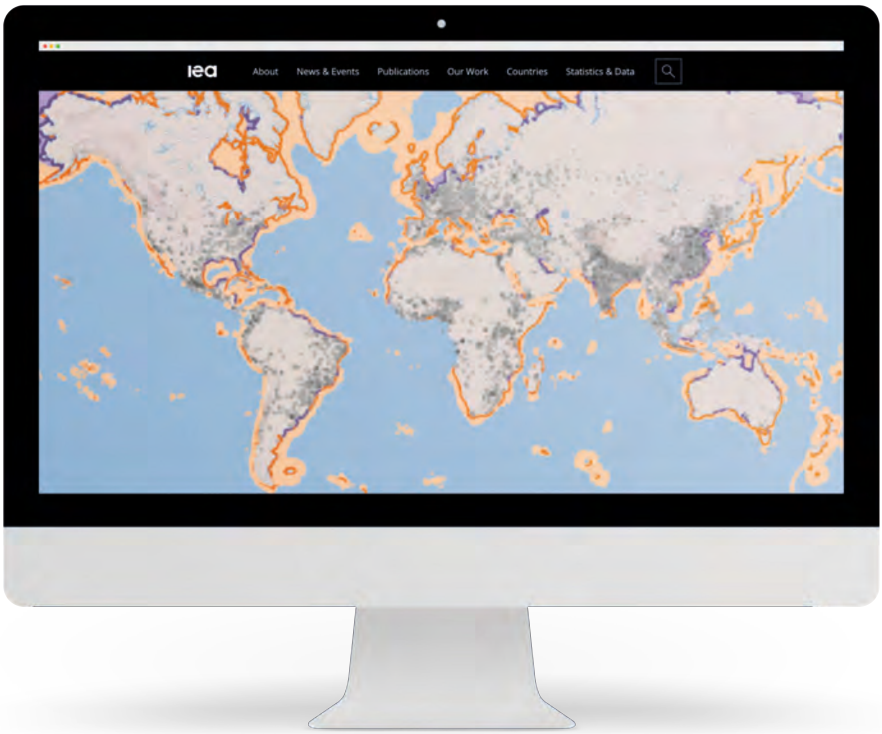
Within the power sector, the characteristics of offshore wind enable it to contribute to system adequacy in a way that is unique among variable renewables. As a result it can be a key contributor to ensuring electricity security in clean energy transitions.

Offshore wind can improve energy security in regions that rely on imported fuels for power generation by enhancing self-sufficiency and energy affordability. For example, a 1 GW offshore wind farm could replace 0.8 billion cubic metres of gas imports to produce the same amount of electricity in an efficient gas-fired power plant. At average spot prices for liquefied natural gas in 2018, such an offshore wind project would reduce annual import fuel bills by over $300 million in Japan and $220 million in Europe. On the other hand, if all electricity production from offshore wind in the Stated Policies Scenario instead were generated with the use of efficient gas-fired power generation, additional gas import bills would be over $400 million per year in Japan, close to $1.9 billion in Korea and nearly $15 billion in the European Union.

The competitiveness of offshore wind enables low-carbon electricity and hydrogen to be produced at a cost lower than otherwise would be possible. Both of these are critical to the achievement of environmental goals. Without the development of offshore wind, efforts to decarbonise electricity in the European Union, China and United States would need to depend more heavily on onshore wind and solar PV. Overall, offshore wind makes energy transitions more affordable, limits the challenges of rising flexibility needs and could, ultimately, accelerate progress towards decarbonisation.

Explore the data behind

Offshore Wind Outlook 2019



iea.org/offshorewind2019

This new *World Energy Outlook* special report provides the most comprehensive analysis to date of the global outlook for offshore wind, its contributions to electricity systems and its role in clean energy transitions. We have also developed an interactive map showing offshore wind's technical potential, based on the geospatial analysis conducted for this report and other data such as existing offshore wind projects and population density. You can explore the map online at iea.org/offshorewind2019.

Tables for scenario projections & technical potential

General note to the tables

Tables A.1 and A.2 provide an overview of offshore wind by region and scenario covering electricity generation, share of total generation, installed capacity, capacity additions; and average annual investments. Electricity generation is expressed in terawatt-hours (TWh), and installed capacity data and capacity additions are both expressed in gigawatts (GW). Electrical data are provided on a gross basis (i.e. includes own use by the generator). Total investment considers the annual capital spending estimated during a plant's construction time. Investment data are presented in real terms in year-2018 US dollars.

Table A.3 details results of the offshore wind technical potential geospatial analysis that was undertaken in collaboration with Imperial College London specifically for this report. The technical potential is expressed in terawatt-hours per year and categorised based on the location of the potential, i.e. distance from shore and water depth.

The definitions for regions are outlined in Annex C. Both in the text of this report and in the tables, rounding may lead to minor differences between totals and the sum of their individual components. Growth rates are calculated on a compound average annual basis and are marked "n.a." when the base year is zero or the value exceeds 200%. Nil values are marked "-".

Data sources

The World Energy Model (WEM) is a very data-intensive model covering the whole global energy system. Much of the data are obtained from the IEA's own databases of energy and economic statistics (www.iea.org/statistics/).

Additional data from a wide range of external sources are also used. Historical data for gross power generation capacity are drawn from the S&P Global Market Intelligence World Electric Power Plants Database (March 2019 version) and the International Atomic Energy Agency PRIS database (www.iaea.org/pris).

The formal base year for the projections is 2017, as this is the last year for which a complete picture of energy demand and production is in place. However, we have used more recent data wherever available, and include our 2018 estimates for energy production in this annex (Tables A.1 and A.2). Estimates for 2018 are based on the recent IEA's *Global Energy* and *CO_2 Status Report* (iea.org/geco/) which is derived from a number of sources, including the latest monthly data submissions to the IEA's Energy Data Centre, other statistical releases from national administrations, and recent market data from the IEA *Market Report Series* that cover coal, oil, natural gas, renewables and power. Investment estimates include the year 2018, based on the IEA's *World Energy Investment 2019* (iea.org/wei2019/).

Table A.1: Stated Policies Scenario

	Offshore wind overview						Shares (%)		CAAGR (%)
	2010	2018	2025	2030	2035	2040	2018	2040	2018-40
Electricity generation (TWh)									
United States	-	0	11	60	112	146	0	11	39.1
European Union	7	60	168	306	462	568	91	44	10.7
China	0	6	49	117	219	339	8	26	20.4
India	-	-	0	11	30	50	-	4	n.a.
Japan	0	0	4	8	12	15	0	1	21.9
Korea	-	0	6	34	60	78	0	6	36.1
World	**8**	**67**	**253**	**567**	**948**	**1 281**	**100**	**100**	**14.4**
Share of total generation									
United States	-	0.0%	0.2%	1.3%	2.3%	2.9%			38.4
European Union	0.2%	1.8%	5.0%	9.0%	13.3%	15.9%			10.3
China	0.0%	0.1%	0.5%	1.1%	2.0%	2.8%			17.6
India	-	-	0.0%	0.4%	0.8%	1.1%			n.a.
Japan	0.0%	0.0%	0.3%	0.7%	1.1%	1.4%			21.9
Korea	-	0.0%	0.9%	5.1%	8.6%	10.9%			34.9
World	**0.0%**	**0.3%**	**0.8%**	**1.7%**	**2.5%**	**3.1%**			**12.1**
Installed capacity (GW)									
United States	-	0	4	17	30	38	0	11	38.3
European Union	3	19	46	77	109	127	83	37	9.1
China	0	4	19	42	74	107	16	31	16.6
India	-	-	0	4	10	16	-	5	n.a.
Japan	0	0	1	2	3	4	0	1	20.8
Korea	-	0	3	12	20	25	0	7	35.8
World	**3**	**23**	**77**	**165**	**262**	**342**	**100**	**100**	**13.2**
Capacity additions (GW)									
United States	-	-	1	3	2	2	-	8	n.a.
European Union	1	3	6	8	7	5	67	29	2.4
China	0	2	3	6	7	7	33	40	7.2
India	-	-	-	1	1	1	-	6	n.a.
Japan	0	-	0	0	0	0	-	1	n.a.
Korea	-	-	1	2	1	1	-	5	n.a.
World	**1**	**5**	**12**	**21**	**19**	**19**	**100**	**100**	**6.3**

	Average annual investments ($2018 billion)			Cumulative	CAAGR (%)
	2010-2018	2019-2030	2031-2040	2019-2040	2018-40
United States	0	5	4	98	16.9
European Union	11	19	15	376	-0.7
China	2	8	10	196	2.9
India	0	1	2	34	43.8
Japan	0	1	0	11	5.3
Korea	0	4	3	70	1.7
World	**14**	**39**	**37**	**842**	**2.2**

Note: CAAGR = compound average annual growth rate; TWh = terawatt-hours; GW = gigawatts.

Table A.2: Sustainable Development Scenario

	Offshore wind overview					Shares (%)		CAAGR (%)
	2018	2025	2030	2035	2040	2018	2040	2018-40
Electricity generation (TWh)								
United States	0	14	72	157	260	0	13	42.8
European Union	60	209	370	559	777	91	37	12.3
China	6	62	179	344	546	8	26	23.1
India	-	3	14	39	70	-	3	n.a.
Japan	0	6	21	41	67	0	3	30.5
Korea	0	10	41	69	88	0	4	36.9
World	**67**	**329**	**764**	**1 362**	**2 072**	**100**	**100**	**16.9**
Share of total generation								
United States	0.0%	0.3%	1.6%	3.3%	5.3%			42.1
European Union	1.8%	6.2%	10.8%	15.1%	19.3%			11.3
China	0.1%	0.7%	1.9%	3.4%	5.0%			20.8
India	-	0.1%	0.5%	1.2%	1.8%			n.a.
Japan	0.0%	0.6%	2.1%	4.2%	6.7%			30.8
Korea	0.0%	1.7%	6.6%	10.5%	13.0%			36.0
World	**0.3%**	**1.1%**	**2.4%**	**3.9%**	**5.4%**			**14.9**
Installed capacity (GW)								
United States	0	5	21	42	68	0	12	42.0
European Union	19	56	92	132	175	83	31	10.7
China	4	25	65	115	173	16	31	19.1
India	-	1	5	13	23	-	4	n.a.
Japan	0	2	6	12	18	0	3	29.3
Korea	0	4	15	23	29	0	5	36.7
World	**23**	**101**	**225**	**385**	**562**	**100**	**100**	**15.7**
Capacity additions (GW)								
United States	-	2	4	5	5	-	13	n.a.
European Union	3	7	8	9	12	67	29	6.0
China	2	6	9	11	12	33	31	9.7
India	-	0	1	2	2	-	5	n.a.
Japan	-	1	1	1	1	-	3	n.a.
Korea	-	2	2	1	1	-	3	n.a.
World	**5**	**18**	**29**	**35**	**40**	**100**	**100**	**10.1**

	Average annual investments ($2018 billion)		Cumulative	CAAGR (%)
	2019-2030	2031-2040	2019-2040	2018-40
United States	6	10	163	23.1
European Union	22	23	498	1.6
China	11	16	295	3.9
India	1	3	46	16.9
Japan	2	2	42	13.4
Korea	4	3	75	1.3
World	**52**	**66**	**1 279**	**4.4**

Note: CAAGR = compound average annual growth rate; TWh = terawatt-hours; GW = gigawatts.

Table A.3: Offshore wind technical potential (TWh per year)

	Shallow water		Deep water		Total potential
	Near shore	Far from shore	Near shore	Far from shore	
North America	9 907	13 238	22 819	58 937	104 901
Canada	3 033	1 172	15 952	32 312	52 469
Mexico	542	903	1 021	3 239	5 705
United States*	6 333	11 163	5 846	23 386	46 727
Central and South America	3 847	4 438	6 439	37 144	51 869
Brazil	1 692	1 622	1 011	6 123	10 448
Europe	2 629	2 390	14 817	52 009	71 845
European Union**	2 266	1 077	7 541	25 844	36 728
Africa	1 123	572	7 699	17 107	26 502
Middle East	478	673	600	1 791	3 543
Saudi Arabia	123	114	63	648	948
Eurasia	9 382	17 402	9 943	48 735	85 462
Russia	8 931	17 264	9 429	47 790	83 413
Asia Pacific	8 508	12 451	14 440	41 357	76 757
Australia	4 093	3 317	4 319	4 404	16 132
China	1 822	2 869	142	3 489	8 323
India	683	280	903	4 130	5 996
Japan	30	13	2 223	6 808	9 074
Korea	27	586	366	2 068	3 048
Southeast Asia	1 318	4 351	1 631	7 832	15 133
World	**35 875**	**51 166**	**76 757**	**257 081**	**420 878**

* Potential available including Alaska and Hawaii. ** Potential available excluding Greenland.

Source: IEA analysis developed in collaboration with Imperial College London.

Assessing the technical potential of offshore wind

Introduction

In collaboration with Imperial College London, a detailed geospatial analysis was undertaken to assess the technical potential for offshore wind worldwide. This annex provides a description of the considerations and approach.

Scope of study

As part of this study, a number of considerations were taken into account including:

- Turbine designs for different wind speeds.
- Wind farm designs.
- Distance from shore.
- Water depth.
- Exclusion of regions with low wind speeds (less than 5 metres per second [m/s]), maritime protection areas, buffer zones for submarine cables, major shipping lanes, earthquake fault lines and competing uses such as existing offshore oil and gas installations.

Data

The availability of high-resolution satellite data and computing gains has significantly improved the granularity and accuracy of wind resource assessments in recent years. Emerging wind turbine designs are also cause to update potential assessments, as they increase performance in well-established areas and make lower quality resources more suitable for energy production.

This study is among the first to use the "ERA-5" reanalysis, which provides four decades of historic global weather data. "Renewables.ninja" extrapolates wind speeds to the desired hub height and converts them to output using manufacturers' power curves for 150 turbine models (Pfenninger and Staffell, 2016).

Tool for assessing annual capacity factors of offshore wind

The assessment of technical potential for offshore wind was conducted using the Renewables.ninja model. This tool simulates the annual capacity factors (and hourly power output) from wind and solar power plants located anywhere in the world by combining scientific-quality weather data with physics-based models of wind and solar farms. It is a publicly available tool, validated and calibrated against real-world output in 70 countries, and is available through a Creative Commons licence at www.renewables.ninja.

Exclusions

Commercially available offshore wind turbines are currently designed for wind speeds of more than 6 m/s. Some companies are also looking into turbine designs for lower wind speeds. For the purpose of this study, we have excluded regions of less than 5 m/s. But this does not limit the industry from developing technology and designs that can be suited for lower wind speeds.

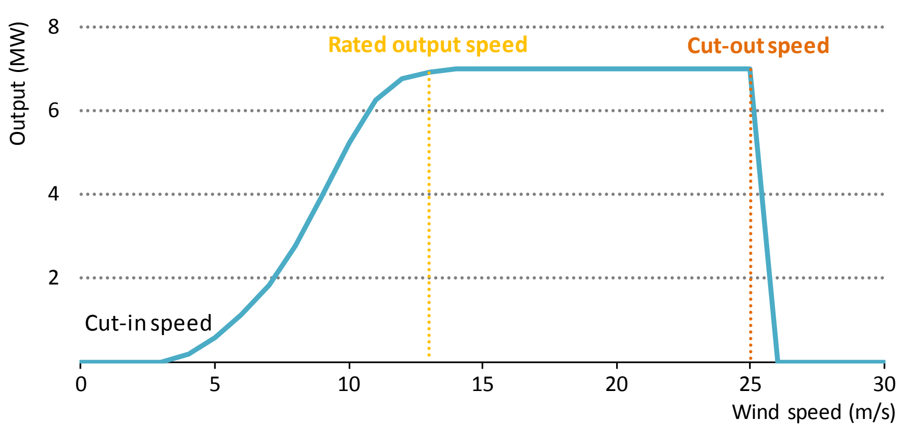
Following the International Union for Conservation of Nature's (IUCN) classification of maritime protection areas, those categorised as Ia, Ib, II and III were excluded from the study (IUCN, 2013). However, at each project level other environmental considerations must also be taken into account and a full environmental impact assessment conducted as mandated by public authorities. Measures to protect biodiversity should also be taken throughout the lifetime of the wind farm i.e. before, during and after construction.

As part of this analysis, buffer zones for existing submarine cables (1 kilometre [km]), major shipping lanes (20 km), earthquake fault lines (20 km) and competing uses such as existing offshore oil and gas installations and fisheries were also considered.

Turbine designs

The power curve of a wind turbine is a graph that indicates the profile of the electrical output corresponding to different wind speeds (Figure B.1). At very low wind speeds, there insufficient torque is exerted by the wind to make the turbine blades rotate. As the wind speed increases, the blades will begin to rotate and generate electrical power. The corresponding wind speed is called the "cut-in speed" and is typically 3-4 m/s.

Figure B.1 ▻ Illustrative power curve for a 7 MW wind turbine



Electrical output of a wind turbine depends on the wind speed and varies across different wind turbine models

Note: MW = megawatt.

As the wind speed increases above the cut-in speed, the electrical output typically rises rapidly until the power output reaches the limit for which the generator is designed, usually when the wind speed is somewhere between 12-17 m/s. This generator output limit is called the “rated power output” and the wind speed needed to reach it is called the “rated output wind speed”.

At even higher wind speeds, strong winds would exert high forces to the turbine structure, which at some point poses a risk of damage to the rotor. As such, a braking system is employed to bring the rotor to a standstill. This wind speed is called the “cut-out speed” and is usually around 25 m/s.

The electrical output that a turbine can generate is determined by the equation:

$$P = \frac{1}{2}\rho A v^3 C_p$$

Where P = power output, ρ = air density (kg/m^3), A = swept area (m^2), v = wind speed (m/s) and C_p = power coefficient

As shown in the equation, a higher swept area, A, i.e. the area through which the turbine blades spin, the higher the power output. This is because a higher swept area means that more wind can be captured by the blades.

In 1919, German physicist Albert Betz concluded that no wind turbine could convert more than 59.3% of the kinetic energy of the wind into mechanical energy turning a rotor, i.e. Betz limit. If a wind turbine was 100% efficient, all the wind would have to stop completely upon the contact with the turbine. This factor is called “power coefficient” and is defined as:

$$C_{p_{max}} = 0.59$$

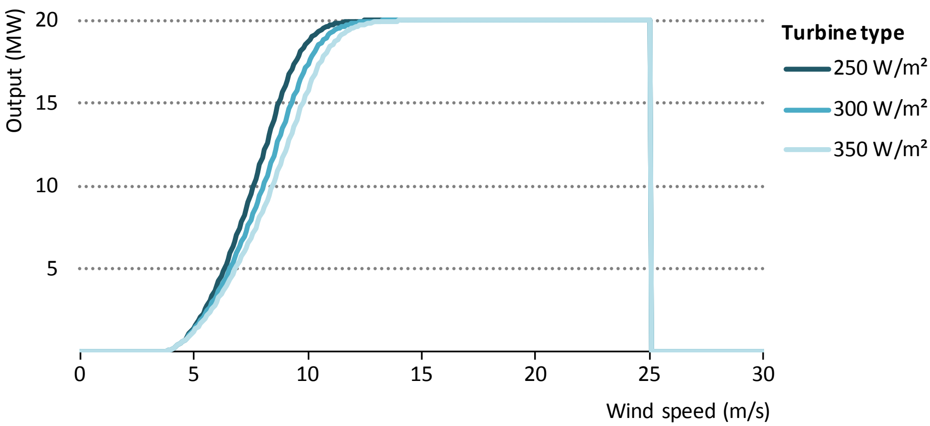
The *Cp* is dependent on various engineering requirements of a wind turbine, such as strength and durability, and the real-world power coefficient is in the range of 0.35 to 0.45.

Different wind turbines can be classified by their specific power (SP), which is defined as the turbine’s specific rated power capacity per swept area:

$$SP = \frac{P}{A} = \frac{\frac{1}{2}\rho A v^3 C_p}{A} = \frac{1}{2}\rho v^3 C_p$$

In order to assess the global technical potential, best-in-class turbines were chosen with specific power of 250, 300 and 350 watt per square metre (W/m^2) that corresponds to low-medium, medium and high wind speeds. The power curves of these turbines were used in conjunction with the global capacity factors of each 5km x 5km cell selected for the analysis (See section on “Global technical potential for offshore wind”) to derive the technical potential of offshore wind in terms of capacity and generation. New power curves were synthesised for next-generation turbines with rated capacity of up to 20 megawatts (MW), for which data are not yet available (Figure B.2) (Saint-Drenan et al., 2019).

Figure B.2 ▻ **Illustrative power curves for 20 MW wind turbines**



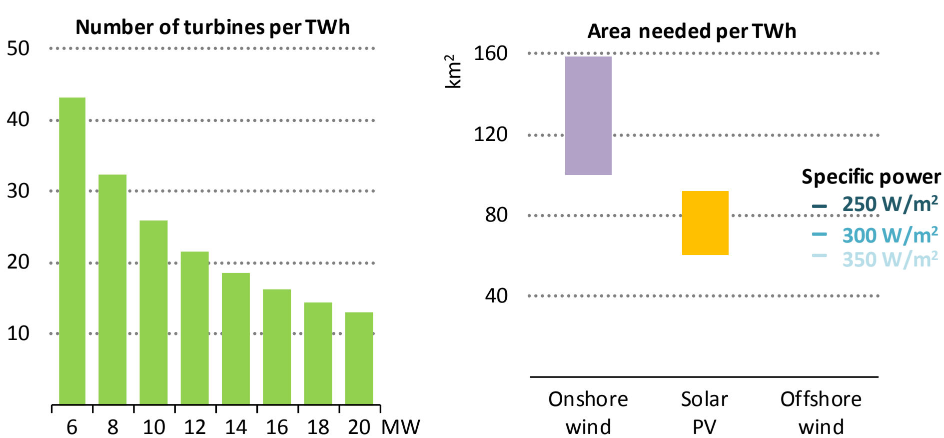
Power curves for three turbine types by specific power were synthesised for this study, which correspond to low-medium, medium and high wind speeds.

Source: Saint-Drenan et al. (2019).

Offshore wind farm designs

The number of turbines needed per unit of generation decreases as the rated power of the turbine increases (left graph of Figure B.3).

Figure B.3 ▻ **Number of turbines and space requirements**



The number of turbines required per unit of electricity generated decreases with bigger turbines, and space requirements are often less than for onshore wind or solar PV

Notes: TWh = terawatt-hour. Based on an 8 x 8 rotor diameter equivalent spacing configuration and 50% capacity factor for offshore wind.

Sources: IEA analysis; van Zalk et al. (2018).

While it would be intuitive to pack as many turbines in a given area, it is important to note that after the wind passes through a turbine, the wind speed on a downstream wind turbine is lowered as energy has been extracted by the turbine upstream. This wake effect can have a significant impact on the generation output of a wind farm ("wake losses"). The losses can be reduced by optimising the layout of wind farms (e.g. turbine orientation and spacing). Subject to site constraints, the current industry norm is to use between 7-10 rotor diameters spacing with associated 11-13% wake losses (Table B.1). Based on simulation models, a higher range of wake loses of around 16-17% would be expected when using a lower rotor diameter spacing (NREL, 2013).

Table B.1 ▹ Wind farm configuration of selected projects

Country	Projects	Capacity	Wind farm configuration (rotor diameter equivalent)
Germany	Sandbank	72 x 4 MW	8 x 9
	Wikinger	70 x 5 MW	6.7 x 4.5
	Arkona	60 x 6 MW	6.4 x 4.7
Denmark	Horns Rev 1	80 x 2 MW	8.7 x 7.0
	Horns Rev 2	91 x 2.3 MW	9.3 x 7.1
	Anholt	111 x 3.6 MW	9.9 x 9.2
United Kingdom	Gunfleet Sands	48 x 3.6 MW	9.3 x 5.8
	Greater Gabbard	140 x 3.6 MW	10.3 x 9.8
	Galloper	56 x 6.3 MW	8.6 x 6.9

Using an 8 by 8 rotor diameter equivalent spacing for offshore wind farm configuration, the area needed per terawatt-hour of generation is lower than onshore wind and comparable with solar photovoltaics (PV) (right graph of Figure B.3). With offshore wind turbines, a turbine with a lower specific power, means that the swept area is bigger (i.e. longer rotor diameter) in order to capture the equivalent energy compared to those designed for higher specific power i.e. higher wind speeds. This translates to larger space requirements per terawatt-hour for turbines with lower specific power.

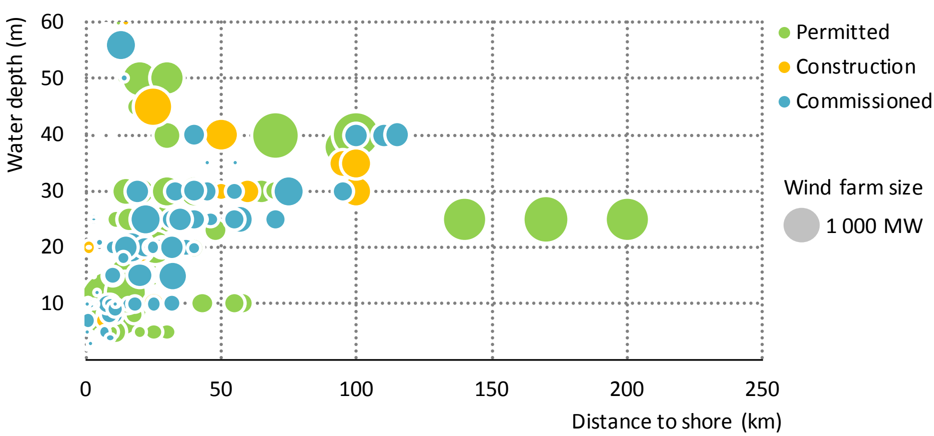
Through digitalisation, the performance of wind farms can be enhanced by deploying sensors for real-time monitoring and utilising advanced techniques for active control of the turbines depending on the wind speed and direction to reduce the wake losses.

Distance from shore and water depth

Offshore wind installations today are moving further from shore and into deeper waters where better quality wind resources are available (Figure B.4). For example, the 864 MW SylWin1 in Germany and the 1 386 MW Hornsea 2 in the United Kingdom projects which are located 160 km and 89 km from shore are among the longest offshore grid connection in the world. In order to transmit the electricity generated to shore, the projects are deploying different technologies; SylWin1 is using high-voltage direct current connection (HVDC) transmission cable while the Hornsea 2 project is using alternating current transmission cable. There are differing cost and energy savings for both options at different lengths with HVDC offering significant cost savings over longer distances. (See section on "Offshore wind costs, value and competitiveness")

Developers are installing turbines in deeper waters, owing to improving construction techniques as a result of learning from earlier projects. The use of relatively low-cost monopile foundations has been the industry standard for the majority of the projects installed in water depths of less than 50 metres (m). Projects located in deeper waters (50-60 m) are pushing for the use of such foundations in favour of higher cost jacket and floating foundations. Beyond water depths of 60 m, the industry is deploying different floating foundation pilots (e.g. Scotland's 30 MW Hywind Scotland Pilot Park and Japan's 3.2 MW Hibiki) to improve the designs. Equinor received approval in June 2019 to build a 200 MW floating offshore wind farm off the coast of the Canary Islands which is expected to be the world's largest when it begins operations in the mid-2020s. (See Box 1 in section on "Offshore wind technology and performance")

Figure B.4 ▹ Water depth and distance to shore for offshore wind projects



Projects are moving further away from shore and also into deeper waters

Source: The Wind Power (2019).

For this study of technical potential, we have limited the analysis to within 300 km from the nearest shoreline. This is assessed based on the latest technology and cost associated with deployment, in particular the length and construction methods for submarine transmission cables needed to bring the electricity generated to shore. However, the distance would not be an issue if instead of being connected to electricity supply on shore, it is a standalone facility coupled with the production of green hydrogen and exported by specialised vessels to shore. (See section on "Increased demand for renewable hydrogen")

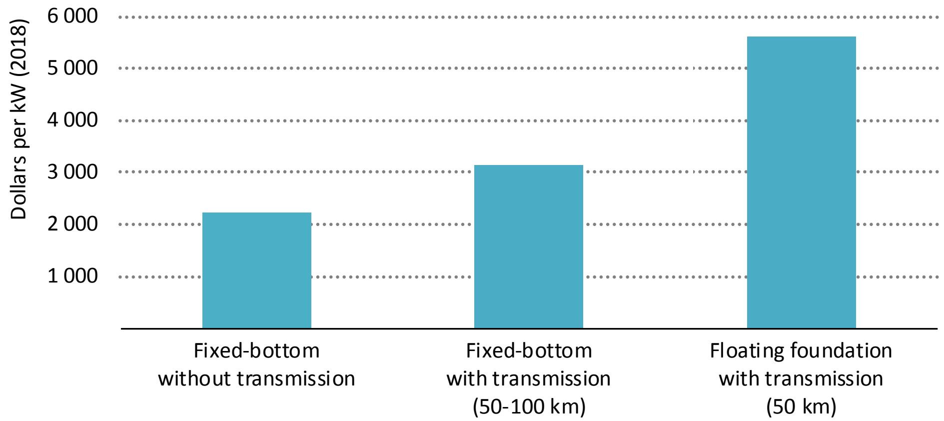
As for the water depth, we have limited the analysis to less than 2 000 m depth. This parameter is sub-divided into two regions, the first being less than 60 m water depth suitable for fixed-bottom foundations, and the second between 60-2 000 m that are suitable for floating foundations. While the limit is 2 000 m for the purpose of this study, this does not preclude floating foundation technology options for depths beyond 2 000 m in the future.

Offshore wind costs: moving to floating structures

Costs are declining. For projects to be commissioned in mid-2020s around the world, offshore wind farm costs are projected to fall to nearly $3 000 per kilowatt (kW), 30% lower than today's levels when offshore transmission assets are included. This is mostly a reflection of project site specifics linked to water depths and distance to shore, but also fixed-bottom foundation types used and the size of the turbines installed.

Meanwhile, the associated costs of the offshore transmission assets stand at over 20% of total project costs, mostly related to the actual distance to shore, the type of cable employed and the size of the required offshore substations. For projects located around 50 to 100 km from shore, this implies offshore wind farm costs would be over $2 000/kW on average when considering just the cost of the offshore wind farm and not including the costs for the offshore substation and connection (Figure B.5).

Figure B.5 ▹ Indicative capital costs for example types of offshore wind projects to be commissioned by mid-2020s



Floating offshore wind capital costs are currently above those of fixed-bottom foundations. However, technology development could reduce the difference in the future

Notes: Transmission includes the cost of associated offshore substations.

Floating offshore wind farms are gaining momentum, opening up deep water project sites. For projects to be commissioned before 2025, costs are expected to remain quite diverse and linked to regional market developments. Floating offshore wind installations do not incur the cost associated with fixed-bottom foundations, however, floating foundations are an emerging technology with components still in an early stage of demonstration. There is significant potential for future cost reductions. There are a few examples on the horizon that will demonstrate floating wind developments: Equinor and its partners took Final Investment Decision (FID) for the 88 MW Hywind Tampen floating project in the Norwegian Sea, and also expressed interest to build a 200 MW floating wind farm near the Canary Islands; the Macquarie Group has teamed with Gyeongbuk Floating Offshore Wind Power to jointly develop a 1 gigawatt (GW) floating wind project in Korea. First experiences with floating offshore substations have been made in Japan with the FORWARD project near to the shore of Fukushima. Large offshore substations where the internal equipment is capable to withstand movements from the sea waves have yet to be developed and might have an impact on the additional costs for floating offshore wind developments.

Offshore wind technical potential

Based on the assessment, we estimate that the technical potential for offshore wind worldwide is more than 120 000 GW, with the potential to generate more than 420 000 terawatt-hours (TWh) of electricity per year.

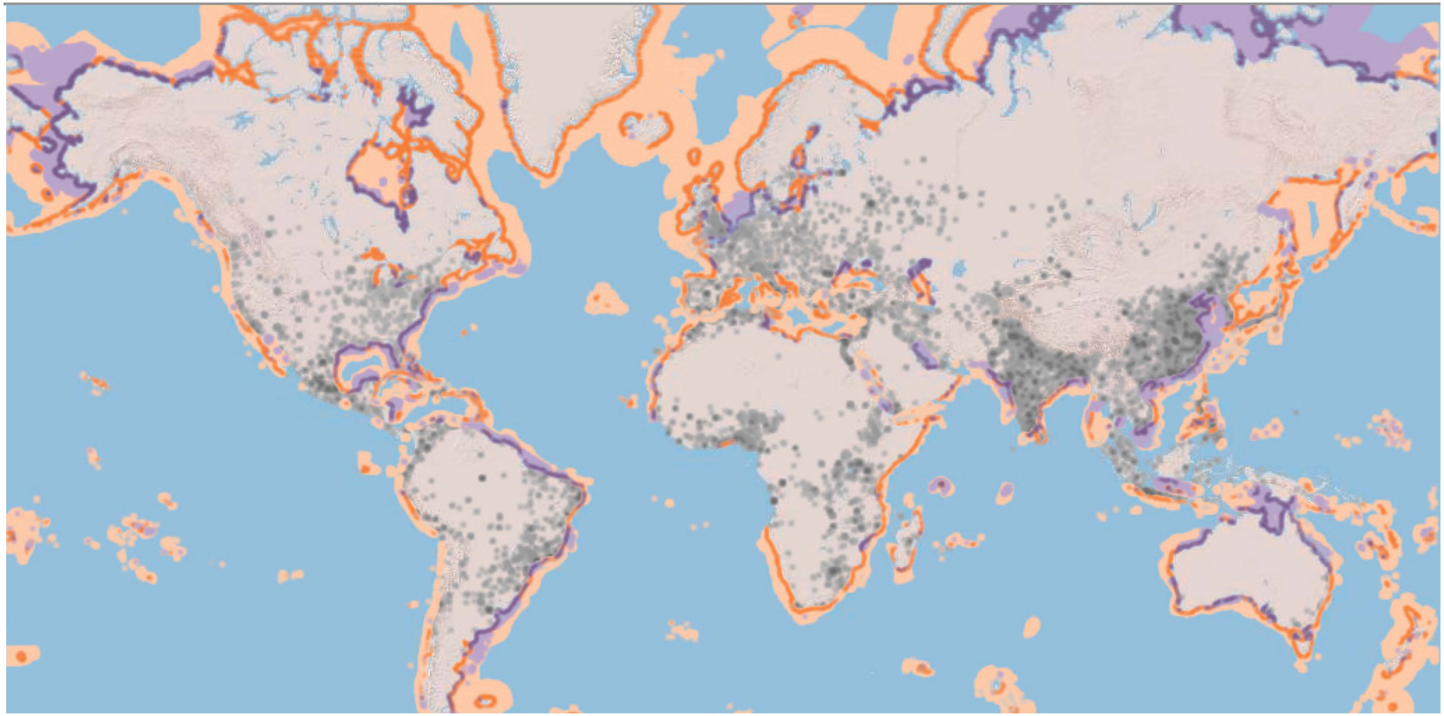
The technical potential can be divided between what is available in shallow water (i.e. < 60 m) and in deep water (i.e. 60-2 000 m). Broadly speaking, shallow water sites are suitable for established fixed-bottom foundations and are easier to access, while those for deeper water sites require floating platforms and are harder to access.

Within these two broad categories, the technical potential can be further sub-divided: sites that are near to shore (i.e. 20-60 km) and within 50 km of existing commissioned projects; other potential sites that are close to shore; sites far from shore (i.e. 60-300 km); and sites with existing restrictions or competing uses such as oil and gas installations.

The following maps (Figures B.6-B.11), illustrate the geospatial locations of the global and regional offshore wind technical potentials based on the four categories.

In addition to the location in assessing suitable sites for offshore wind deployment, other considerations including the quality of wind resources (i.e. capacity factor) and associated costs are key factors. (See section on “Offshore wind costs, value and competitiveness”)

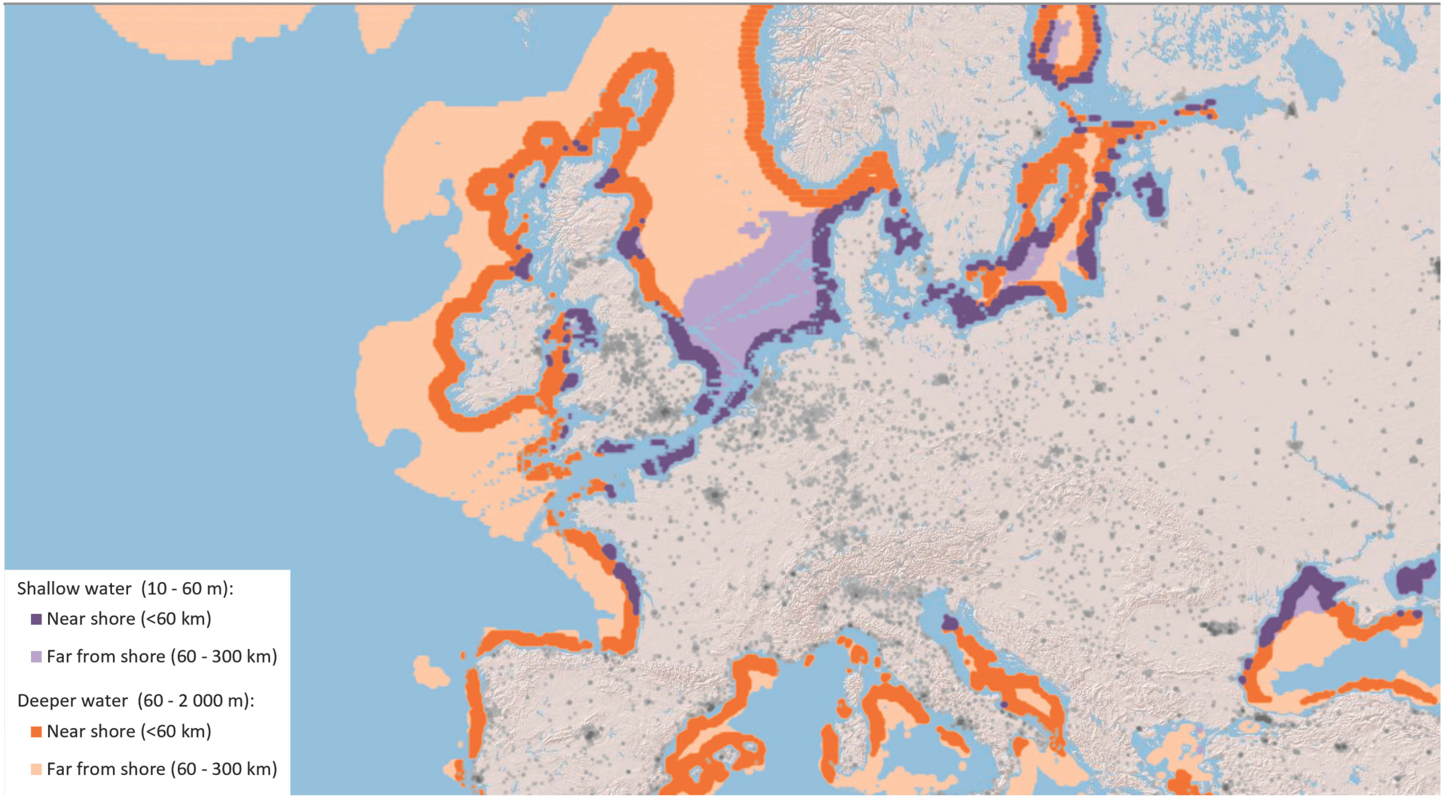
Figure B.6 ▷ Global offshore wind technical potential map



Note: Inland dots depict population density of more than 500, 2 000 and 8 000 people per km^2 with darker shades of grey.

Source: IEA analysis developed in collaboration with Imperial College London

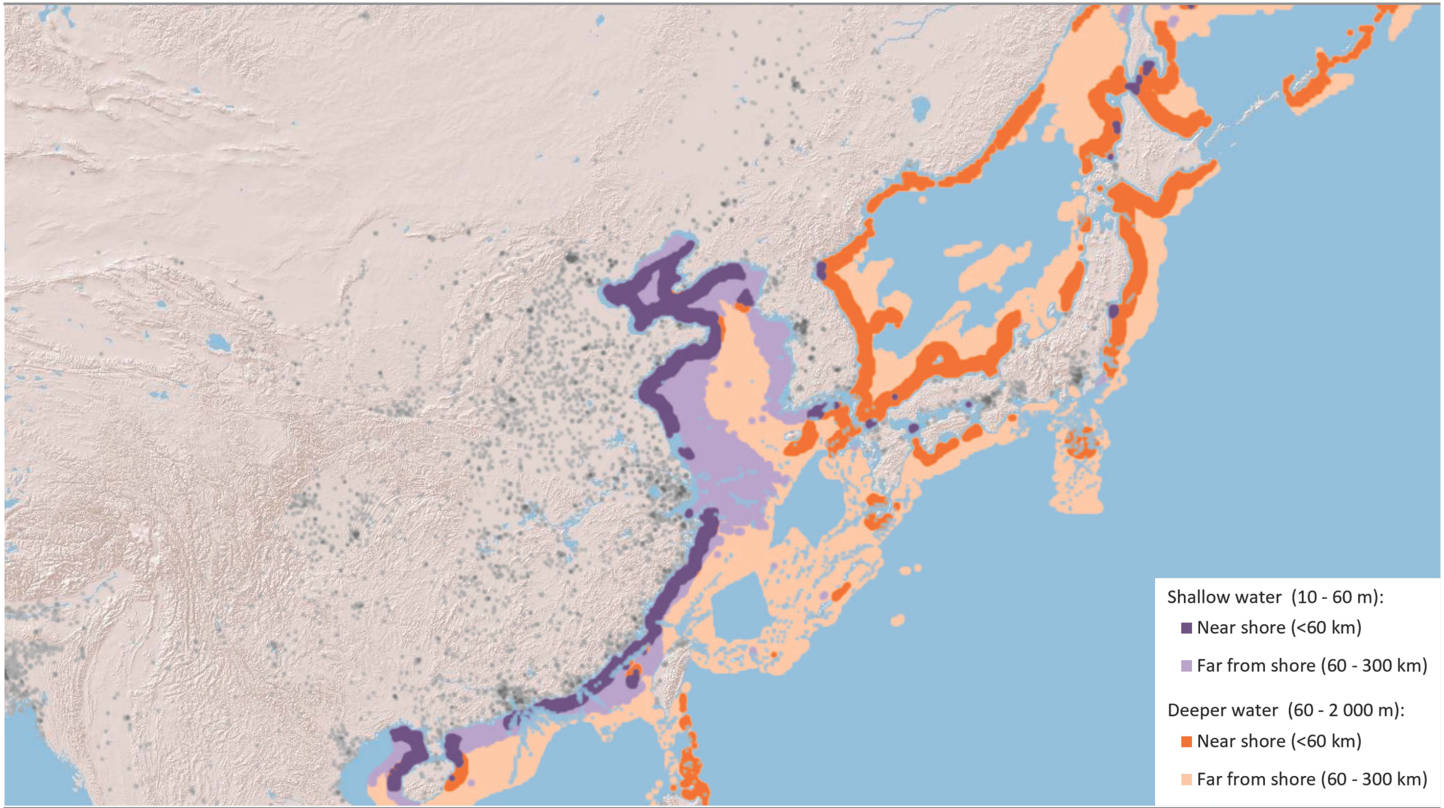
Figure B.7 ▷ **Offshore wind technical potential map for Europe**



Note: Inland dots depict population density of more than 500, 2 000 and 8 000 people per km^2 with darker shades of grey.

Source: IEA analysis developed in collaboration with Imperial College London

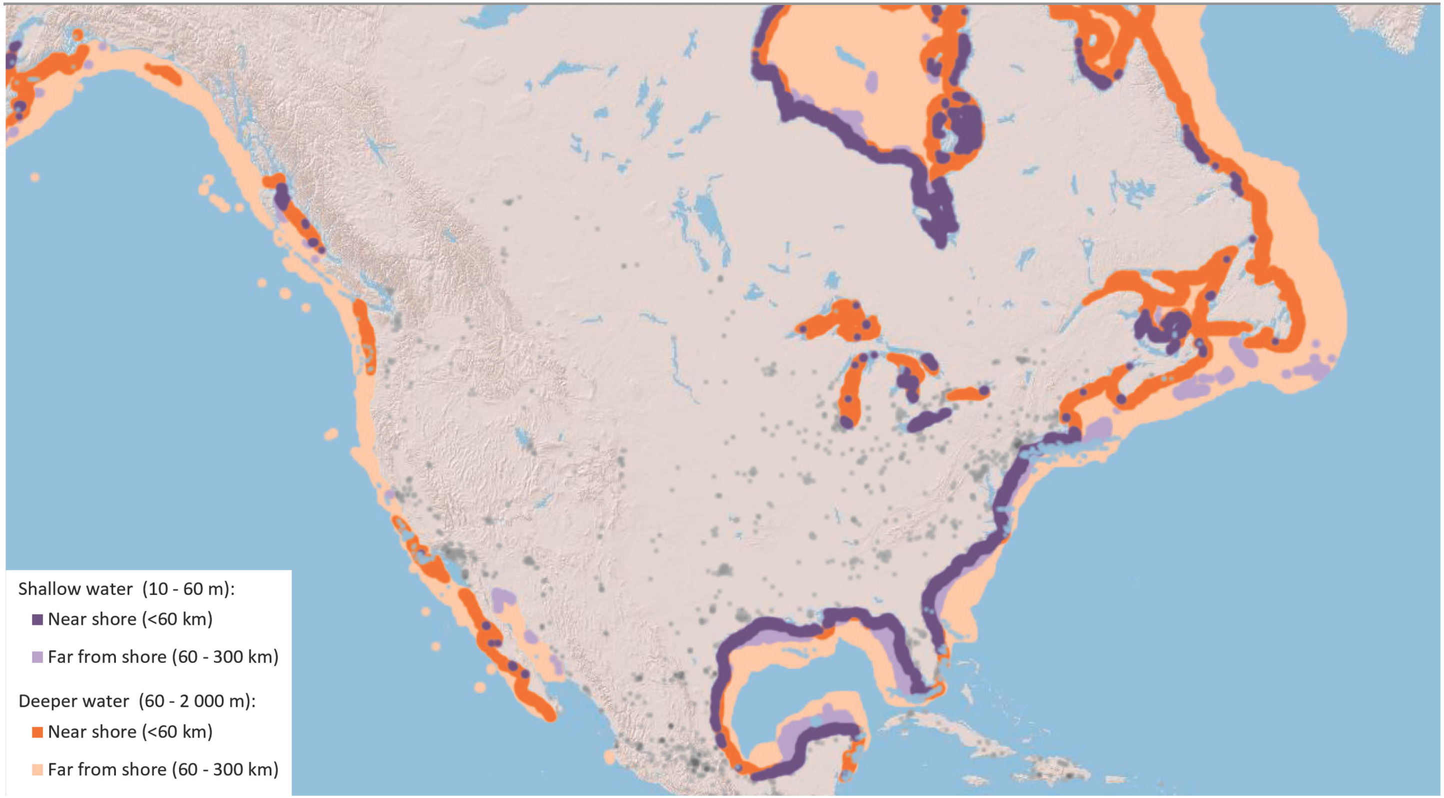
Figure B.8 ▷ Offshore wind technical potential map for East Asia



Note: Inland dots depict population density of more than 500, 2 000 and 8 000 people per km^2 with darker shades of grey.

Source: IEA analysis developed in collaboration with Imperial College London

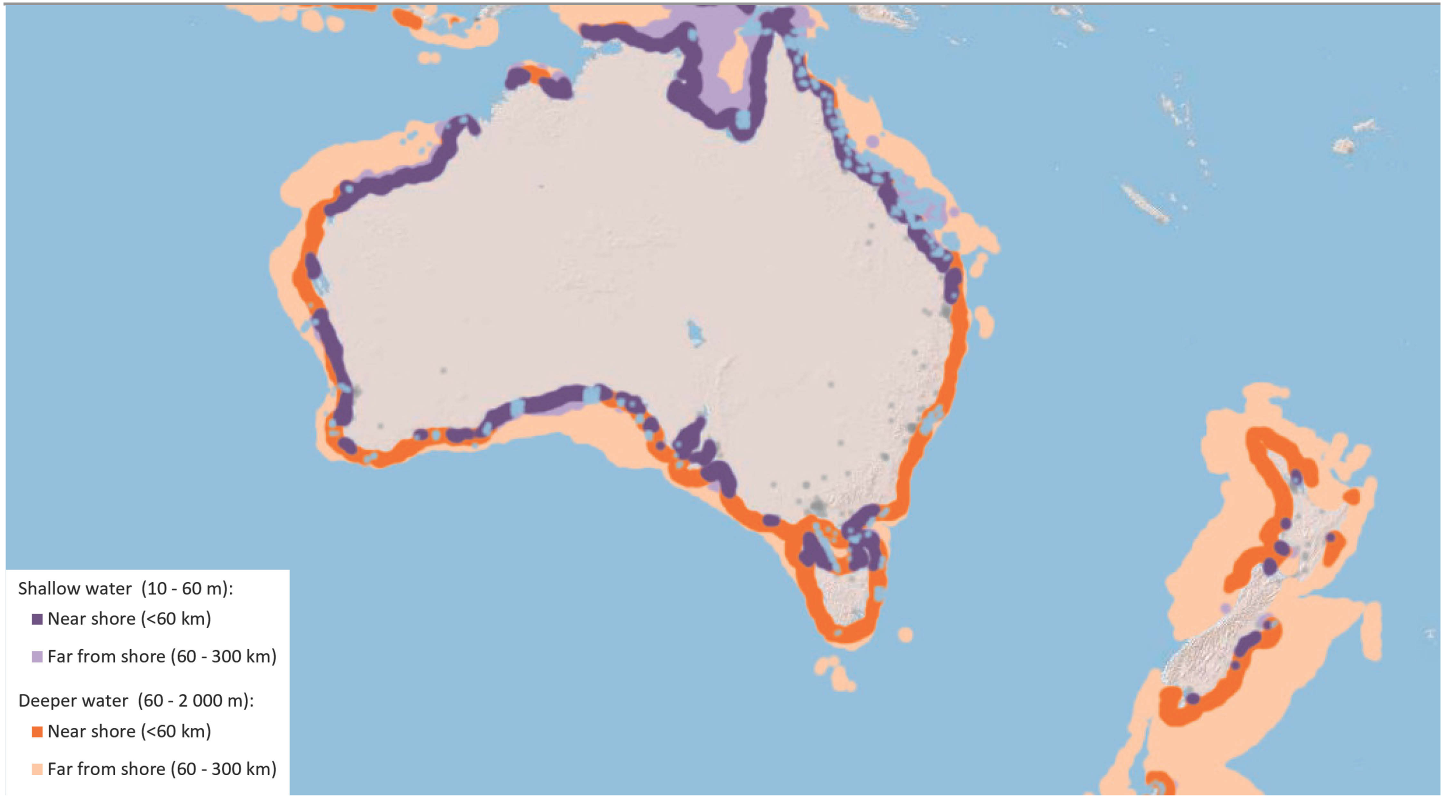
Figure B.9 ▷ Offshore wind technical potential map for North America



Note: Inland dots depict population density of more than 500, 2 000 and 8 000 people per km^2 with darker shades of grey.

Source: IEA analysis developed in collaboration with Imperial College London

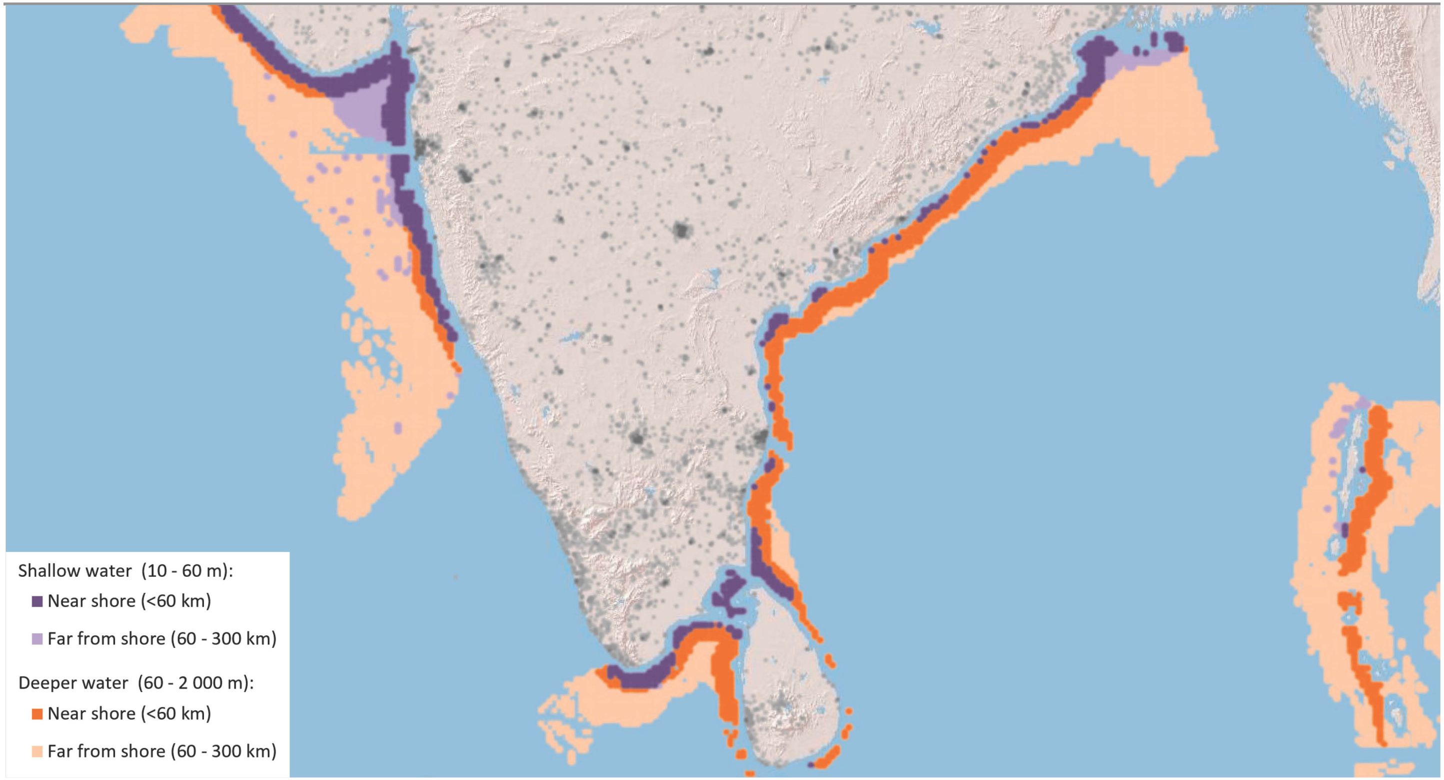
Figure B.10 ▷ Offshore wind technical potential map for Australia and New Zealand



Note: Inland dots depict population density of more than 500, 2 000 and 8 000 people per km^2 with darker shades of grey.

Source: IEA analysis developed in collaboration with Imperial College London

Figure B.11 ▷ Offshore wind technical potential map for India



Note: Inland dots depict population density of more than 500, 2 000 and 8 000 people per km^2 with darker shades of grey.

Source: IEA analysis developed in collaboration with Imperial College London

Definitions

This annex provides general information on terminology used throughout this publication including: units and general conversion factors; definitions of fuels, processes and sectors; regional and country groupings; and abbreviations and acronyms.

Units

Area	km^2	square kilometre
Emissions	g CO_2/kWh	grammes of carbon dioxide per kilowatt-hour
Energy	toe	tonne of oil equivalent
	ktoe	thousand tonnes of oil equivalent
	Mtoe	million tonnes of oil equivalent
	MBtu	million British thermal units
	Gcal	gigacalorie (1 calorie x 10^9)
	TJ	terajoule (1 joule x 10^{12})
	kWh	kilowatt-hour
	MWh	megawatt-hour
	GWh	gigawatt-hour
	TWh	terawatt-hour
Mass	kg	kilogramme (1 000 kg = 1 tonne)
	kt	kilotonnes (1 tonne x 10^3)
	Mt	million tonnes (1 tonne x 10^6)
	Gt	gigatonnes (1 tonne x 10^9)
Monetary	$ million	1 US dollar x 10^6
	$ billion	1 US dollar x 10^9
	$ trillion	1 US dollar x 10^{12}
Power	W	watt (1 joule per second)
	kW	kilowatt (1 watt x 10^3)
	MW	megawatt (1 watt x 10^6)
	GW	gigawatt (1 watt x 10^9)
	TW	terawatt (1 watt x 10^{12})

General conversion factors for energy

Convert to:	TJ	Gcal	Mtoe	MBtu	GWh
From:	multiply by:				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11 630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3 412	1

Currency conversions

***Exchange rates** (2018 annual average)*	**1 US Dollar equals:**
British Pound	0.75
Chinese Yuan Renminbi	6.62
Euro	0.85
Indian Rupee	68.39
Indonesian Rupiah	14 236.94
Japanese Yen	110.42
Russian Ruble	62.67
South African Rand	13.24

Source: OECD National Accounts Statistics: purchasing power parity and exchange rates, September 2019.

Definitions

Capacity credit: Proportion of the capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.

Capacity factor: Describes the average output over the year relative to the maximum rated power capacity.

Coal: Includes both primary coal (including lignite, coking and steam coal) and derived fuels (including patent fuel, brown-coal briquettes, coke-oven coke, gas coke, gas-works gas, coke-oven gas, blast-furnace gas and oxygen steel furnace gas). Peat is also included.

Decomposition analysis: Statistical approach that decomposes an aggregate indicator to quantify the relative contribution of a set of pre-defined factors leading to a change in the aggregate indicator. The *World Energy Outlook* uses an additive index decomposition of the type Logarithmic Mean Divisia Index I (LMDI).

Dispatchable: Dispatchable generation refers to technologies whose power output can be readily controlled - increased to maximum rated capacity or decreased to zero - in order to match supply with demand.

Electricity demand: Defined as total gross electricity generation less own use generation, plus net trade (imports less exports), less transmissions and distribution losses.

Electricity generation: Defined as the total amount of electricity generated by power only or combined heat and power plants including generation required for own use. This is also referred to as gross generation.

Gas (also referred to as natural gas)**:** Comprises gases occurring in deposits, whether liquefied or gaseous, consisting mainly of methane. It includes both "non-associated" gas originating from fields producing hydrocarbons only in gaseous form, and "associated" gas produced in association with crude oil as well as methane recovered from coal mines (colliery gas). Natural gas liquids (NGLs), manufactured gas (produced from municipal or industrial waste, or sewage) and quantities vented or flared are not included. Gas data in cubic metres are expressed on a "gross" calorific value basis and are measured at 15 °C and at 760 mm Hg ("Standard Conditions"). Gas data expressed in tonnes of oil equivalent, mainly for comparison reasons with other fuels, are on a "net" calorific basis. The difference between the "net" and the "gross" calorific value is the latent heat of vaporisation of the water vapour produced during combustion of the fuel (for gas the net calorific value is 10% lower than the gross calorific value).

Hydrogen: Defined as an energy carrier, which can be produced by various energy sources and technologies, similar to electricity.

Hydropower: The energy content of the electricity produced in hydropower plants, assuming 100% efficiency. It excludes output from pumped storage and marine (tide and wave) plants.

Industry: The sector includes fuel used within the manufacturing and construction industries. Key industry branches include iron and steel, chemical and petrochemical, cement, and pulp and paper. Use by industries for the transformation of energy into another form or for the production of fuels is excluded and reported separately under "other energy". Consumption of fuels for the transport of goods is reported as part of the transport sector, while consumption by off-road vehicles is reported under industry.

Investment: All investment data and projections reflect spending across the lifecycle of a project, i.e. the capital spent is assigned to the year when it is incurred. Investments for oil, gas and coal include production, transformation and transportation; those for the power sector include refurbishments, uprates, new builds and replacements for all fuels and technologies for on-grid, mini-grid and off-grid generation, as well as investment in transmission and distribution, and battery storage. Investment data are presented in real terms in year-2018 US dollars unless otherwise stated.

Note that this investment definition is new and our methodology to assess investment has changed from the previous editions of the *World Energy Outlook*. Previously, the investment data reflected "overnight investment", i.e. the capital spent is generally assigned to the year production (or trade) is started, rather than the year when it is incurred.

Nuclear: Refers to the primary energy equivalent of the electricity produced by a nuclear plant, assuming an average conversion efficiency of 33%.

Offshore wind: Refers to the primary energy equivalent of the electricity produced by wind turbines that are installed in near-shore or farther from shore, usually in the ocean.

Oil: Oil production includes both conventional and unconventional oil. Petroleum products include refinery gas, ethane, liquid petroleum gas, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin, waxes and petroleum coke.

Other energy sector: Covers the use of energy by transformation industries and the energy losses in converting primary energy into a form that can be used in the final consuming sectors. It includes losses by gas works, petroleum refineries, blast furnaces, coke ovens, coal and gas transformation and liquefaction. It also includes energy used in coal mines, in oil and gas extraction and in electricity and heat production. Transfers and statistical differences are also included in this category.

Power generation: Refers to fuel use to produce electricity at power stations, heat plants and combined heat and power (CHP) plants. Both main activity producer plants and small plants that produce fuel for their own use (auto-producers) are included.

Renewables: Includes bioenergy, geothermal, hydropower, solar photovoltaics (PV), concentrating solar power (CSP), onshore and offshore wind and marine (tide and wave) energy for electricity and heat generation.

Total final consumption (TFC)**:** Is the sum of consumption by the various end-use sectors. TFC is broken down into energy demand in the following sectors: industry (including manufacturing and mining), transport, buildings (including residential and services) and other (including agriculture and non-energy use). It excludes international marine and aviation bunkers, except at world level where it is included in the transport sector.

Total final energy consumption (TFEC)**:** Is a variable defined primarily for tracking progress towards target 7.2 of the Sustainable Development Goals. It incorporates total final consumption (TFC) by end-use sectors but excludes non-energy use. It excludes international marine and aviation bunkers, except at world level. Typically this is used in the context of calculating the renewable energy share in total final energy consumption (Indicator 7.2.1 of the Sustainable Development Goals), where TFEC is the denominator.

Total primary energy demand (TPED)**:** Represents domestic demand only and is broken down into power generation, other energy sector and total final consumption.

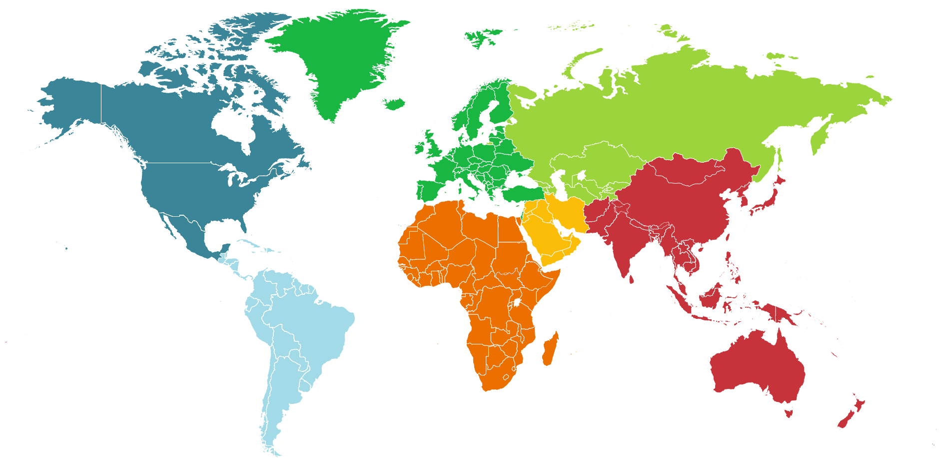
Transport: Fuels and electricity used in the transport of goods or persons within the national territory irrespective of the economic sector within which the activity occurs. This includes fuel and electricity delivered to vehicles using public roads or for use in rail vehicles; fuel delivered to vessels for domestic navigation; fuel delivered to aircraft for domestic aviation; and energy consumed in the delivery of fuels through pipelines. Fuel delivered to international marine and aviation bunkers is presented only at the world level and is excluded from the transport sector at a domestic level.

Variable renewable energy: Refers to technologies whose maximum output at any time depends on the availability of fluctuating renewable energy resources. VRE includes a broad array of technologies such as wind power, solar PV, run-of-river hydro, concentrating solar power (where no thermal storage is included) and marine (tidal and wave).

Wake losses: The effect on the space behind a turbine that is marked by decreased wind speed on a downstream wind turbine due to the fact that the turbine itself used the energy in turning the blades.

Regional and country groupings

Figure C.1 ▷ ***World Energy Outlook* main country groupings**



Advanced economies: OECD regional grouping and Bulgaria, Croatia, Cyprus,[1,2] Malta and Romania.

Africa: North Africa and sub-Saharan Africa regional groupings.

Asia Pacific: Southeast Asia regional grouping and Australia, Bangladesh, China, India, Japan, Korea, Democratic People's Republic of Korea, Mongolia, Nepal, New Zealand, Pakistan, Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[3]

Caspian: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

Central and South America: Argentina, Plurinational State of Bolivia (Bolivia), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Bolivarian Republic of Venezuela (Venezuela), and other Central and South American countries and territories.[4]

China: Includes the (People's Republic of) China and Hong Kong, China.

Developing Asia: Asia Pacific regional grouping excluding Australia, Japan, Korea and New Zealand.

Developing economies: All other countries not included in the "advanced economies" regional grouping.

Eurasia: Caspian regional grouping and the Russian Federation (Russia).

Europe: European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, Republic of North Macedonia, Gibraltar, Iceland, Israel,[5] Kosovo, Montenegro, Norway, Serbia, Switzerland, Republic of Moldova, Turkey and Ukraine.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus,[1,2] Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and United Kingdom.

IEA (International Energy Agency)**:** OECD regional grouping excluding Chile, Iceland, Israel, Latvia, Lithuania and Slovenia.

Latin America: Central and South America regional grouping and Mexico.

Middle East: Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

Non-OECD: All other countries not included in the OECD regional grouping.

Non-OPEC: All other countries not included in the OPEC regional grouping.

North Africa: Algeria, Egypt, Libya, Morocco and Tunisia.

North America: Canada, Mexico and United States.

OECD (Organisation for Economic Co-operation and Development)**:** Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States.

OPEC (Organisation of the Petroleum Exporting Countries)**:** Algeria, Angola, Republic of the Congo (Congo), Ecuador, Equatorial Guinea, Gabon, Islamic Republic of Iran (Iran), Iraq, Kuwait, Libya, Nigeria, Saudi Arabia, United Arab Emirates and Bolivarian Republic of Venezuela (Venezuela).

Southeast Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Sub-Saharan Africa: Angola, Benin, Botswana, Cameroon, Republic of the Congo (Congo), Côte d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Zambia, Zimbabwe and other African countries and territories.[6]

Country Notes

[1] Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

[2] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[3] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Lao People's Democratic Republic (Lao PDR), Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste and Tonga and Vanuatu.

[4] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, Saba, Saint Eustatius, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten, Turks and Caicos Islands.

[5] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[6] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Equatorial Guinea, Kingdom of Eswatini, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Réunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia and Uganda.

Abbreviations and Acronyms

AC	alternating current
BNEF	Bloomberg New Energy Finance
CAAGR	compound average annual growth rate
CCGT	combined-cycle gas turbine
CCUS	carbon capture, utilisation and storage
CO_2	carbon dioxide
CO_2-eq	carbon-dioxide equivalent
COD	Commercial operation date
COP	Conference of Parties (UNFCCC)
CPS	Current Policies Scenario
CSP	concentrating solar power
DC	direct current
ECMWF	European Centre for Medium-Range Weather Forecasts
EU	European Union
ENTSO-E	European Network of Transmission System Operators for Electricity
GDP	gross domestic product
GHG	greenhouse gases
HVDC	high-voltage direct current
IEA	International Energy Agency
IJGLOBAL	Infrastructure Journal and Project Finance Magazine

IRENA	International Renewables Energy Agency
ITC	Investment Tax Credit
IUCN	International Union for Conservation of Nature
LCOE	levelised cost of electricity
LNG	liquefied natural gas
MER	market exchange rate
NDCs	Nationally Determined Contributions
NDRC	National Development and Reform Commission
NREL	US National Renewables Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
O&M	operation and maintenance
OPEC	Organization of Petroleum Exporting Countries
PBL	PBL Netherlands Environmental Assessment Agency
PTC	Production Tax Credit
PV	photovoltaics
SDS	Sustainable Development Scenario
STEPS	Stated Policies Scenario
T&D	transmission and distribution
TFC	total final consumption
TFEC	total final energy consumption
TPED	total primary energy demand
TSO	Transmission system operator
UK	United Kingdom
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
US DOE	United States Department of Energy
VALCOE	value-adjusted levelised cost of electricity
VRE	variable renewable energy
WACC	weighted average cost of capital
WEO	*World Energy Outlook*
WEM	World Energy Model
WWF	World Wide Fund for Nature

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Offshore Wind Outlook 2019

World Energy Outlook Special Report

Offshore wind is a rapidly maturing renewable energy technology that is poised to play an important role in future energy systems. In 2018, offshore wind provided a tiny fraction of global electricity supply, but it is set to expand strongly in the coming decades into a $1 trillion business. Turbines are growing in size and in terms of the power capacity they can provide, which in turn is delivering major performance and cost improvements for offshore wind farms.

This new World Energy Outlook special report provides the most comprehensive analysis to date of the global outlook for offshore wind, its contributions to electricity systems and its role in clean energy transitions. The report is a deep dive into offshore wind, giving a snapshot of where the market, technology and policies stand today – and mapping out how they may develop over the next two decades. It draws on a state-of-the-art geospatial analysis of the world's offshore wind resources and explores the implications of the technology's growth for global environmental goals and energy security.