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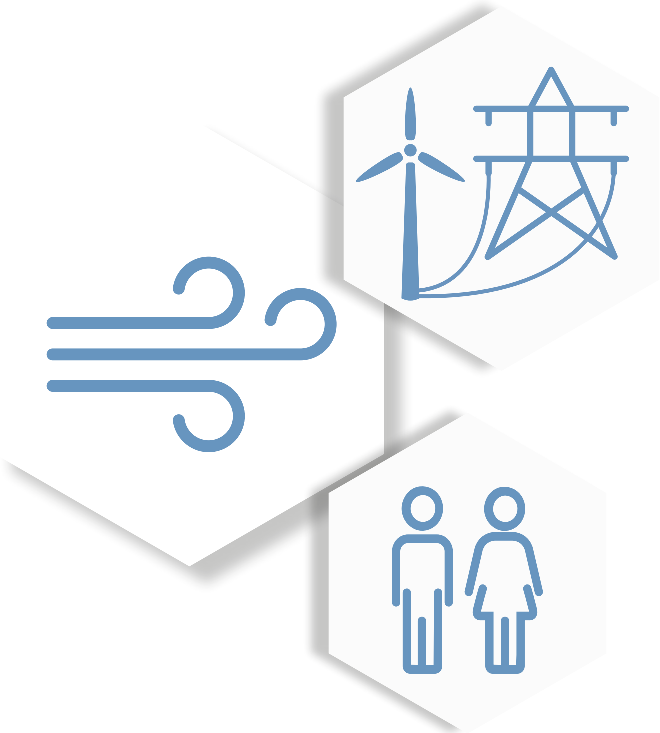

FUTURE OF WIND

Deployment, investment, technology, grid integration and socio-economic aspects

A Global Energy Transformation paper

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About IRENA

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

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Disclaimer

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Annual global temperatures from 1850–2017 Warming Stripes, by **Ed Hawkins**, climate scientist in the National Centre for Atmospheric Science (NCAS) at the University of Reading.

The visualisation ***illustrates the changes witnessed in temperatures*** across the globe over the past century and more. The colour of each stripe represents the temperature of a single year, ordered from the earliest available data at each location to now. The colour scale represents the change in global temperatures covering 1.35 °C.

ABBREVIATIONS

°C	degree Celsius
AC	alternating current
CAGR	compound annual growth rate
CAPEX	capital expenditure
CMS	condition monitoring systems
CO_2	carbon dioxide
CSP	concentrating solar power
DC	direct current
DOE	US Department of Energy
EU	European Union
EV	electric vehicle
G20	Group of Twenty
GBP	British pound
Gt	gigatonne
GW	gigawatt
GWEC	Global Wind Energy Council
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IRENA	International Renewable Energy Agency
IPCC	Intergovernmental Panel on Climate Change
km^2	square kilometre
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelised cost of electricity
m^2	square metre
MW	megawatt
MWh	megawatt-hour
NDC	Nationally Determined Contributions
NREL	US National Renewable Energy Laboratory
O&M	operations and maintenance
OPEX	operating expenditure
PPA	power purchase agreement
PTC	US Production Tax Credit
PV	photovoltaic
R&D	research and development
RD	rotor diameter
REmap	IRENA's renewable energy roadmap
TW	terawatt
TWh	terawatt-hour
UK	United Kingdom
US	United States
USD	US dollar
V2G	vehicle-to-grid
VRE	variable renewable energy
W	watt
yr	year

EXECUTIVE SUMMARY

DECARBONISATION OF THE ENERGY SECTOR AND THE REDUCTION OF CARBON EMISSIONS TO LIMIT CLIMATE CHANGE IS AT THE HEART OF THE INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA)'S ENERGY TRANSFORMATION ROADMAPS. These roadmaps examine and provide an assertive yet technically and economically feasible pathway for the deployment of low-carbon technology towards a sustainable and clean energy future.

IRENA HAS EXPLORED TWO ENERGY DEVELOPMENT PATHWAYS TO THE YEAR 2050 AS PART OF THE 2019 EDITION OF ITS GLOBAL ENERGY TRANSFORMATION REPORT. The first is an energy pathway set by current and planned policies (Reference Case). The second is a cleaner climate-resilient pathway based largely on more ambitious, yet achievable, uptake of renewable energy and energy efficiency measures (REmap Case), which limits the rise in global temperature to well below 2 degrees and closer to 1.5 degrees above pre-industrial levels and is aligned within the envelope of scenarios presented in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C.

THIS REPORT OUTLINES THE ROLE OF WIND POWER IN THE TRANSFORMATION OF THE GLOBAL ENERGY SYSTEM BASED ON IRENA'S CLIMATE-RESILIENT PATHWAY (REMAP CASE), specifically the growth in wind power deployments that would be needed in the next three decades to achieve the Paris climate goals.

KEY FINDINGS:

- **ACCELERATED DEPLOYMENT OF RENEWABLES, COMBINED WITH DEEP ELECTRIFICATION AND INCREASED ENERGY EFFICIENCY, CAN ACHIEVE OVER 90% OF THE ENERGY-RELATED CARBON DIOXIDE (CO_2) EMISSIONS REDUCTIONS NEEDED BY 2050 TO SET THE WORLD ON AN ENERGY PATHWAY TOWARDS MEETING THE PARIS CLIMATE TARGETS.** Among all low-carbon technology options, accelerated deployment of wind power when coupled with deep electrification would contribute to more than one-quarter of the total emissions reductions needed (nearly 6.3 gigatonnes of carbon dioxide (Gt CO_2) annually) in 2050.
- **ACHIEVING THE PARIS CLIMATE GOALS WOULD REQUIRE SIGNIFICANT ACCELERATION ACROSS A RANGE OF SECTORS AND TECHNOLOGIES**. Wind power, along with solar energy, would lead the way for the transformation of the global electricity sector. Onshore and offshore wind would generate more than one-third (35%) of total electricity needs, becoming the prominent generation source by 2050.

- **SUCH A TRANSFORMATION IS ONLY POSSIBLE BY GREATLY SCALING UP WIND CAPACITY INSTALLATIONS IN THE NEXT THREE DECADES**. This entails increasing the global cumulative installed capacity of onshore wind power more than three-fold by 2030 (to 1 787 gigawatts (GW)) and nine-fold by 2050 (to 5 044 GW) compared to installed capacity in 2018 (542 GW). For offshore wind power, the global cumulative installed capacity would increase almost ten-fold by 2030 (to 228 GW) and substantially towards 2050, with total offshore installation nearing 1 000 GW by 2050.

- **THE WIND INDUSTRY WOULD NEED TO BE PREPARED FOR SUCH A SIGNIFICANT GROWTH IN THE WIND MARKET OVER THE NEXT THREE DECADES.** Annual capacity additions for onshore wind would increase more than four-fold, to more than 200 GW per year in the next 20 years, compared to 45 GW added in 2018. Even higher growth would be required in annual offshore wind capacity additions – around a ten-fold increase, to 45 GW per year by 2050 from 4.5 GW added in 2018.

- **AT A REGIONAL LEVEL, ASIA WOULD LARGELY DRIVE THE PACE OF WIND CAPACITY INSTALLATIONS, BECOMING THE WORLD LEADER IN WIND ENERGY**. Asia (mostly China) would continue to dominate the onshore wind power industry, with more than 50% of global installations by 2050, followed by North America (23%) and Europe (10%). For offshore wind, Asia would take the lead in the coming decades with more than 60% of global installations by 2050, followed by Europe (22%) and North America (16%).

- **SCALING UP WIND ENERGY INVESTMENTS IS KEY TO ACCELERATING THE GROWTH OF GLOBAL WIND POWER INSTALLATIONS OVER THE COMING DECADES**. This would imply increasing global average annual onshore wind power investments by more than two-fold from now until 2030 (USD 146 billion/year) and more than three-fold over the remaining period to 2050 (USD 211 billion/year) compared to 2018 investments (USD 67 billion/year). For offshore wind, global average annual investments would need to increase three-fold from now until 2030 (USD 61 billion/year) and more than five-fold over the remaining period to 2050 (USD 100 billion/year) compared to 2018 investments (USD 19 billion/year).

- **INCREASING ECONOMIES OF SCALE, MORE COMPETITIVE SUPPLY CHAINS AND FURTHER TECHNOLOGICAL IMPROVEMENTS WILL CONTINUE TO REDUCE THE COSTS OF WIND POWER**. Globally, the total installation cost of onshore wind projects would continue to decline in the next three decades with the average cost falling in the range of USD 800 to 1 350 per kilowatt (kW) by 2030 and USD 650 to 1 000/kW by 2050, compared to the global-weighted average of USD 1 497/kW in 2018. For offshore wind projects, the average total installation cost would further drop in coming decades to between USD 1 700 and 3 200/kW by 2030 and between USD 1 400 and 2 800/kW by 2050.

  The levelised cost of electricity (LCOE) for onshore wind is already competitive compared to all fossil fuel generation sources and is set to decline further as installed costs and performance continue to improve. Globally, the LCOE for onshore wind will continue to fall from an average of USD 0.06 per kilowatt-hour (kWh) in 2018 to between USD 0.03 to 0.05/kWh by 2030 and between USD 0.02 to 0.03/kWh by 2050. The LCOE of offshore wind is already competitive in certain European markets (for example, Germany, the Netherlands with zero-subsidy projects, and lower auction prices). Offshore wind would be competitive in other markets across the world by 2030, falling in the low range of costs for fossil fuels (coal and gas). The LCOE of offshore wind would drop from an average of USD 13/kWh in 2018 to an average between USD 0.05 to 0.09/kWh by 2030 and USD 0.03 to 0.07/kWh by 2050.

- **ONGOING INNOVATIONS AND TECHNOLOGY ENHANCEMENTS TOWARDS LARGER-CAPACITY TURBINES AS WELL AS INCREASED HUB HEIGHTS AND ROTOR DIAMETERS HELP IMPROVE YIELDS FOR THE SAME LOCATION**. The ongoing increase in wind turbine size for onshore applications is set to continue, from an average of 2.6 megawatts (MW) in 2018 to 4 to 5 MW for turbines commissioned by 2025. For offshore applications, the largest turbine size of around 9.5 MW today will soon be surpassed, with expectations that projects to be commissioned in 2025 would comprise of turbines with ratings of 12 MW and above (although some legacy projects with long lead times may have lower ratings). Research and development will likely lead to a potential to increase this to 15 to 20 MW in a decade or two.

The combination of improved wind turbine technologies, deployment of higher hub heights and longer blades with larger swept areas leads to increased capacity factors for a given wind resource. For onshore wind plants, global weighted average capacity factors would increase from 34% in 2018 to a range of 30% to 55% in 2030 and 32% to 58% in 2050. For offshore wind farms, even higher progress would be achieved, with capacity factors in the range of 36% to 58% in 2030 and 43% to 60% in 2050, compared to an average of 43% in 2018.

- **TECHNOLOGICAL DEVELOPMENTS IN WIND TURBINE FOUNDATIONS ARE A KEY FACTOR ENABLING THE ACCELERATED DEPLOYMENT OF OFFSHORE WIND, PERMITTING ACCESS TO BETTER WIND RESOURCES**. Floating foundations are potentially a "game-changing" technology to effectively exploit abundant wind potential in deeper waters and thus could lead the way for rapid future growth in the offshore wind power market. By 2030, industry experts estimate that around 5 GW to 30 GW of floating offshore capacity could be installed worldwide and that, based on the pace of developments across various regions, floating wind farms could cover around 5% to 15% of the global offshore wind installed capacity (almost 1 000 GW) by 2050.

- **TECHNOLOGICAL SOLUTIONS ACCOMPANIED BY ENABLING MARKET CONDITIONS AND INNOVATIVE BUSINESS MODELS, ARE ESSENTIAL TO PREPARE FUTURE POWER GRIDS TO INTEGRATE RISING SHARES OF WIND POWER**. To effectively manage large-scale variable renewable energy sources, flexibility must be harnessed in all sectors of the energy system, from power generation to transmission and distribution systems, storage (both electrical and thermal) and increasingly flexible demand (demand side management and sector coupling). Globally, to integrate 60% variable renewable generation (35% from wind) by 2050 as is envisioned in the REmap Case, average annual investments in grids, generation adequacy and some flexibility measures (e.g. storage) would need to rise by more than one-quarter to USD 374 billion/year, compared to investments made in electricity networks and battery storage in 2018 of USD 297 billion/year.

- **IF ACCOMPANIED BY SOUND POLICIES, THE TRANSFORMATION CAN BRING SOCIO-ECONOMIC BENEFITS**. The wind industry can employ 3.74 million people by 2030 and more than 6 million people by 2050, a figure nearly three times higher and five times higher respectively than the 1.16 million jobs in 2018. To maximise outcomes of the energy transition, however, a holistic policy framework is needed. Deployment policies will need to co-ordinate and harmonise with integration and enabling policies. Under the enabling policy umbrella, particular focus is needed on industrial, labour, financial, education and skills policies to maximise the transition benefits. Education and skills policies can allow for the retention and reallocation of existing expertise in the oil and gas sector to support the installation of offshore wind foundation structures. Similarly, sound industrial and labour policies that build upon domestic supply chains can enable income and employment growth by leveraging existing economic activities in support of wind industry development.

- **UNLEASHING THE MASSIVE POTENTIAL OF WIND IS CRUCIAL TO ACHIEVE THE PARIS CLIMATE TARGETS**. This is only possible by mitigating the existing barriers at different scales (technology, economic, socio-political and environmental) that could hinder the deployment of wind capacities in the next three decades. Grid access, public acceptance, planning procedures and planning uncertainties, economies of scale, access to finance, subsidies for traditional energy are among the key barriers. Mitigating the existing barriers immediately, through a range of supportive policies and implementation measures including innovative business models, financial instruments is vital to boost future deployment of wind capacities to enable the transition to a low-carbon, sustainable energy future.

Figure ES 1. Wind roadmap to 2050: tracking progress of key wind energy indicators to achieve the global energy transformation.

	2010	2018	REMAP CASE 2030	REMAP CASE 2050	ON/OFF TRACK
CO_2 EMISSIONS (ENERGY-RELATED) AND REDUCTION POTENTIAL BY WIND POWER					
Energy-related CO_2 emissions under current plans and planned policies (Reference Case) (Gt CO_2/yr)	29.7	34.5	35	33.1	
Energy-related CO_2 emissions under IRENA's climate resilient pathway (REmap Case) (Gt CO_2/yr)	29.7	34.5	24.9	9.8	Off track
Avoided emissions due to accelerated deployment of wind power coupled with deep electrification (Gt CO_2/yr)				6.3	
WIND POWER IN TOTAL GENERATION MIX					
Onshore and offshore wind generation share (%)	1.7%	6%	21%	35%	Progress
TOTAL INSTALLED CAPACITY					
Onshore wind (GW)	178	542	1 787	5 044	Off track
Offshore wind (GW)	3	23	228	1 000	Progress
ANNUAL DEPLOYMENT*					
Onshore wind (GW/yr)	30	45	147	202	Off track
Offshore wind (GW/yr)	0.9	4.5	28	45	Progress
TOTAL INSTALLATION COST					
Onshore wind (USD/kW)	1 913 (average)	1 497 (average)	800 – 1 350 (average range)	650 – 1 000 (average range)	Off track
Offshore wind (USD/kW)	4 572 (average)	4 353 (average)	1 700 – 3 200 (average range)	1 400 – 2 800 (average range)	Progress

	2010	2018	REMAP CASE 2030	REMAP CASE 2050	ON/OFF TRACK
LEVELIZED COST OF ELECTRICITY (LCOE)					
Onshore wind (USD/kWh)	0.08 (average)	0.06 (average)	0.03–0.05 (average range)	0.02–0.03 (average range)	On track
Offshore wind (USD/kWh)	0.16 (average)	0.13 (average)	0.05–0.09 (average range)	0.03–0.07 (average range)	Progress
AVERAGE ANNUAL INVESTMENT					
Onshore wind (USD billion/yr)	57	67	146	211	Off track
Offshore wind (USD billion/yr)	4.2	19.4	61	100	Progress
CAPACITY FACTORS					
Onshore wind (%)	27 (average)	34 (average)	30–55 (average range)	32–58 (average range)	Progress
Offshore wind (%)	38 (average)	43 (average)	36–58 (average range)	43–60 (average range)	On track
EMPLOYMENT					
Onshore and offshore wind (million)	0.75**	1.12	3.74	6.06	Off track

* The data includes new capacity additions and replacement of end-of-lifetime capacity

** The data denotes wind sector jobs by 2012

1 ENERGY TRANSFORMATION PATHWAYS AND WIND ENERGY

1.1 PATHWAYS FOR THE GLOBAL ENERGY TRANSFORMATION

The International Renewable Energy Agency (IRENA) has explored global energy development options from two main perspectives to the year 2050 as part of the 2019 edition of its *Global Energy Transformation* report (IRENA, 2019a). The first is an energy pathway set by current and planned policies (the Reference Case), and the second is a cleaner, climate-resilient pathway based largely on more ambitious, yet achievable, uptake of renewable energy and energy efficiency measures (the REmap Case).

Box 1. PRACTICAL OPTIONS FOR GLOBAL ENERGY DECARBONISATION.

IRENA's renewable energy roadmap, or REmap approach[2] and analysis, includes several key steps (IRENA, 2019b):

- Identifying the **current plans** for global energy development as a baseline scenario (or **Reference Case**) as far as 2050. This presents a scenario based on governments' current energy plans and other planned targets and policies, including climate commitments made since 2015 in Nationally Determined Contributions under the Paris Agreement.
- Assessing the **additional potential** for scaling up or optimising low-carbon technologies and approaches, including renewable energy, energy efficiency and electrification, while also considering the role of other technologies.
- Developing a realistic, **practical Energy Transformation scenario, referred to as the REmap Case**. This calls for considerably faster deployment of low-carbon technologies, based largely on renewable energy and energy efficiency, resulting in a transformation in energy use to keep the rise in global temperatures this century well below 2 degrees Celsius (°C) and closer to 1.5 °C compared to pre-industrial levels. The scenario focuses primarily on cutting energy-related carbon-dioxide (CO_2) emissions, which make up around two-thirds of global greenhouse gas emissions.
- Analysis of the costs, benefits and investment needs for low-carbon technologies worldwide to achieve the envisaged energy transformation.

Note: The findings in this report consider policy targets and developments until April 2019. Any new policy changes and targets announced since then are not considered in the analysis and therefore could influence the findings presented in this report.

The findings in this report are based on IRENA's climate-resilient pathway (REmap Case), which is well below 2 °C and closer to the 1.5 °C carbon budget levels provided in the IPCC Special Report on Global Warming of 1.5 °C (SR1.5).

REmap
A Renewable Energy Roadmap

2 For more on the global roadmap and its underlying analysis, see **www.irena.org/remap**.

1.2 THE ENERGY TRANSFORMATION: RATIONALE

Reducing energy-related CO_2 emissions is at the heart of the energy transformation. Rapidly shifting the world away from the consumption of fossil fuels that cause climate change and towards cleaner, renewable forms of energy is key if the world is to reach the agreed-upon climate goals. There are many drivers behind this transformation (Figure 1).

Firstly, the **rapid decline in renewable energy costs**. The global weighted average cost of electricity from all commercially available renewable power generation technologies continued to fall in 2018. For onshore wind projects commissioned in 2018, the global weighted average cost of electricity reached a low of USD 0.056 per kilowatt-hour (kWh), which was 13% lower than in 2017 and 35% lower than in 2010 (USD 0.085/kWh) (IRENA, 2019c). The costs of electricity from onshore wind are already competitive at the lower end of the fossil fuel cost range and are even undercutting new fossil fuel-fired power generation costs in many cases. With rapid cost declines in solar PV in recent years (the levelised cost of electricity declined by 77% in 2018 compared to 2010 (IRENA, 2019c), albeit from a much higher starting point), the complementary nature of these two technologies and resource availability over different seasons of a year can yield a very low-cost system. In Europe, offshore wind projects are increasingly competing at wholesale electricity prices (for example, subsidy-free bids in the Netherlands and Germany), while in the United States (US), non-hydropower renewable energy resources such as solar PV and wind are expected to be the fastest growing source of electricity generation in the next two years.

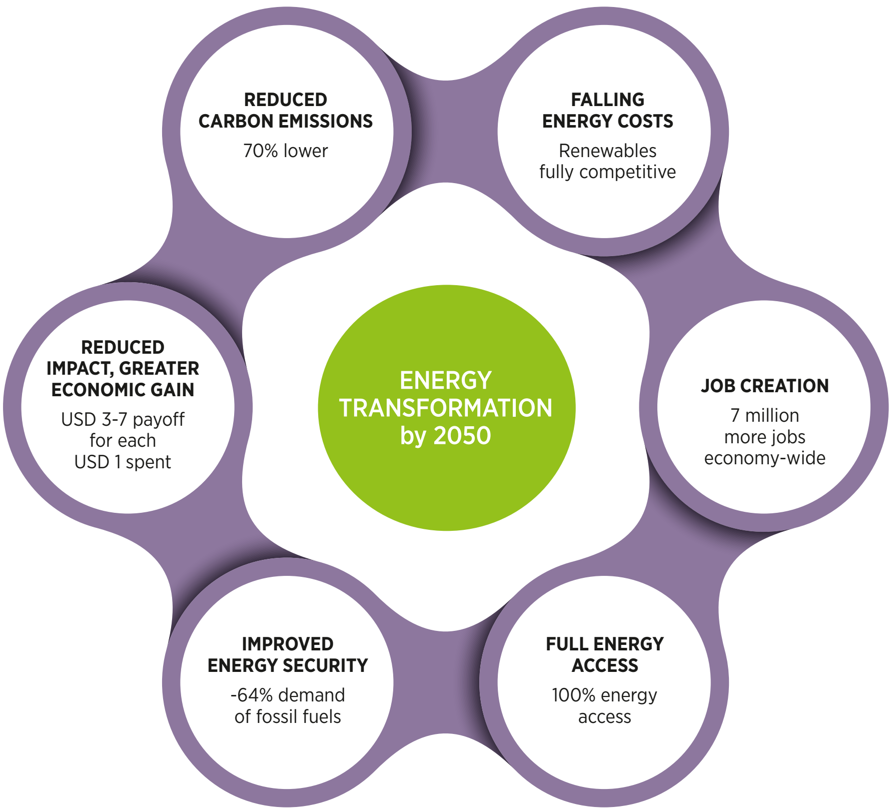
Secondly, **air quality improvements**. Air pollution is a major public health crisis, caused mainly by unregulated, inefficient and polluting energy sources (fossil fuels, chemicals, etc.). The switch to clean, renewable energy sources would bring greater prosperity, improving the air quality in cities and preserving and protecting the environment. With the rise in the use of renewables, a drop in net energy subsidies would potentially lead to decline in health costs from air pollution and climate effects. The savings from reduced externalities with respect to air pollution and climate change along with avoided subsidies outweigh the additional cost of energy in the system. For every dollar invested in transforming the global energy system over the period to 2050, there is a payoff of at least USD 3 and potentially more than USD 7, depending on how externalities are valued (IRENA, 2019a).

Thirdly, **reduction of carbon emissions**. The gap between observed emissions and the reductions that are needed to meet internationally agreed climate objectives is widening. The transformation of the global energy system needs to accelerate substantially to meet the objectives of the Paris Agreement, which aim to keep the rise in average global temperatures to closer to 1.5 °C in the present century, compared to pre-industrial levels. A 70% reduction in energy-related emissions would be needed by 2050 compared to current levels (IRENA, 2019a).

Transforming the global energy system would **improve energy security and enhance affordable and universal energy access**. For countries that depend heavily on imported fossil fuels, energy security is a significant issue, and renewables can provide an alternative by increasing the diversity of energy sources through local generation and thus contribute to the flexibility of the system and resistance to shocks. Similarly, energy access is an area of great inequality, and renewable energy technologies can be adopted and applied in rural areas where the national grid has not yet been extended, through rural electrification, community energy projects and distributed renewable energy resources.

Finally, transforming the global energy system would **bring significant socio-economic benefits**, which are key to influence any political decision. The development of a local renewable energy industry has the potential to create jobs that can accommodate men and women from all disciplines and backgrounds. If no local industries are developed, countries with energy security problems would just move from importing fossil fuels to renewable energy renewable equipment (IRENA, 2019a, 2019b).

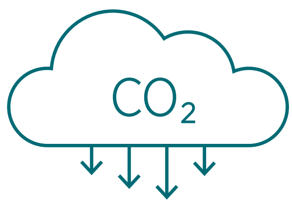
Figure 1: Pressing needs and attractive opportunities are driving the transformation of the world's energy system.



Note: The key drivers for energy transformation presented in this figure is based on IRENA's REmap Case by 2050 compared to current levels.
Source: IRENA, 2019b.

CO_2 EMISSIONS REDUCTIONS AS A MAJOR GOAL

Decarbonisation of the energy sector and the reduction of carbon emissions to limit climate change is at the heart of IRENA's energy transformation roadmaps, which examine and provide an ambitious yet technically and economically feasible low-carbon technology deployment pathway towards a sustainable and clean energy future.



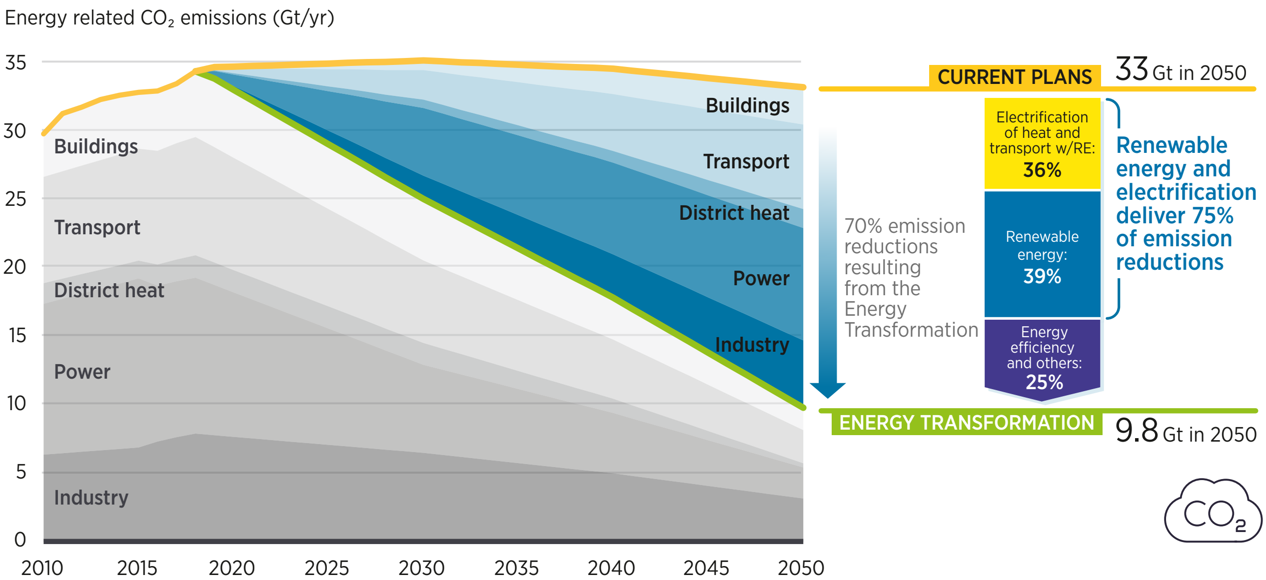
1.3 GLOBAL ENERGY TRANSFORMATION: THE ROLE OF WIND ENERGY

Climate change has become a major concern of this century. The Paris Agreement sets forth efforts to limit the global temperature rise to "well below" 2 °C and ideally to limit warming to 1.5 °C in the present century, compared to pre-industrial levels (IRENA, 2019a). To realise the climate targets of the Paris Agreement, a profound transformation in the global energy landscape is essential. Such a transformation is possible with the rapid deployment of low-carbon technologies replacing conventional fossil fuel generation and uses.

To set the world on a pathway towards meeting the aims of the Paris Agreement, energy-related CO_2 emissions would need to be reduced by around 3.5% per year from now until 2050, with continued reduction afterwards. The transition to increasingly electrified forms of transport and heat, when combined with increases in renewable power generation, would deliver around 60% of the energy-related CO_2 emissions reductions needed by 2050. If additional reductions from direct use of renewables are considered, the share increases to 75%. When adding energy efficiency, the share increases to over 90% of energy-related CO_2 emissions reductions needed to set the world on a pathway to meeting the Paris Agreement (Figure 2) (IRENA, 2019a).

The energy transformation would also boost gross domestic product (GDP) by 2.5% and total employment by 0.2% globally in 2050. In addition, it would bring broader social and environmental benefits. Health, subsidy and climate-related savings would be worth as much as USD 160 trillion cumulatively over a 30-year period. Thus, every dollar spent in transforming the global energy system provides a payoff of at least USD 3 and potentially more than USD 7, depending on how externalities are valued (IRENA, 2019a).

Figure 2: Renewables and efficiency measures, boosted by substantial electrification, can provide over 90% of necessary CO_2 emission reductions by 2050.



Note: Renewables" implies deployment of renewable technologies in the power sector (wind, solar PV, etc.) and end-use direct applications (solar thermal, geothermal, biomass). "Energy efficiency" contains efficiency measures deployed in end-use applications in the industry, buildings and transport sectors (e.g., improving insulation of buildings or installing more-efficient appliances and equipment). "Electrification" denotes electrification of heat and transport applications, such as deploying heat pumps and electric vehicles.

Source: IRENA, 2019a.

Scaling up electricity from renewables would be crucial for the decarbonisation of the world's energy system. The most important synergy of the global energy transformation comes from the combination of increasing low-cost renewable power technologies and the wider adoption of electric technologies for end-use applications in transport and heat. To deliver the energy transition at the pace and scale needed would require almost complete decarbonisation of the electricity sector by 2050. The REmap Case sets a pathway to achieve a renewables share of 86% in the power generation mix by 2050 (Figure 3). On the end-use side, the share of electricity in final energy consumption would increase from just 20% today to almost 50% by 2050. The share of electricity consumed in industry and buildings would double. In transport, it would increase from just 1% today to over 40% by 2050 (IRENA, 2019a).

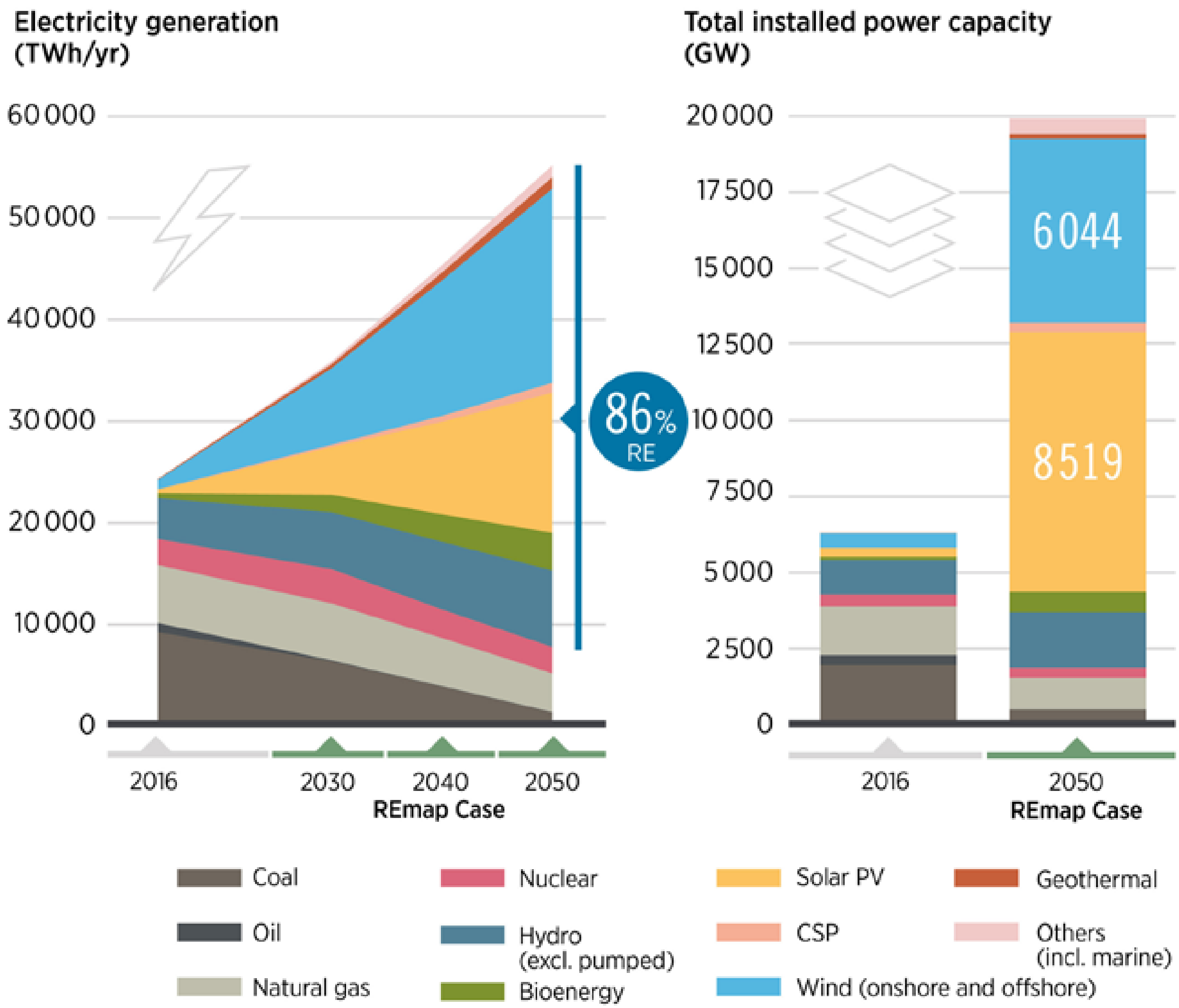
Wind and solar energy will lead the way in the transformation of the global electricity sector. Wind power would supply more than one-third of total electricity demand by 2050 and is well aligned with energy transformation scenarios of various institutions, clearly highlighting the importance of scaling up the wind power generation share in order to decarbonise the energy system in the next three decades (Box 2). This represents a nearly nine-fold rise in the wind power share in the total generation mix by 2050 compared to 2016 levels. However, in the context of total installed capacity by 2050, much larger capacity expansion would be needed for solar PV (8 519 GW)[3] as compared to wind (6 044 GW) given the average lower capacity factors achieved by solar PV projects.

WIND POWER – THE PROMINENT GENERATION SOURCE BY 2050

Wind and solar energy will lead the way for the transformation of the global electricity sector. Onshore and offshore wind together would generate more than one-third (35%) of total electricity needs, becoming the prominent generation source by 2050.

3 A similar IRENA working paper exploring the role of solar PV in the context of global energy transformation to 2050 is forthcoming and will be available for download at https://www.irena.org/publications.

Figure 3: Wind would be the largest generating source, supplying more than one-third of total electricity generation needs by 2050.

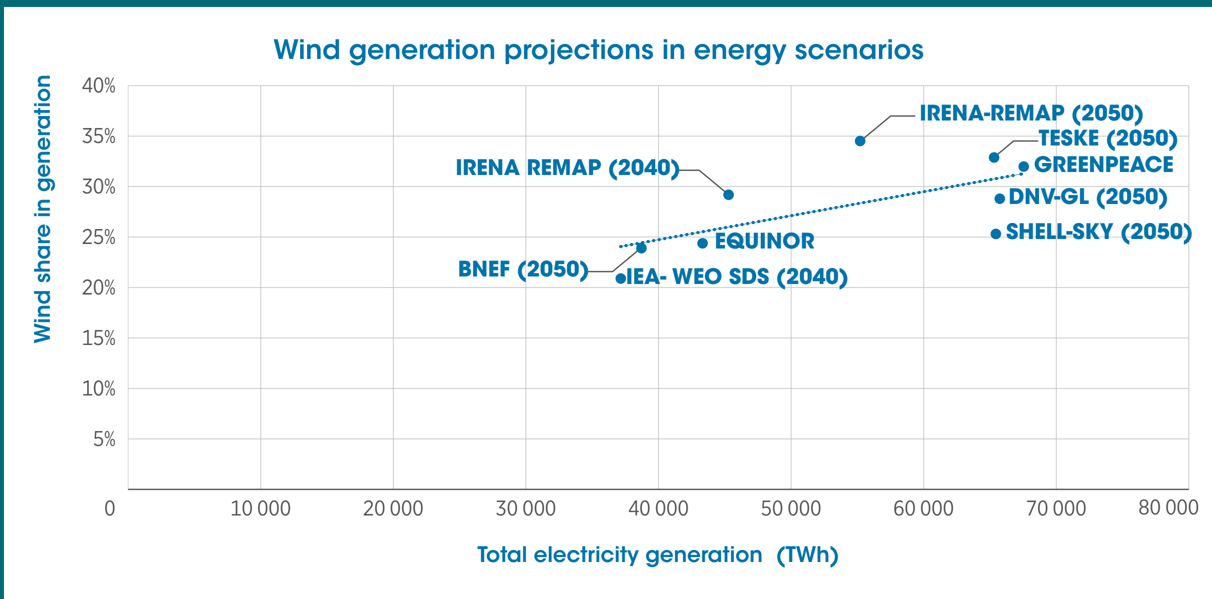


Source: IRENA, 2019a.

Box 2. THE PREDOMINANCE OF WIND POWER IN VARIOUS ENERGY TRANSFORMATION SCENARIOS.

An analysis of energy scenarios shows that there is increasing consensus on the important role that wind power would play in the energy mix in the coming decades. A comparison analysis shows a correlation between total power generation and the share of wind power generation in the total generation mix, and the scenarios with high wind power generation shares are also the ones with high total power generation. The highest wind share can be observed in IRENA's REmap Case, which positions wind as the major renewable technology source essential to decarbonise the power sector. However, in the REmap Case, with wind accounting for 86% of overall renewable power generation by 2050, the total generation needed is less than in some other energy scenarios with similar wind shares, such as DNV GL, 100% renewables by Teske, Shell Sky and Greenpeace (Figure 45). The wind generation share of 35% in IRENA's REmap Case is well in line with the World Wind Energy Association's global study published in 2015, which foresees a global wind power share of 40% for the year 2050 (WWEA, 2015a). However, updated assumptions of modelling scenarios to meet net-zero/1.5 °C targets would almost certainly have higher wind shares.

Figure 4: Comparison of scenarios for the global energy transition, with a focus on wind power generation.



Source: Shell – Sky Scenario (Shell, 2018); IEA – World Energy Outlook Sustainable Development Scenario (WEO-SDS) (IEA, 2018a); DNV GL, 2018; Teske, 2019; BNEF, 2018; Greenpeace, 2015 and Equinor, 2018a.

The comparison also suggests that the goal of limiting global temperature increase to well below 2 °C would be most achievable with lower overall energy demand (total primary energy supply), while achieving the 1.5 °C target would also require significant structural and lifestyle changes.

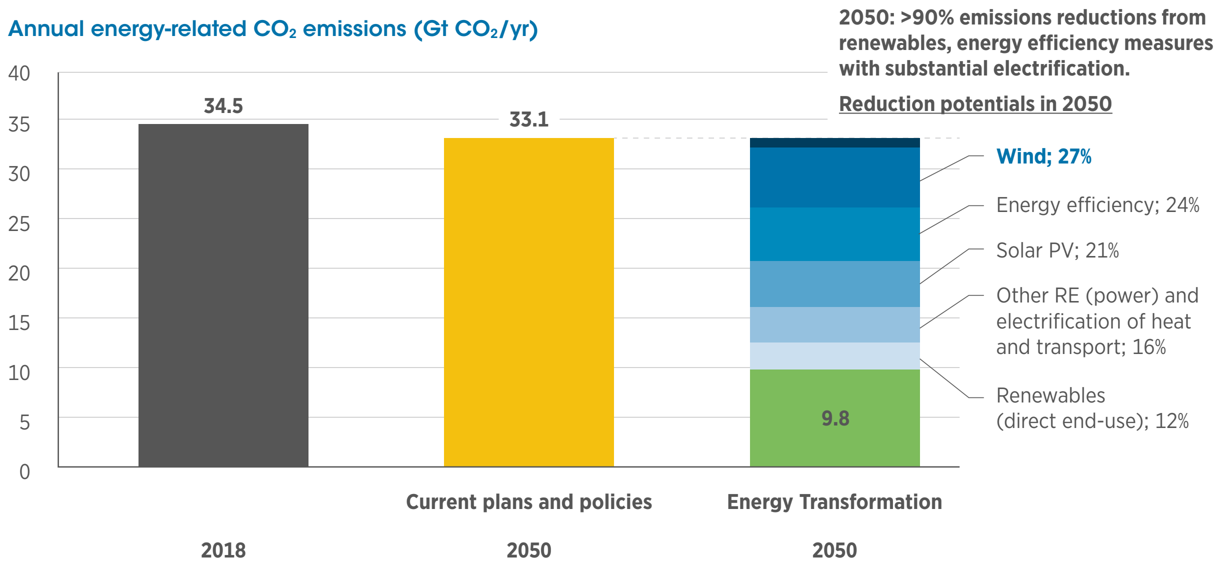
However, despite the similarities, differences can also be found in the scenarios in aspects such as the level of electrification in end-use sectors and reductions in CO_2 emissions. The divergence in results can be explained mainly by the different objectives behind the scenarios. For many, the analysis is defined by the need to reduce energy-related CO_2 emissions to limit the temperature increase to between 2 °C and 1.5 °C. Others have modelled the energy system in a more conservative (business-as-usual) way.

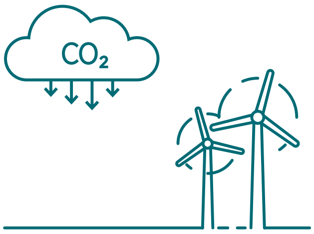
With regard to the total installed capacity levels by 2050, IRENA's REmap Case, with more than 6 000 GW of wind capacity, is in the median range compared to other energy transition scenarios. IRENA's wind capacity projection for 2050 is well below Greenpeace's wind capacity projection of more than 8 000 GW and Teske's 100% renewables scenario with total wind capacity of around 7 700 GW, while higher than the World Energy Council's projection of around 3 000 GW.

ENERGY-RELATED CARBON EMISSIONS MITIGATION POTENTIAL OF WIND POWER

Deploying more than 6 000 GW of wind power capable of generating more than one-third of total electricity needs in 2050 would potentially mitigate a massive amount of energy-related carbon emissions (6.3 gigatonnes (Gt) of CO_2), which is more than one-quarter of the total emissions reduction potential from renewables and energy efficiency measures (Figure 5). Among all low-carbon technology options, wind power contributes to major emissions reduction potential by 2050. This is due mainly to large deployments of wind power replacing conventional power generation sources by utilising the ample resource availability with the best technological solutions at better resource locations across various regions and benefiting from drastic cost reductions, significant end-use electrification of transport and heat applications, shifting energy demand to electricity that can then be supplied by wind (either directly or in-directly, for example power-to-hydrogen) and rising socio-economic benefits.

Figure 5: Wind power would contribute to 6.3 Gt of CO_2 emissions reductions in 2050, representing 27% of the overalL emissions reductions needed to meet paris climate goals.





ACCELERATED WIND POWER DEPLOYMENTS CONTRIBUTES TO CO_2 EMISSIONS REDUCTIONS

Among all low-carbon technology options, accelerated deployment of wind power when coupled with deep electrification would contribute more than one-quarter of the total emissions reductions needed (nearly 6.3 Gt CO_2) in 2050.

2 THE EVOLUTION AND FUTURE OF WIND MARKETS

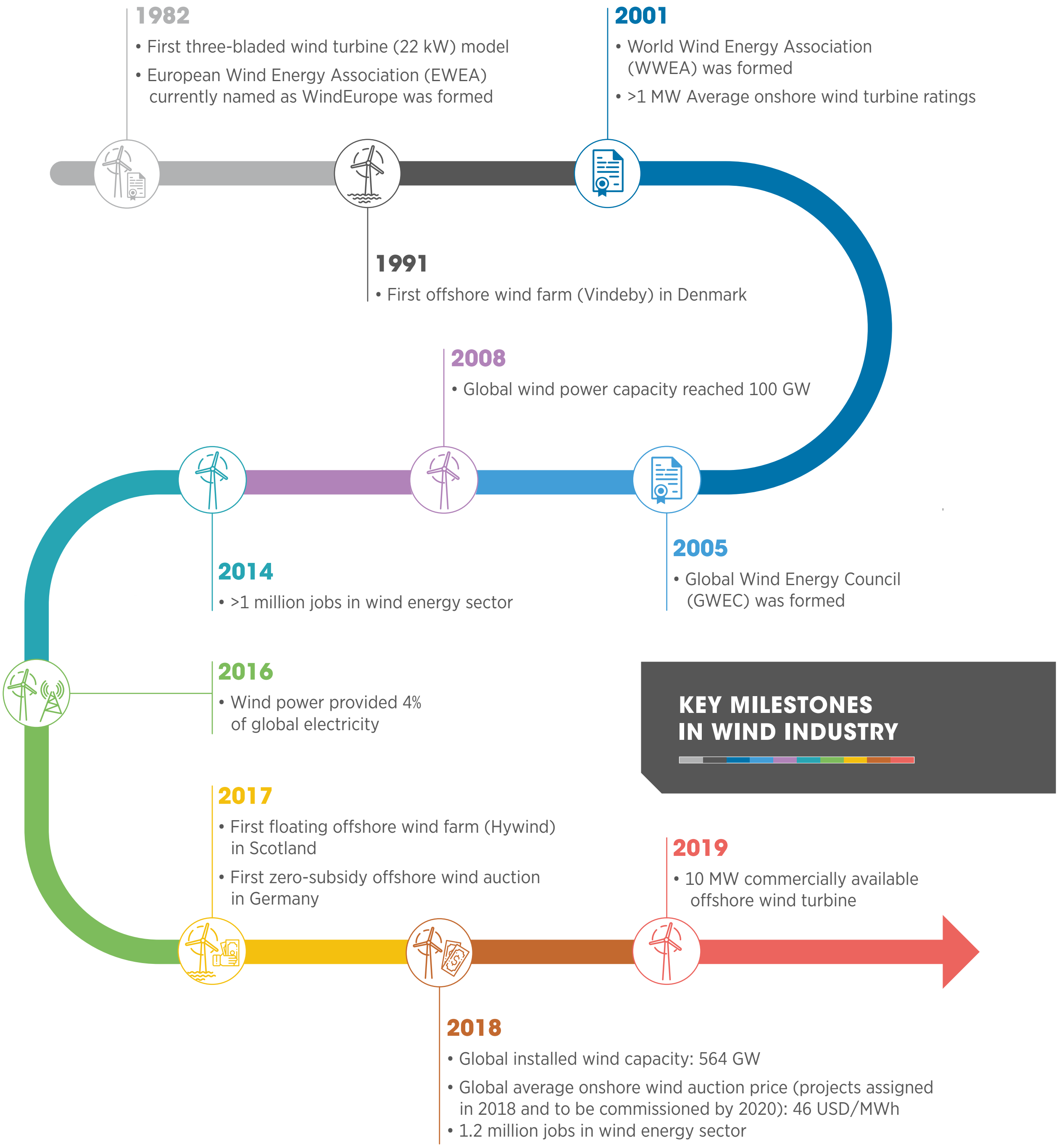
2.1 EVOLUTION OF THE WIND INDUSTRY

Rising concerns about climate change, the health effects of air pollution, energy security and energy access, along with volatile oil prices in recent decades, have led to the need to produce and use alternative, low-carbon technology options such as renewables. Wind power has been a pioneering renewable technology in recent decades. In terms of total installed capacity, wind power is the leading renewable energy technology after hydropower, with more than half a terawatt installed globally as of the end of 2018. Along with solar, wind also dominated total renewable capacity additions, with around 43 GW of wind capacity added globally in 2018 (IRENA, 2019d).

The evolution of the wind industry has been remarkable, and in the last four decades several milestones have been achieved in installations, technology advancements and cost reductions along with the establishment of key wind energy associations (Figure 6). By 2020, onshore wind is set to consistently offer a less expensive source of new electricity than the least-cost fossil fuel alternative in most regions (IRENA, 2019c).

Wind power will remain a key renewable energy option in the coming decades. This report sheds light on the prominent role of wind power in transforming the global energy landscape by 2050. The following sections cover an accelerated deployment pathway for wind power (onshore and offshore) until 2050 under the REmap Case in IRENA's global energy transformation roadmap, along with perspectives on cost reductions, technology trends and the need to prepare future grids to integrate rising wind power shares.

Figure 6: Overview of key milestones achieved by the wind industry since 1982.



Source: Equinor, 2017; GWEC, 2019a; IRENA, 2019d, 2019e, 2019a, 2019f, 2015; MHI Vestas, 2018; Wind Power Offshore, 2017; WindEurope, 2019a; WWEA, 2015

WIND ENERGY – A FAST GROWING AND MATURE RENEWABLE ENERGY TECHNOLOGY

Wind power is one of the fastest growing, most mature and cost-competitive (onshore) renewable energy technologies.

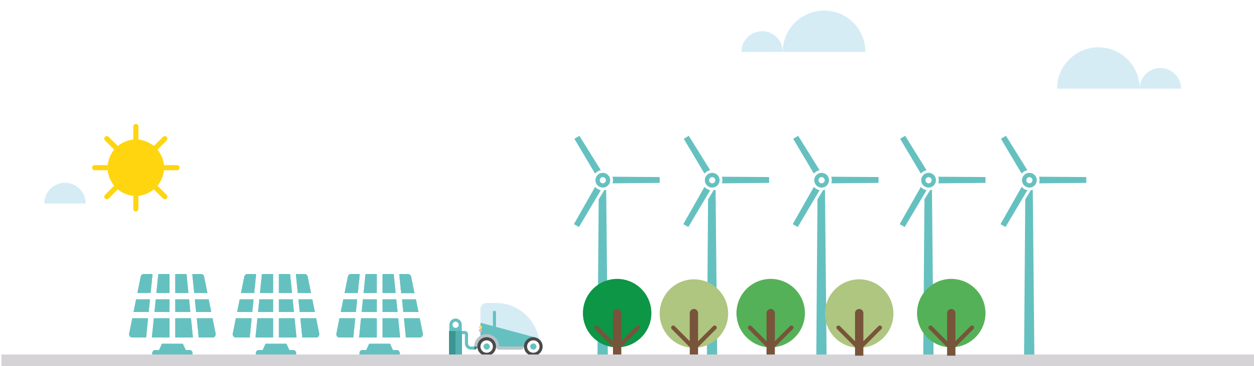
2.2 ONSHORE WIND OUTLOOK TO 2050

ACCELERATED UPTAKE AND EMERGING MARKETS

The deployment of renewables has accelerated since 2010, reaching record levels and outpacing annual additions of conventional power capacity in many regions. Among all renewable energy technologies, wind power, after hydropower, has dominated the renewables industry for many decades. At the end of 2018, the global cumulative installed capacity of onshore wind power reached 542 GW (IRENA, 2019d). Wind power has increased at an average compound annual growth rate (CAGR) of more than 21% since 2000 (IRENA, 2019d).

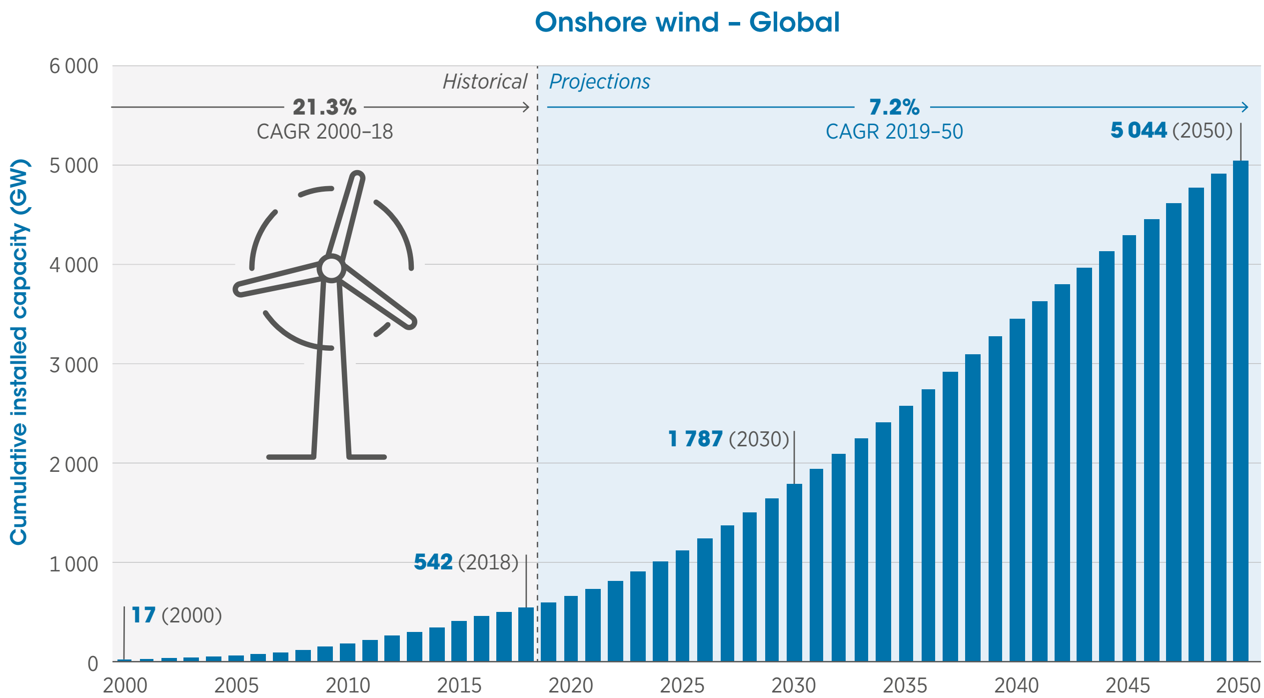
Considering the ample resource availability, large market potential and cost competitiveness, onshore wind is expected to drive overall renewables growth in several regions over the next decade. For the next three decades, onshore wind power installations would need to have a year-on year CAGR of more than 7% (Figure 7). This implies that the total installed capacity of onshore wind would grow more than three-fold by 2030 (to 1 787 GW) and nearly ten-fold by 2050, nearing 5 044 GW, compared to 542 GW in 2018. An average CAGR of more than 7% for the next three decades is well below what has been achieved since 2000, with the historical average CAGR between 2000 and 2018 at around 21%. This shows the feasibility and ease of scaling up onshore wind installations in the next three decades by simply continuing the historical pace. In addition, a global onshore wind installed capacity of 5 044 GW by 2050 represents only a fraction (5.3%) of the global wind resource potential of at least 95 000 GW, as estimated by a technical committee of the World Wind Energy Association (WWEA) in available wind resource studies (WWEA, 2014). The total land area required for global onshore installation of 5 044 GW by 2050 is between 1 008 800 square kilometres (km^2) (around the size of Ethiopia) and 1 664 520 km^2 (around the size of Iran). In terms of total disrupted area, the range would be between 50 440 km^2 (around the size of Costa Rica) and 83 226 km^2 (around the size of Azerbaijan)[4].

During the initial years of wind power deployment, Europe was the key enabler for global wind installations. In 2010, the region accounted for 47% of global onshore installations. Since 2010, rapid wind deployment has been observed in other regions, especially China with a CAGR of around 27%. By 2018, China outpaced Europe to become the largest onshore wind market with nearly one-third of the global installed capacity (IRENA, 2019d). The European Union (EU) had a record year in 2018 in terms of financing new wind capacity, with almost 16.7 GW of future wind power projects attaining Final Investment Decision. Almost USD 29.4 billion was invested in new wind farms in 2018, with onshore wind financed at an average of USD 1.54 million per megawatt (MW), and offshore wind at USD 2.57 million per MW (WindEurope, 2019b).



4 The land area was estimated using 2.5 MW/km^2 as the lower end, and 5 MW/km^2 as the upper end.

Figure 7: Onshore wind cumulative installed capacity would grow more than three-fold by 2030 and nearly ten-fold by 2050 relative to 2018 levels.



Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d) and future projections based on IRENA analysis (IRENA, 2019a).

RAPID GROWTH IN ONSHORE WIND POWER TOTAL INSTALLATIONS TO 2050

The global installed capacity of onshore wind power would increase three-fold by 2030 (to 1 787 GW) and ten-fold by 2050 (to 5 044 GW) compared to installations in 2018 (542 GW).

Asia – mainly China (at more than 2 000 GW) and India (at more than 300 GW) – would continue to lead global onshore wind power installations, with the region accounting for more than half (2 656 GW) of the total global capacity by 2050 (Figure 8). After Asia, significant onshore wind power deployments would occur in North America (mainly the US, at more than 850 GW), where the installed capacity would grow more than ten-fold from 2018 levels, reaching around 1 150 GW by 2050. Africa would be a key market for rapid onshore wind deployment in the next three decades. Finding a sustainable way to meet growing energy needs is a core development challenge for the continent. Given the rich resource potential of renewable sources including wind, a major shift from reliance on fossil fuel energy sources and rapidly increasing renewable shares in the energy mix is crucial for the continent. As such, prioritising the rapid deployment of onshore wind projects among other renewables projects from now would result in a total installed onshore wind capacity of more than 500 GW by 2050.

Annual onshore wind capacity additions have increased gradually since the beginning of this century, with an initial drop observed in 2010 followed by fluctuating annual capacity additions through the end of 2018. So far, 2015 has been the record year – adding 65 GW of onshore wind capacity to the global power capacity mix – with smaller amounts in subsequent years due mainly to the expiration of a policy support scheme in China (Figure 9).

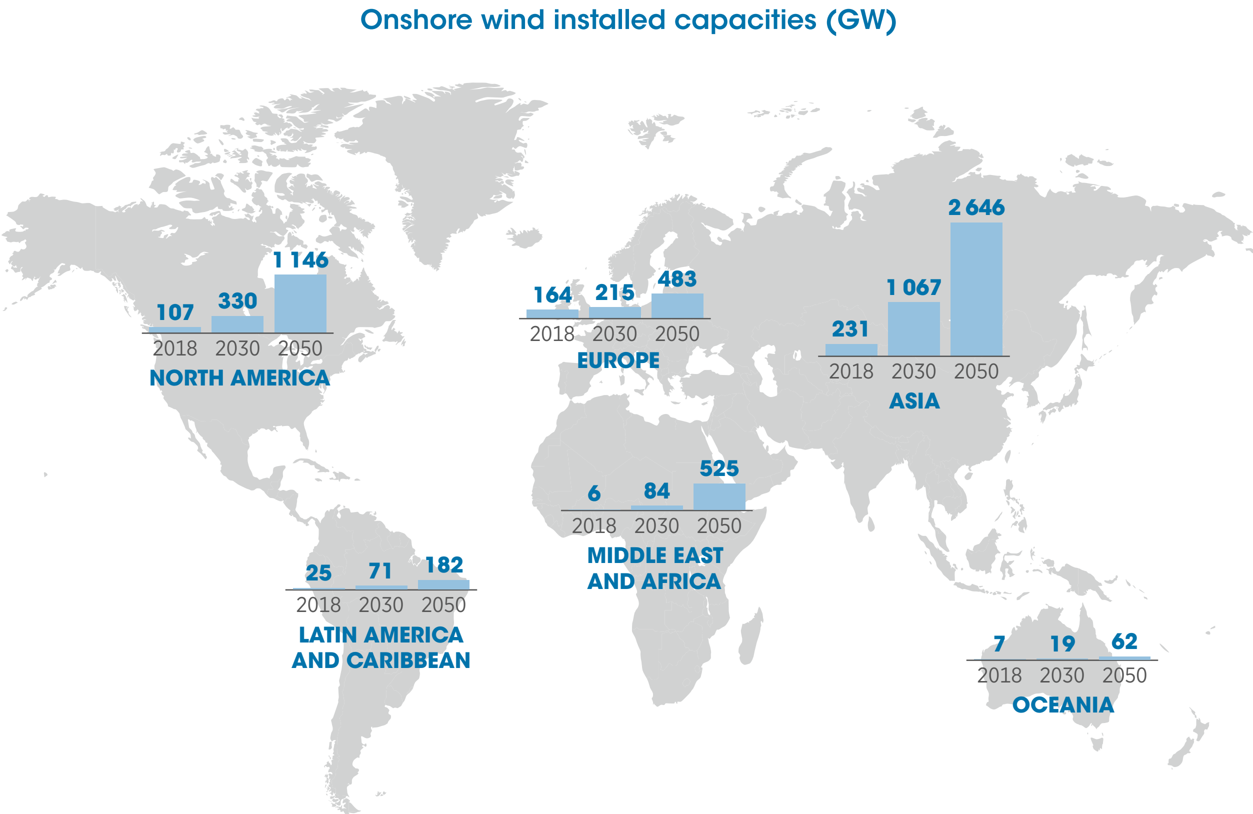
With continuous technology advancements and cost reductions, along with the right policies and supportive measures in place, the onshore wind market would grow rapidly over the next three decades. The total onshore wind capacity additions would need to be scaled up more than three-fold by 2030 (closer to 150 GW/year) and more than four-fold by 2050 (more than to 200 GW/year). Considering just the net capacity additions (without replacements), a peak would near 180 GW/year in 20 years, which is almost four-fold higher than the onshore wind capacity global additions of 45 GW in 2018. A slight decline in new capacity additions could be observed from 2040, attributed to many reasons including the availability of land, increasing deployment of offshore wind as well as aiding the growth of other renewables technologies (including hybrid projects).

Along with the growth in net wind capacity additions over the next three decades, another key issue is the replacement of wind turbines that are approaching the end of their technical lifetimes, and the repowering of existing projects to extend their operating lifetimes. System-level maintenance and upgrades, including replacing older components with advanced technologies, can help enhance the socio-economic benefits attained from the initial installations. So far, there are no regulatory or political drivers for repowering. Some turbines could last many more years, and only in some markets is it economically attractive to replace them (for example, through the Production Tax Credit in the US (AWEA, 2019; US DOE, 2019)). Repowering also makes it possible to use the most advanced turbines at locations that have the best onshore wind resources (for example, Delabole wind farm in the United Kingdom (UK).

Repowering has started in various countries in recent years (Box 3). When supported by adequate supportive measures including financial incentives and price signals, and by stable regulatory frameworks along with prioritized projects planning and local acceptance measures (WindEurope, 2017a), repowering could open more opportunities for newer installations, especially in the final two decades to 2050, which is not yet considered in the analysis. As such, the onshore wind annual market by 2050 would still be two-to three-fold larger than the current market in terms of new installations, and more than four-fold larger with replacements of existing capacities. Accounting for new capacity additions as well as replacements, the total annual additions would stabilise at an average of 200 GW/year in the last decade to 2050[5].

5 The analysis in this report accounts for "replaced capacity" as just the installed capacity or projects that approaches the end of the technical lifetime. This does not include any new capacity. Basically, it indicates the difference between the "old" and the "new" capacity additions.

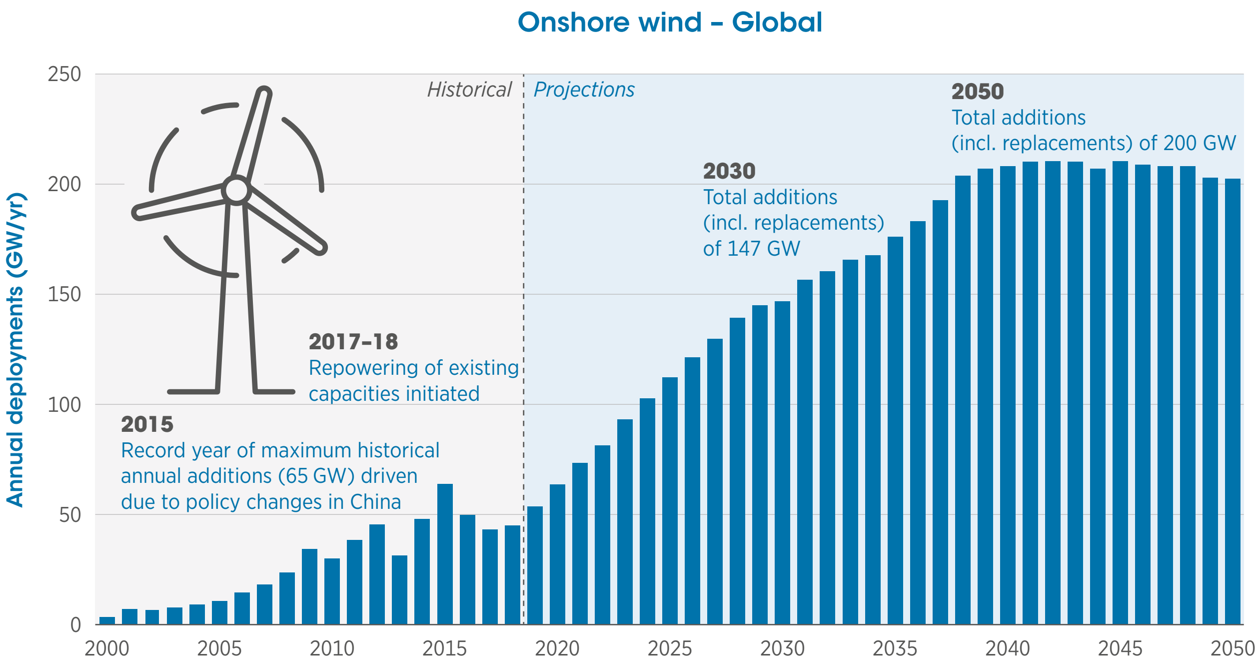
Figure 8: Asia would continue to dominate global onshore wind power installations by 2050, followed by North America and Europe.



The designations employed and the presentation of material herein do not imply the expression of any opinion on the part of IRENA concerning the legal status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d) and future projections based on IRENA's analysis.

Figure 9: Global onshore wind power additions would need to grow more than three-fold by 2030 and more than five-fold by 2050 relative to 2018 levels.



Source: Historical values based on IRENA's renewable energy statistics (IRENA, 2019d), future projections based on IRENA's analysis.

SIGNIFICANT GROWTH OF ANNUAL ONSHORE WIND ADDITIONS TO 2050

Annual capacity additions for onshore wind would increase four-fold, to more than 200 GW in the last decade to 2050 compared to 45 GW added in 2018.

Box 3. REPLACEMENT AND REPOWERING OF ONSHORE WIND ASSETS

- **Replacement of wind assets generally refers to the replacement of wind turbine system components at the end-of-life period with the latest operating and cost-effective technology components.** aThis results in improved energy yield, especially at the best resource sites, as many of the projects that are now 10–15 years old were located in some of the best resource sites. Many of the existing projects with great wind resources also suffer from smaller interconnections to the grid due to the smaller turbines installed earlier compared to the latest turbines available in the market. Getting the complete value of the repowering would also require a fast track for expanding the project grid interconnections so the full benefit of larger turbines can be realised and would result in better integration of variable wind energy into power grids along with their contribution to grid services. In addition, repowering of wind projects instead of decommissioning could aid in improving social acceptance by local communities that are already accustomed to the wind farms and could potentially benefit from additional revenues and local job creations (WindEurope, 2017a).

- Repowering could signify either replacing entire wind turbine system components (full repowering) or upgrading older turbines or specific components (rotor, gearbox) with advanced and efficiency technologies while still retaining existing components such as the foundation and tower (partial repowering). Replacing foundations involves complexities and is expensive, and thus requires in-depth design review to assess the ability of foundations to withstand additional service years (30 to 40 years instead of 20 years). In some cases, repowering of wind assets is done well before the end of the technical lifetime of wind plants, due to economic gains and resource utilisation purposes at the older, best resource sites with improved technology designs potential (AWEA, 2019; US DOE, 2019).

- **US:** The US Production Tax Credit (PTC), along with improvements in turbine technology, are aiding the growth of partial wind farm repowering activity in the country, which is expected to accelerate further in the coming years. More than 1.3 GW of onshore wind capacity was partially repowered in 2018. At present, the PTC is only a temporary economic tool that drives repowering in the US, and its expiration could slow the repowering effort, impacting the overall onshore wind market. A quarter of North America's wind turbine fleet is expected to reach the end of its life span by 2030, and repowering of this fleet starting now is important to utilise the rising wind power potential (AWEA, 2019; US DOE, 2019).

- **Europe:** In 2016, nearly 12% of the region's installed wind turbine capacity crossed the 15-year lifetime, and this share will increase to 28% by 2020 (Ziegler et al., 2018). Repowering the EU wind fleet that will reach the end of its lifetime by 2020 or later is crucial for achieving or even exceeding the EU's renewables target by 2030. The key markets in Europe for repowering are the UK, Germany, Denmark, Spain, Italy, Portugal and France, where the total repowering volume is expected to grow from 1–2 GW in 2017 to 5.5–8.5 GW by 2027 (WindEurope, 2017a). In the UK, repowering of the Delabole wind farm (initially commissioned in 1991) between 2009 and 2011 led to a more than two-fold increase in the plant's installed capacity, from 4 MW to 9.2 MW. Repowering a further 60 onshore wind farms in the country over the next five years – replacing turbines of less than 1 MW with contemporary turbines (2–3 MW) or upcoming models (4 MW) – would result in a net capacity increase of more than 1.3 GW (Energy & Climate, 2018).

DEPLOYMENT STRATEGIES FOR SELECTED COUNTRIES

The huge expected increase in global onshore wind installed capacity over the coming decades inevitably raises technical questions regarding how and where to accommodate the new wind facilities. Other than the presence of the primary wind source, fundamental aspects to be considered are the availability of land, the need for additional infrastructure and power system flexibility measures, adequate manufacturing facilities and transport needs to allow the development and operation of the new wind farms.

China: China's onshore wind installed capacity would grow from 205 GW in 2018 (CWEA, 2019) to almost 2 150 GW in 2050. This represents nearly a quarter of China's total land-based wind potential, which is estimated at around 8 800 GW considering an average wind turbine height of 80 metres (this value excludes forested areas, areas occupied by permanent snow/ice/water and developed/urban areas) (McElroy et al., 2009). This indicates the technical feasibility of deploying more than 2 000 GW, but China would need to overcome its current challenges of integrating wind power with existing power infrastructure, along with supply-side expansion needs.

TECHNICAL POTENTIAL [GW]	IRENA'S REMAP CASE BY 2050 [GW]	% OF TECHNICAL POTENTIAL
8 800	2 150	24%

In particular, China's northern regions have abundant onshore wind potential. The provinces of Qinghai, Xinjiang and Inner Mongolia, and the country's north-east, have the highest power density (average values between 400 and 600 watts per square metre (W/m^2)), and most new onshore installations are expected to be deployed in these areas. In the near and medium terms, due to potential power transmission constraints, the wind energy needs to get to demand areas and the north-west is not the only prioritised option. China is also considering areas to utilise the wind resource with higher power demand and/or with more flexible sources (e.g., hydro). As such, the potential from central and eastern China would be better utilised as distributed wind projects. In the meantime, considering the hydro resource in the north-west and south-west, land-based wind capacity could also expand in these regions (excluding forested and mountain areas).

To exploit such good wind resources, substantial investments in improving the existing grid infrastructure and developing additional power lines, along with the necessary flexibility measures, are required to integrate rising shares of wind power while avoiding energy curtailment. Increasing grid connection is a key enabling factor to fully benefit from the expected onshore wind capacity growth, making it possible to increase inter-provincial power transfer and strongly reduce curtailment (Luo et al., 2018). China is currently building the largest transmission networks in the world, including high and ultra-high voltage lines capable of delivering large amounts of power (2 000 MW of electricity) over thousands of kilometres from renewable resource-rich sites in the north and north-west to population-centric areas in the east and south-east (Prosser, 2019).

From a market perspective, the forward-looking outlook presented in this report offers two relevant opportunities for investors. First, the increase in the demand for wind turbines and associated technical equipment represents a strong investment opportunity. The Chinese onshore wind market is expected to grow steadily in the coming decades, with rising needs for key components and materials, not only for the national market but also for international exports. By 2021, China is expected to develop full-scale, subsidy-free onshore wind projects due to the cost competitiveness of onshore wind with fossil fuel generation sources. Second, grid extension and infrastructure improvements could offer great opportunity for wind farm developers (Luo et al., 2018).

US: The onshore wind installed capacity in the US would grow from 94 GW in 2018 to almost 857 GW by 2050. According to the National Renewable Energy Laboratory (NREL), the total land-based wind potential in the country is more than 10 000 GW, equivalent to almost 3.5 million km^2 of land excluding protected areas, cities and water This massive potential is mostly concentrated in a central area of the country from Minnesota/North-Dakota to Texas, which is likely to see the most deployment of future in land wind installations (NREL, 2018).

TECHNICAL POTENTIAL [GW]	IRENA'S REMAP CASE BY 2050 [GW]	% OF TECHNICAL POTENTIAL
10 000	857	8.5%

However, this will require new transmission lines to accommodate the growing onshore wind capacity in the centre of the country to deliver it to the population centres on the coasts. In addition, investments in the deployment of adequate flexibility measures and demand-response regulation mechanisms are fundamental to correctly operate the grid especially during low resource periods. Increasing the number of grid interconnections should also be considered as a priority to facilitate inter-regional energy exchanges and to simplify grid management. An NREL study on US grids shows that even with limited transmission expansion, the utility grids can reliably operate with a more than 35% wind generation share by 2050, and such a huge potential of wind can greatly contribute to energy security and improved socio-economic benefits (NREL, 2017).

As the US PTC phases out by 2024, and as natural gas and solar PV prices continue to decrease, uncertainty in access to finance in the short term for wind projects may be an equal or greater constraint than the needs for grid improvements and flexibility solutions.

With regard to wind manufacturing, in 2017 the US manufacturing and assembly capability was roughly 15 GW for nacelles, around 9.2 GW for blades and around 8.9 GW for towers (US DOE, 2019). With on average nearly 22 GW of new annual capacity deployment until 2050, the manufacturing capacity in North America (the US, Canada and Mexico) needs to be strongly expanded, benefitting from a combination of domestic production along with imports and exports among neighbouring countries in the regions.

Europe: After China and the US, Europe is the third largest market for onshore wind in the coming three decades. The installed onshore capacity is expected to increase more than two-fold by 2050 compared to the 161 GW installed as of the end of 2018. The region's total land-based wind potential is an estimated 13 900 GW (EEA, 2009). The best sites for onshore installations are in northern and central continental Europe as well as in the UK (EEA, 2009).

TECHNICAL POTENTIAL [GW]	IRENA'S REMAP CASE BY 2050 [GW]	% OF TECHNICAL POTENTIAL
13 900	406	3%

With regard to grid infrastructure, the European grid is facing challenges different from those in China and the US. The primary objective is to increase interconnections among countries and to relieve grid constraints with improved power system flexibility options (for example, In Germany for North Sea wind) to accommodate larger shares of variable renewables. To this end, reinforcing and expanding the grid infrastructure would be fundamental in the coming decades, not only at a national level but also at a regional level, favouring cross-country connections.

From an investment perspective, Germany, France, Denmark, Spain, Italy, Sweden, Norway, Poland and Ireland would remain the top wind markets, where the largest share of new installations would take place. On a regional level, European manufacturers show overcapacity in all key wind turbine components when compared to present and future European demand. The average annual deployment capacity is around 7.7 GW/year, enough to deploy the additional capacity until 2050. Nevertheless, the global onshore wind market trend shows a positive market for European manufacturers, indicating additional market potential outside the region (Magagna, et al., 2017)

COST REDUCTIONS AND CAPACITY FACTOR IMPROVEMENT

The breakthrough in renewable capacity additions over the past few years has been achieved largely because of the significant cost reductions in renewables driven by technology improvements, specialisation and standardization, broader and more competitive supply chains, economies of scale, competitive procurement and a wide base of experienced, internationally active project developers. Key renewable technologies such as solar PV, wind, concentrating solar power (CSP) and bioenergy are already cost competitive and are expected to further outpace fossil fuels by 2020 (IRENA, 2019c).

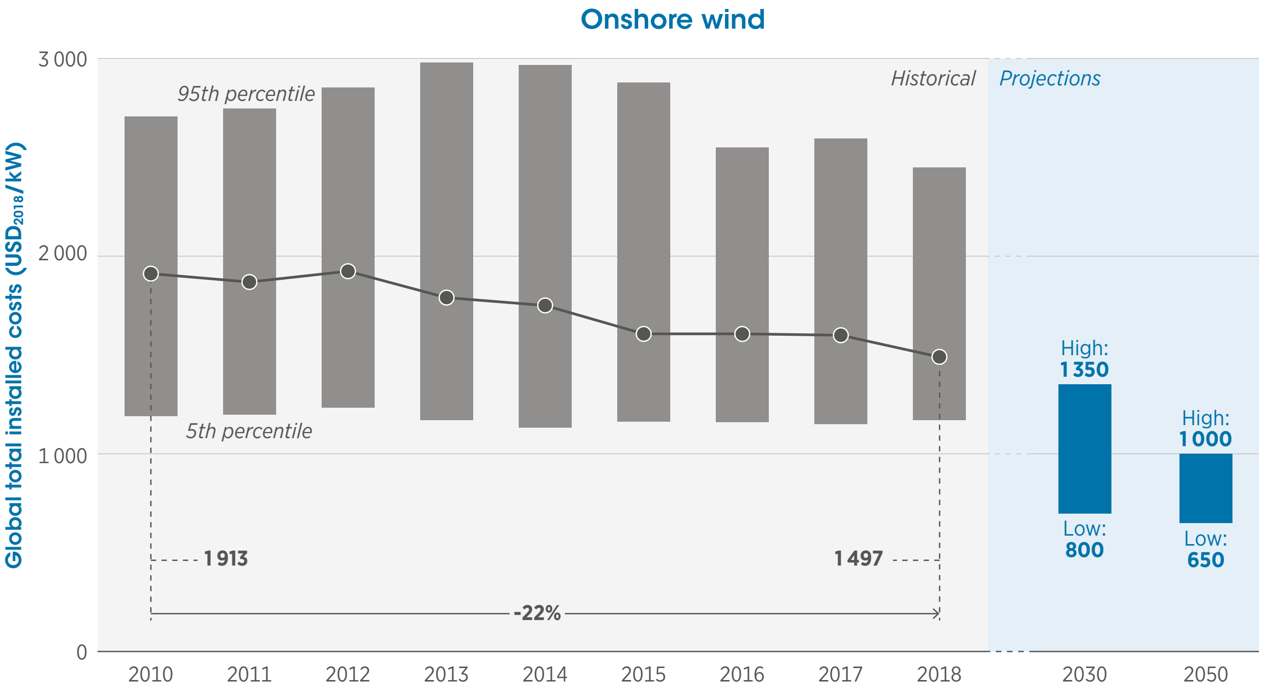
Currently, onshore wind is one of the most competitive sources of new power generation capacity. Globally, the total installed costs of onshore wind fell by an average of 22% between 2010 and 2018, and declined by 6% in 2018 compared to 2017 (Figure 10), notably as deployment in China and India grew, given their relatively low-cost structures (IRENA, 2019c). The total installed cost is expected to drop further in the next three decades, reaching an average range of USD 800 to 1 350/kW by 2030 and USD 650 to 1 000/kW by 2050[6] compared to current average levels of USD 1 497/kW in 2018.

Improvements in technology and manufacturing processes, regional manufacturing facilities and competitive supply chains are all putting downward pressure on turbine prices. In 2018, with the exception of China and India, average turbine prices were between USD 790 and USD 900/kW depending on their size, down from between USD 910 and USD 1 050/kW in 2017 (IRENA, 2019c). For onshore wind farms installed in 2018, the country-specific average total installed costs were around USD 1 170/ kW in China, 1 200/ kW in India, USD 1 660/kW in the US, USD 1 820/ kW in Brazil, USD 1 830/kW in Germany, USD 1 870/ kW in France and USD 2 030/kW in the UK (Figure 11) (IRENA, 2019c).

The total installed costs for onshore wind projects are very site and market specific. For projects commissioned in 2018, the range between the lowest and the highest installed cost was significant for onshore wind in most regions, except for China and India.

6 The future cost projections in this report are based on IRENA's ongoing cost analysis as part of the upcoming report Power to change – Solar and wind cost reduction potential to 2030. This report addresses some of the detailed cost efficiencies and reductions.

Figure 10: Total installed cost of onshore wind projects has fallen rapidly and is expected to decline further by 2050.



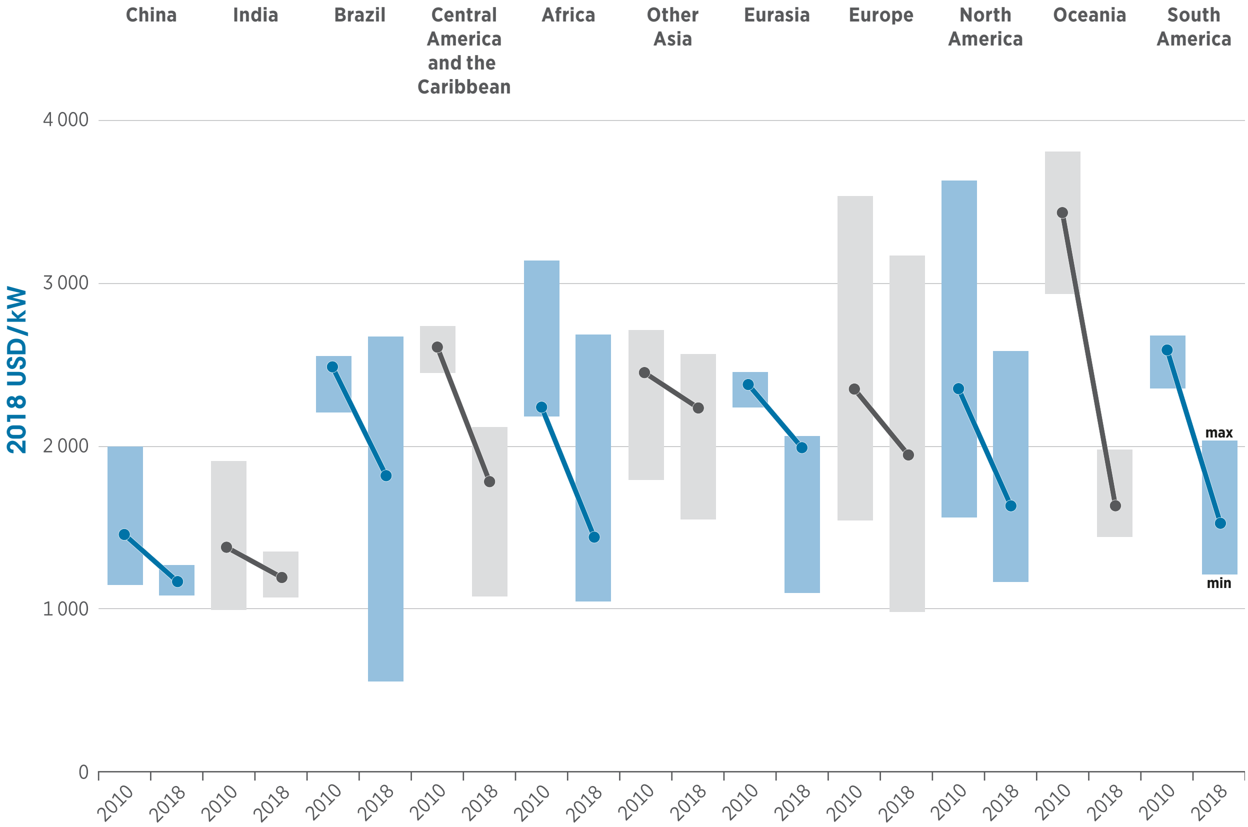
Note: The costs in the figure represent the total capital costs of a wind power plant assigned to four main categories: wind turbine cost (rotor blades, gearbox, generator, power converter, nacelle, tower and transformer), civil works (construction works for site preparation and foundations for tower), grid connection costs (transformers, substations and connection to the local distribution or transmission network) and planning and project costs (development cost and fees, licences, financial closing costs, feasibility and development studies, legal fees, owners' insurance, debt service reserve and construction management) (IRENA, 2016a).

Source: Historical data based on IRENA, 2019c and future projections based on IRENA's forthcoming report: Solar and wind cost reduction potential to 2030 in the G20 countries (IRENA, n.d.).

ONSHORE WIND INSTALLATION COSTS WOULD DECLINE DRAMATICALLY FROM NOW TO 2050

Globally, the total installation cost of onshore wind projects would continue to decline dramatically in the next three decades, averaging in the range of USD 800 to 1 350/kW by 2030 and USD 650 to 1 000/kW by 2050, compared to the average of USD 1 497/kW in 2018.

Figure 11: Total Installed cost ranges and weighted averages for onshore wind projects have declined in many countries/regions since 2010.



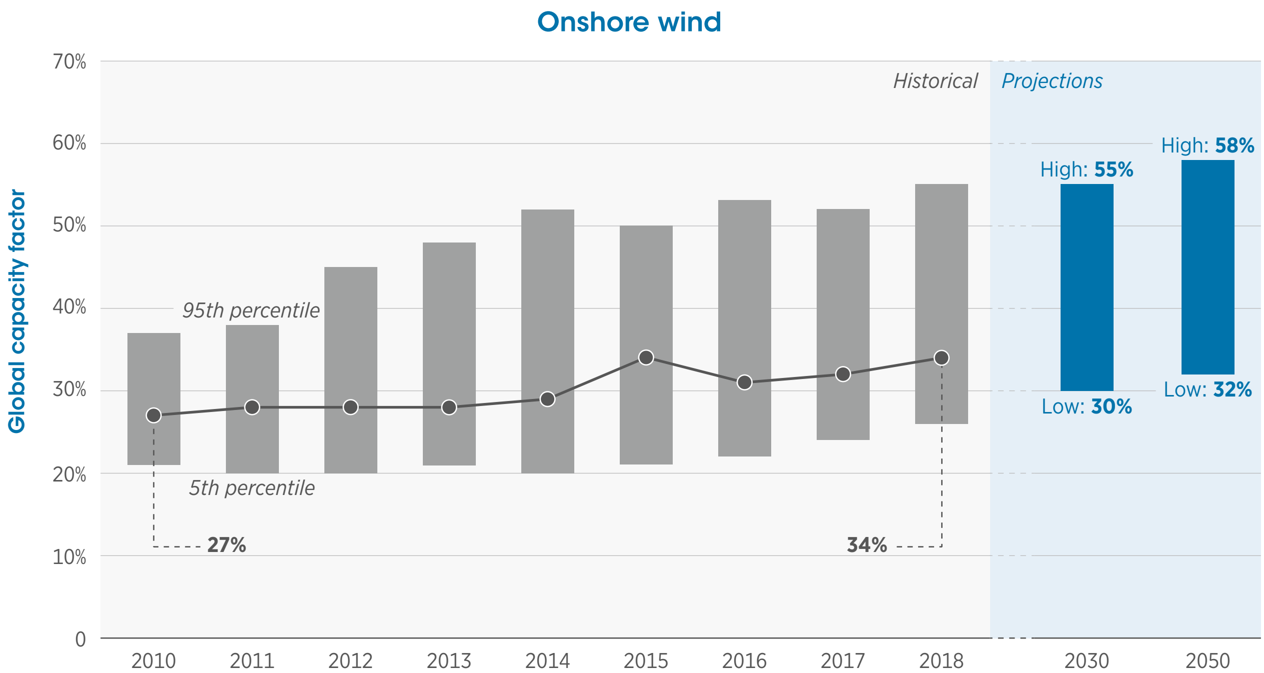
Source: IRENA, 2019c.

A combination of improved wind turbine technologies, deployment of higher hub heights and longer blades with larger swept areas has led to increased capacity factors for a given wind resource. Project siting and operational efficiencies also drove improvements in capacity factors. The global weighted average capacity factor for newly commissioned projects increased from an average of 27% in 2010 to 34% in 2018 (IRENA, 2019c). Ongoing improvements in wind turbine technologies, higher turbine dimensions and deployment of the latest technologies in markets such as China and India (among others) would further improve the average capacity factor, to reach 55% by 2030 and 58% by 2050 (Figure 12).

The global weighted average levelised cost of electricity (LCOE) of onshore wind projects commissioned in 2018, at USD 0.056/kWh, was 13% lower than in 2017 and 35% lower than in 2010[7] (Figure 13). Factors driving this trend include continued improvements in turbine design and manufacturing; more competitive global supply chains; and an increasing range of turbines designed to minimise the LCOE in a range of operating conditions. Costs of electricity from onshore wind are now at the lower end of the fossil fuel cost range. In 2018, the weighted average LCOEs of newly commissioned onshore wind farms in China and the US were identical[8] at USD 0.048/kWh, which was 4% lower than in 2017 (IRENA, 2019c).

7 See IRENA, 2019c for details of the LCOE methodology. Note tha these calculations are based on a conservative weighted-average cost of capital of 7.5% in the OECD and China and 10% elsewhere.
8 Although China has lower capacity factors than the US, this is offset by lower installed costs in 2018. Capacity factors in China could be increased over time if and when the old turbines are replaced with new-generation turbines and the layout of turbines at existing wind farms is improved.

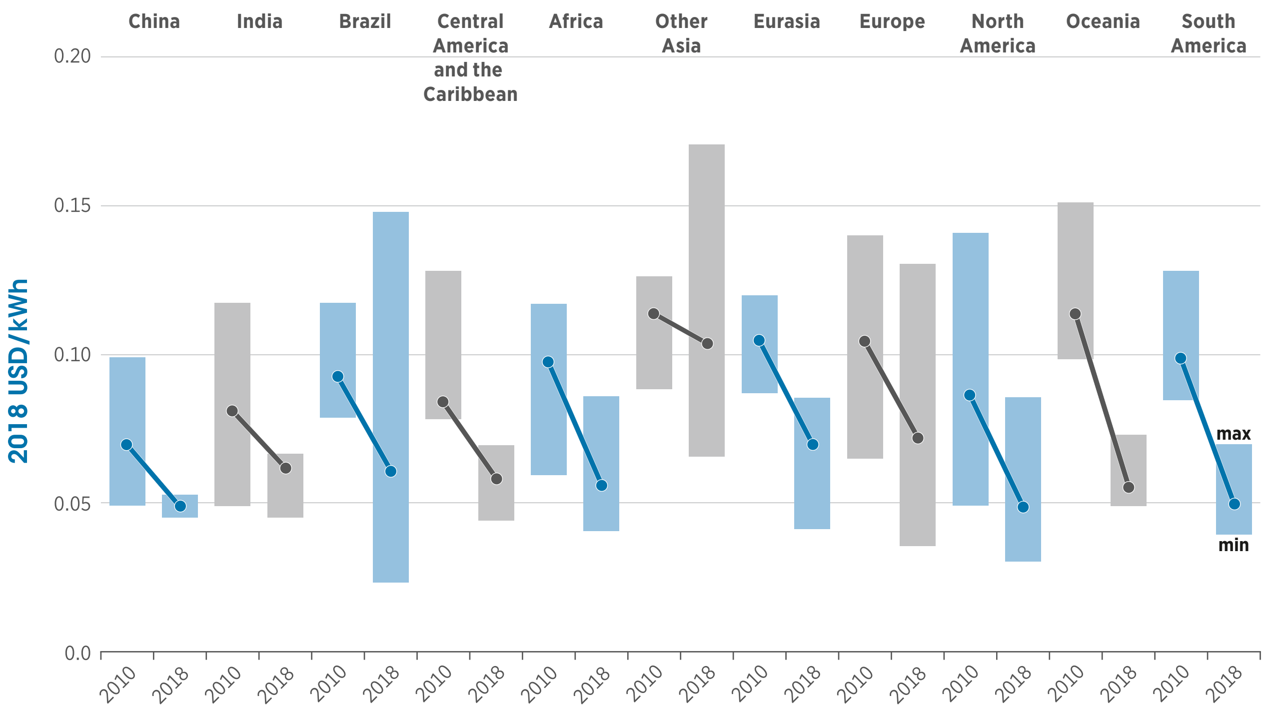
Figure 12: The global weighted average capacity factor for new turbines has increased from 27% in 2010 to 34% in 2018 and would increase substantially in next three decades.



Note: The capacity factor is based on the project commissioning year.

Source: Historical data based on (IRENA, 2019c) and future projections are based on IRENA's forthcoming report: Solar and wind cost reduction potential to 2030 in the G20 countries (IRENA, n.d.).

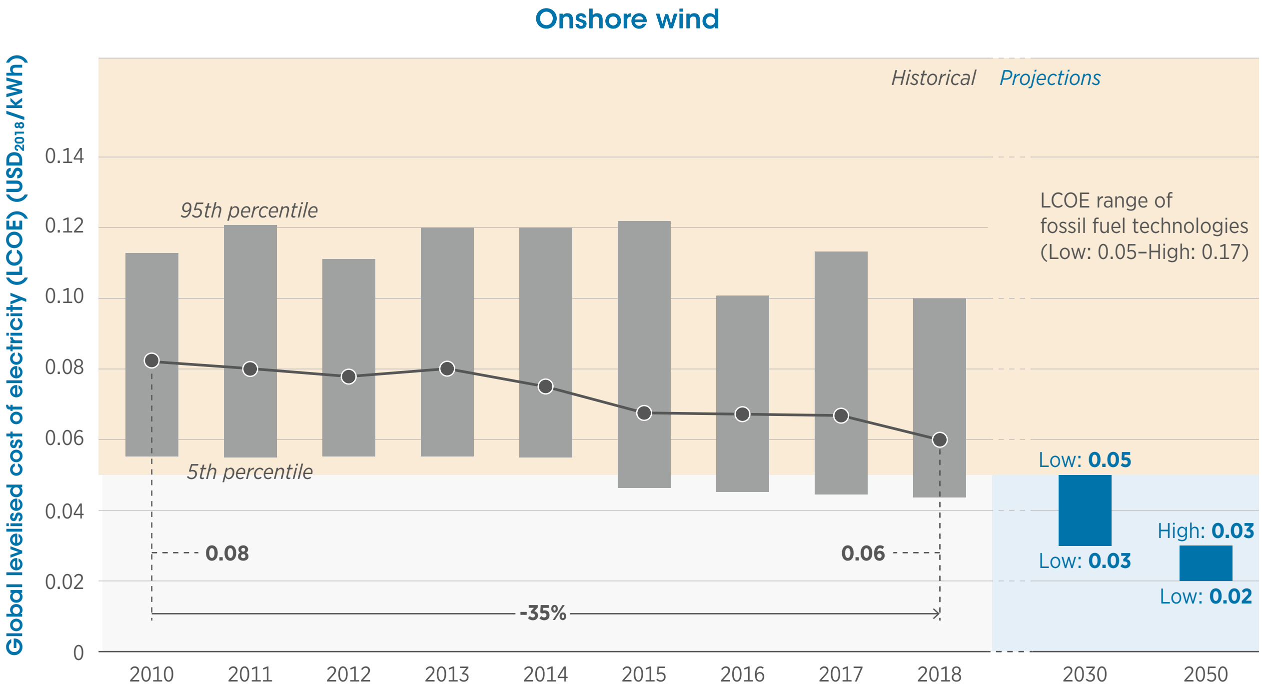
Figure 13: Regional weighted average levelised cost of electricity and ranges for onshore wind in 2010 and 2018.



Source: (IRENA, 2019c).

Looking towards 2050, the global weighted average LCOE of onshore wind generation capacity is expected to decline at levels comparable to the historical reductions since 2010. By 2030, the cost of onshore wind power would be fully competitive, well below the lower fossil fuel range at around USD 0.03 to 0.05/kWh and would decline further towards 2050, reaching a rane of between USD 0.02 and 0.03/kWh (Figure 14).

Figure 14: The Levelized cost of Electricity for onshore wind is already competitive now compared to all fossil fuel generation sources and would be fully competitive in a few years.



Source: Historical data based on IRENA, 2019c and future projections based on IRENA's forthcoming report: Solar and wind cost reduction potential to 2030 in the G20 countries (IRENA, n.d.).

ONSHORE WIND WOULD BE ONE OF THE CHEAPEST GENERATING SOURCES

The levelised cost of electricity for onshore wind is already competitive now compared to all generation sources (including fossil fuels) and is expected to decline further in the coming decades, falling within the range of USD 0.03 to 0.05/kWh by 2030 and USD 0.02 to 0.03/kWh by 2050.

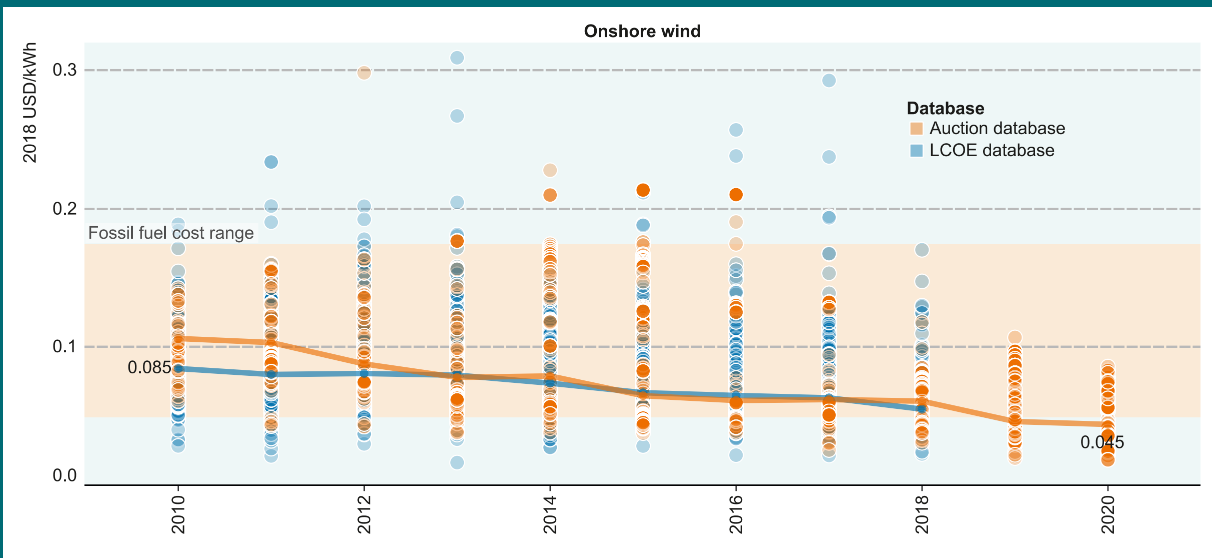
Box 4. CURRENT AUCTION/SUBSIDY PRICES FOR ONSHORE WIND AND THE IMPACT ON DRIVING DOWN LCOEs

In addition to the project-level LCOE data in the IRENA Renewable Cost Database based on project-specific installed costs and capacity factors, IRENA also collects data on power purchase agreement (PPA) and auction results. These provide a different set of cost metrics that can be used to look at the costs for projects that will be commissioned in the near future (see (IRENA, 2019c) for caveats to this analysis). IRENA's database of auction results and PPAs for onshore wind is overlaid with the LCOE data in Figure 15 and shows the continuous downward trend in prices for onshore wind up to 2018 for commissioned projects and to 2020 with the auction and PPA results (IRENA, 2019c).

Comparing the 2018 global-weighted average LCOE for onshore wind to the 2021 global weighted average auction and PPA results in 2021 of USD 0.031/kWh shows a 45% reduction n the cost of electricity. Even so, the differences between the PPA/auction price and the LCOE are worth noting, as discussed in (IRENA, 2019c).

Onshore wind is expected to provide cheaper electricity than fossil fuel generation by 2019. IRENA's upcoming report on the cost reduction potential for solar and wind up to 2030 will provide a detailed discussion of the total installed cost, LCOE and PPA/auction prices for both wind and solar technologies (IRENA, *n.d.*).

Figure 15: Levelised cost of electricity and global weighted average values for onshore wind projects, 2010–2020.



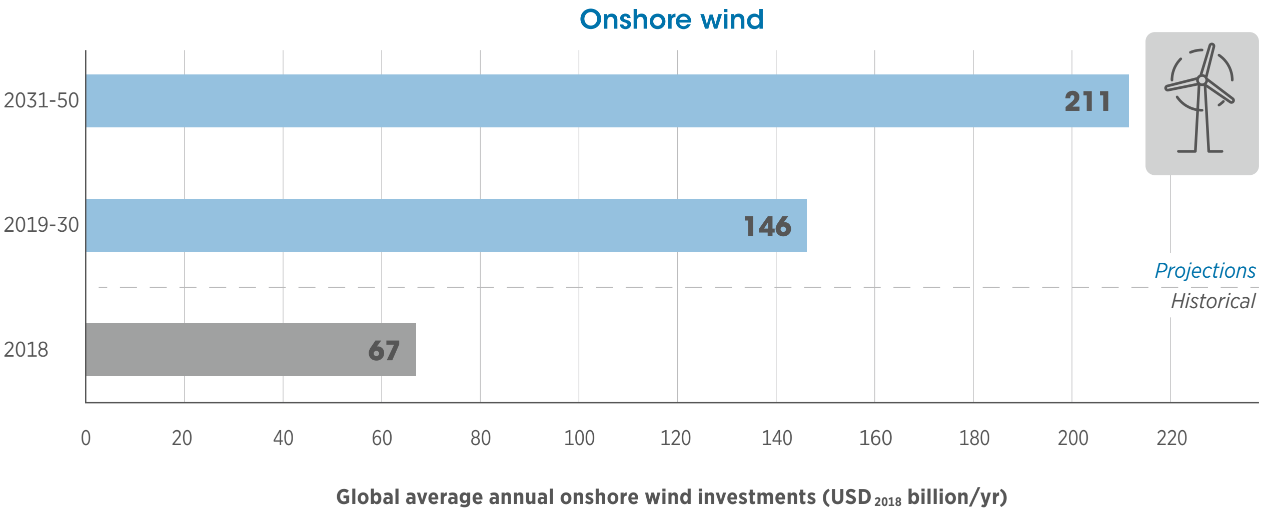
Source: IRENA, 2019c

INVESTMENT NEEDS

Onshore wind investments rose steadily from USD 63 billion in 2013 to USD 80 billion in 2016 (BNEF, 2019). In 2018, investments made in deploying onshore wind capacities amounted to nearly USD 67 billion. Deploying a total installed onshore wind capacity of more than 5 000 GW by 2050 would require an average annual investment of USD 146 billion/year over the period to 2030 and USD 211 billion/year over the remaining decades to 2050 (Figure 16). This means scaling up annual onshore wind investments by a factor of more than two from now until 2030 and even higher over the remaining period to 2050 compared to investments made in 2018.

Currently, the bulk of annual wind power investment goes to the installation of new onshore wind power capacities, and a virtually insignificant share is needed for replacement of retired installed capacities. However, in the coming decades, a share of investments will be needed to replace the existing wind capacities reaching the end of their lifetimes. From 2040, more than one-third of total average annual onshore wind investment will be needed to replace these existing capacities with advanced technologies.

Figure 16: Scaling up onshore wind energy investment is key to accelerate the pace of global onshore wind installations over the coming decades.



Source: Based on IRENA analysis.

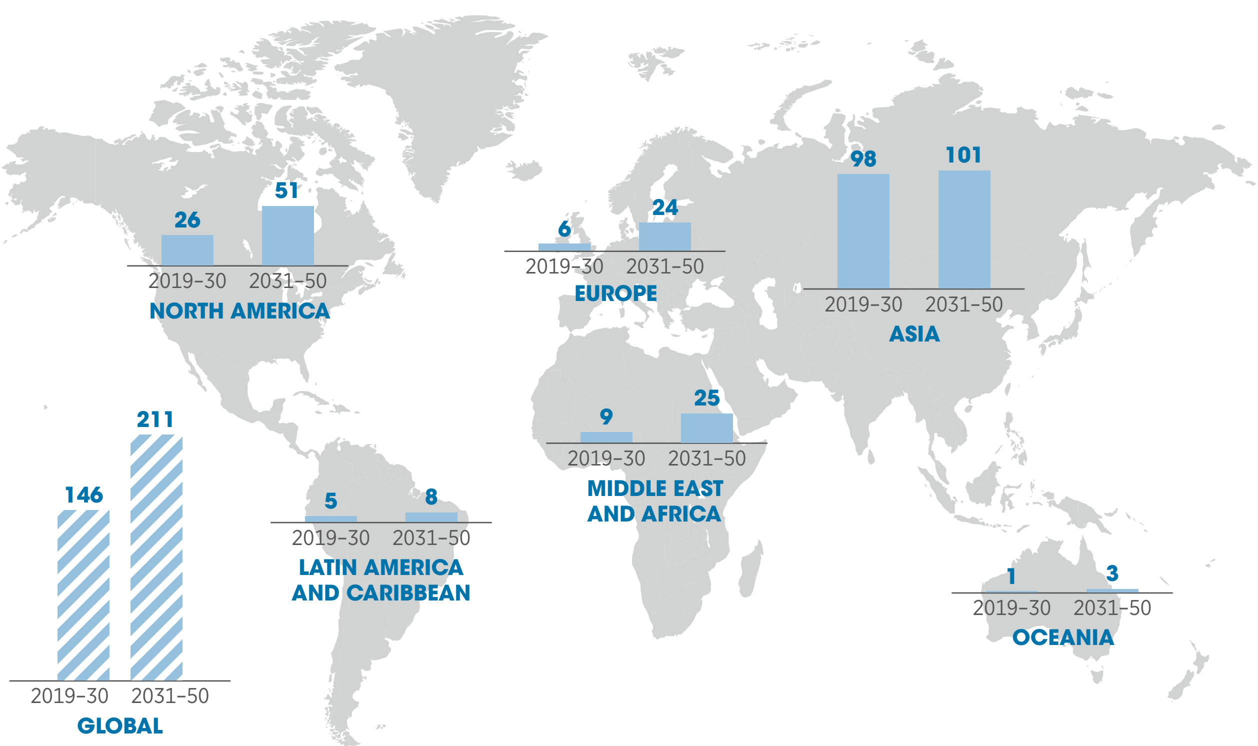
SCALING UP ONSHORE WIND INVESTMENTS IS KEY TO FACILITATE THE UPTAKE OF THE ONSHORE WIND MARKET

Global average annual onshore wind power investment needs to scaled up a factor of more than two until 2030 (USD 146 billion/year) and more than three over the remaining period to 2050 (USD 211 billion/year), compared to 2018 investment (USD 67 billion/year).

At the regional level, Asia would account for more than half of the global average annual investments, with almost USD 98 billion/year invested in the region from now until 2030 and USD 101 billion/year invested in the last two decades to 2050 (most of it in China and India), followed by North America with USD 26 billion/ year until 2030, and nearly double that until 2050 (USD 51 billion/year). Emerging onshore markets in regions such as Middle east and North Africa would need an average annual onshore wind investments of USD 9 billion/year until 2030 and USD 25 billion/year until 2050 (Figure 17).

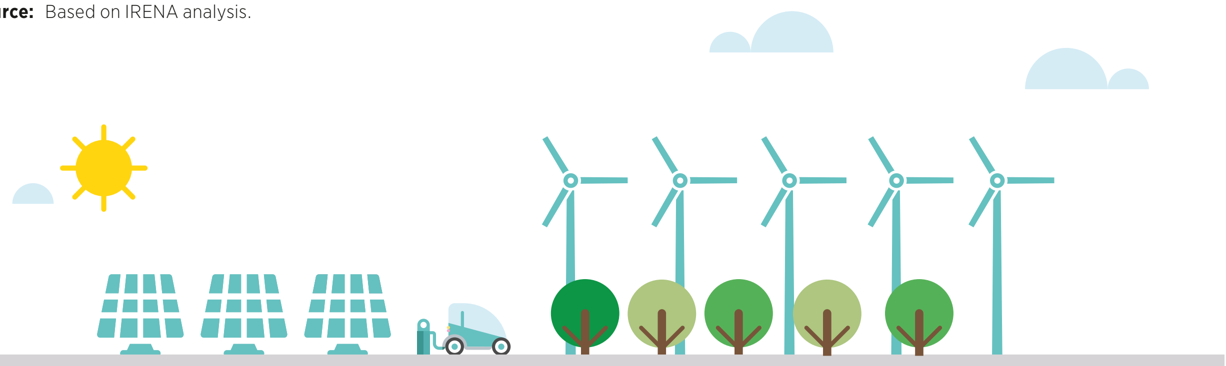
Figure 17: total investments in global onshore annual wind power deployment, including new capacity installations and replacement of end-of-lifetime capacities.

Average annual investments for onshore wind deployment (USD billion/yr)



The designations employed and the presentation of material herein do not imply the expression of any opinion on the part of IRENA concerning the legal status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Source: Based on IRENA analysis.

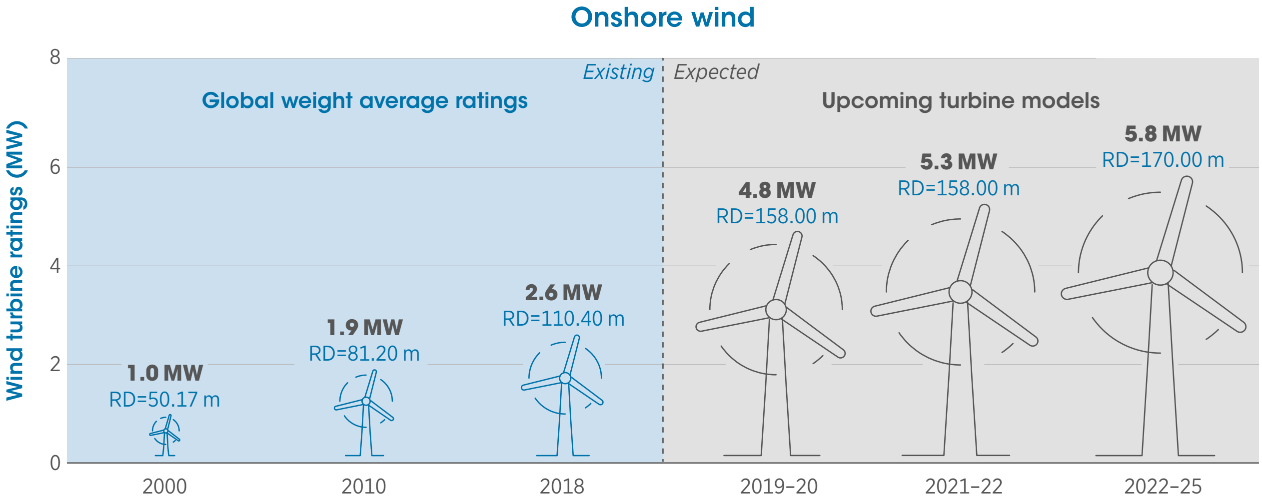


ONGOING AND FUTURE INNOVATIONS

GRADUAL INCREASE IN ONSHORE TURBINE SIZE AND RATINGS TO CONTINUE

Wind power cost reductions are driven mainly by advancements in wind turbine technology. The key parameters that denote the improvements in wind turbine technologies are the rotor diameter and the hub height to access more power from wind turbines, even in areas with lower wind speeds. Larger rotors aid in decreasing specific power, which eventually boosts capacity factors and opens up low-wind areas to more wind. The maximum size of turbines added in 2018 was 4.3 MW, up from 3.3 MW in 2015 (IRENA, 2019c) (Figure 18). GE is now offering improved onshore turbine technologies rated at 4.8 MW and 5.3 MW, respectively (Wind Power Monthly, 2018). Siemens-Gamesa presented its 5.8 MW, 170-metre rotor diameter model, which is larger than the largest offshore turbine currently available in the market (Vestas's V164 10 MW) (Wind Power Monthly, 2019).

Figure 18: Ongoing innovations and technology enhancements towards larger-capacity turbines, increased hub heights and rotor diameters would improve energy yields and reduce capital and operation costs per unit of installed capacity.



*denotes turbine developments happening from now and latest models available in that specific year.

Source: (IRENA, 2019c; Wind Power Monthly, 2019, 2018).

OTHER INNOVATIONS TO STIMULATE FUTURE WIND MARKET GROWTH

Taking advantage of the fast-growing wind capacities across the globe, several research projects or prototypes are under way exploring innovations in design, materials requirement and manufacturing techniques to stimulate future market growth, for a wide range of applications. Major trends include:

- **Innovation in rotor blade design and materials: The research is focused on improving the blades' aerodynamic profiles and materials in order to maximise energy production and reduce operation and maintenance (O&M) costs.** Innovative materials for wind turbines are critical to improve performances, especially in harsh and corrosive environments such as deserts or seas and to limit leading-edge erosion (Windtrust, 2016).

- **Optimised power electronics: Optimising the power inverters reliability and dimensions could reduce turbine installation and operation costs**.In this context, the German firm Semikron has already implemented the optimised design of its power electronics component by focusing on aspects such as humidity protection (reducing the failure of power modules due to condensation and water accumulation), scalability (creating new intelligent power modules, such as sintered modules, which have a power density of almost 30% higher than their predecessor) and reducing the number of parts (to improve the reliability of power electronics by reducing the number of active elements in power modules and thereby reducing defects or breakdowns). In addition, advanced predictive algorithms are being tested and deployed to improve maintenance activities through reduced costs from reduced failure counts (detecting the faults in advance by monitoring the health condition of the modules) and making the power electronics operationable even in humid conditions (Windtrust, 2016).

- **"Smart/Intelligent" wind turbines: The digital revolution is affecting wind energy with new technologies for turbine monitoring and controls**. The aim is to improve the forecasting mechanism (using big data and artificial intelligence) and the automatic regulations of turbines (pitch control and yaw control) to maximise the overall energy output (Windtrust, 2016). This is crucial to cut down the unplanned costs due to failures, which currently make up more than half of total maintenance costs (Wood Mackenzie, 2019a).

  Digitalisation has enabled pro-active management of turbine live performances, which has helped to control future damages, translating these apparent expenditures into savings that ultimately have expanded wind farm lifetimes. Predictive analytics can take sensor data from a wind turbine to monitor wear and tear and to predict with a high degree of accuracy when the turbine would need maintenance (IRENA, 2019g). With the help of artificial intelligence, GE in Japan succeeded in enhancing wind turbine efficiency, reducing maintenance costs by 20% and increasing power output by 5% (IRENA, 2019h). McKinsey's Utilityx achieved maintenance and replacement cost savings of 10-25% through predictive maintenance (IRENA, 2019h).

- **Recycling of materials:** Reducing, reusing and recycling of the water, metals, resources, residues and raw materials used in the wind energy sector should be increased. Wind turbine blades are mostly made of a composite material that enables lighter and longer blades and thus higher performance. Currently, nearly 2.5 million tonnes of composite materials are in use in the wind energy sector (RECYCLING, 2019). In Europe alone, almost 12 000 wind turbines are expected to be decommissioned in the next five years (RECYCLING, 2019). This would entail a huge amount of materials to be recycled and would require a wide range of recycling options. The thermoset composites could be recycled commonly through either mechanical processes (cutting the turbine blades into smaller slices for easy transport) or thermal processes (combustion or pyrolysis) (WindEurope, 2017b).

  For the newer turbine blades now being manufactured, different sustainable materials along with cost effective recycling processes should be considered pave the way for the circular economy (WindEurope, 2017b). The Dreamwind project is focused on developing a chemical substance to separate the glass from the plastic fibres by heating them to 600 °C in order to recycle the large and expensive fibreglass components from wind turbines in the future. The separated glass after cleaning could then be reused for new fiberglass components for turbines (Dreamwind, *n.d.*).

2.3 OFFSHORE WIND OUTLOOK TO 2050

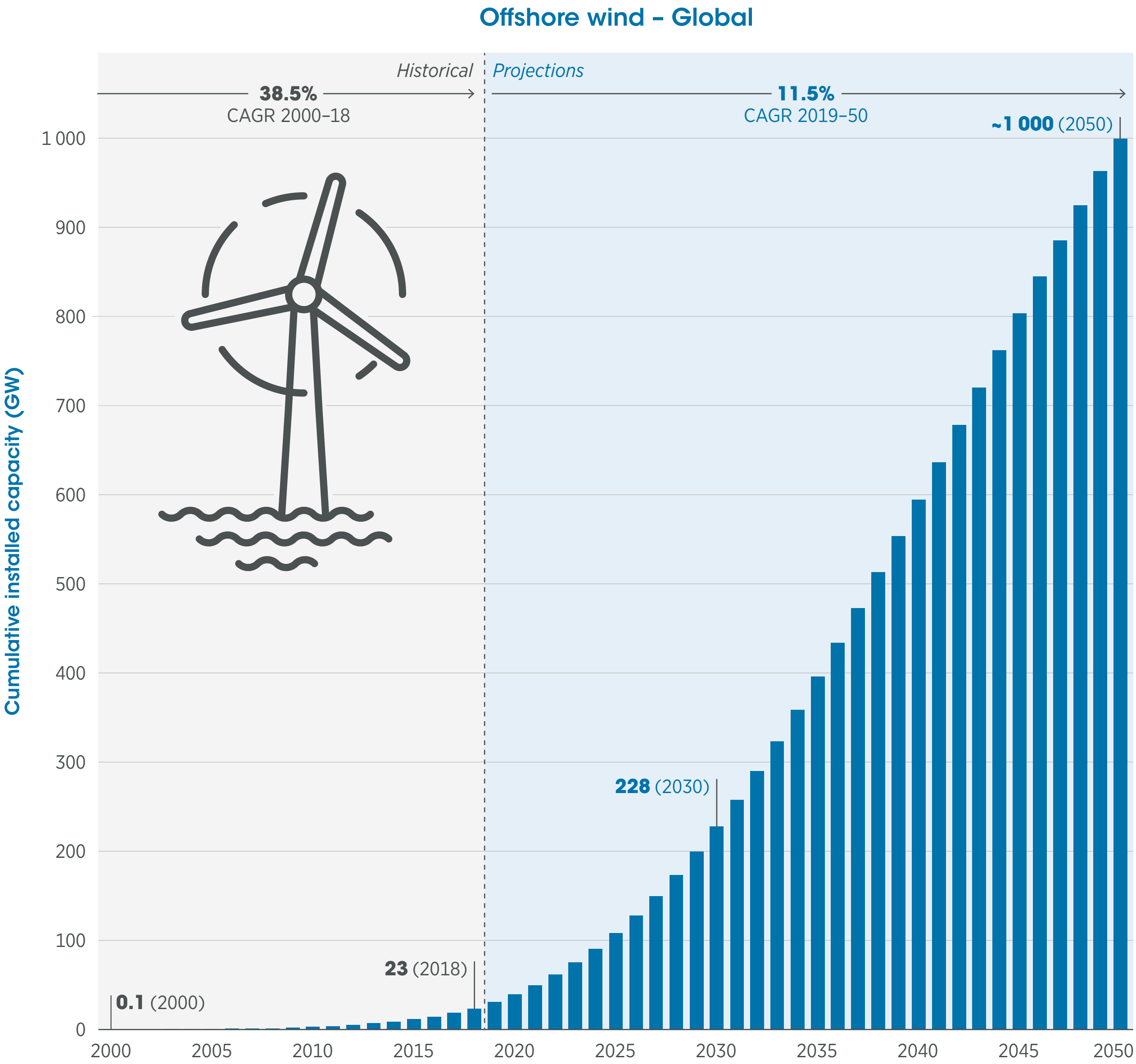
SURGING CAPACITY AND SHIFTED FOCUS TO ASIA

Offshore wind technology allows countries to exploit the generally higher and sometimes smoother wind resources offshore, while achieving gigawatt-scale projects close to the densely populated coastal areas prevalent in many parts of the world. This makes offshore wind an important addition to the portfolio of low carbon technologies available to decarbonise the energy sector of many countries. Offshore wind energy is one of the emerging renewables technology that has come of age in the last two-to-three years, as rapid technology improvements, supply chain efficiencies and logistical synergies in closely linked markets in Europe have seen rapid cost reductions and the beginnings of substantial uptake in new markets. Spurred by policy support and financial incentives, offshore wind is gaining momentum as it provides a complementary alternative to some of the challenges faced by onshore wind deployments mainly with respect to transmission congestion and land limitations, that makes it more challenging to deploy onshore wind in some locations (such as Europe).

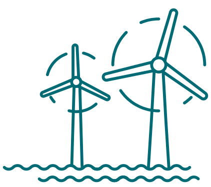
The offshore market would grow significantly over the next three decades, with the total installed offshore wind capacity rising nearly ten-fold from just 23 GW in 2018 to 228 GW in 2030 and near 1 000 GW in 2050 (Figure 19). Offshore wind would represent nearly 17% of the total global installed wind capacity of 6 044 GW in 2050 (IRENA, 2019a). This reflects an average CAGR of 11.5% for the next three decades, which is well below the historical average of 38.5% between 2000 and 2018, implying the feasibility and ease of scaling up offshore wind installations by just continuing the historical pace. Nearly ten-fold growth in offshore wind capacities by 2030 is well in line with the Global Wind Energy Council's 2019 offshore wind market report, which estimates that the offshore wind industry will grow above 200 GW (GWEC, 2019b).

Currently, 90% of global installed offshore wind capacity is commissioned and operated in the North Sea and nearby Atlantic Ocean. In 2018, almost 4.5 GW of new offshore wind capacity was added, most of which was concentrated in China (close to 37% of the total), with much of the growth in capacity in the UK (29%) and Germany (22%). Deployment is set to broaden to North America and Oceania with projects that would be developed in the coming years (IRENA, 2019d). The expansion of offshore wind markets is moving beyond the front runners, with several emerging markets setting targets for offshore deployment (IEEFA, 2018) (Box 5).

Figure 19: Offshore wind power deployment would grow gradually to nearly 1 000 GW of total installed capacity by 2050.



Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d), future projections based on IRENA's analysis (IRENA, 2019a).



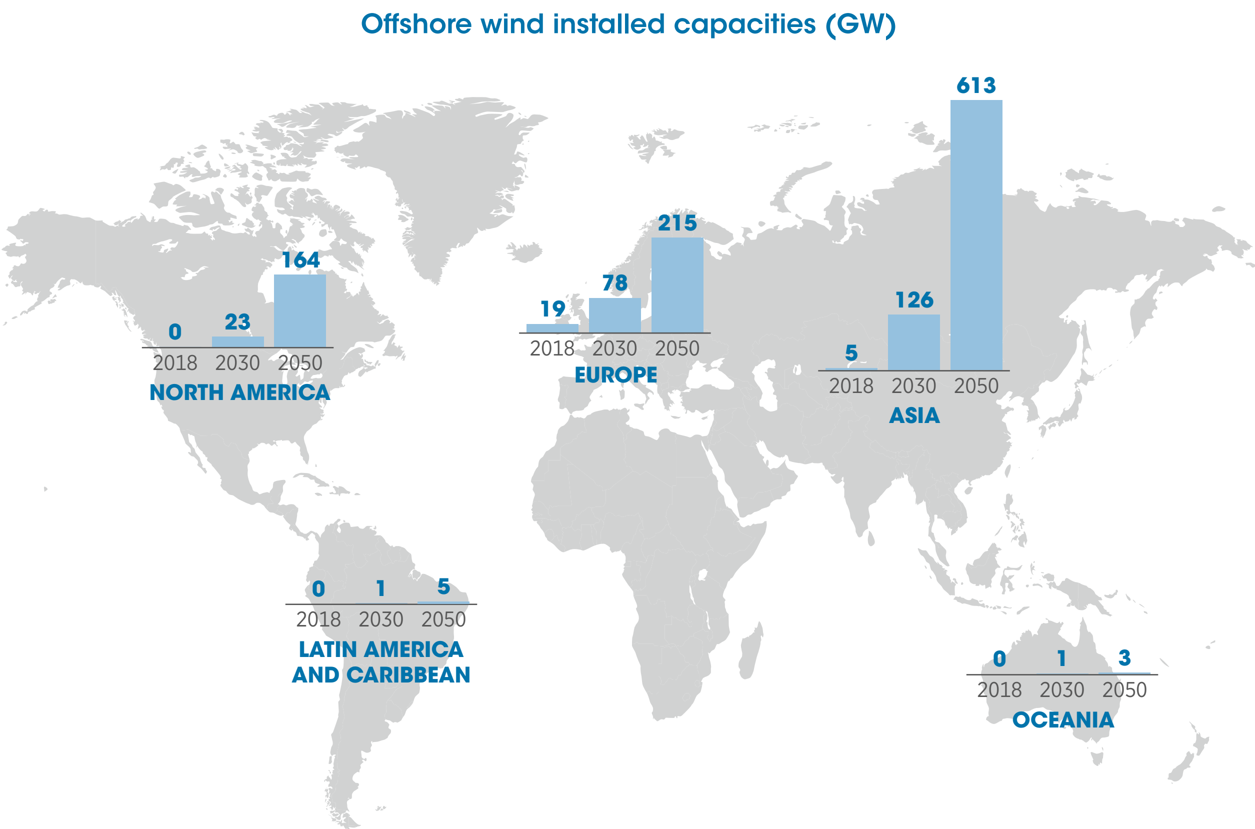
OFFSHORE WIND – AN EMERGING GIANT TECHNOLOGY

Global cumulative offshore wind capacity would increase almost ten-fold by 2030 (to 228 GW) and even more towards 2050, with total offshore installation nearing 1 000 GW by 2050.

Moving forward, a prominent shift in deployment would happen in Asian waters (mostly in China, India, Chinese Taipei, the Republic of Korea, Japan, Indonesia, the Philippines and Viet Nam) in the next three decades. Asia would eventually dominate global offshore wind power installations with a total capacity exceeding 100 GW by 2030 and 600 GW by 2050 (Figure 20). Within Asia, significant offshore wind deployment would occur in China, where the installed capacity would reach around 56 GW by 2030 and 382 GW by 2050.

China would dominate offshore wind installations, outpacing Europe in less than two decades from now. Europe would continue to dominate offshore wind installations for a decade or so, with total offshore wind capacity growing four-fold to 78 GW by 2030 and more than eleven-fold to 215 GW by 2050, compared to 19 GW in 2018. After Asia and Europe, North America would be another emerging offshore wind market. In the US, offshore wind installed capacity would grow more strongly, from less than 1 GW today to almost 23 GW by 2030 and 164 GW by 2050.

Figure 20: Asia would dominate global offshore wind power installations by 2050, followed by Europe and North America.



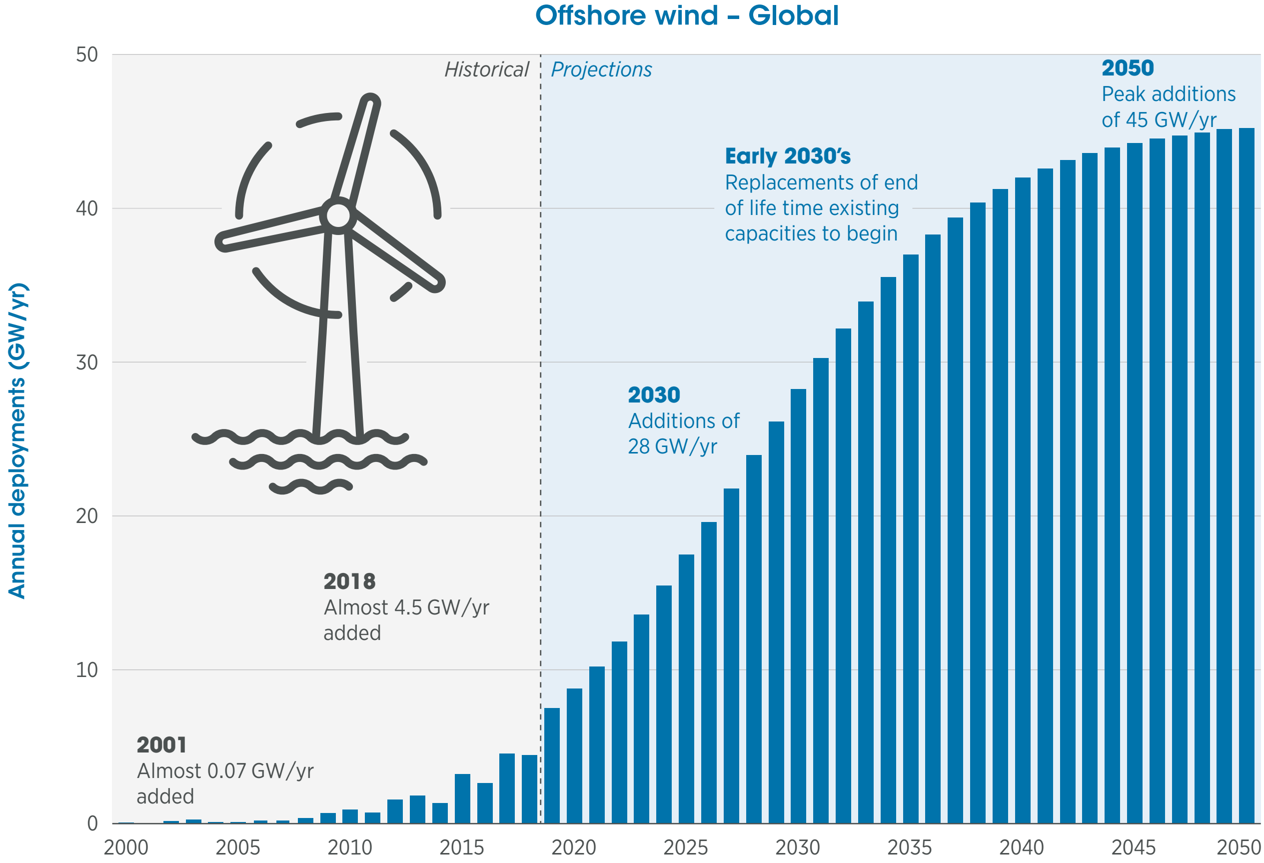
The designations employed and the presentation of material herein do not imply the expression of any opinion on the part of IRENA concerning the legal status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d), and future projections based on IRENA analysis (IRENA, 2019a).

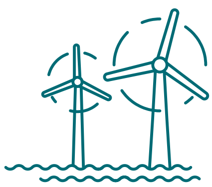
A significant increase in new offshore wind installations would happen in the next three decades. In addition to the large increase in new offshore wind power installations, existing wind turbines that were built before 2010 would approach the end of their technical lifetime and would need to be replaced with improved technological designs. Replacement of retired capacities should begin in the early 2030s and would gradually increase from 2040.

Overall, the total annual offshore wind capacity addition would need to increase more than six-fold by 2030 (to 28 GW/year) and ten-fold by 2050 (to 45 GW/year), compared to the 4.5 GW of capacity added in 2018 (Figure 21).

Figure 21: Annual offshore wind capacity additions would need to scale up more than six-fold to 28 GW in 2030 and almost ten-fold to 45 GW in 2050 from 4.5 GW added in 2018.



Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d), and future projections based on IRENA analysis (IRENA, 2019a).



RAPID GROWTH IN OFFSHORE WIND ANNUAL MARKET TO 2050

Globally, annual offshore wind capacity additions would rise more than six-fold in 2030 (to 28 GW/year) and around ten-fold in 2050 (to 45 GW/year), from 4.5 GW added in 2018.

Box 5. OFFSHORE WIND: KEY COUNTRY TARGETS AND PLANS

Offshore wind has been an emerging giant over the last few years, and deployment is expected to accelerate due to significant benefits attained with technology advancements, performance improvements and competitive offshore electricity generation costs. Although major installations at present are mostly in the North Sea and near the Atlantic Ocean, several countries have set plans and targets for offshore wind deployment. Major Asian economies such as China, Chinese Taipei, India, Indonesia, Japan, the Philippines, the Republic of Korea, and Viet Nam have targets for a cumulative offshore wind installation of 100 GW by 2030, which would potentially replace around 300 to 350 metric tonnes of coal annually (IEEFA, 2018).

Table 1: Offshore wind deployments and targets in countries.

COUNTRY PLANS FOR OFFSHORE WIND POWER DEPLOYMENT	
CHINA	China's 13th financial year power planning for offshore wind targets 5 GW by 2020.
CHINESE TAIPEI	The country has set an offshore wind target of 5.5 GW by 2025 and 10 GW by 2030.
GERMANY	The German Renewable Energy Sources Act defines a total installed offshore wind energy capacity expansion target of 6.5 GW by 2020 and 15 GW by 2030.
INDIA	The Ministry of New and Renewable Energy has announced ambitious plans for 5 GW of offshore wind by 2022 and 30 GW by 2030.
JAPAN	Japan has set an installation target of 0.82 GW by 2030. A new law on offshore wind development, enforced in 2019, establishes a legal framework for an exclusive use of sea areas over 30 years.
THE REPUBLIC OF KOREA	The Ministry of Trade, Industry and Energy, as part of its renewable energy 2030 implementation plan, aims for 12 GW of total offshore wind installations by 2030.
THE NETHERLANDS	The country set an offshore wind generation target of more than 49 TWh, which implies a total installed capacity of 11.5 GW by 2030.
THE UNITED KINGDOM	The UK government has confirmed a deal with the offshore wind industry to help the sector reach 30 GW of installed capacity in UK waters by 2030, up from 8.2 GW in 2018.
THE UNITED STATES	Massachusetts approved state-level energy legislation that calls for 3.2 GW of new offshore wind energy to help reduce carbon emissions. It is among several US states – including Maryland, New Jersey and New York – targeting a combined addition of almost 8 GW by 2030. New York, as part of its ambitious plan to achieve carbon neutrality, has set an offshore wind target of 9 GW by 2035 (CleanTechnica, 2018).

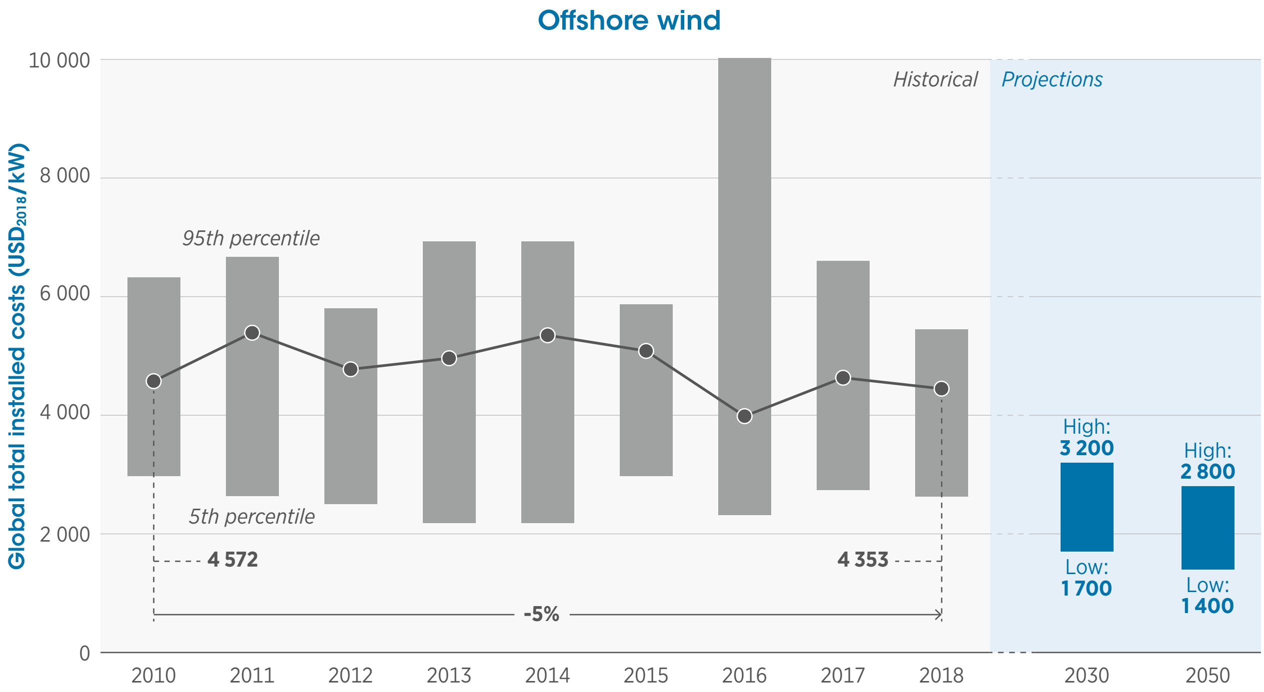
Source: IEEFA, 2018; CleanTechnica, 2018

COST REDUCTIONS AND CAPACITY FACTOR IMPROVEMENTS

Advances in offshore wind turbine technology, wind farm development, and O&M are helping to drive down the cost of electricity from offshore wind farms. Other factors contributing to this improvement in competitiveness include increasing developer experience (which reduces project development costs and risks), increasing industry maturity (lower cost of capital) and economies of scale across the value chain.

Total installed costs for offshore wind in the early 2000s climbed as projects shifted from shallow waters close to shore into deeper waters farther offshore – raising the foundation, grid connection and installation costs – and as dedicated offshore wind turbine designs were developed. The total installed costs have since peaked and come down in recent years with a steeper reduction in 2015 and 2016, which were breakthrough years for offshore wind. With the shift to deeper water and sites farther from shore, among other factors, the total installed costs of offshore wind farms rose, from an average of around USD 2 500/kW in 2000 to around USD 5 400/kW by 2011–2014, before falling to around USD 4 350/kW in 2018 (Figure 22) (IRENA, 2019c).

Figure 22: The global weighted average installed costs for offshore wind have declined by a modest 5% since 2010 and would decline greatly in the next three decades.



Note: The costs in the figure above represent the total capital costs of wind power plant assigned to four main categories: wind turbine cost (rotor blades, gearbox, generator, power converter, nacelle, tower and transformer), civil works (construction works for site preparation and foundations for tower), grid connection costs (transformers, substations and connection to the local distribution or transmission network) and planning and project costs (development cost and fees, licenses, financial closing costs, feasibility and development studies, legal fees, owners' insurance, debt service reserve and construction management) (IRENA, 2016a).

Source: Historical data based on IRENA (2019c), and future projections based on IRENA's forthcoming report Solar and wind cost reduction potential to 2030 in the G20 countries (IRENA, n.d.).

CONTINUOUS COST DECLINE IN OFFSHORE WIND TO 2050

With the shift to deeper waters and sites farther from shore, among other factors, the global weighted average total installation cost for offshore wind projects would drop in the coming decades to USD 1 700 to 3 200/kW by 2030 and USD 1 400 to 2 800/kW by 2050.

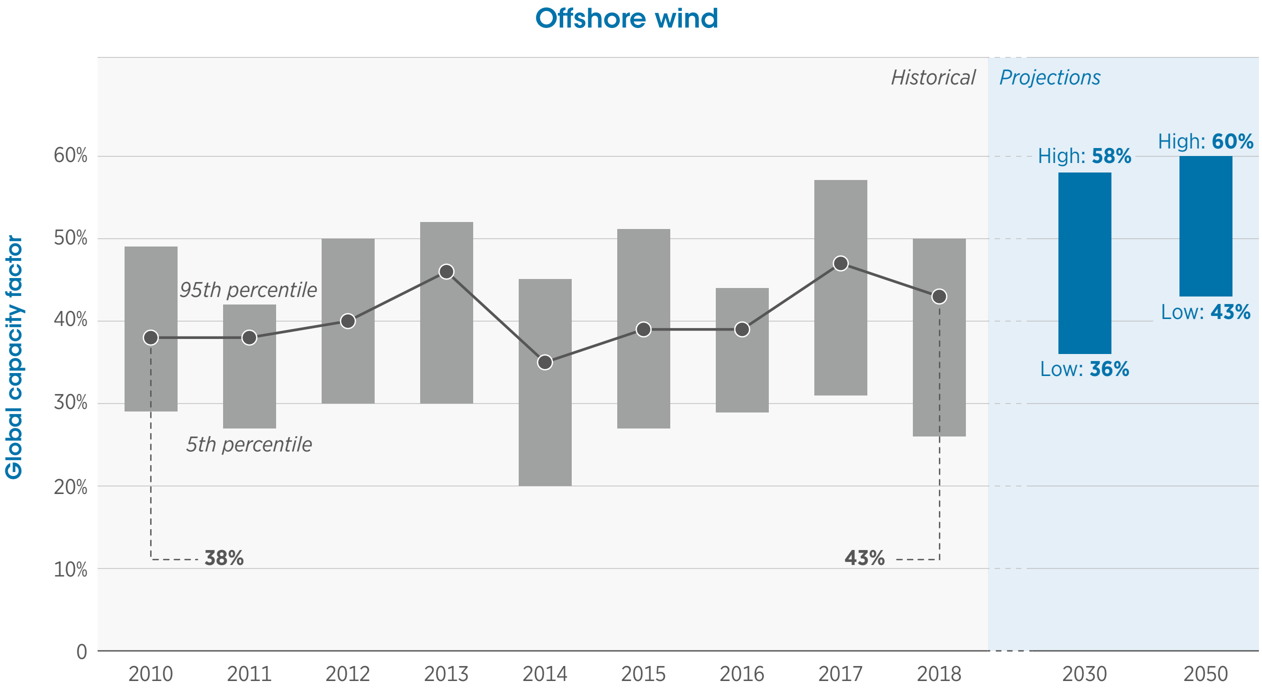
The main cost components for offshore wind farms are the turbines (including towers), the foundations, the grid connection to shore and the installation. The turbine represents the largest cost component, accounting for up to 45% of total installed costs for offshore wind. Improvement in wind turbine technology is helping to further drive down costs. The total installed costs in 2018 were 5% lower than those commissioned in 2010. Total installed costs in 2018 were 5% lower than for projects commissioned in 2010. Total installed costs are higher in Europe than in China because Chinese deployment to date has been largely in shallow coastal waters (5–25 metres from shore). The weighted average offshore wind turbine installation cost is expected to drop in the coming decades to a range of USD 1 700 to 3 200/kW by 2030 and USD 1 400 to 2 800/kW by 2050 (Figure 22) (IRENA, 2019c).

The growth in turbine size helps to increase wind farm output. Larger turbines with greater swept areas yield higher capacity factors for the same resource quality. The global weighted average capacity factor of offshore wind farms made progress in 2018, at 43% as compared to the 2010 average of 38%. Considering the improvements in turbine designs as well as technology trends, offshore wind power capacity factors for new projects to be commissioned would stay in the range of 36% to 58% in 2030 and 43% to 60% in 2050 (Figure 23) (IRENA, *n.d.*).

The cost reductions for offshore wind farms have been driven by technology improvements that have raised capacity factors, as well as by declines in total installed costs, O&M costs and the cost of capital as project risk has declined. O&M costs have been reduced through the optimisation of O&M strategies, preventative maintenance programmes based on predictive analysis of failure rates, and economies of scale in servicing offshore wind zones rather than individual wind farms (IRENA, 2019c).

Overall, the global weighted average LCOE for offshore wind in 2018 was USD 0.127/kWh, more than 20% lower than in 2010. Looking at the period to 2050, the global weighted average LCOE of offshore wind generation would fall, reaching a range of USD 0.05 to USD 0.09/kWh by 2030 and USD 0.03 to USD 0.07/kWh by 2050 (Figure 24) (IRENA, *n.d.*). This makes offshore wind a particularly attractive proposition given its scalability and the fact that at these prices it would compete directly with fossil fuel-fired electricity without major financial support (IRENA, 2019c).

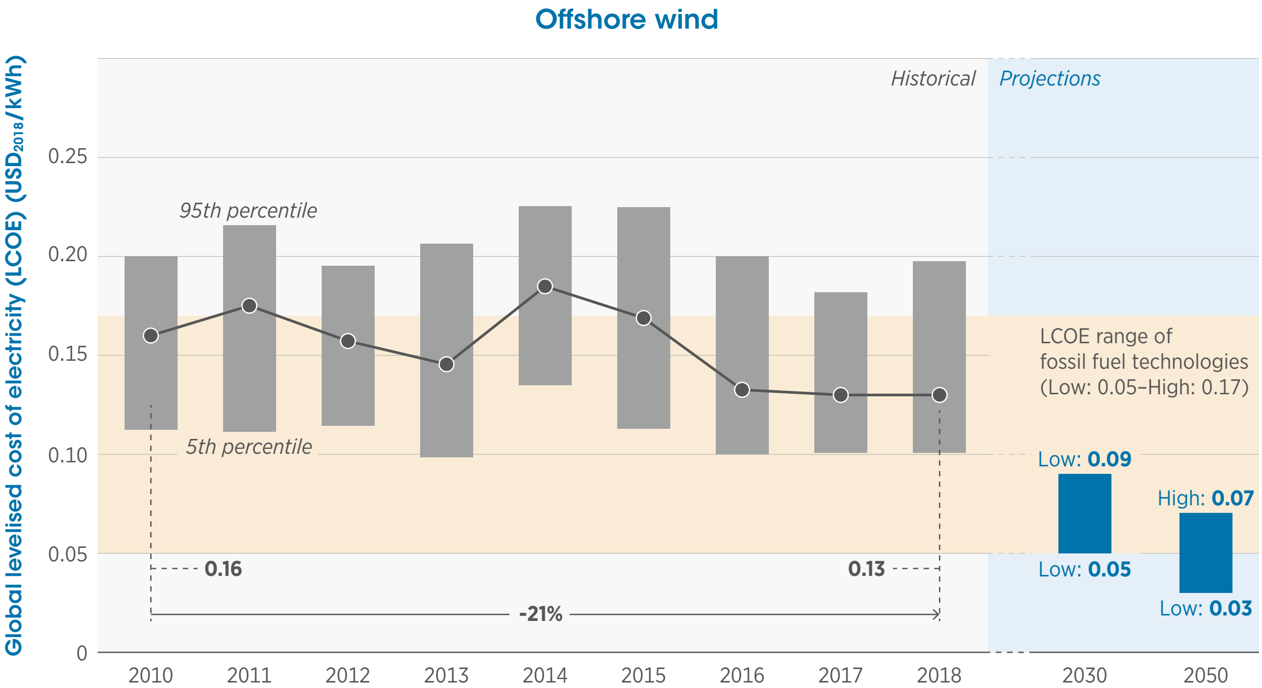
Figure 23: The global weighted average capacity factor for offshore wind has increased 8 percentage points since 2010, to 43%, and upcoming projects would have capacity factors up to 58% in 2030 and 60% in 2050.



Source: Historical data based on IRENA (2019c), and future projections based on IRENA's forthcoming report Solar and wind cost reduction potential to 2030 in the G20 countries (IRENA, n.d.).

At the regional level, Europe, with the largest deployment of offshore wind capacities, experienced a 14% decline in LCOE between 2010 and 2018, from USD 0.156/kWh to USD 0.134/kWh. The largest drop (28%) occurred in Belgium, from USD 0.195/kWh to USD 0.141/kWh. Germany and the UK were the largest markets for commissioned projects in Europe in 2018, with reductions in LCOE of 24% and 14%, respectively and the LCOEs falling to USD 0.125/kWh and USD 0.139/kWh, respectively, for projects commissioned that year. In Asia, the LCOE fell 40% between 2010 and 2018, from USD 0.178/kWh to USD 0.106/kWh, driven mainly by China with over 95% of offshore wind installations in Asia. Compared to China, the LCOE in Japan is high at an estimated USD 0.20/kWh, given that projects to date are small in scale and are perhaps better categorised as demonstration projects (IRENA, 2019c).

Figure 24: By 2050, the Levelised cost of offshore wind would be competitive, reaching lower fossil fuel ranges.



Source: Historical data based on IRENA (2019c), and future projections based on IRENA's forthcoming report Solar and wind cost reduction potential to 2030 in the G20 countries (IRENA, n.d.)

OFFSHORE WIND WOULD BE COST COMPETITIVE IN THE COMING DECADES.

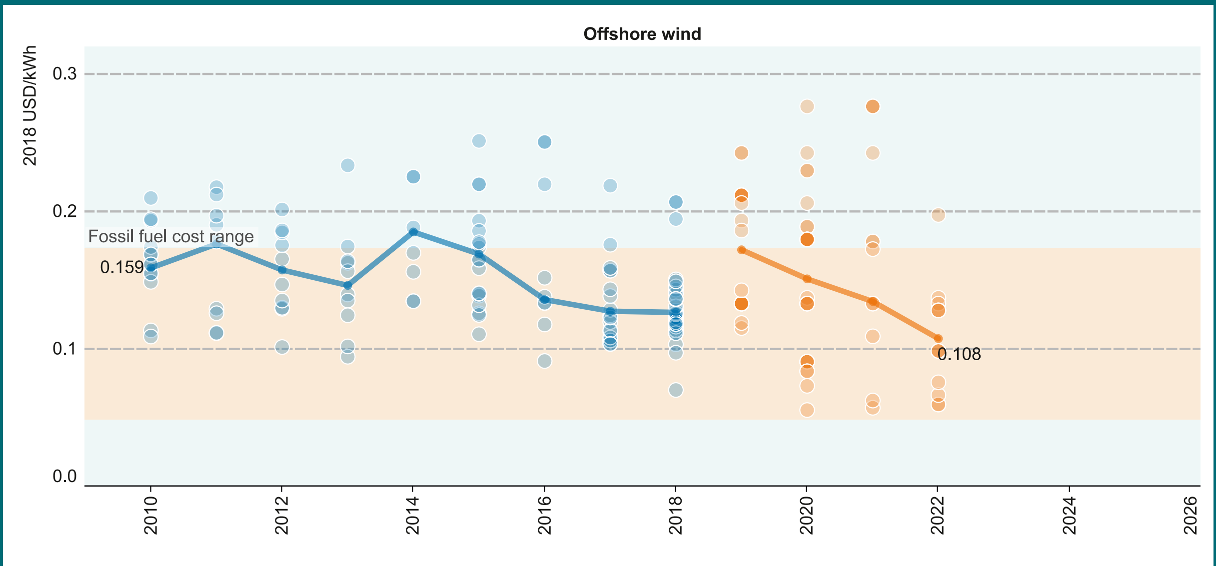
The LCOE of offshore wind is already competitive in certain European markets (for example, Germany, the Netherlands with zero-subsidy auctions, lower auction bids in France) and is on the cusp of competitiveness in other European markets (notably the UK). It is expected to be competitive in other markets across the world by 2030, falling within the low range of costs for fossil fuels (coal and gas).

Box 6. CURRENT AUCTION/SUBSIDY PRICES FOR OFFSHORE WIND AND THE IMPACT ON DRIVING DOWN LCOEs

IRENA's database of auction results and PPAs for offshore wind, illustrated in Figure 25, shows the drop in prices for offshore wind projects up to 2022 (IRENA, 2019c).The auction results and PPA prices spur innovation and competition in the supply chain for both onshore and offshore wind, which drives down the capital and operational expenditure, in both established and emerging markets for wind energy. Hence the auction and PPA results can be used as an indicator to ascertain the expected LCOE levels in the years up to 2030 (IRENA, *n.d.*).

For offshore wind, the global weighted average LCOE in 2018 compared to the global weighted average auction and PPA results in 2025 of USD 0.071/kWh shows a 44% reduction in the cost of electricity. Even so, the differences between the PPA/auction price and LCOE are worth noting, as discussed in IRENA (2017).

Figure 25: Levelised cost of electricity and global weighted average values for offshore wind projects, 2010–2022.



Source: IRENA, 2019c

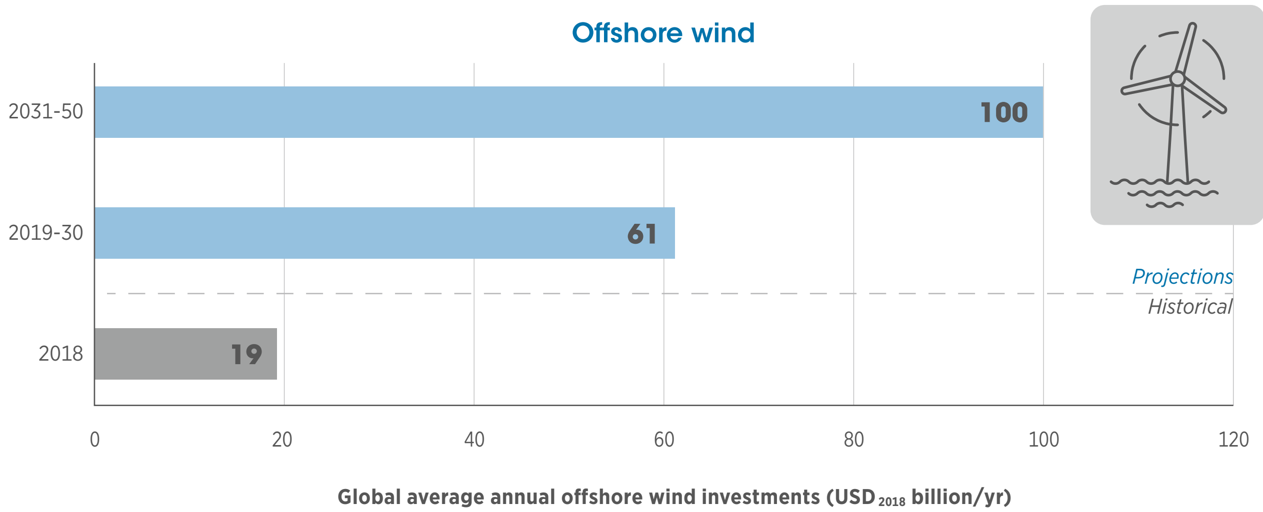
Offshore wind, with a much lower deployment than onshore wind, is also dropping towards the bottom of the fossil fuel range, as illustrated in Figure 25. As deployments and auctions for offshore wind continue in Europe – where zero-subsidy bids have been accepted in Germany, Denmark and the Netherlands and are being initiated in China and in new offshore wind markets such as Chinese Taipei and Turkey – the competitive pressure is expected to continue driving down the LCOE. IRENA's upcoming report on the cost reduction potential for solar and wind up to 2030 will provide a detailed discussion on the total installed cost, LCOE and PPA/auction prices for both wind and solar technologies (IRENA, n.d.).

INVESTMENT NEEDS

Global offshore wind investment rose to a record high of USD 27.6 billion in 2016, fell to USD 18.9 billion in 2017 (BNEF, 2019), then increased to an estimated USD 19.4 billion in 2018. Nearly half of the global offshore wind investment in 2018 was in China, with overall spending of USD 11.4 billion on 13 new offshore wind farms (BNEF, 2019). In early 2019, the Chinese government also approved 24 offshore wind projects with a capacity of 6.7 GW, expected to be operation by 2020, with an investment of around USD 18 billion (The Maritime Executive, 2019).

Globally, investment in offshore wind would need to grow substantially over the next three decades, with overall cumulative investment of over USD 2 750 billion from now until 2050. In annual terms, global average annual offshore wind investment would need to increase more than three-fold from now until 2030 (USD 61 billion/year) and five-fold during the last two decades to 2050 (USD 100 billion/year) compared to investment in 2018 (USD 19.4 billion/year) (Figure 26). Major investments are required for rapid installation of new offshore wind power capacities. However, after 2030, a share of the annual investment would be needed to replace existing or retired capacities with advanced technologies. From 2040, nearly one-third of total annual investments would be required for replacing end-of-lifetime capacities.

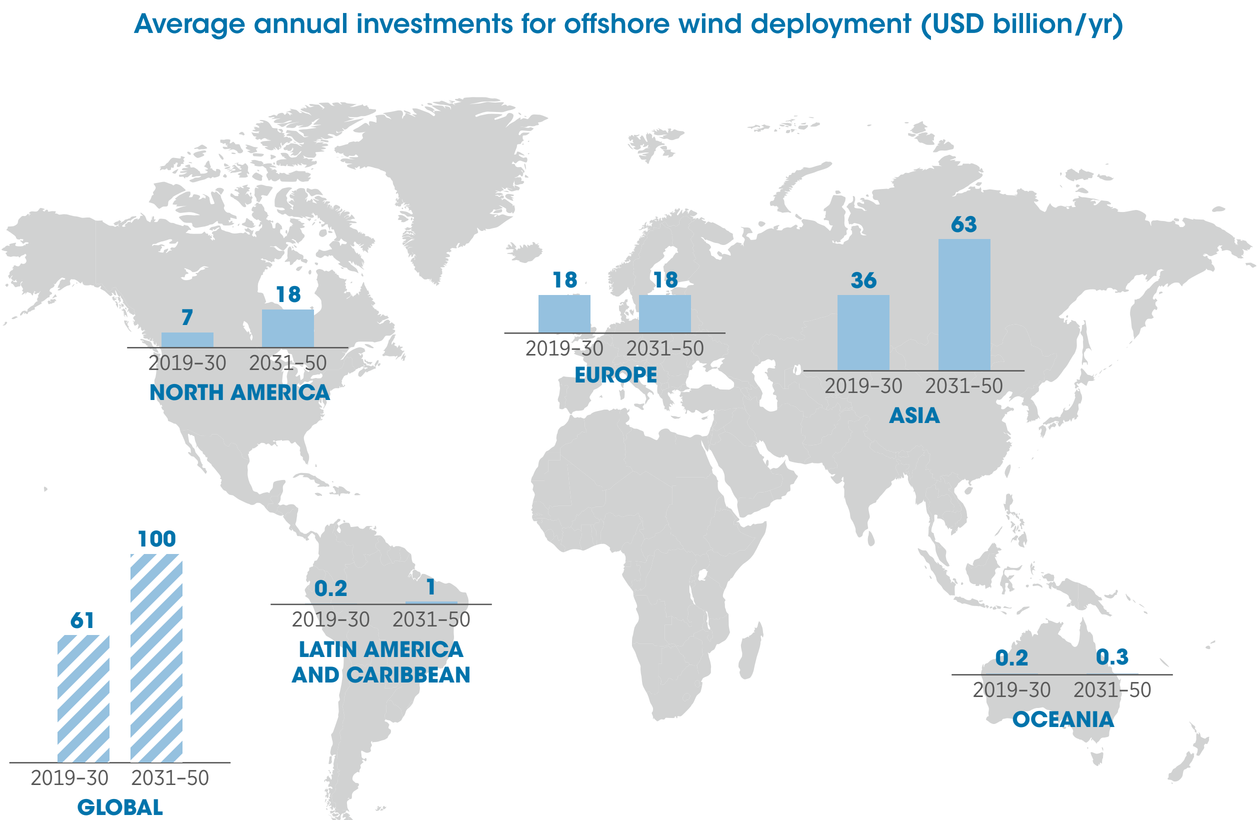
Figure 26: Global offshore annual wind power deployment total investments including new capacity installations and replacements of end-of-lifetime capacities.



Source: Based on IRENA analysis.

At the regional level, more than half of the overall global average annual offshore wind investments would be needed to accelerate offshore wind deployments in key emerging markets in Asia, with around USD 36 billion/year over the period to 2030 and USD 63 billion/year over the last two decades to 2050. The majority of the region's investments would be needed in China (with more than one-third of global offshore wind investments) followed by India, the Republic of Korea, Japan and other Asian countries (including south-eastern countries and Chinese Taipei). Europe would have stable investment flows driven in particular by rising offshore wind potential in Germany, Denmark, the UK, the Netherlands and France in the coming three decades at around USD 18 billion/year. More than one-sixth of global investments would be shifted to North America (USD 7 billion/year until 2030 and USD 18 billion/year from 2031 until 2050), primarily the US (Figure 27).

Figure 27: Investments would need to be shifted to emerging offshore wind markets such as Asia and North America followed by stable investments needed in Europe.



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Source: Based on IRENA analysis.

INNOVATIONS AND TECHNOLOGY ENHANCEMENTS

Key areas of technology innovation for the uptake of offshore wind in the coming decades have been identified as having the highest overall potential impact on different goals. The identified technologies are sorted in priority order in Table 2. The high-medium-low impact scale is objective for goal A (reducing the cost of energy) but subjective for the other goals (increasing grid integration, opening up new markets, decreasing environmental impact, and improving health and safety levels). In each case, they are set to ensure that the range of innovations presented covers the full range of impact on each goal, from low to high. However, the relative importance of innovations may change for specific countries or site conditions and in different periods (Figure 28) (IRENA, 2016b).

Table 2: High-potential-impact technologies in approximate order of priority.

TECHNOLOGY	BENEFICIAL IMPACT ON:				
	A. REDUCING THE COST OF ENERGY	B. INCREASING GRID INTEGRATION	C. OPENING UP NEW MARKETS	D. DECREASING ENVIRONMENTAL IMPACT	E. IMPROVING HEALTH AND SAFETY
Future generation turbines	H	M	M	M	H
Floating foundations	M	L	H	H	M
Repowering of sites	H	L	L	M	L
Integrated turbine and foundation installation	H	L	M	M	H
HVDC infrastructure	L	H	M	L	L
DC power take-off and array cables	M	M	M	L	L
Site layout optimisation	M	L	L	M	L

Source: (IRENA, 2016b).

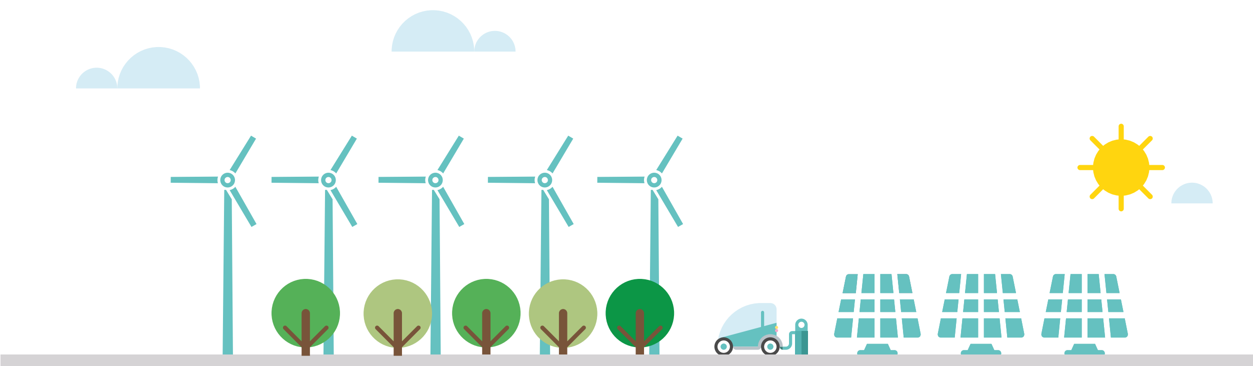
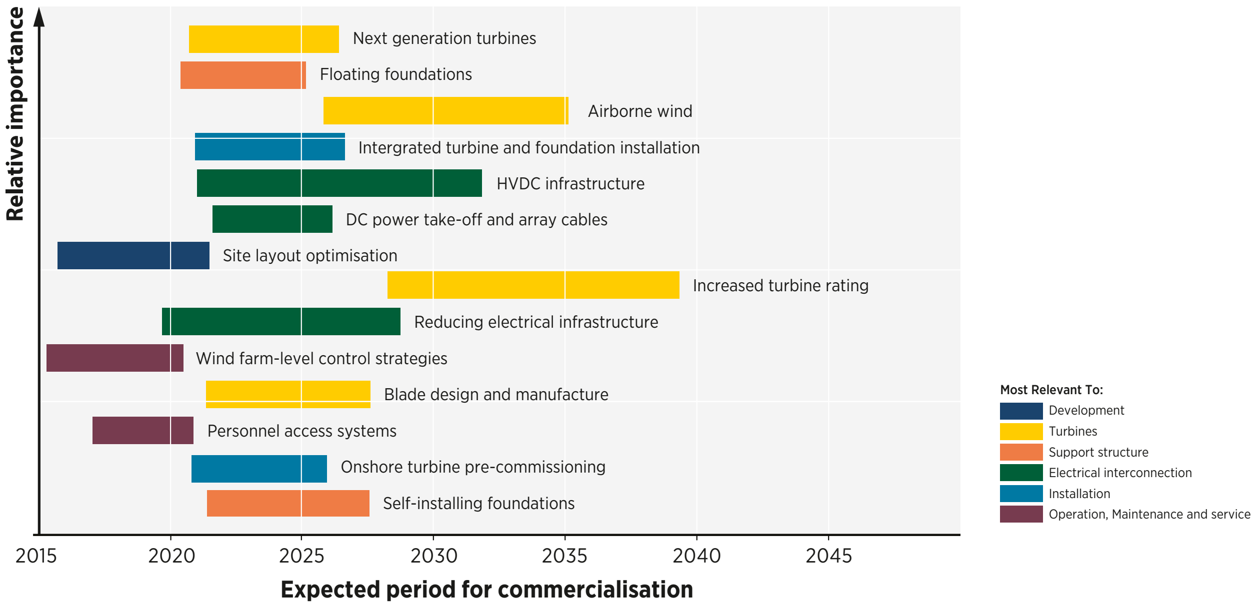


Figure 28: Anticipated timing and importance of innovations in offshore wind technology.

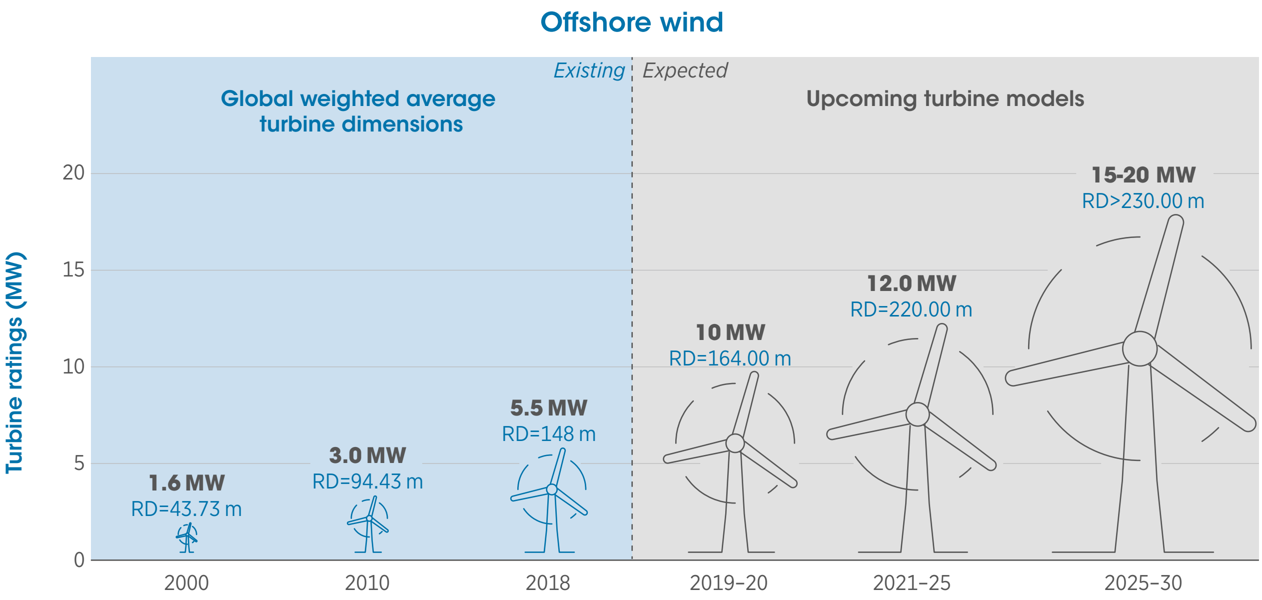


Source: (IRENA, 2016b).

FUTURE GENERATION TURBINES

Developments in blade, drivetrain and control technologies, in particular, would enable the development of larger, more reliable turbines with higher capacity ratings. Turbine sizes have increased rapidly in recent decades (Figure 29). By 2018, offshore wind turbines with an average rated capacity of 5.5 MW with rotor diameters of around 150 metres were being deployed (IRENA, 2019c). Offshore wind farms commissioned in Europe in 2018 used turbines of between 3.5 MW and 8.8 MW capacity (WindEurope, 2019b). MHI Vestas' turbines of up to 10 MW capacity and 164-metre diameter blades have been commercially available since 2018 (with the first deliveries expected for 2021) (MHI Vestas, 2018). These technology improvements are set to continue beyond 2022, with the largest turbine being developed by GE: the 12 MW Haliade-X turbine for offshore applications, with 107-metre-long blades resulting in blade diameters of over 200 metres (GE Renewable Energy, 2018). The industry is also working on concepts for even larger turbines of 15 MW by 2030, and up to 20 MW turbines for offshore application can be expected by 2030 (IRENA, 2016b, *n.d.*). These turbines are likely to have higher capital costs (CAPEX) per MW of rated capacity than existing turbines, but they would allow for a much lower cost of energy through higher energy production and lower CAPEX per MW for the foundations and installation. Further improved reliability and maintainability would both decrease the operating expenditure (OPEX) and increase energy production, further reducing the cost of energy. With fewer turbines for a wind farm of a given rated capacity, there would be fewer maintenance visits required, improved health and safety, and fewer foundations, reducing the cost and environmental impact. However, blade tip heights would be higher with these turbines, making them more visually intrusive if sited near to shore.

Figure 29: The average size of offshore wind turbines grew by a factor of 3.4 in less than two decades and is expected to grow to output capacity of 15–20 MW by 2030.



Source: GE Renewable Energy, 2018; IRENA, 2019c, 2016b; MHI Vestas, 2018.

FLOATING FOUNDATIONS

Technological developments in wind turbine foundations are one of the key factors enabling the accelerated deployment of offshore wind, permitting access to better wind resources. Turbines are now routinely being installed in water depths of up to 40 metres and as far as 80 kilometres from shore. These turbines, rooted in the seabed by monopile or jacket foundations, are currently restricted to waters less than 60 metres deep. This is a major limitation, as some of the largest potential markets for offshore wind, such as Japan and the US, have few shallow-water sites (IRENA, 2018).

In such cases, floating foundations may be a better choice (Box 6). The world's first small commercial-scale floating wind farm is Equinor's Hywind in Scotland, commissioned in 2017 with a total capacity of 30 MW and the only successfully operational large-scale floating wind farm so far (it has been operating at 65% of its maximum theoretical capacity) (Equinor, 2017). As of the end of 2018, the world had nine floating offshore wind installations – four in Japan and five in Europe – with a cumulative installed capacity of around 50 MW. Some 13 floating offshore wind projects have been announced globally, 9 in Europe (in France, Portugal and the UK), 3 in Asia (in Japan and the Republic of Korea) and 1 in the US (GlobalData, 2019a).

The prospect of offshore wind is expected to grow in the coming years. By 2030, industry experts estimate that around 5–30 GW could be installed worldwide (GlobalData, 2019a), with the potential for significant further growth through 2050. Based on the pace of developments across various regions, as per IRENA's REmap Case, floating wind farms could cover around 5–15% of the global offshore wind installed capacity (almost 1 000 GW) by 2050.

The UK is home to the only operational floating offshore wind farm so far, but the country's resource potential and surrounding sea areas are vast, which could be a major driver for the uptake of additional floating projects, with at least 10 GW of floating offshore wind capacity installed by 2050 (CleanTechnica, 2018).

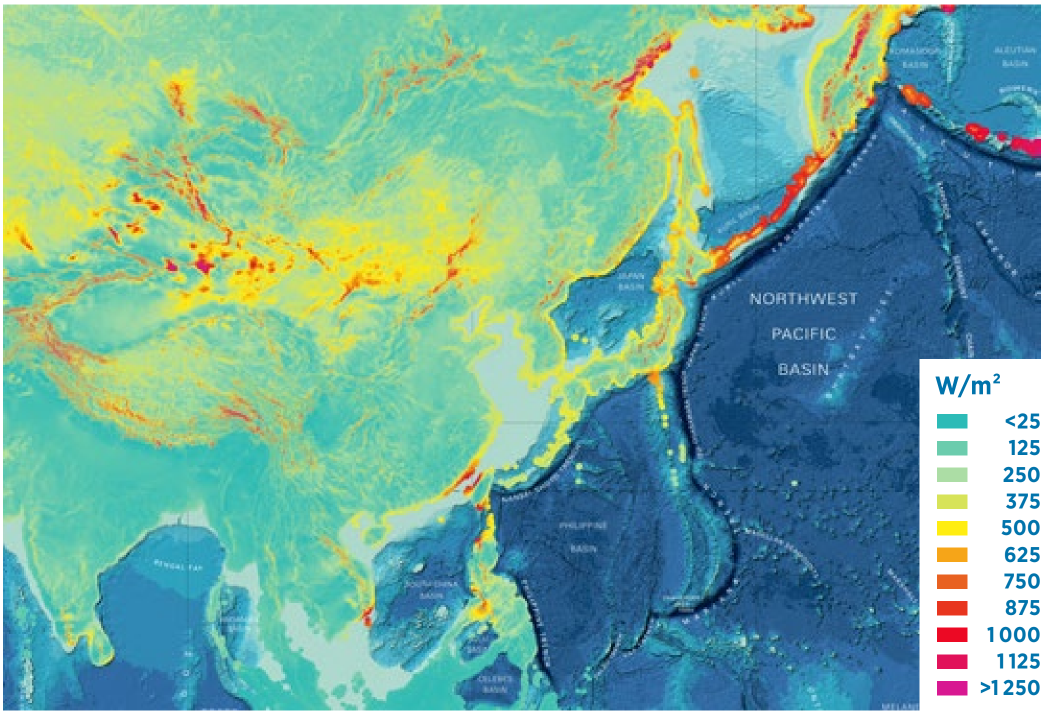
Floating foundations could also contribute to significant growth in offshore wind capacities in Asia in the coming decades. For example, China has 496 GW of offshore wind potential in water depths of less than 20 metres, 1 127 GW in depths between 20 and 50 metres and 2 237 GW in depths between 50 and 100 metres in its exclusive economic zone (Table 3 and Figure 30). Only 10% of that potential would be used by 2050. In India and Japan, the development of floating offshore wind will be critical for significant roll-out in the longer term.

Table 3: Estimated floating wind potential in China for different depths and average wind power densities.

DEPTH [m]	OFFSHORE AREA [km^2]	WIND POWER [W/m^2]	WIND TURBINE POTENTIAL [MW]	FLOATING WIND POTENTIAL [GW]
0–20	310 815	110	1.6	496
20–50	363 322	214	3.1	1 127
50–100	377 240	409	5.9	2 237

Note: The results considering maritime boundaries and Exclusive Economic Zones (200NM) for China. The potential for offshore wind (Table 3) is estimated based on wind turbines with average of 136m diameter and 0.4 of efficiency (Fraunhofer IEE, n.d).

Figure 30: Offshore Coastal wind power: potential of floating offshore wind power – zoom in China



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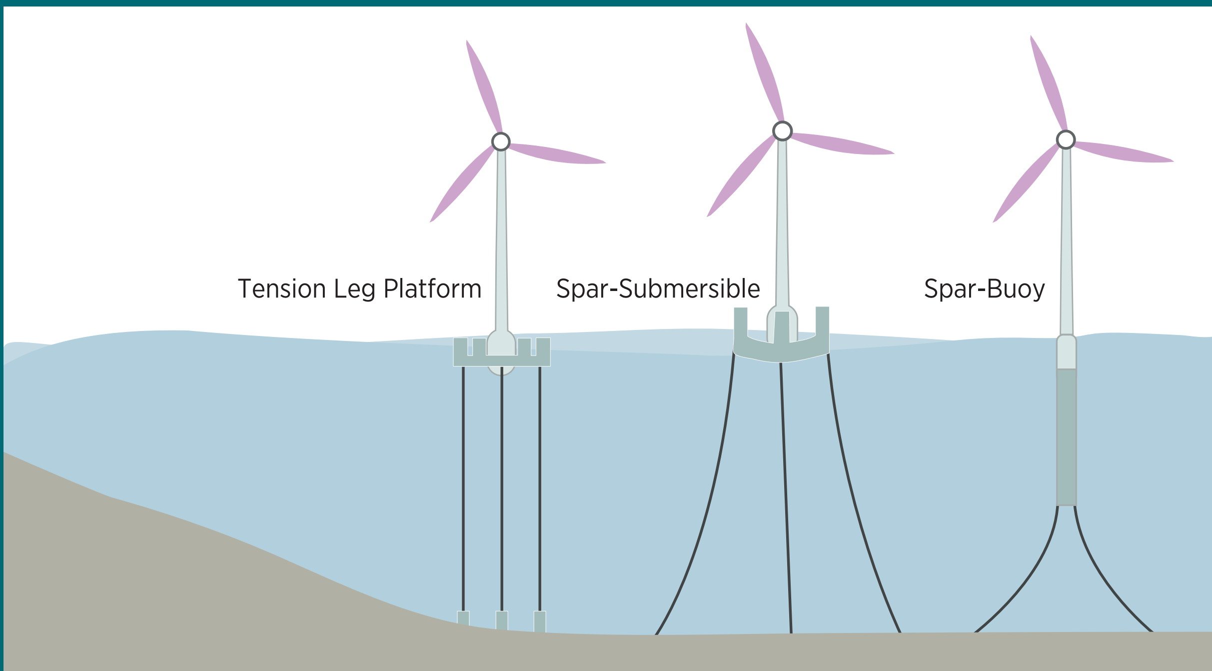
Note: Combining map of China with wind power [W/m^2] and black lines delimiting the water depth [m]. Potential accounting for 5 MW per hectare max installation. The results considering maritime boundaries and Exclusive Economic Zones (200 NM) for China. The yellow color, in the figure above corresponds to wind with a power density of 450–500 W/m^2 (a mean power output of 3 MW/26 GWh for a turbine of average 136 m of diameter and 0.4 efficiency (Fraunhofer IEE, n.d).

Source: IRENA's analysis: combining global wind atlas, marine forecast publication and bathymetric data Offshore for China – Maritime boundaries and exclusive economic zones.

Box 7. UNLEASHING THE POTENTIAL OF FLOATING OFFSHORE WIND

Floating wind farms are one of the most exciting developments in ocean energy technologies. Floating foundations offer the offshore wind industry two important opportunities: 1) they allow access to sites with water deeper than 60 metres, and 2) they ease turbine set-up, even for mid-depth conditions (30–50 metres) and may in time offer a lower-cost alternative to fixed foundations (IRENA, 2016b). In addition, floating foundations generally offer environmental benefits compared with fixed-bottom designs due to less-invasive activity on the seabed during installation. Three main designs are under development and have been tested: spar-buoys, spar-submersibles and tension-leg platforms (Figure 31).

Figure 31: Offshore wind turbine foundation technologies.



Source: (IRENA, 2018a).

The ability of floating offshore wind turbines to unlock areas of deep water close to shore and large population centres, notably in Japan and the US, could greatly expand offshore wind deployment. Floating technologies can also be applied intensively in south-east Asia, Oceania and Northern Europe. Floating foundations therefore are potentially a "game-changing" technology to effectively exploit abundant wind potential in deeper waters and thus are leading the way for rapid future growth in the offshore wind power market.

Table 4: Technical potential for floating wind in major economies.

COUNTRY/ REGION	SHARES OF OFFSHORE WIND RESOURCE REQUIRING FLOATING FACILITY (>60M DEPTH)	TECHNICAL POTENTIAL FOR FLOATING WIND [GW]
EUROPE	80%	4 000
THE US	60%	2 450
JAPAN	80%	500

Source: (Carbon Trust, 2015).

Already, several projects and testing facilities have been implemented in North America, Europe and Asia with promising outcomes for potential future expansion. The diffusion and deployment of offshore wind would be strongly dependent on technology development and on country plans/targets. Several countries are in the process of installing floating wind farms and some have set specific targets for this technology in their respective national strategies (Table 5). However, current national plans do not appear to be sufficient to deliver the scale needed to drive rapid cost reduction of the technology itself.

Table 5: Country status and forecasts on floating offshore wind power deployment.

COUNTRY STATUS AND FORECASTS ON FLOATING OFFSHORE WIND POWER DEPLOYMENT	
CHINESE TAIPEI	The government has a floating offshore wind target of 1 GW by 2030.
EUROPE	Floating offshore wind is expected to be deployed massively after 2030 to meet the 450 GW EU target for offshore wind. France's first 2 MW floating offshore wind turbine, Floatgen, became fully operational in September 2019. The national government, in partnership with the Brittany region, is preparing for public debate around the first commercial floating offshore wind tender, to be awarded in 2021.
JAPAN	As per the Japan Wind Energy Association, 18 GW of floating wind turbines is expected to be installed in the country by 2050.
THE REPUBLIC OF KOREA	The first trial of a 750 kW floating offshore wind turbine was to be delivered in 2019. An additional USD 1.3 billion has been invested to install 50 more turbines by 2022. Equinor, along with the Republic of Korea's National Oil Corporation and the Republic of Korea's East-West Power, recently announced development of the 200 MW Donghae 1 floating offshore project, to be operational by 2024 (CleanTechnica, 2019).
THE US	Around USD 1 billion has been invested to develop the technology and realise demonstration plants (IRENA, 2019b).

Source: (Carbon Trust, 2015).

REPOWERING OF SITES

Repowering offshore wind farms is an alternative to continued operation in the same configuration. It involves replacing the generating assets (turbines and their foundations and array cables), most likely with larger units spaced farther apart. The harsh and corrosive offshore environment as compared to onshore could have implications for repowering (IRENA, 2016b).

Repowered sites may retain transmission assets after some refurbishment. As the transmission asset CAPEX would have been fully depreciated, this greatly reduces the costs of the repowered wind farm, reducing the cost of energy during the repowered period and the LCOE over the lifetime of the wind farm site (IRENA, 2016b).

Commercialisation would take place when the first generation of offshore wind farms reaches the end of their design lifetimes in the early 2030s.

INTEGRATED TURBINE AND FOUNDATION INSTALLATION

Most offshore installation operations can be eliminated through the development of technologies and processes that enable assembling and pre-commissioning of wind turbines in a harbour followed by installation of the complete, integrated turbine (including rotor, tower and foundation) in a single operation offshore (IRENA, 2016b).

In this innovation, the combined turbine-foundation structure is towed to the site by a customised vessel or tugboats. This innovation can be readily used with floating systems. For fixed foundations, the most promising technology uses the gravity base foundation that can be floated out and sunk at the site. These innovations reduce both the installation cost and the exposure to health and safety risks (IRENA, 2016b).

Commercialisation is anticipated around 2025, but technology developments would need to continue to meet the needs of larger turbines.

HVDC INFRASTRUCTURE

For projects far offshore, high-voltage direct current (HVDC) transmission is preferable to high-voltage alternating current (HVAC) transmission in order to overcome the reactive resistance (capacitance) caused by the export cables in a long grid connection (offshore and onshore). HVDC infrastructure costs would come down through learning and innovations in offshore arrangements and component technologies. For wind farms closer to shore, however, HVDC infrastructure is likely to remain more expensive (in terms of LCOE) than HVAC infrastructure. HVDC becomes cost effective at a grid connection length of between around 80 kilometres and 150 kilometres. The benefit of HVDC is that it makes it possible to install wind farms farther from shore that have higher wind resources, leading to higher annual energy production with fewer planning constraints. HVDC infrastructure therefore can open up new markets where near-shore developments are not possible (IRENA, 2016b).

Today, HVDC infrastructure is used to connect two points, but it cannot be used to create a multi-nodal network. Once such direct current (DC) nodes are developed, then HVDC infrastructure for wind farms can become integrated within broader offshore “supergrids” that link national onshore infrastructure, providing balancing of supply and demand across borders (IRENA, 2016b).

Commercialisation of HVDC infrastructure for wind farms is under way, with point-to-point grid connections used on a few projects in European waters. The use of HVDC in subsea interconnectors is well established because all conversion equipment is onshore.

DC POWER TAKE-OFF AND ARRAY CABLES

A DC take-off system eliminates the second half of the conventional turbine power conversion system that converts back to grid-frequency alternating current (AC), saving capital cost and increasing reliability. Moving to DC collection also reduces the number of array cable cores from three to two and the volume of material by 20–30%, which results in savings on array cable CAPEX (IRENA, 2016b).

The first commercialisation is likely to be in wind farms commissioned by 2025, although the pace of progress in this area has slowed somewhat in the last two years, as the industry still has not adopted higher-voltage AC array cables.

SITE LAYOUT OPTIMISATION

Improvements in the characterisation of wind resources, aerodynamic wake effects, meteorology oceanic climate and seabed conditions, combined with more parameterised foundation and installation process design methods, is enabling much more informed and holistic layouts of offshore wind farms (IRENA, 2016b).

Progress is incremental, and early versions of software tools already were used on projects with Final Investment Decision in 2015, although there is potential for further progress.

OTHER INNOVATIONS

Many innovations in other areas are reaching a commercial stage. For instance, the development of airborne wind solutions (flying turbine devices with 90% less mass than traditional wind turbines and with the ability to generate power from low wind speeds at altitudes just above 300 metres) would, at least in the early stages, cover a variety of concepts, including kites, rigid wings and airborne rotors. Airborne wind offers a significant potential LCOE benefit through lower material use, lower CAPEX and higher energy production than conventional turbines (IRENA, 2016b).

Innovation opportunities also exist and are being harnessed rapidly in operation, maintenance and service (IRENA, 2016b). Due to the increased number of offshore wind turbines, global offshore O&M spending is expected to grow 17% annually during the next decade, exceeding USD 11 billion (Wood Mackenzie, 2019b). Technology systems are needed to better monitor turbines, avoid failures, improve maintenance schedules and cut associated costs. Condition Monitoring Systems (CMS) are an O&M tool to help asset owners and operators monitor the health of wind turbine components and related electrical components. The purpose of CMS is to predict in advance any issues with the wind turbine components, to schedule maintenance activities and only in extreme conditions to lead to replacement of components prone to failures (Froese, 2017).

Box 8. STANDARDISATION IN OFFSHORE WIND WOULD BE CRUCIAL TO SPUR WIDESPREAD DEPLOYMENT.

Standardisation in offshore wind technologies would be crucial to spur widespread deployment of these technologies in the future. Countries require a blueprint, drawing on the experience of leading actors, to explore their full offshore wind potential. Development is needed of a harmonised and documented global standardisation framework that enables countries to access the cost-effective potential of offshore wind (IRENA, 2018b).Offshore wind has relied on key standards from the more-established onshore wind industry, especially for the top-side structure (the tower, rotor and nacelle). It has also incorporated standards from the offshore oil and gas industry, mainly for the support transition piece. In addition, it has adopted standards for the underwater substructure, mooring, anchors and piles to permit installation (IRENA, 2018b).

As wind turbines keep improving, the latest designs need to be documented in new standards, which reflect specific adaptations to offshore wind conditions. Given that the first offshore wind markets emerged in Europe – a region with large areas of relatively shallow waters (particularly in Denmark and Germany) – the focus has traditionally been on fixed structures, and floating turbines have emerged only recently. The standards for floating offshore wind are only now being developed for new markets such as Japan and the US. An added complication is that the natural and climatic conditions in Europe do not reflect the extreme conditions found in other parts of the world, leading to the need to adjust standards to address, for example, typhoons, cyclones, earthquakes and icing. In China, the offshore wind industry started by applying components and equipment used in other industries; now, however, the industrial supply chain for offshore wind is focusing on technology development of specialised installation equipment (e.g., vessels) and methods tailored for national conditions (IRENA, 2018b).

The International Electrotechnical Commission's sub-committee TC 88/PT 61400-3-2 is working on standards for the "Design requirements for floating offshore wind turbines". The aim is to minimise the technical risks for this technology, facilitating its scale-up. The sub-committee is currently led by the US and the Republic of Korea. It includes experts from European countries, such as Denmark, France, Germany, the Netherlands, Norway, Spain and the UK, as well as from other countries with a potential market for this technology, such as China, Japan and South Africa (IRENA, 2018b).

3 TECHNOLOGICAL SOLUTIONS AND INNOVATIONS TO INTEGRATE RISING SHARES OF WIND POWER GENERATION

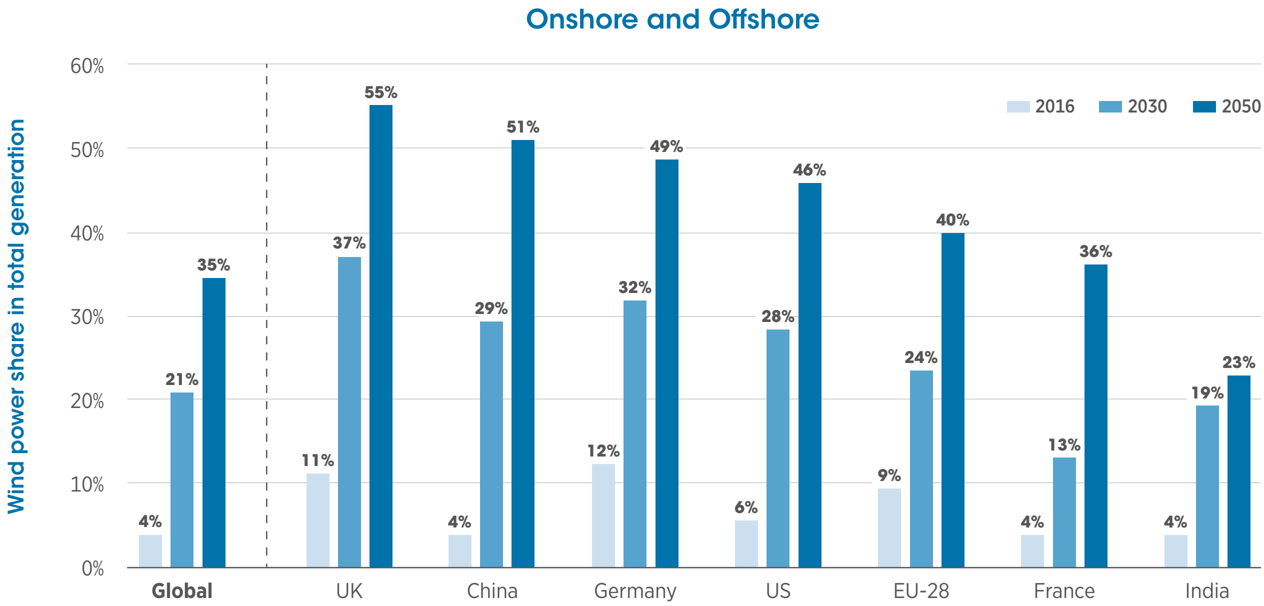
The variable nature of the wind and solar resource requires significant changes in how the power system operates as the share of variable renewable energy (VRE) grows to high levels in different markets. Especially with rising shares of variable renewable generation in the grid, adequate measures need to be deployed to maintain grid stability and reliability. Changes are required in the operation and management of the grid on a minute-by-minute basis, while also taking into consideration seasonal variations in solar and wind output.

In an age of low-cost renewable power generation, the success of the energy transition will be underpinned by the implementation of strategies to integrate high shares of VRE into power systems at the lowest possible cost. At present the share of VRE in electricity generation in G20 countries is about 10%. Some countries, particularly in Europe, have achieved much higher shares: in 2017 the VRE share in Denmark reached 53%, in South Australia 48%, and in Lithuania, Ireland, Spain and Germany greater than 20% (IRENA, 2019g). The three largest power systems in the world – China, India and the US – are expected to double their VRE shares to more than 10% of annual generation by 2022 (IRENA, IEA, REN21, 2018). India covered 7.7% of its load with VRE generation between 2017 and 2018 and was on track to reach 9% VRE generation by 2019 (IRENA, 2019g). In the US, 7.6% of electricity came from wind and solar in 2017 (IRENA, 2019g).

Under the REmap Case, the global share of variable renewables (wind and solar PV) would increase to 34% by 2030 and 60% by 2050. This growth in VRE power requires establishing new power market rules and procedures, developing markets for short-term balancing and flexibility needs, and ensuring adequate firmed capacity to manage periods of low solar and wind output (IRENA 2018c; 2019a). It will also require developing new business models and implementing technical solutions for both the supply and demand sides (for example, through aggregators and the deployment of new technologies, such as behind-the-meter batteries and demand response) (IRENA, 2019g). The deployment of adequate system flexibility measures (Box 7) along with the extension and reinforcement of power grids are essential to manage the higher shares of VRE generation projected in the REmap Case by 2050. The global wind generation share of total power generation would exceed 20% by 2030 and 35% by 2050. The UK would have the highest wind power share in its total electricity mix, at nearly 37% by 2030 and 55% by 2050, followed by China with 29% by 2030 and 51% by 2050 (Figure 32).

IRENA estimates that the investments in grids, generation adequacy and some flexibility measures (such as storage) across the entire electricity system would total USD 13 trillion for the period 2016–2050 (USD 3 trillion higher than in the Reference Case) to integrate 60% variable renewables (35% of which is wind generation) by 2050 (Figure 33). Nearly two-thirds of the incremental investments in the REmap Case over the Reference Case are needed for extending or enhancing transmission and distribution grids, while the remaining investments are needed for adequacy and flexibility measures (including storage) of the power system along with subsequent investment in smart meter deployment (IRENA, 2019a, 2019b). In annual terms, more than one-quarter increase in average annual investments would be needed to USD 374 billion/year over the period to 2050 (IRENA, 2019b), compared to investments made in electricity networks and battery storage in 2018 (USD 297 billion/year) (IEA, 2018b)

Figure 32: Higher shares of wind power would be integrated in various G20 countries by 2050



Source: Based on IRENA analysis.

Given the complexity of developing a global model that addresses medium- and long-term planning for VRE and overall power system development, a high-level approach has been applied to identify potential power systems issues in the REmap Case in 2050. Additional investments required to address these issues have been estimated at the global level, based on a bottom-up analysis of G20 countries. Reinforcement, replacement and expansion of grids are considered to supply projected electricity demand towards 2050 (IRENA, 2019a).

Storage contributes to adequacy and flexibility and is assumed to be widely deployed. This includes some additional pumped hydropower capacity and battery storage as part of decentralised power generation, dedicated utility-scale batteries and also the use of some electric vehicle (EV) battery capacity to support the grid through vehicle-to-grid (V2G) services. By 2050, around 14 terawatt-hours (TWh) of EV batteries could be available to provide grid services, compared to just 9 TWh of stationary batteries (IRENA, 2019i). Hydrogen is one of the emerging technologies that could potentially contribute to the flexibility of power system, acting as "seasonal storage" thereby aiding in integrating high shares of variable renewables. IRENA sees a global economic potential for 19 exajoules of hydrogen from renewable electricity in total final energy consumption by 2050. This would translate to 5% of total final energy consumption and 16% of all electricity generation being dedicated to hydrogen production in 2050 (IRENA, 2019j).

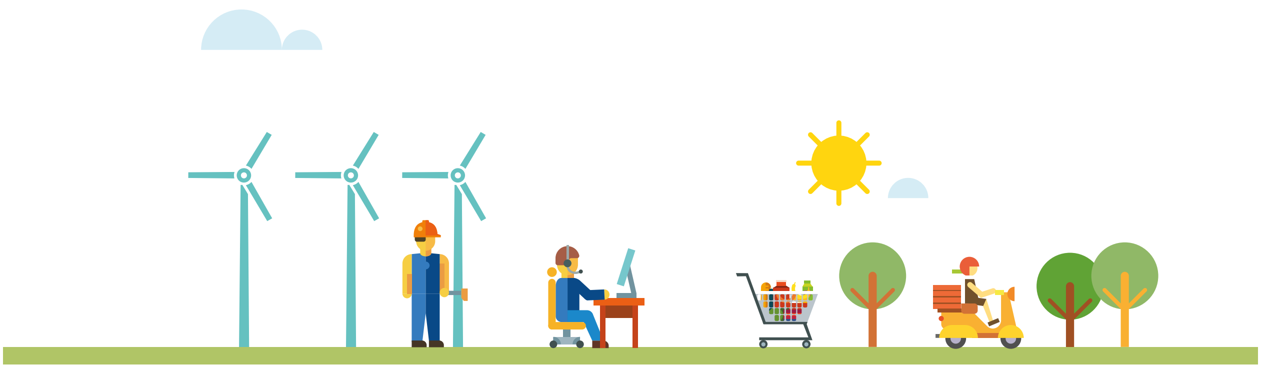
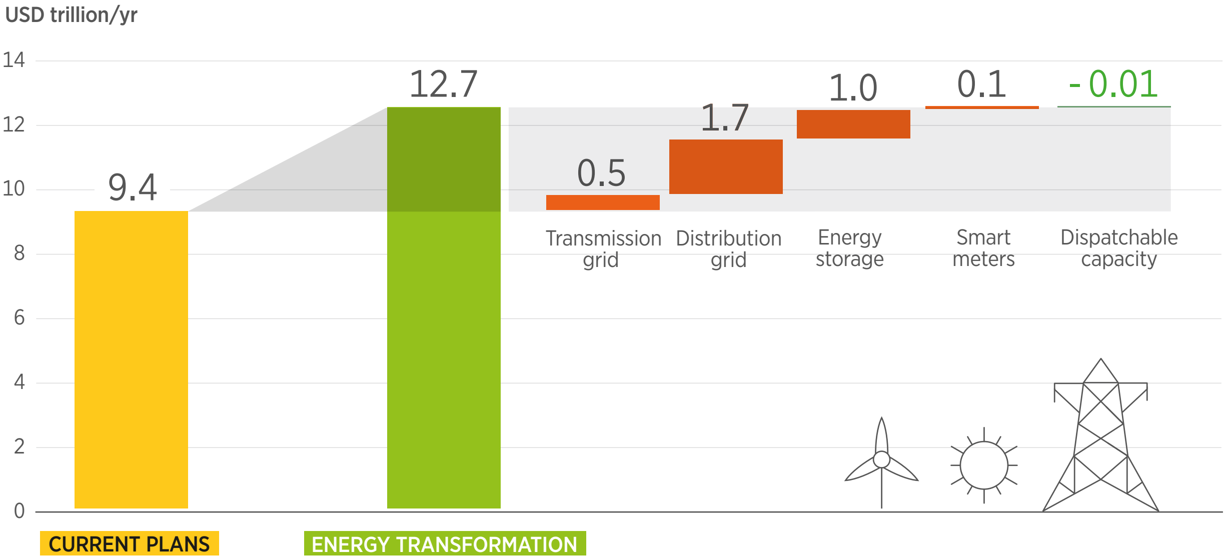


Figure 33: Additional investments are required in grids, generation adequacy and some flexibility measures (such as storage) across the entire electricity system to integrate raising shares of variable renewable sources.



Note: Investment needs for other flexibility resources, including power-to-heat, power-to-hydrogen, demand-side management and thermal storage, are not considered in this estimation.

Source: (IRENA, 2019b).

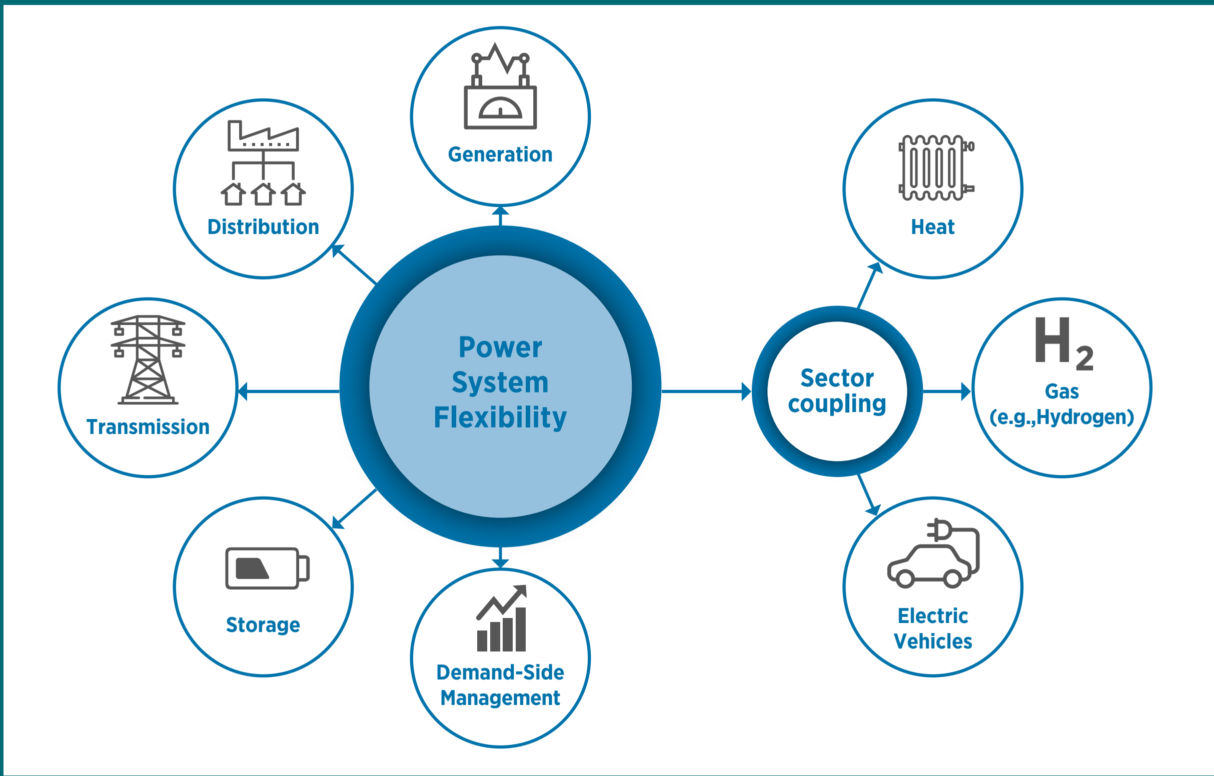
The optimal strategy for integrating even higher shares of VRE is country- and context-specific. Solutions emerging from the synergies among innovations across all dimensions of the system would make it possible to create reliable and affordable power systems that are based predominantly on renewable energy (Box 10). These innovations offer a broader portfolio of solutions that can be combined and optimised to reduce costs and maximise system benefits (IRENA, 2019g).

In addition, deployment policies (such as auctions) are increasingly designed in a way that focuses on supporting the integration of VRE, especially in countries where shares of wind and solar are increasing (IRENA, 2019e).

Box 9. POWER SYSTEM FLEXIBILITY TO INTEGRATE RISING SHARES OF VARIABLE RENEWABLE ENERGY

To effectively manage large-scale VRE, flexibility must be harnessed in all sectors of the energy system, from power generation to transmission and distribution systems, storage (both electrical and thermal) and, increasingly, flexible demand (demand-side management and sector coupling) (IRENA, 2018c).

Figure 34: Power system flexibility enablers in the energy sector.



Source: (IRENA, 2018c).

In conventional power systems, flexibility has been provided mainly by generation, with dispatchable generators adjusting their output to follow demand and, if available, pumped hydropower dealing with inflexible baseload and reducing the need for power plants to cover peak demand. Important progress has been made in recent years towards increasing the flexibility of conventional power plants, as the demand side was largely unresponsive and provided very little flexibility. Emerging innovations are not only further increasing flexibility on the supply side but are now also widening the availability of flexibility to all segments of the power system, including grids and the demand side (IRENA, 2018c).

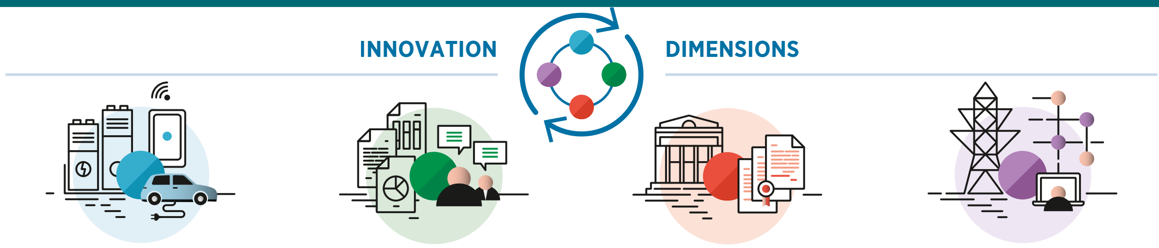
Electric vehicles lead the way to unleash synergies between low-carbon transport modes and renewable electricity generation, contributing to sector coupling. The EV fleet could be used as an electricity storage option contributing to improved flexibility of power systems with raising shares of variable renewable sources. If unleashed starting today, the use of EVs as a flexibility resource especially via smart charging approaches would reduce the need for additional investment in flexible, but carbon-intensive, fossil-fuel power plants to balance the system with renewables (IRENA, 2019i).

Hydrogen contributes to “Sector Coupling” between the electricity system and industry, buildings and transport, increasing the level of flexibility while facilitating the integration of VRE into the power system. The gas grid can also be decarbonised via renewable hydrogen by taking advantage of low electricity prices, providing seasonal storage for solar and wind, and providing grid services from electrolysers. The deployment of hydrogen requires specific efforts such as targeted applications, dedicated supply system and conversion pathways (IRENA, 2019j).

Box 10. INNOVATION LANDSCAPE TO INTEGRATE HIGH SHARES OF VARIABLE RENEWABLE ENERGY

IRENA's work confirms that there is no single game-changing innovation. No innovation, in isolation, may have a significant impact, but rather it needs to be accompanied by innovations in all segments of the power sector. IRENA has investigated the landscape of abundant innovations that can facilitate the integration of high shares of VRE into the power system, identifying and clustering 30 transformative innovations across four dimensions: enabling technologies, business models, market design and system operation (IRENA, 2019g).

Figure 35: The Four dimensions of innovation.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

Source: (IRENA, 2019g).

Enabling technologies: Battery storage, demand-side management and digital technologies are changing the power sector, opening doors to new applications that unlock system flexibility. Electrification of end-use sectors is emerging as a new market for renewables but could also provide additional ways of flexing demand, if applied in a smart way.

Business models: Innovative business models are key to monetising the new value created by these technologies and therefore enable their uptake. At the consumer end, numerous innovative business models are emerging, alongside innovative schemes that enable renewable electricity supply in places with limited options, such as off-grid or densely populated areas.

Market design: Adapting market design to the changing paradigm – towards low-carbon power systems with high shares of VRE – is crucial for enabling value creation and adequate revenue streams.

System operation: With new technologies and sound market design in place, innovations in system operation are also needed and are emerging in response to the integration of higher shares of VRE in the grid. These include innovations that accommodate uncertainty and the innovative operation of the system to integrate distributed energy resources.

4 SUPPLY SIDE AND MARKET EXPANSION

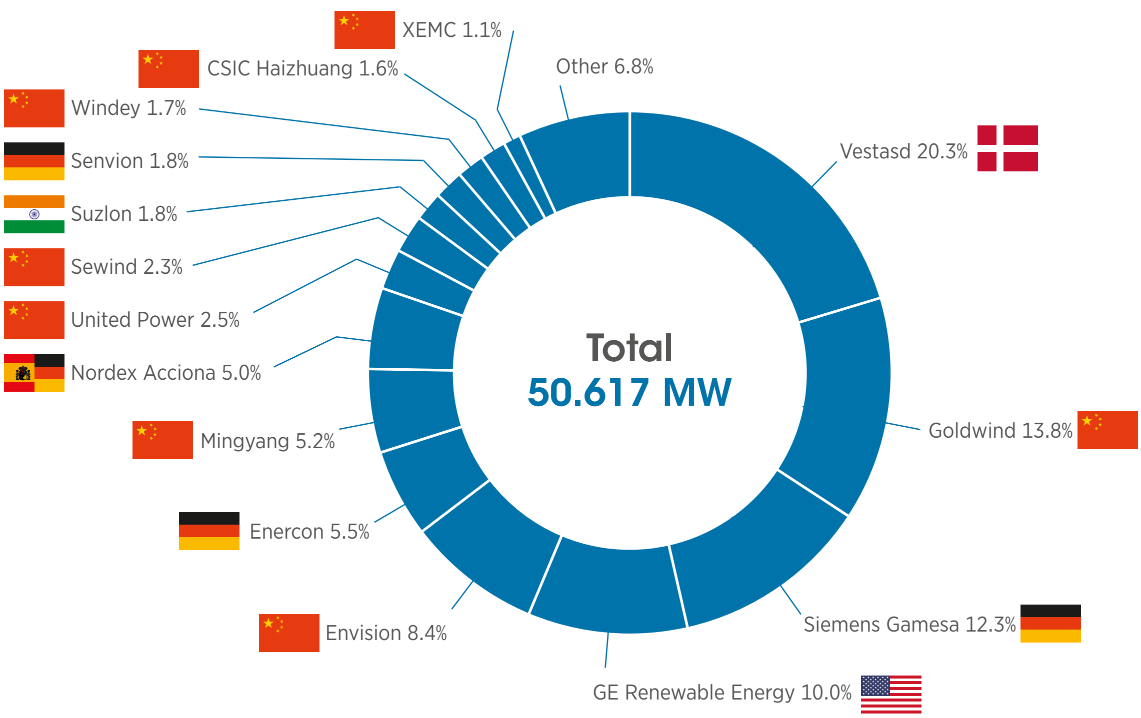
4.1 CURRENT STATUS OF WIND SUPPLY INDUSTRY

By 2018, wind turbines accounted for nearly a quarter of the market for wind energy system equipment (USD 50.3 billion) followed by rotor blades with a 15% share, gear boxes at 7% and generators covering the remainder (GlobalData, 2019b). Globally, the European producers occupy a major share of the supply side of wind turbine technologies. In 2018, some 37 wind turbine manufacturers installed an estimated 20 641 individual wind turbines globally (GWEC, 2019c).

As of the end of 2018, Denmark's Vestas remained the world's largest wind turbine supplier with more than 60 000 turbines installed, a total joint capacity of over 100 GW and manufacturing facilities in North and Latin America, Europe and Asia. Vestas alone supplied 20% of the global wind installations in 2018 — installing one in every five turbines – dominating the supply side of the wind industry with its long-lasting experience and stronger market presence (GWEC, 2019c).

The German/Spanish company Siemens Gamesa held more than 12% of the overall market share in 2018, while other German suppliers like Enercon and Senvion moved down the list because of the decline in installations in Germany (Figure 36). Chinese wind turbine producers are progressively gaining importance (Goldwind was the second leading wind turbine supplier in 2018). Nevertheless, their strength has been mainly driven by the growth of the Chinese domestic market as their international role remains limited. Due to strong performance in the US market, GE Renewable Energy remained the fourth largest supplier (GWEC, 2019c).

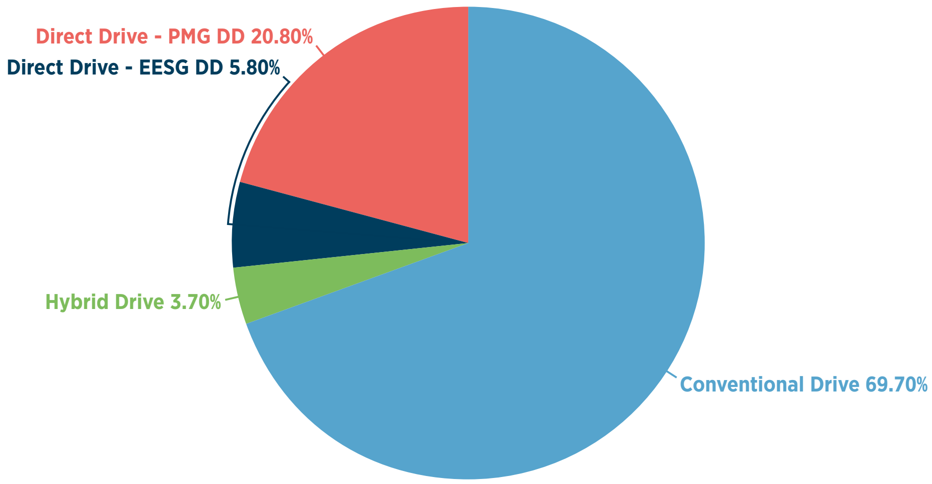
Figure 36: In 2018, Vestas remianed the world's largest wind turbine supplier followed by Goldwind and Siemens Gamesa.



Source: (GWEC, 2019c).

In the context of wind turbine technologies, Denmark's Vestas and China's Mingyang and Goldwind were the top suppliers in high-speed geared drive, medium-speed geared drive and direct drive turbine technologies, respectively. Geared wind turbine systems continue to be the preferred turbine technology based on market size. Conventional high-speed geared systems and medium-speed turbines occupied market shares of 69.7% and 3.7%, respectively, in 2018 (Figure 37). The market share of direct drive turbine technologies was 26.6% in 2018, which was 2% less than in 2017 due mainly to the reduction in wind turbine installations by Germany's Enercon in 2018 (GWEC, 2019c).

Figure 37: Geared wind turbine systems continue to be the preferred turbine technology based on market size in 2018.



Note: EESG DD refers to Electrically Excited Synchronous Generator Direct Drive turbine technologies. PMG DD refers to Permanent Magnet Generator Direct Drive turbine technologies. "

Source: (GWEC, 2019c).

IRENA's REmap Case shows that annual wind capacity additions would exceed 200 GW/year in the next two decades, indicating the need to scale up manufacturing facilities starting now in order to prepare well in advance for the huge market rise in the next three decades. The key wind industry suppliers would have to plan adequately to expand their supply needs with facilities in emerging wind markets to cut down the complications involved with transport and to benefit from various market developments. Overall, the number of manufacturing plants for wind turbines and associated equipment would need to grow, which requires substantial investment to set up and operate the manufacturing facilities. These investments can be recovered based on the capital cost (with pricing revenues of the wind turbine components) over the period of time. Such investments should also cover requirements with respect to the labour, materials and equipment of each segment of the value chain. Henceforth, a detailed analysis is essential to estimate the overall cost needed to expand the total production sites of wind plant components to facilitate the uptake of wind installation in various countries for the next three decades.

Box 11. DOMESTIC WIND MARKETS IN KEY ECONOMIES

The status of key wind suppliers in major economies is listed in Table 6. The supply market trend on a country level is expected to continue and possibly to further consolidate soon, with domestic players gaining even more relevance.

Table 6: Domestic wind markets as of 2018.

SUPPLY SIDE MARKET STATUS BY REGION AS OF 2018	
CHINA	China, the world's largest wind market, has remained partially isolated from the global market. National manufacturers cover almost all internal demand and have very few exports to other markets. Chinese manufacturers comprise nearly 95% of the overall market. As of the end of 2018, the top turbine manufacturer in China was Goldwind (31.7%), followed by Envision (17.5%) and Mingyang (11.8%). The small non-Chinese presence (4%) is held by three main foreign manufacturers: Vestas (2%), Siemens-Gamesa (1%) and GE (1%) (GlobalData, 2019b).
EUROPE	Most of Europe's wind turbines are produced locally. Vestas (29%) and Siemens-Gamesa (26%) hold more than half of the overall European market. Enercon is in third place with a market share of 19%, followed by Senvion (11%), Nordex-Acciona (8%) and GE (6%), the only non-European wind turbine producer with a meaningful presence (GlobalData, 2019b).
INDIA	The Indian market is structured very differently compared to other wind markets in Europe and the US. Siemens-Gamesa is the only European player with meaningful market penetration, with a share of 23.8% in 2018. The market has been almost uniquely dominated by local manufacturers (Suzlon 33.7%, Inox 12.1%). GE is the only other non-Indian producer in the top six suppliers (4.5%) (GlobalData, 2019b).
US	The US market seems to be in line with the global market. The main manufacturers are Denmark's Vestas and the US-based GE Renewable Energy, with market shares of 35.4% and 29.4%, respectively. Siemens-Gamesa is in third place, with a 23.2% share (GlobalData, 2019b).

5 SOCIO-ECONOMIC AND OTHER BENEFITS OF WIND ENERGY IN THE CONTEXT OF ENERGY TRANSFORMATION

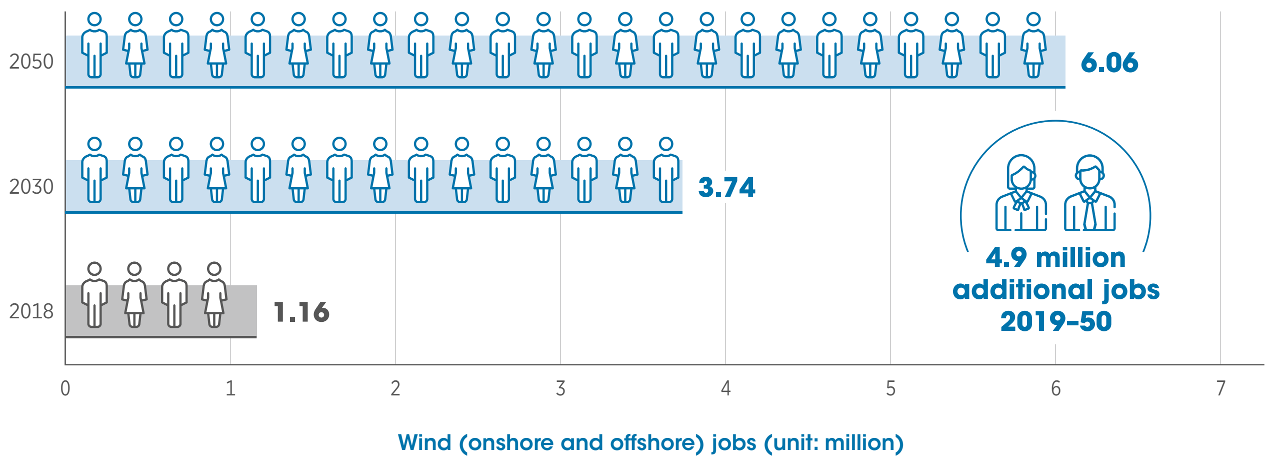
5.1 WIND SECTOR EMPLOYMENT AND LOCAL VALUE CHAIN

Employment opportunities are a key consideration in planning for low-carbon economic growth. Many governments have prioritised renewable energy development, primarily to reduce emissions and meet international climate goals, but also in pursuit of broader socio-economic benefits.

Together, the onshore and offshore wind industries employed 1.16 million people worldwide in 2018. Most wind jobs are found in a small number of countries, although the concentration is less than in the solar PV sector. Asia accounted for nearly half of the global wind employment (620 000 jobs) followed by Europe (28%) and North America (10%). On a country level, China remains the global leader in wind installations, with 44% of global wind employment (510 000 jobs) in 2018. Germany ranked second with 140 800 wind jobs, followed by the US, where wind employment grew 8% to a new peak of 114 000 jobs by the end of 2018 (IRENA, 2019e).

Arising out of its modeling work that assesses the socio-economic implications of the REmap Case, IRENA estimates that employment in the wind industry would continue to rise, exceeding 3.7 million jobs by 2030 and 6 million jobs by 2050 (Figure 38) (IRENA, 2019b)**.** Of the more than 6 million jobs by 2050, 5 million would be in the onshore wind sector and the rest would be offshore jobs (1 million). By project segment, of the more than 5 million onshore wind sector jobs by 2050, 1.7 million would be in construction and installation, 2.18 million in manufacturing and 1.17 million in O&M. For offshore wind, out of the total of 1 million jobs by 2050, an estimated 0.45 million would be in construction and installation, 0.39 million in manufacturing and 0.17 million in O&M (IRENA, 2019b)**.**

Figure 38: The onshore and offshore wind industries would employ more than 3.7 million people by 2030 and more than 6 Million people by 2050.



Source: (IRENA, 2019e, 2019b).

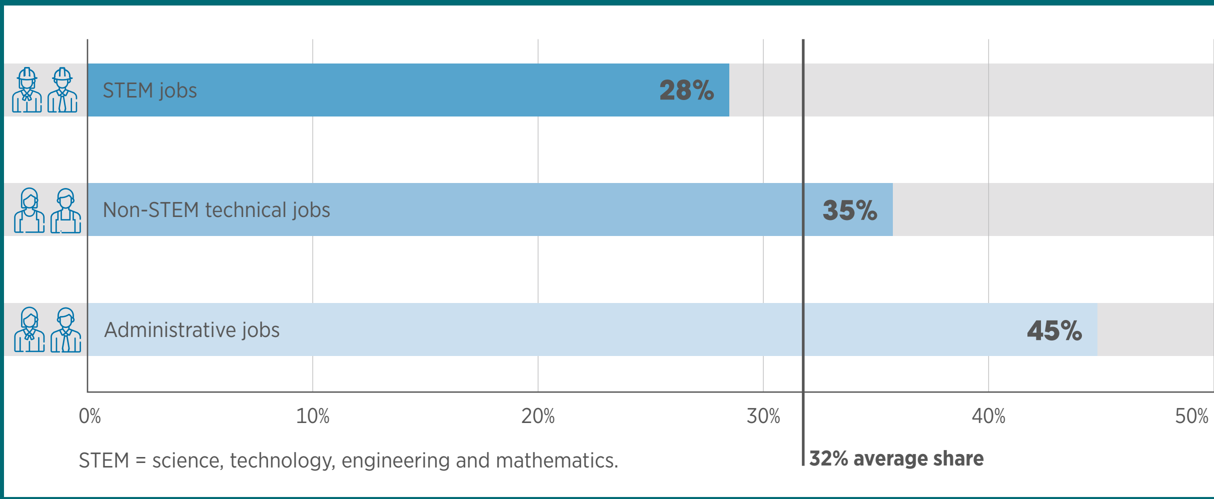
Shifting to a renewable-powered future creates employment opportunities and potentially allows for retaining existing expertise from the fossil fuel industry, particularly for renewable technology developments such as offshore wind. For instance, the expertise of workers and technicians in building support structures for offshore oil and gas sites could potentially be utilised to build foundations and sub-stations for offshore wind turbines (IRENA, 2018d).

The rising traction of the wind energy industry demands a growing array of skills, including technical, business, administrative, economic and legal, among others. Widening the talent pool is thus a pragmatic reason for boosting the participation of women in renewable energy[9], in addition to considerations of greater gender equity and fairness (Box 12) (IRENA, 2019k).

Box 12. IRENA'S WORK ON GENDER BALANCE IN THE ENERGY SECTOR

Recognising a gap in gender-disaggregated data for the renewable energy sector, IRENA presented in 2019 a stand-alone report on gender that integrates up-to-date information from around the world as well as results from a global survey conducted by IRENA with the support of GWNET and REN21. The survey benefited from the participation of around 1 500 women, men and organisations in 144 countries. Survey results show that the sector employs a larger share of women (35%) compared to the conventional energy field (22%) (IRENA, 2019k).

Figure 39: Women in STEM, NON-STEM technical and administrative jobs in the energy sector.



Source: (IRENA, 2019k).

While this share is for the renewable energy workforce, IRENA aims to estimate the number of women working in the wind sector10. In addition, the agency is working on a new analysis of the gender dimension of employment impacts among local rural communities affected by large-scale renewable energy project development. The study gathers primary data from solar and wind projects being developed across sub-Saharan Africa (IRENA, forthcoming).

9 The International Renewable Energy Agency along with the Women in Wind Global Leadership Program (jointly organised by Global Women's Network for the Energy Transition (GWNET) and GWEC have launched The Global Gender Survey of the Wind Industry to collect insights and feedback to produce estimates and analysis of the representation and roles of women in the wind industry worldwide. See https://survey.eu.qualtrics.com/jfe/form/SV_bjFmXOzW9BjSBcV.

WIND PROJECTS CREATE AMPLE OPPORTUNITIES FOR LOCAL VALUE CREATION

Local wind energy industries have the potential to create jobs and develop local manufacturing. Opportunities for domestic value creation can be created at each segment of the value chain, in the form of jobs and income generation for enterprises operating in the country. In the case of domestic industry participation in onshore wind farm development, key aspects such as the labour, materials and equipment requirements of each segment of the value chain need to be analysed. Based on this, opportunities for leveraging local labour markets and existing industries can be identified to maximise the domestic value chain. Regional and global market dynamics also strongly influence the decision to pursue domestic industry development (IRENA, 2017).

For the offshore wind industry, domestic manufacturing of the main components of an offshore wind farm, such as the foundation and the sub-station, as well as parts of the turbine, blades, tower, and monitoring and control system could be considered. Socio-economic gains in terns of local income and jobs can be maximised by leveraging existing economic building on domestic supply chain markets. Sufficient education and training are crucial to build capable local supply chains (IRENA, 2018d).

Maximising value creation from the development of a domestic wind industry, for example, requires leveraging capacities in industries such as steel and fibreglass. For a typical 50 MW onshore wind facility, almost 23 000 tonnes of concrete is needed for the foundations, and nearly 6 000 tonnes of steel and iron is needed for the turbines and foundations. The requirements are similar for offshore wind. Manufacturing the main components of a wind turbine requires specialised equipment as well as welding, lifting and painting machines that are used in other industries, such as construction and aeronautics. The foundations also require the use of specialised equipment including rolling, drilling and welding machinery. Special vessels and cranes are needed to move these big structures. Examining these requirements provides insights on the industrial capabilities to be leveraged (IRENA, 2018d, 2017).

IRENA's *Leveraging local capacity* report series generates valuable information for policy makers on the occupational and skill structure along the value chain. Figure 40 shows the labour requirement for onshore and offshore wind farms. For example, a total of 144 000 person-days is needed for the development of a 50 MW onshore wind project. The labour requirements are highest in O&M (43% of the total), followed by construction and installation (30%) and manufacturing (17%) (IRENA, 2017).

For offshore wind, the majority of the labour requirements (totalling 2.1 million person-days for a 500 MW farm) are found in the manufacturing and procurement segment. Existing manufacturing facilities for onshore wind can serve the needs of the offshore sector, as many components are comparable. Significant synergies also exist between the offshore oil and gas industry and the offshore wind sector (IRENA, 2018d).

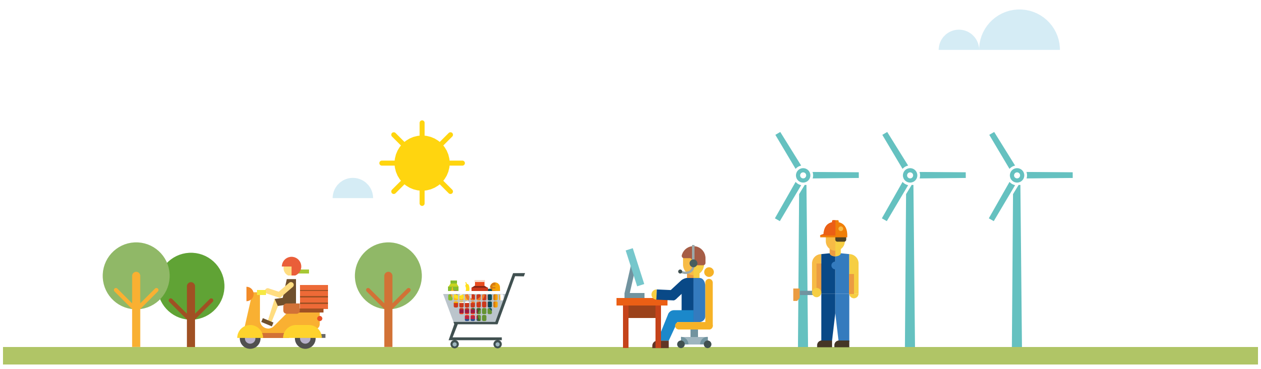
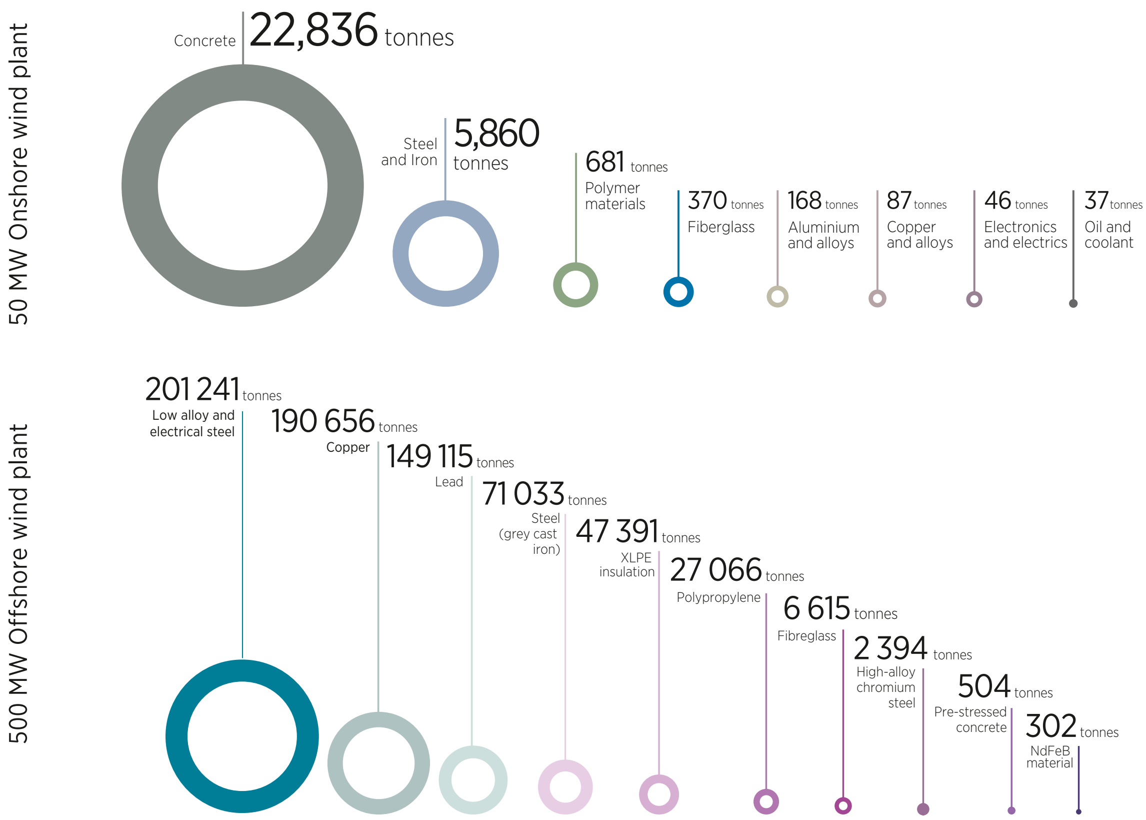
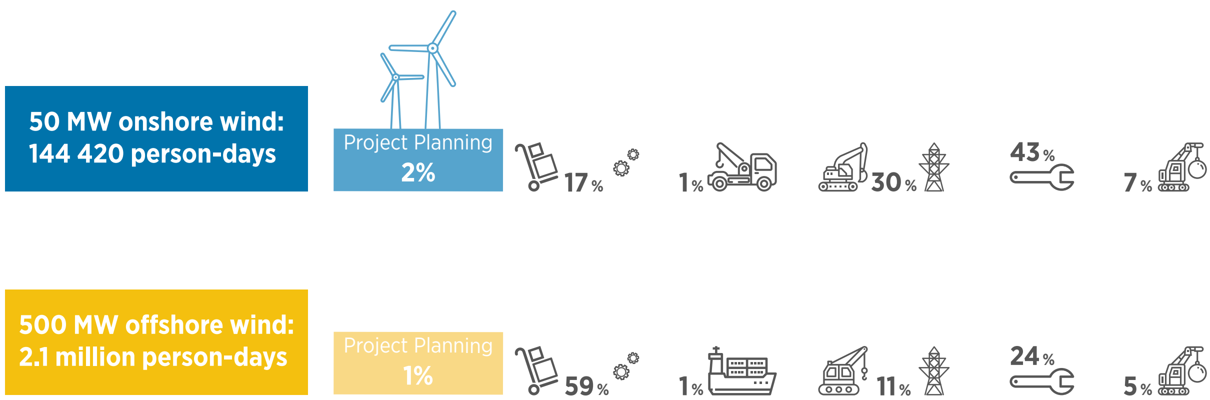


Figure 40: Materials required for a 50 MW onshore wind plant and a 500 MW offshore wind plant.



Source: (IRENA, 2018d, 2017).

Figure 41: Distribution of human resources and occupational requirements along the value chain (50 MW onshore wind, 500 MW offshore wind).



Source: (IRENA, 2018d, 2017).

5.2 CLUSTERING WITH OTHER LOW-CARBON TECHNOLOGIES: HYBRID SYSTEMS

To overcome the intermittency issue arising from the variable nature of wind energy, and to maintain the reliability and continuous operation of the power system in times of low resource availabilities, a solution would be to combine wind systems with other renewable generation sources such as solar PV, hydro or storage technologies, or with emerging technologies such as hydrogen. In 2012, the world's first hybrid project – combining 100 MW of wind and 40 MW of solar PV generation along with a 36 MW lithium-ion energy storage capacity unit – was installed by Build Your Dreams (BYD) and the State Grid Corporation of China in Zhangbei, Hebei Province (JRC, 2014). In 2017, the wind supplier Vestas announced a large-scale hybrid project that combines 43.2 MW of wind and 15 MW of solar generation along with a 2 MW battery storage capacity unit. The global hybrid solar-wind market is expected to grow from more than USD 0.89 billion in 2018 to over USD 1.5 billion by 2025, reflecting a CAGR of nearly 8.5% over the seven-year period (Zion Market Research, 2019). China was the major market for solar-wind hybrid systems in 2018 and is expected to dominate in coming decades. Countries have already deployed a variety of hybrid projects (Box 13), and a steady rise in such projects can be expected, especially as a complementary solution for solving grid integration issues.

Box 13. HYBRID RENEWABLE ENERGY DEVELOPMENTS

Considering the key benefits of combining renewable power generation with storage, efforts have been initiated in various countries.

Table 7: Hybrid renewable developments in countries.

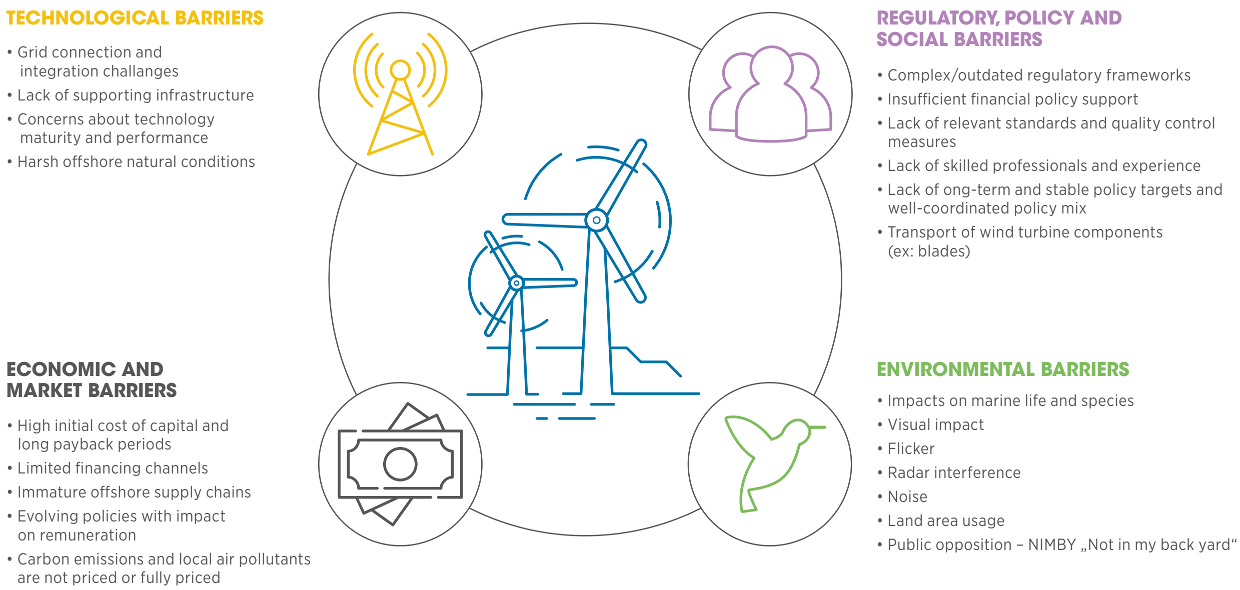
HYBRID RENEWABLE DEVELOPMENTS	
EUROPE	**Germany:** GE Renewable Energy and Max Bögl Wind AG are developing a 13.6 MW wind farm combined with a 16 MW hydropower plant in Germany's Swabian-Franconian Forest, which was slated for operation by end of 2018 (GE Renewable Energy, *n.d.*). **Scotland:** In 2018, the world's first hybrid offshore project (Batwind) connected the largest floating offshore wind farm (Hywind) with a 1.2 MW battery storage system (Equinor, 2018b). **Spain:** Vestas and EDP completed Spain's first hybrid 3.3 MW wind-solar project in 2018 (PV magazine, 2018). **The Netherlands:** In March 2019, Denmark's Orsted announced pioneering efforts to develop green hydrogen projects produced by offshore wind power as part of its bid for the Holland Coast South 3 and 4 projects in the Netherlands (Ørsted, 2019).
INDIA	In 2016, India had introduced a national wind-solar hybrid policy to resolve grid integration issues, with a proposed target of 10 GW of hybrid projects to be installed by 2022 (Zion Market Research, 2019). Just prior to approval of this policy, Hero Future Energies completed India's first hybrid project, combining a 50 MW wind farm with a 28.8 MW solar PV site in Raichur district in April 2018. This project is aimed to be retrofitted with lithium-ion battery storage technology to combat curtailment during times of strong wind resource availability. The Solar Energy Corporation of India recent issued tenders for 2.5 GW of hybrid wind and solar projects to be connected to the country's Interstate Transmission System.
THE US	GE Renewable Energy aims to develop the country's first commercial integrated 4.6 MW hybrid wind and solar project, in the state of Minnesota. NextEra and the US utility Portland General Electric will build a 380 MW wind-solar plus storage hybrid project in eastern Oregon.

6 ACCELERATING WIND POWER DEPLOYMENT: EXISTING BARRIERS AND SOLUTIONS

This report clearly points out that wind energy is one of the key renewable technologies needed to realise global energy transformation in line with the Paris climate goals. The technology is available now, could be deployed quickly at a large scale and is cost-competitive (especially onshore). Despite the strong momentum, wind power projects still face serious constraints, hampering their further development and commercialisation.

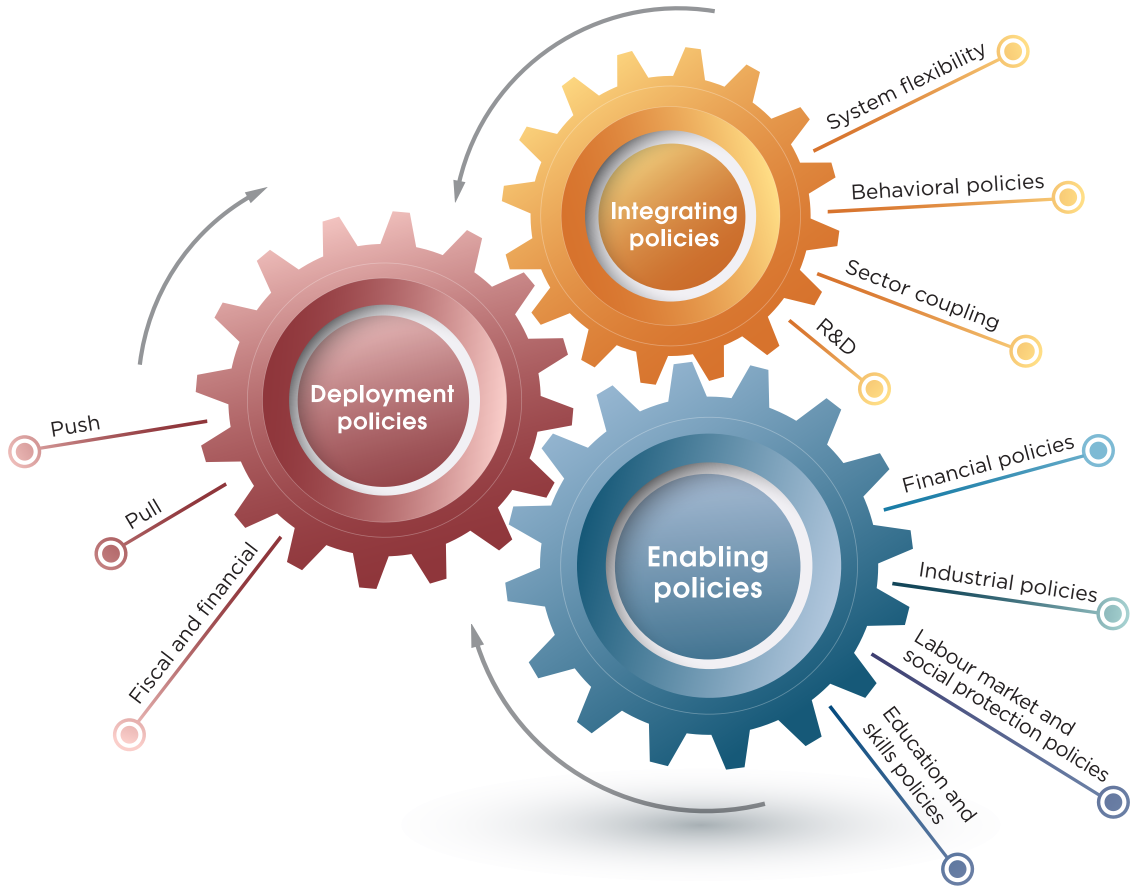
In general, renewable energy sources are affected to different degrees based on problems resulting from varying project specifications, geographical contexts and maturity levels. For wind power, existing barriers at different scales (technology, economic, socio-political and environmental) could hinder the deployment of wind capacities in the next three decades (Figure 42). Mitigating these barriers immediately, through a range of support policies and implementation measures, is vital to boost future deployment.

Figure 42: Existing barriers in the wind energy sector.



While energy transformation could bring positive overall socio-economic benefits at the global level, a deeper look at the regional level highlights how the benefits (and costs) of the transformation would impact various parts of the world differently. Such differences are due mainly to: 1) countries having different energy transition starting points, 2) the depths, strengths and diversity of supply chains, 3) the degree to which economies depend on fossil fuels, and 4) different levels of national ambition and means of implementation (IRENA, 2019b). Levelling out the regional and country-level effects of the energy transformation depends on a policy framework that operates on two fronts. The framework should promote the deployment of renewables both to reduce energy consumption and to increase energy access. Simultaneously, the deployment of renewables must be embedded into broader policies that make energy a catalyst of economic, inclusive and sustainable growth. Such a "just transition" policy framework rests on three transformative sets of policies: deployment policies, integrating policies and enabling policies. These sets of policies would need to work together to ensure a just and inclusive energy transition, mainly to overcome all the existing barriers (technical, economic, socio-political and economic) listed in figure 43 (IRENA, 2019b).

Figure 43: The policy framework for a just transition



Source: (IRENA, 2019b) and (IRENA, IEA, REN21, 2018).

The choice of the instrument and its design should be made based on country-specific conditions and objectives. The solutions and measures henceforth are wider and needs a specific study focussing on just addressing the barriers in the industry. This report present an overview of some of the key aspects to be considered to accelerate wind capacity deployments along with some successful examples based on IRENA's comprehensive work on renewables so far along with additional literature review.

DEPLOYMENT POLICIES

Wind has been supported by a range of policy instruments. For onshore wind, this support has mainly come in the form of feed-in tariffs (for example, in Europe), tax incentives, and quotas and obligations (for example, in India and the US), but it is increasingly moving towards auctions globally. Meanwhile, offshore wind is driven mostly by auctions, whereby the government supports developers primarily by providing sites, resource assessment and grid connection, along with other rules incentivising compliance.

In general, when choosing the right instrument and its design, three key elements should be considered: 1) policies should be tailored to country-specific conditions and objectives, 2) deployment policies should offer long-term stability to attract investments, and 3) policies should consider all relevant points in the cost trends (IRENA, 2019b).

- **Set long-term, well-defined and stable wind power targets to attract investments.**

- **Provide long term stability of policy instruments.**
  - Policy making needs to minimise swings from strong supportive measures to aggressive curbs. Likewise, prolonged periods of policy uncertainty can greatly impact the future of the wind industry. For example, the expiration of a policy support scheme in China led to a decline in wind capacity additions in 2016. The final years of the extended Production Tax Credit in the US will also provoke uncertainty in wind market progress in the coming years.

- **Adapt policies to changing market conditions.**

- **Deploy renewable energy auctions that achieve policy objectives**, which include ensuring timely project completion, integrating solar and wind power, and supporting a just and inclusive energy transition.

- **Promote wind projects in clusters**, where O&M efficiencies and hub grid connections can be exploited to bring down project costs.

- **Deploy intertidal and near-shore projects** that are cheaper to build than projects farther offshore (for new offshore wind markets); for developed offshore markets, deploy projects farther from shore to access the often-higher wind speeds.

- **Consider financing costs not only for cost-effective deployment strategies for decarbonising power generation but also to explicitly address as part of renewable policies** in order to mitigate the barriers with the growth of renewable energy investments.

- **Streamline the permitting process to avoid longer construction periods and long lead times, project sizes, market risks and operating risks.**
  - In general, streamlining the processes around applying for grid and construction consents to responsible authorities – especially if solely borne by the developer – during permitting can reduce the long lead times. This is also linked to the need to reduce the uncertainties of regulatory and policy frameworks in countries where offshore wind is being deployed, as this could severely impact the permitting process, investor confidence and the overall project risk, which feeds down to project costs.
  - Underperformance at key stages of an auction – bidding, contracting, construction or operational – can hinder the timely completion of projects. While certain design elements ensure higher rates of completion, policy makers must find a balance between inclusive, flexible participation requirements, with some risk of delay or underbuilding, and overly strict requirements that may discourage potential bidders, reducing competition. In Germany, onshore wind auctions have been undersubscribed following a re-design requiring projects to obtain permits before bidding. Likewise, strict compliance rules can deter small or new players, reducing inclusiveness (IRENA, 2019f).

- **Enable and scale-up corporate sourcing of wind projects** (IRENA, 2018e).
  - An effective, credible and transparent system for certification and tracking of renewable energy attributes should be supported.
  - Companies should be empowered to engage in direct investments for corporate production of renewable electricity for self-consumption.
  - Companies should be allowed to work with utilities or electricity suppliers to provide corporate renewable procurement options.
  - An energy market structure that allows for direct trade between companies of all sizes and wind project developers (such as PPAs) should be considered.

SOLUTION	SUCCESSFUL EXAMPLES
Streamlining the planning process	**UK's competitive approach to offshore wind development:** Although the wind developer builds the grid connection, it auctions it off to a third party after the transmission assets are built. This has driven down the cost of grid connection in the UK and streamlined the planning process because only one party is responsible for planning and permitting for the wind farm and the transmission asset.
Corporate sourcing of wind farm	**IKEA's second wind farm purchase in Canada:** In early 2017, IKEA had increased its direct ownership of wind energy assets for self-generation in North America to almost 400 MW with its second purchase of second wind farm in Canada (IRENA, 2018e).

INTEGRATING POLICIES

Integrating policies, such as national infrastructure, sector coupling, and research and development (R&D) policies, promote planning and co-ordination. Integrating measures, meanwhile, enhance system flexibility as the share of variable renewables rises (IRENA, IEA and REN21, 2018).

SYSTEM INTEGRATION POLICIES:

The National policies should promote energy transformation planning as part of a wider infrastructure development, to integrate raising share of renewables (IRENA, 2019d).

- **Adopt a systemic approach, drawing together innovations in enabling technologies, market design, business models and system operation.**
  - The implementation of innovations mapped in Box 10 to unlock flexibility across the whole power sector would result in lower costs to integrate VRE and so support the energy transformation. Potential synergies among the different solutions also exist, which can result in lower investments when implementing them together (IRENA, 2019g).

- **Support the deployment of distributed energy resources** (IRENA, 2019g).
  - Emerging distributed energy resources that are connected at the consumer end – such as rooftop solar PV, micro wind turbines, battery energy storage systems, plug-in EVs, demand response and power-to-X solutions (e.g., power-to-hydrogen or power-to-heat) – are decentralising the system and should be supported and deployed.
  - Distributed resources should be enabled to participate in established markets, such as wholesale electricity markets, ancillary service markets and capacity markets (if applicable), so that distributed energy resources are exposed to market price signals. This can be done either via aggregators or by decreasing the minimum capacity requirement for participating in such markets
  - Various emerging digital technologies such as the Internet of Things, artificial Intelligence, and big data and blockchain could support distributed energy resources in responding to system conditions and providing services to the grid, turning them into flexibility providers.

- **Improve existing infrastructure along with building a high-voltage grid, or super grid**, to transport electricity to another region and avoid renewable energy curtailment.
  - The cost of building such a grid is high and must be measured against the economic benefits of both of the systems that the grid is linking. In addition, co-ordination by multiple layers of government (federal, regional and state) is important (IRENA, 2019g).
  - To improve resilience of the grid and the energy access rate with renewable sources, microgrids could be deployed. To strengthen the interconnections among countries within a region, super grids could be a solution.

- **Reduce the uncertainty of wind generation through advanced weather forecasting.**
  - This depends on the methodology and technique used. Enhancements from the use and management of big data and artificial intelligence can increase the accuracy of the forecast and hence the overall reliability of the system (IRENA, 2019g).

SOLUTION	SUCCESSFUL EXAMPLES
Transmission lines and interconnections	**Texas, US:** Under the Competitive Renewable Energy Zone (CREZ) initiative, upgrades and new construction along 5 790 kilometres of high-voltage transmission lines across a broad part of central and western part of Texas aided in the reduction in wind power curtailment on the state's grid, from a range of 8% to 17% between 2009 and 2011 to only 1% in recent times (IRENA, 2019g).
Energy storage	**Alaska, US:** The installation of an advanced lead-acid battery storage system of 3 MW (750 kWh) with a 4.5 MW wind power project by a local utility Kodiak Electric Association, in collaboration with Younicos (Berlin-based energy storage firm resulted in additional wind integration of 8 million kWh (IRENA, 2019g).
Power-to-hydrogen	**Denmark:** For grid balance purpose, under the "HyBalance" project, excess wind power is used to produce hydrogen by electrolysis. The produced hydrogen is then used in the transport and industrial sectors in the city "Hobro" in Denmark. This project is expected to help identify potential revenue streams from hydrogen as well as changes in the regulatory environment that are required to improve the financial feasibility of power-to-hydrogen technology option (IRENA, 2019d).
Advanced weather forecasting techniques	**Colorado, US:** A 37.1% improvement in wind generation forecasting saved customers of Colorado utility Xcel Energy USD 60 million between 2009 and 2016. The improvement was achieved by deploying a state-of-the-art wind forecasting system that was specific to each farm and that provided hub-height speeds and was updated every 15 minutes. Its wind production displaces around 11.7 million tonnes of CO_2 emissions annually (IRENA, 2019g).

SOCIAL INTEGRATION POLICIES:

For wind projects, public opposition is one of main existing barrier (NIMBY (Not in my backyard) and land use) that affects the deployment rate. Supportive measures to local communities are henceforth needed to accelerate deployment of wind projects with shared revenues.

- **Engage local communities from the early stages of wind farm development and promote community ownership models.**
  - Work with local planning authorities and maintain engagement at different stages of wind farm development and operation (Aitken et al., 2014). For onshore wind projects, this applies mainly to local communities, whereas for offshore projects, fishing communities should be engaged.
  - Promote equitable distribution of the economic benefits and costs. Provide additional lease income to landowners in the immediate location of wind farm facilities and create jobs during the phases of wind farm installation and operation. This could potentially increase the annual income of local beneficiaries (especially in the case of agricultural lands and areas) and aid in supporting the wind farm development (Ledec et al., 2011).
  - Provide other local services such as educational visits or programmes, landscape maintenance and enhancement measures, tourism facilities, sponsorship of local events, etc. (Munday et al., 2011).

SOLUTION	SUCCESSFUL EXAMPLES
Community-owned wind installation	**The UK:** Baywind Energy co-operative, the first community-owned wind installation in the UK, built in 1996, generates around 10 TWh of electricity annually, powering some 30 000 homes. This initiative not only provides income and clean energy for its members, but also directs funds into educational visits to the wind farm and environmental books for local schools in the community.
Community engagement	**ONSHORE:** **Denmark:** In the case of the Northern Jutland wind farm, which operates across 15 sites, the public communities were involved in pre-project planning through various community engagement methods, such as discussion forums and meetings, online maps, GIS models, reports, and meetings between citizens, politicians and energy experts (Aitken et al., 2014). **OFFSHORE:** **Germany:** In the case of the Baltic 1 wind farm, local companies were provided the chance to test developments in the offshore area along with measures such as involvement in hearings, opportunities to comment on project documents, etc., (Aitken et al., 2014).

RESEARCH AND DEVELOPMENT POLICIES:

Advanced research strategies are essential for cross-sectoral integration and broader application of renewable energy technologies across the economy (IRENA, 2019b).

- **Promote R&D strategies**, as well as institutions to advance their uptake in the public and private sectors.
- **Facilitate competitive environments** in which reduction in the cost of energy is both rewarded through the right to deliver new projects and supported through the provision of targeted public R&D funding (IRENA, 2016b).

SOLUTION	SUCCESSFUL EXAMPLES
Funding for future foundation technologies	**The US**: The US Department of Energy (DOE) has announced up to USD 28 million in funding for upcoming new floating offshore wind turbines via the Advanced Research Projects Agency-Energy (ARPA-E) programme "Aerodynamic Turbines, Lighter and Afloat, with Nautical Technologies and Integrated Servo-control" (ATLANTIS) (IRENA, 2016b).

ENABLING POLICIES

Strengthening policy connectivity and co-ordination between energy and the rest of the economy will draw maximum systemic benefits from the energy transformation. Such policies must focus on building capabilities for renewables production, use and application, as well as reform of the broader institutional architecture to enable systemic effects between the energy sector and the wider economy. The enabling framework links four crucial national policies: industrial policy, labour market and social protection policy, education and skills policy, and financial policy.

INDUSTRIAL POLICY:

Industrial policies generally are intended to support economic diversification. Mainly, a transition-enabling industrial policy should make the energy sector into a lead sector of the economy. Some recommendations on this aspect are listed below (IRENA, 2019b):

- **Promote consumer awareness.**

- **Enable targeted public investment to support the uptake of renewables** (including wind and to create additional jobs and capabilities.

- **Strengthen and maximise value creation from the development of a domestic wind industry**
  - To strengthen the industrial capability of domestic firms, policy measures and interventions are needed that contribute to increased competitiveness. These measures could include industrial upgrading programmes, supplier development programmes, promotion of joint ventures, development of industrial clusters and investment promotion schemes (IRENA, 2018d).

SOLUTION	SUCCESSFUL EXAMPLES
Funding for future foundation technologies	**The US:** The US Department of Energy (DOE) has announced up to USD 28 million in funding for upcoming new floating offshore wind turbines via the Advanced Research Projects Agency-Energy (ARPA-E) programme "Aerodynamic Turbines, Lighter and Afloat, with Nautical Technologies and Integrated Servo-control" (ATLANTIS) (IRENA, 2016b).

FINANCIAL POLICY

Adequate financing is essential to foster deployment of wind projects in next decades. Some key recommendations on this aspected are listed below:

- **Mobilise significant revenue streams through carbon pricing and other measures**, including green bonds, and devise revenue recycling schemes to achieve a just transition (IRENA, 2019b).
  - Revenues can support strategic investments to build new infrastructure and reallocate and recycle budgets in a way that benefits education, health care and other sectors.
  - Carbon taxation revenues can be used to foster new employment creation and to limit the financial burdens of carbon pricing on low-income families and small businesses.

- **Deploy sustainable finance initiatives and programs to enlarge the fiscal space and to foster sector diversification to finance** the energy transition process in the medium and long term (IRENA, 2019b).

EDUCATION AND SKILLS POLICY

Sufficient training and programs are essential to improve the knowledge of renewables and this calls for a strong focus on education in science, technology, engineering and mathematics (STEM) education that can help build or augment technical capacity and technological learning (IRENA, 2019b).

- **Support skills and supply chain development in order to enable the commercialisation of wind technology.**
  - Facilitate reskilling of the work force from the fossil fuel industry to renewables (e.g., offshore wind). Successful job migration between sectors, however, depends on dedicated retraining policies. Specific policy measures, such as upgrading and supplier development programmes, support for joint ventures, and industrial promotion schemes, may be needed to strengthen the industrial capacity of domestic firms (IRENA, 2018d).
  - To meet the human resource requirements associated with deployment targets, education and training policies need to consider the occupational and skills requirements of the wind energy sector. Prospects for local employment improve to the extent that the provision of education and training/re-training sufficiently matches evolving skills needs (IRENA, 2018d).

SOLUTION	SUCCESSFUL EXAMPLES
Re-skilling and transferability of work force	**The UK:** Scotland established the GBP 12 million (USD 14.8 million) Transition Training Fund to offer training opportunities to workers affected by the downturn to work in industries that include renewables and low-carbon technologies. Several training providers in and around Scotland are utilising the Fund to offer training courses. Maersk Training, for example, provided the oil and gas workforce with essential safety and technical competencies required to target new roles in the wind energy sector. Upon completion of the training, the provider also supports candidates to secure employment opportunities using its extensive industry connections (IRENA, 2018d).

LABOUR MARKET AND SOCIAL AND ENVIRONMENTAL PROTECTION POLICY

The policies should also consider improved employment measures and services to motivate people to engage in the sector development. On environmental protection side, currently wind technology is being blamed for causing mortality of species (birds, bats) and given the improvements in the turbine blades, this raised a question on “sustainability” aspect. On this regard, wind industry is currently working on implementing various measures to address this through the lifecycle of the projects. Few recommendations are listed below:

- **Promote employment services** (matching jobs with qualified applicants; promoting employee well-being; facilitating on- and off-job training; and providing safety nets) (IRENA, 2019b).

- **Deploy social protection measures** that lighten the load of the weak and the vulnerable, including women and marginalised communities, to ensure that equal distribution of transformation impacts (IRENA, 2019b).

- **Reduce and avoid significant harm to biodiversity through careful selection of wind farm sites** (less-concentrated areas), selection of wind power equipment with different wildlife mitigation devices, night lighting and turbine rotation speed control with adequate sensors (Ledec et al., 2011).

- **Handle and manage local impacts in appropriate ways that are acceptable to most stakeholders**.
  - Activate damping systems that neutralise the noise based on frequency measurements without causing any change in the wind power generator speed (Ledec et al., 2011).

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