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Growth onshore, hope offshore

Wind Power

A.T. Kearney Energy Transition Institute
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Compiled by the A.T. Kearney Energy Transition Institute

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About the FactBook – Wind Power

This FactBook summarizes the status of the wind industry and its prospects, lists the main technological hurdles and principal areas for research and development, and analyzes the economics of this technology. Wind power is by far the largest renewable energy after hydro power. The development of wind power has accelerated over the past decade and growth is expected to continue, increasingly driven by Asia, but also by emerging markets in Latin America or Africa. It is important to distinguish onshore wind power, a mature, proved technology, from offshore, which has taken off, predominantly in Europe, and that still has to demonstrate its economic viability (without subsidies).

About the A.T. Kearney Energy Transition Institute
The A.T. Kearney Energy Transition Institute is a nonprofit organization. It provides leading insights on global trends in energy transition, technologies, and strategic implications for private sector businesses and public sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences and opportunities for decision makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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Wind energy uses rotor blades and an electricity generator to convert kinetic energy into electrical energy

Wind energy has been used for millennia to power windmills and pump water, for instance. Now, its primary use is to generate electricity from wind turbines. As with all sources of energy – with the exception of tidal, geothermal, and nuclear – solar is the root source of wind energy. When sunlight heterogeneously heats the Earth and its atmosphere, temperature gradients are formed, resulting in air motion – wind – moving from cold to warm regions. The global technical potential for wind energy exceeds current global electricity production, although the quality of resources varies by location.

The kinetic energy theoretically available for extraction increases with wind speed; power is proportional to the cube of the velocity. Wind energy is harnessed by turbines that use rotor blades and an electricity generator to convert the kinetic energy of moving air into electrical energy.

Several designs exist, but horizontal three-bladed upwind rotors with variable speed operation have become dominant. Over time, turbines have grown larger and taller to maximize energy capture over a range of wind speeds, while reducing cost per unit of capacity. In addition, turbines are now being sited offshore in order to capture higher wind speed and be located closer to electrical load centers in coastal cities. Best practices from offshore oil and gas industry activities can be relevant for developing safe and efficient offshore wind facilities.

Energy efficiency is an important parameter as converting wind energy to useful electricity through wind power systems results in power losses of around 55 percent. However, as wind energy is available for free and doesn’t directly engender greenhouse emissions its impact is somewhat not comparable to that of fossil fuels.

Although the technical fundamentals of onshore and offshore wind are the same – offshore wind turbines installed in recent years are essentially scaled-up, marinized versions of land turbines or those installed in shallow waters – the technologies used in onshore and offshore wind systems are likely to diverge further in the future. In addition, different wind turbine systems are at different stages of maturity with onshore wind now an established mature renewable energy technology.

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Wind-power capacity has accelerated rapidly over the past decade in the OECD, China, and India

Global wind-power capacity increased by an average of 20%a year since 2006, reaching 540 GW at the end of 2017. Growth has been driven primarily by onshore technology, which accounts for about 97%of capacity. However, since 2008 offshore wind has been growing at a faster rate than onshore albeit on a much smaller base, reaching only 19 GW of globally installed capacity in 2017, with 3.8 GW added in 2017 – a record for offshore wind. With about 150 existing wind farms at the end of 2017, the offshore sector remains in its infancy stage compared to the onshore sector, which has about 22,000 wind farms.

China accounted for 38%of capacity additions in 2017 and was the principal driver of market growth during that year. The market in the United States continued to add capacity in 2017, with 7 GW of capacity additions, even though the pace of addition has slowed down over previous years. Germany (12%of capacity additions in 2017) was the third-largest market globally and largest in Europe followed by the UK and France. In 2017, European countries accounted for 85%of the global offshore installed capacity with the UK and Germany having 67%of the total global capacity.

Despite this impressive rate of deployment, wind still accounts for no more than 6.8%of electricity-generation capacity installed globally and supplies just 4%of the world's electricity. (The average load factor for onshore wind farms built to date is 23 percent. The load factors of new onshore and offshore projects are 34%and 49%respectively.) Wind penetration is significantly higher in some European countries (above 8 percent).

Wind power is expected to continue to grow, with cumulative capacity increasing to more than 841 GW by 2022 with offshore wind growing at 18 percent, which is more than double the growth rate of 8%for onshore wind. Asia will continue to make the most capacity additions, with 140 GW of new capacity expected in the next five years. North American and European markets are also expected to remain dynamic. Wind development should continue to expand in other regions, in emerging wind markets such as Russia, India, Brazil, Mexico, Turkey, Iran, Saudi Arabia, and South Africa. Despite European and Chinese interest, offshore is unlikely to account for more than 5.5%of global wind capacity in 2020.

The IEA estimates that, in its Sustainable Development Scenario, offshore wind will get a major boost as worldwide installed capacity rises above 350 GW in 2040, corresponding to electricity generation of 1200 TWh. Even in the more conservative forecast (New Policies Scenario), offshore wind is expected to play a greater role in the power mix, meeting at least 1.5%of electricity demand by 2040.

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Wind R,D&D efforts focus on increasing capacity factor, reducing costs, and solving network-integration difficulties

Contrary to the popular perception, R&D efforts are imperative to further improve wind technology efficiency and performance. Maximizing energy capture, minimizing per unit cost of capacity, and meeting network requirements for enhanced predictability are key focus areas for wind R&D.

The industry is designing and commissioning larger and taller turbines. This is being driven by offshore wind, with the aims of mitigating relatively high infrastructure costs (for example, building foundations offshore) and lowering the number of units per kW of installed capacity, which improves access and facilitates maintenance. Onshore, meanwhile, tower height tends to be restricted because of public acceptance of noise and visual disturbance, as well as road-access constraints and, in some cases, economics (for example, where higher capital investment does not result in a higher capacity factor). Nevertheless, in some regions, rotor diameter in onshore turbines continues to increase. Finally, unconventional designs – mainly airborne wind-energy systems – are also arousing curiosity, although there is no large-scale pilot plant at this stage.

Both onshore and offshore wind technologies are seeking to achieve similar objectives: increase capacity factor and reduce production, operation, and maintenance costs. The need to ensure that wind power meets network requirements has also resulted in a significant effort to create innovative transmission systems and to develop power-control systems. Coupling wind and battery storage can provide efficient solutions to address power network requirements. The battery helps maximize utilization of power produced by wind turbines and contributes to stabilizing the system. Additionally, wind resource assessment and forecast are crucial to identifying the most suitable locations and developing appropriate solutions to ease integration.

R&D is crucial in offshore wind to improve components and reduce technology costs. Large-scale demonstration activities are under way in Europe. Global R&D investment for wind energy has stabilized around $1.5–2 billion per year since the start of this decade with the private sector increasingly taking a lead role. However, the investment in wind R&D remains substantially lower than investment in other mainstream renewable power sources (for example, solar).

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Onshore wind is competitive with fossil-fuel power in some locations, but further cost reduction is required in offshore

With zero fuel costs, wind is a capital-driven industry. As with most other renewables, up-front investment accounts for the bulk of the full cost of wind power, although operation and maintenance costs are more significant in offshore projects compared to onshore projects. Investment costs are significantly lower for onshore than for offshore, ranging from \$1,300 to \$2,800 per kW and from \$2,400 to \$5,900 per kW, respectively. This gap can be explained by offshore wind's relative lack of maturity, as well as the marine environment's need for expensive foundations, specialized installation vessels and costly grid connections. A moderate decrease is expected for onshore investment costs in the future, while offshore should benefit from a decline in investment costs per unit of power. However, these reductions remain sensitive to commodity prices and supply chain bottlenecks.

If wind conditions are favorable, onshore projects can be competitive with fossil fuel generation sources. Over the period 2016–2017, the regional weighted average levelized cost of electricity (LCOE) for onshore wind was \$55–92 per MWh. Onshore LCOE can be as low as \$30 per MWh for the most competitive projects without financial support. Offshore wind is not yet competitive with fossil fuel, with a regional weighted average LCOE of \$145–240 per MWh on the same period. Cost estimates are system specific and dependent on the wind resources available (and possible additional integration costs). But, in general, the higher the wind penetration, the higher the integration costs (and lower market value). As was the case with investments costs, LCOE for offshore wind will decrease at a steeper rate compared to onshore wind due to its relatively lower level of maturity.

National wind energy targets, policies, and regulatory support mechanisms are in place in many countries to encourage and subsidize wind energy development. Recently, multiple subsidy-free offshore contracts have been awarded in Germany and Netherlands with plans to offer more such tenders in the future. However, the viability of subsidy-free projects might not be uniform across the markets technological challenges.

In parallel with the expansion in capacity, wind finance took off during the 2000s, but it now faces growing competition from solar photovoltaic. The ecosystem of wind power has developed and matured in recent years, with various financing entities playing a growing role. Whereas the onshore wind-turbine market is relatively fragmented – with a significant presence of non-OECD players – offshore is still dominated by European companies.

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Wind does not face any major environmental hurdles currently, but public opposition is rising

Wind power is one of the lowest greenhouse-gas-emitting energy technologies, with median emissions of 11 and 12 grams of CO_2 equivalent per kWh over its full life cycle for onshore and offshore technology, respectively. However, wind CO_2 abatement is highly system specific and its overall impact depends on the penetration level and on the power system's ability to compensate for wind's intermittency without relying on carbon-intensive peaker power plants.

However, the reluctance of the public to accept wind power because of the noise of turbines and their aesthetic impact, and relatively high space requirements, can lead to social or environmental hurdles. In recent years, several key markets (including the United States, Australia, and European countries) have registered an increase in consumer opposition against wind projects – both in planning and operational stages. Increased prevalence of turbines along-with size and height increase might lead to increase in public opposition.

Fabricating and decommissioning of large number of installed wind turbines can also pose an environment challenges such as heavy equipment disposal issues, mineral scarcity, etc.

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Wind energy raises major network integration issues that are system-specific

Wind is an intermittent source of energy; its output is variable, imperfectly controllable and predictable, and can be subject to changes in availability over several distinct timescales, from sudden, short-term turbulence to inter-annual events. In addition, wind output tends to be poorly correlated with demand.

As a consequence, wind power tends to increase flexibility needs, which is apparent in the residual load (in other words, demand minus wind and solar generation). At the same time, it makes a limited contribution to the flexibility pool of resources, mirrored by the low capacity credit that system operators allocate to wind power. Therefore, despite the smoothing of output that can be achieved by building wind turbines in diverse geographic regions, wind requires back-up resources, whether in the form of dispatchable plants, energy storage, interconnection with adjacent markets, or demand response. These resources are system- and location-specific.

The best wind resources are often far from large consumption centers or in offshore locations, requiring long-distance or marine transmission lines. Therefore, it is highly likely that wind will foster the development of additional high-voltage direct current and alternative current transmission investments. Europe is leading the way in interconnecting offshore wind projects via HVDC (high voltage direct current) systems through multiple projects in the North Sea. In the United States, a private consortium is aiming to link mainland demand centers on the East Coast with offshore wind capacity through undersea transmission lines. However, high cost of transmission lines are key challenges to the immediate implementation of the project.

Wind still lags far behind solar, which stands to benefit more due to its different diurnal generation profile, in storage adoption. However, wind projects are increasingly being developed with electricity storage capacities to address intermittency, especially in Europe.

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1. Key concepts of wind power

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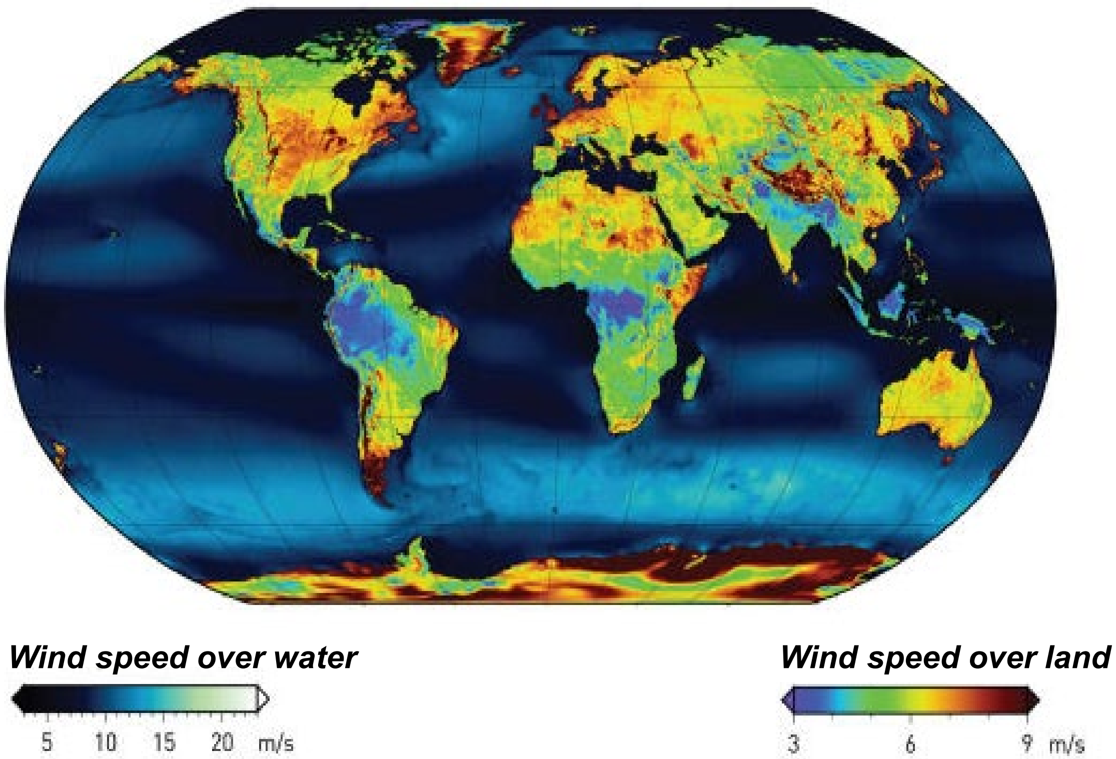
The global technical potential for wind energy exceeds current global electricity production

Global wind resource map

Meters per second (m/s)



- **As with all sources of energy – with the exception of tidal, geothermal, and nuclear – solar is the root source of wind energy.** When sunlight heterogeneously heats the Earth and its atmosphere, temperature gradients are formed, resulting in air motion – wind – from cold to warm regions.
- **The technical potential of wind exceeds current global electricity production.[1]** Estimates range from 70-450 EJ/year, while the global electricity production is of 60 EJ/year.[2]
- **Wind is location- and weather-dependent.** Though wind speeds vary considerably by location, ample technical potential exists in most regions to enable significant wind energy deployment.

[1] FactBook utilizes the definition of technical potential given by the IPCC "as the amount of renewable energy output obtainable by full implementation of demonstrated technologies or practices. No explicit reference to costs, barriers or policies is made"
[2] EJ is exajoules (1018 Joules). According to the IEA, 189 EJ are transformed every year in heat and power co-generation plants, generating 60 EJ of electricity, 11 EJ of commercial heat, and 118 EJ of losses.
Sources: IPCC (2011), "Special report on renewable energy"; IEA (2012), "Energy Technology Perspectives"; picture credit to CNET; A.T. Kearney Energy Transition Institute analysis

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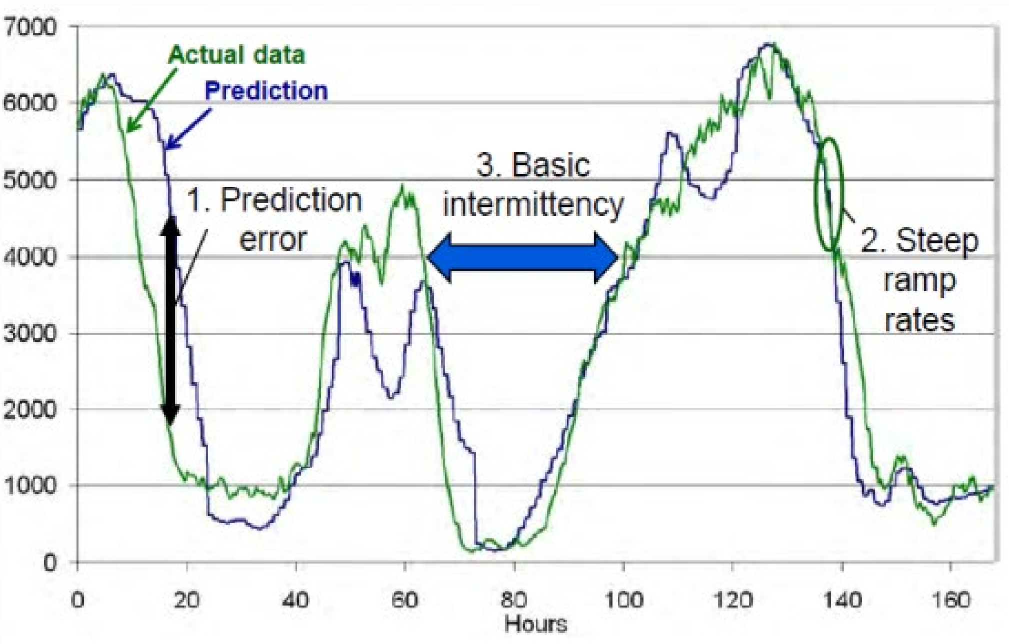
Wind is weather-dependent and therefore variable, imperfectly predictable, and subject to strong ramping effects

Wind intermittency illustration

MW – Germany 2007



- **Wind output is imperfectly predictable** with (i) lower level of predictability than fossil-fired power plants; and (ii) less accurate forecast over longer time horizon (multiple hours to days).
- **Wind output is subject to ramp events.** The output of a wind turbine can vary from zero to its rated capacity, sometimes changing very rapidly. In particular, wind turbines can ramp down in case of high wind speeds (over cut-out speed) with production falling from rated power to zero in a matter of seconds.
- **Wind output is variable and imperfectly controllable over several time scales**. Wind output depends on weather, and variations can occur on multiple time scales, from sub-hourly to inter-annually.
- Intermittency is a crucial challenge for grid stability and to match demand and supply.[1]

[1] Interestingly, intermittency can be smoothed mechanically (larger and taller turbines can benefit from increased inertia) and electronically (with capacitor storing energy).
Sources: IPCC (2011), "Special report on renewable energy"; A.T. Kearney Energy Transition Institute analysis

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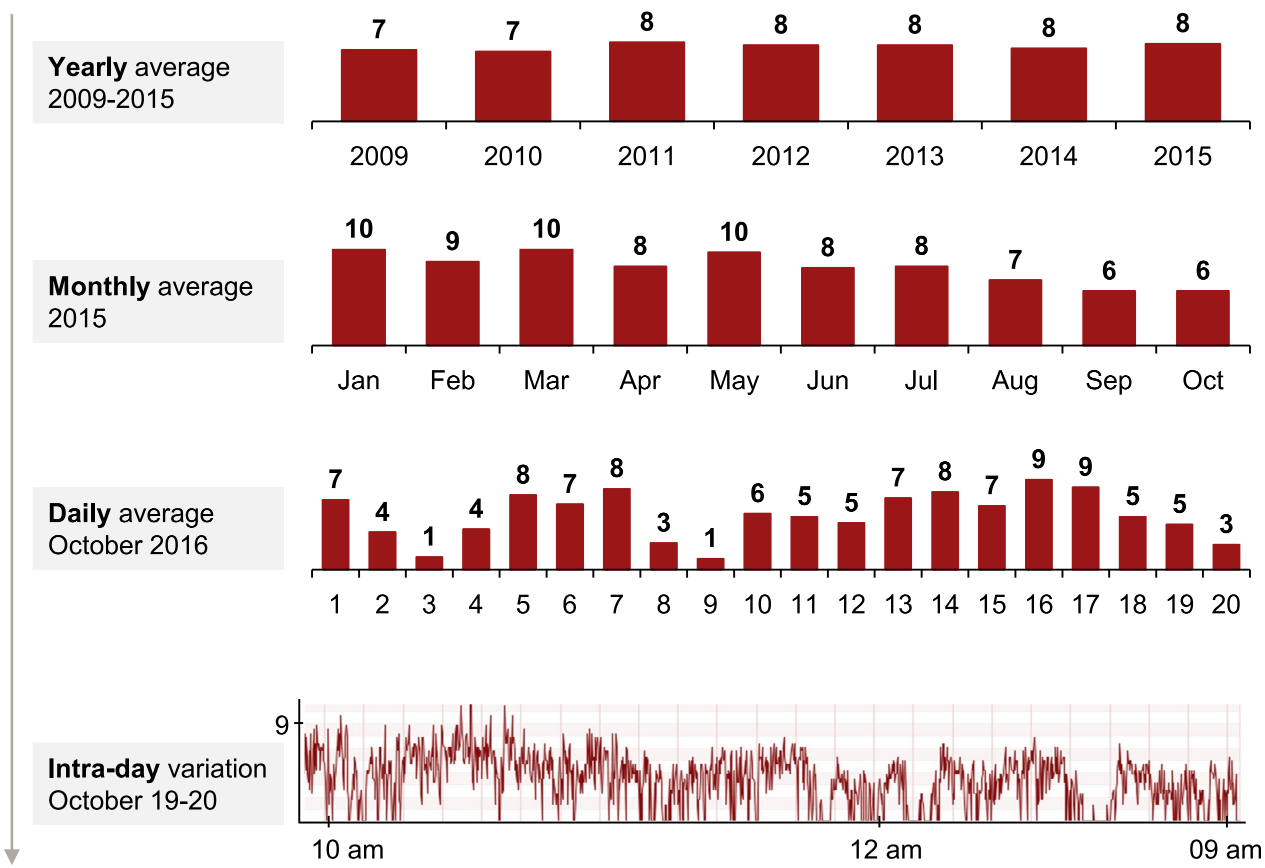
Wind speed varies over several time scales, from short-term turbulence to inter-annual events

Illustration of wind variability according to time scale[1]

Wind speed in km per hour in London (Hampstead)



- Wind variations can be categorized by time period. As illustrated by the figures on the left, fluctuations may appear over the following time horizons:
  - Inter-annual (time scale greater than a year – for example, El Niño)
  - Annual (less than a year – for example, seasonal variation)
  - Synoptic (a few days in duration, typically due to weather systems)
  - Diurnal (daily variation – for example, day/night)
  - Short-term (turbulence)

[1] Graphs are plotted based on wind speed data measured in Hampstead by nw3 weather. Daily graph is reproduced directly from the website (picture credits).
Sources: nw3 weather; A.T. Kearney Energy Transition Institute analysis

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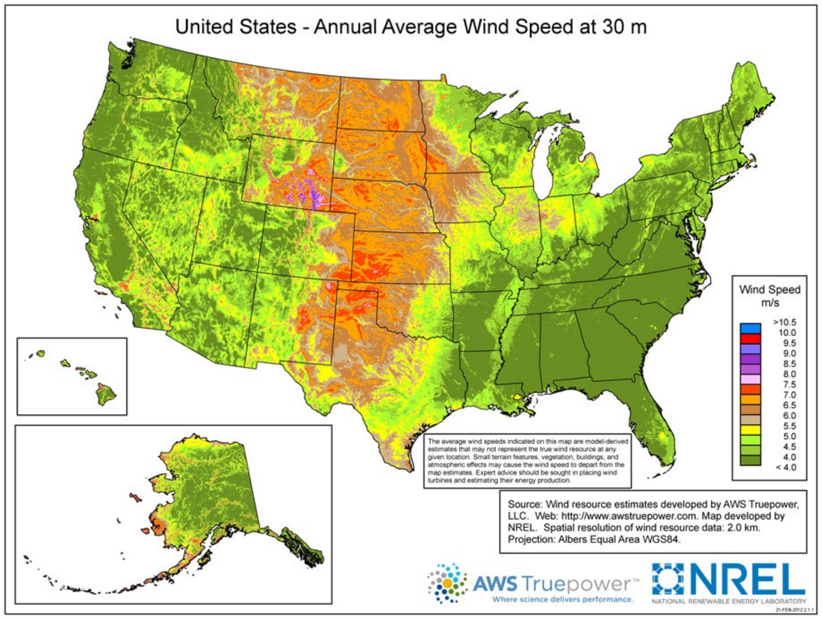
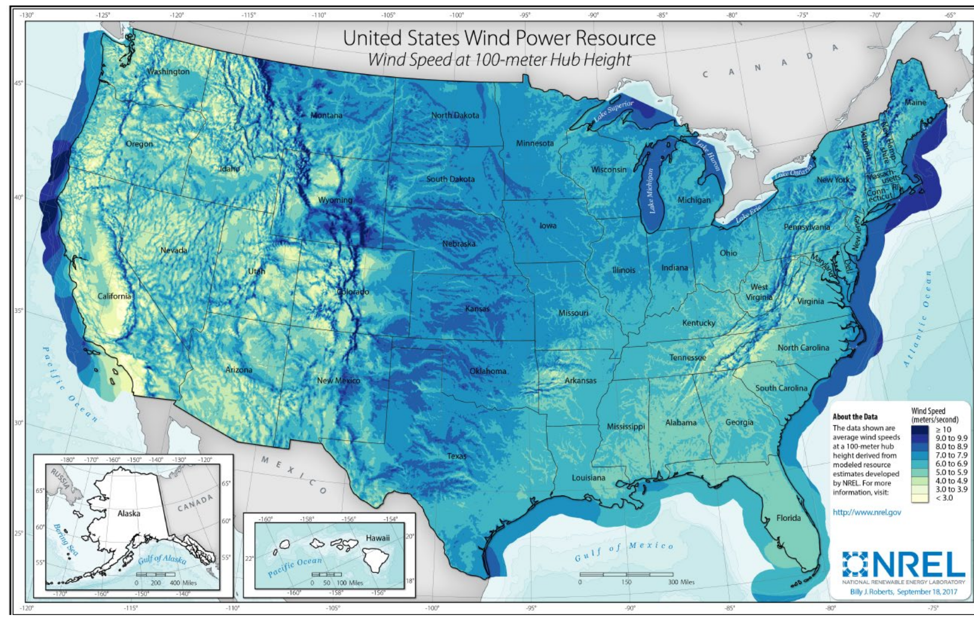
Wind potential increases with elevation

Annual average wind speed

United States, at 30m (left) and at 100m (right)





- From the point of view of wind energy, the most striking characteristic of the wind resource is its **variability**. Wind, by its nature, is highly variable, geographically, temporally and by altitude.
- The reality is that buildings, hills, and even trees can change wind turbine behavior. As elevation increases, wind is less affected by Earth's **boundary layer** – in other words, Earth's friction effect loses its strength. Hence, winds at higher altitudes tend to be stronger and more predictable.

Sources: https://www.nrel.gov/gis/wind.html; A.T. Kearney Energy Transition Institute analysis

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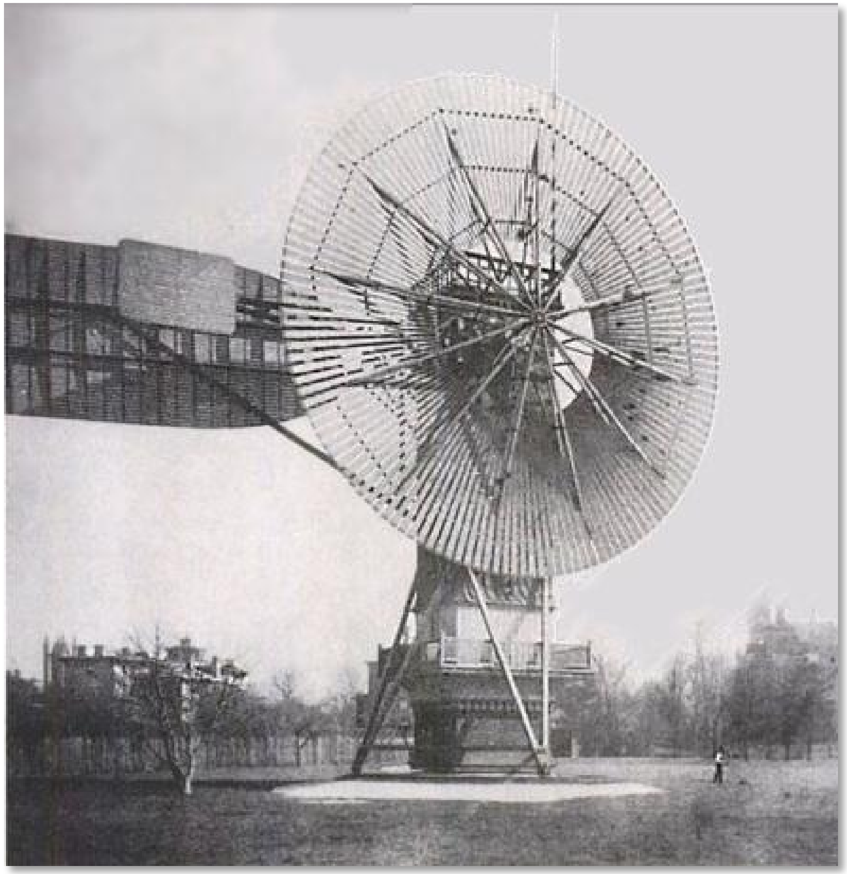
Wind turbines use rotor blades and an electricity generator to convert kinetic energy into electrical energy

The first wind turbine to generate electricity in the US

Cleveland, Ohio, 1888



- **Wind energy has been used for millennia** (for example, windmills to pump water, grind grain, and for propulsion), with the first successful electricity production observed in the late 19th century.
- **Today, the primary use of wind energy is to generate electricity** from large, grid-connected wind turbines. The use of wind to generate electricity on a commercial scale started in the 1970s in Denmark, followed by California.
- Wind turbines use rotor blades and an electricity generator to **convert the kinetic energy of moving air into electrical energy.**

Sources: IPCC (2011), “Special report on renewable energy”; picture credit to Robert W. Righter; A.T. Kearney Energy Transition Institute analysis

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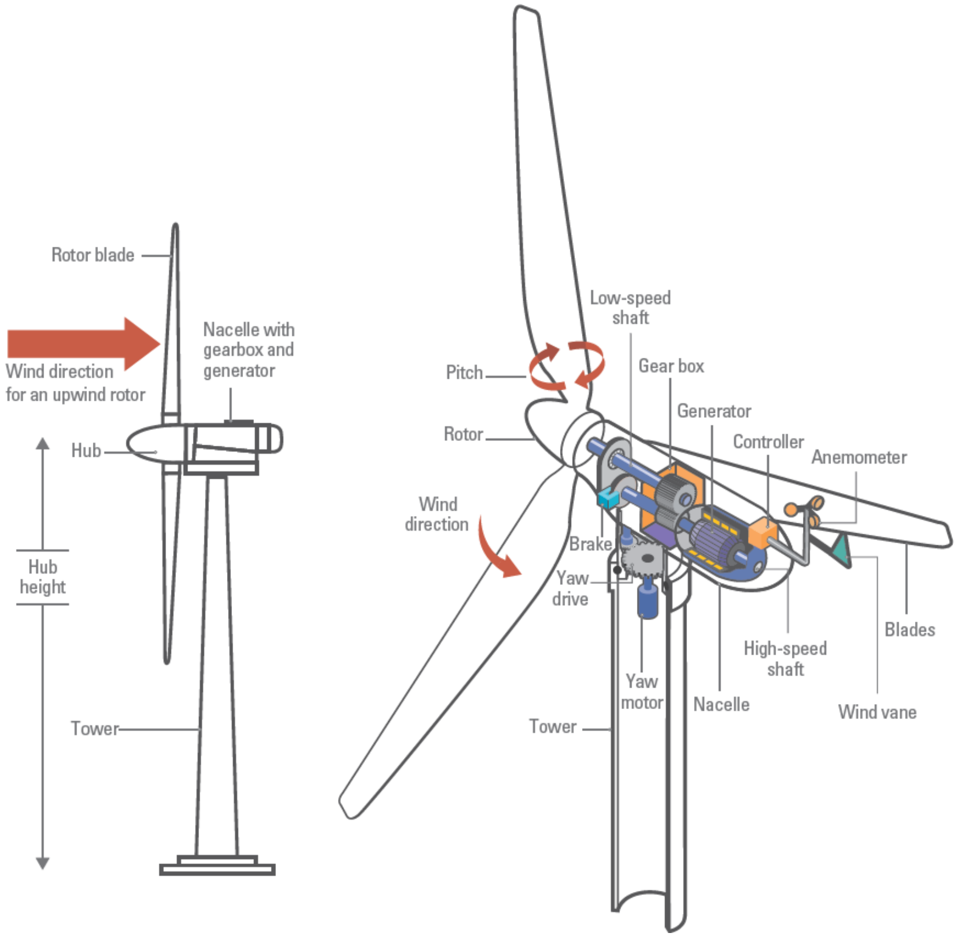
A typical wind turbine is composed of three blades attached to a hub, containing a gearbox, generator, and control system mounted on a tower

Key components of a wind turbine



- Most turbines have an upwind rotor with a yaw motor to turn the rotor and preserve alignment with wind direction. **Blades are attached to the hub, from which power is transferred through a gearbox to a generator.**
- **There are several designs for the layout of the rotor support, gearbox, and generator,** depending on the manufacturer. Some designs avoid the use of a gearbox by using direct-drive instead.
- **The gearbox, generator, and control system are contained within a housing unit called a nacelle.** Electricity is transmitted down the tower from the generator to a transformer at the base of the tower.
- **Support structures are commonly tubular steel towers** tapering in some way (for example, in metal wall thickness and in diameter). Tower height is site specific.

[1] Yaw control consists in orientating the hub so that it faces the wind, whereas pitch control consists in orientating the blades. For more information, refer to appendix 2.
Sources: IPCC (2011), "Special report on renewable energy"; A.T. Kearney Energy Transition Institute analysis

Several designs have been investigated and have converged to horizontal three-bladed upwind rotors with variable speed operation

Leading wind system design options

Location	Land (onshore)	Marine (offshore)	Air (airborne)
Foundation	Onshore foundation	Offshore pile foundation	Floating
Rotation axis	Vertical	Horizontal	
Blades: number	1	2	3
Blades: type[1]	Stiff	Teetered	Flexible
Rotor	Upwind	Downwind	
Tower	Lattice	Tubular	
Drive train[2]	Geared	Hybrid	Direct
Speed control[3]	Stall	Pitch	Yaw
Generators	Fixed-speed	Two-speed	Variable-speed

Most popular | Not applicable

Example of wind turbine design

[1] Wind blades have different mechanical properties, depending on their design, especially with regard to material elasticity.
[2] For more information, refer to slide 51.
[3] There are two ways to regulate the power output of wind turbines: orienting the nacelle to face the wind (known as yaw control) or rotating the blades (pitch and stall). For more information, refer to appendix 2.
Sources: A.T. Kearney Energy Transition Institute, IPCC (2011), "Special report on renewable energy"; Global Wind Energy Council (2015), "Global Wind Report 2014"

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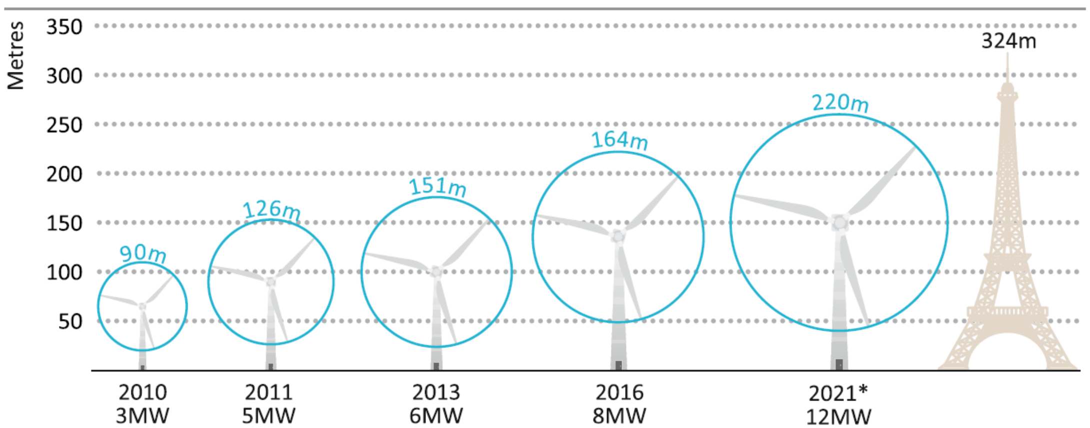
Turbines have grown larger and taller to maximize energy capture over a range of wind speeds while lowering cost per unit of capacity

Evolution of the largest commercially available offshore turbines

Length of rotor blade + hub height and rating (MW)



- **There is an important trade-off for wind-power developers between investment costs and capacity factor.** Higher turbines may incur higher up-front capital costs, but this may be offset by a higher capacity factor and lower generation costs.[1]
- **Improved blade efficiency** should help to capture more energy at lower wind speeds.

- One key trend is the **increasing physical size** of turbines in terms of height and swept area, which raises their **maximum output**.
- The total (i.e. tip) height of commercially available **offshore turbines** has increased from just over **100 m** in 2010 (**3 MW** turbine) to more than **200 m** in 2016 (**8 MW** turbine), which contributed to 230% increase in the swept area. A **12 MW** turbine now under development by **GE Renewable Energy** is expected to reach **260 m** in tip height.
- **Onshore turbines** have increased in size, but their size may be limited by constraints in the construction process.[2] These limitations may be circumvented if efforts to develop self-erecting, telescopic towers or segmented blades are successful.
- A second key trend in offshore wind is that installations are **moving further from shore and into deeper waters** (IRENA, 2018). The increasing ability to install offshore wind in deeper waters has helped to mitigate visual concerns from land, and has also enabled the industry to tap better quality wind resources, resulting in higher capacity factors.

[1] This is measured by levelized cost of electricity. Fore more information refer to slide 44.
[2] For example, transporting components by road and finding large enough cranes.
* Announced expected year of commercial deployment
Sources: IEA (2018), Special Report – Offshore Energy Outlook WEO 2017; A.T. Kearney Energy Transition Institute analysis

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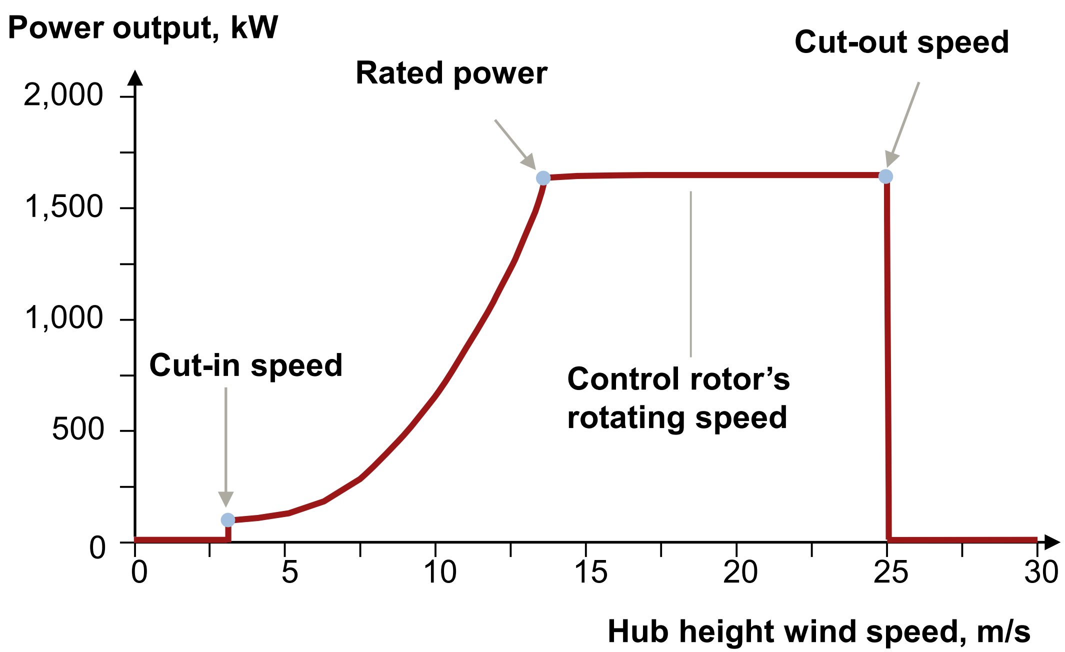
The kinetic energy theoretically available for extraction increases with wind speed but is controlled to protect the turbine

Conceptual power curve of a wind turbine

kW, m/s



Power received from the wind turbine is equal to kinetic energy of wind flow through the rotor period of time

$$P(v) = \frac{1}{2}\rho v^3$$

Air density ρ=1.225 kg/m^3
v=wind velocity
P=power

How to read this graph

- **Cut-in speed:** rotors start extracting energy from the wind at a defined speed, the cut-in speed (usually ~3 to 4 m/s).
- **Rated power:** power production increases with wind speed until it reaches its rated power level (usually ~11 to 15 m/s). The energy available in the wind is a function of the cube of the wind speed.
- **Controlled speed:** after rated power, control systems limit power output to avoid overloading the wind turbine through stall control, pitching the blades, or a combination of both (see appendix).
- **Cut-out speed:** most turbines stop producing at a defined speed to limit loads on the rotor and prevent damage to the turbine (usually ~20 to 25 m/s). The blades are feathered and the gearbox is locked (see appendix).

Note: m/s is meters per second.
Source: A.T. Kearney Energy Transition institute; IPCC (2011), "Special report on renewable energy"

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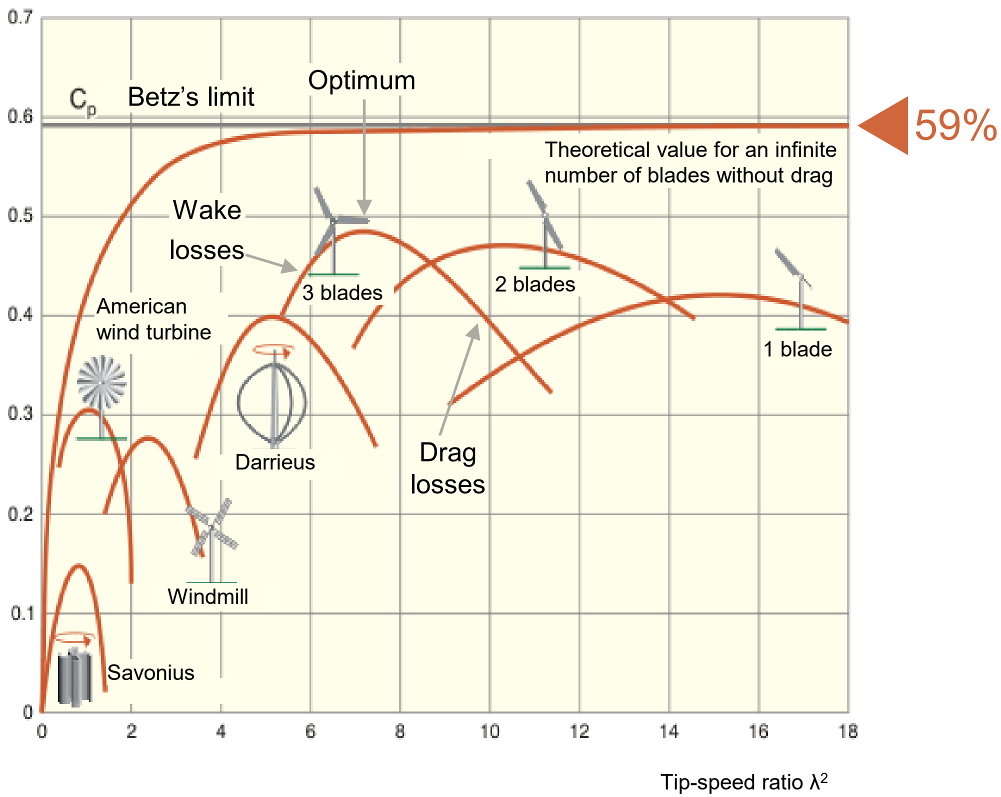
According to Betz's law, a maximum of about 59% of the energy in wind can theoretically be extracted from it

Power extraction of wind turbines

Power coefficient C_p



- Physical law, called **Betz's Law**, states that no turbine can capture more than **16/27 (59.3 percent)** of available kinetic energy of the wind, **regardless of the design of the wind turbine in open flow**. This implies that power coefficient **Cp** will never exceed Betz's limit.[1]
- In general all **horizontal-axis wind turbines** (**HAWT**) are more efficient than **vertical-axis wind turbines** (**VAWT**) (darrieus or savonius rotor).
- However, despite the fact that **extracting maximum available power** from kinetic energy of wind is the main goal, these two designs have significant issues with **aerodynamical forces** and **balance** which make them difficult to commercialize.
- On the other hand, **three-blade** design provides most **reliability** and **stable power output**. Any design with greater number of blades is simply inefficient due to large air resistance caused by too many blades, assuming current blade design. However, as industry evolves towards larger rotors, there seams to be some room still left for experimental design.

[1] Fraction of the wind power that can be effectively harnessed by the turbine.
[2] Tip-speed ratio is the ratio between the tangential speed of the tip of a blade and the actual speed of the wind.
Sources: A.T. Kearney Energy Transition Institute; Thermo radiances "Le rendement des eoliennes" (link); Gundtoft (2009), "Wind turbines" (link)

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Converting wind energy to useful electricity through wind power systems results in power losses of around 55%

Theoretical power conversion losses for wind power

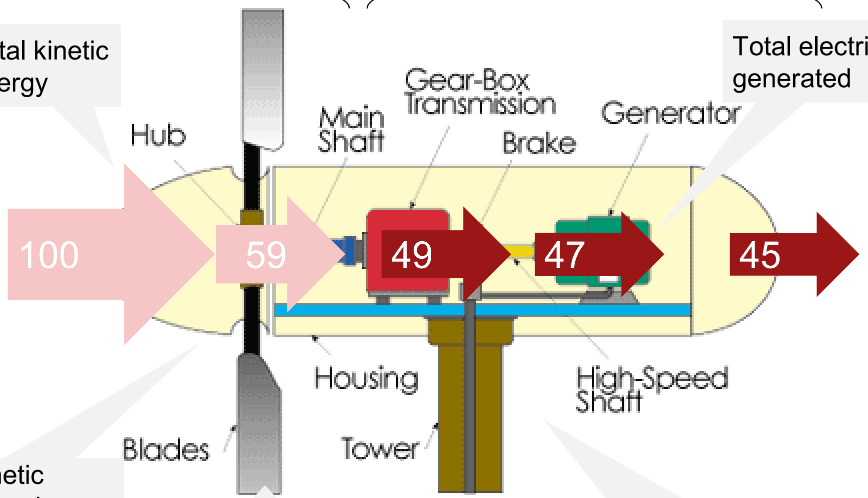
Base 100 on rated power

Wind energy capture (Betz's law)

Power generation

Total kinetic energy

Total electricity generated



Maximum kinetic energy that can be extracted from the wind (Betz's law):

Pmax = 0.59 * Pwind

Typical values for rotor efficiency – 3 blades, at optimum tip speed ratio and for a glide ratio of 100:[1]

Rotor: 0.83

Typical efficiency ranges for the energy transformation – at nominal power:

Gearbox: [0.95–0.98]

Generator: [0.95–0.97]

- **The rotation of the blades**, which drag the shaft, transmitting mechanical energy through a gearbox, leads to additional losses of about 20%.
- **The generator**, which converts mechanical energy into electrical energy, engenders losses of around 4%. Therefore, a wind turbine with a typical three-bladed power system and an optimal tip-speed ratio can theoretically convert around 45% of wind energy into electricity.
- **Conversion efficiencies from installed systems are lower than theoretical efficiencies obtained in laboratories.** In real-world conditions, inferior performance results from manufacturing defects, bad electrical connections, maintenance, and malfunctions. Also, the electricity produced needs to be transmitted to end-users via transmission and distribution feeders (lines), further increasing losses.[2]
- **Energy efficiency is an important parameter.[3] However, its impact is somewhat lower than for fossil fuels**, since wind energy is available for free and does not directly engender greenhouse gas emissions.

[1] The glide ratio corresponds to lift coefficient over drag coefficient.
[2] Transmission and distribution losses depend on distance and technologies, but also vary greatly by country. The global average transmission and distribution loss is 8%, but it ranges from 2% in Qatar to 46% in the Republic of Congo.
[3] Energy efficiency is particularly important from an economic perspective since it affects the levelized cost of electricity of wind power.
Sources: A.T. Kearney Energy Transition Institute; Gundtoft (2009), "Wind Turbines"(link); A.T. Kearney Energy Transition Institute (2015), "Introduction to smart grids"

Although the fundamentals of the technology are the same, onshore and offshore wind systems are likely to diverge further

Typical onshore and offshore technology features

Worldwide

	Onshore	Offshore
Resources[1]	• ~23% capacity factor on average to date • **~34% load factor on average for new installations**	• ~40% capacity factor on average to date • **~49% load factor on average for new installations** (above 50% in some cases)
Dimensions	• 1–6 MW turbine size • 20–1,500 MW wind farm • $30–1,800 million investment	• 3–9.5 MW turbine size (avg 3.7 MW) • 100–630 MW wind farm (average 368 MW) • $450–4,500 million investment
Environment	• Land-based conditions • Unrestricted access • Land constraints for large turbines (roads)	• Rough marine conditions • Remote from shore (~22.7 km in 2017 for a 21.9 m depth) • Access limited by waves and storms
Foundations	• Built on solid ground • Standard concrete foundations cast on site	• Built on different types of soil (sand, clay, rock...) • Foundations depend on water depth and soil consistency

- **Offshore wind has a greater energy potential but marine conditions make project delivery and maintenance more difficult.**
- **Offshore wind turbines installed in recent years are essentially scaled-up, marinized versions of land turbines** installed in shallow waters.
- **However, a new approach to wind power is needed** and is under development:
  - Turbine technology and scale
  - Foundation types, infrastructure
  - Logistics (dedicated vessels)
  - Operation and maintenance (remote control, accessibility…)

[1] Capacity factors have been calculated as the ratio of yearly average output to annual full-load production (dividing these numbers by 8,760).
Sources: E.ON (2011), “Offshore Wind Energy Factbook”; European Wind Energy Association (2018), “The European offshore wind industry key 2014 trends and statistics”; IEA (2015), “Renewable Energy, Medium-term market report 2014”; IEA, WEO 2018, A.T. Kearney Energy Transition Institute analysis

2. Status and future development

Wind capacity has spread worldwide over the past four decades

Wind development timeline

1977
First wind farm in Denmark (52kW)

1980s
First large-scale development in California

1980

1990s
Development in Denmark, Spain, and Germany

1991
First offshore wind farm in Denmark (Windeby), ~5 MW in total

1990

2000s
Massive expansion of European, US, Chinese, and Indian capacities, with Europe accounting for less than 50% of cumulative capacity at the end of the decade

2000

2003
First offshore wind farm in the U.K. (North Hoyle), 60 MW in total

2004
Wind development starts in China and India

2009
EU introduces Third Energy Package along with set 20-20-20 objectives

2010s
China becomes leader, with most installed capacity, surpassing the US and Germany

2010

2012
London Array, offshore wind farm projected 630 MW in total

2015
Germany overtakes the U.K. for offshore capacity additions in 2015, but the U.K. remains leader in terms of cumulated capacity

2018
~560 GW of operational capacity (including 18.8 GW offshore)

2018

Sources: A.T. Kearney Energy Transition Institute, Global Wind Energy Council (2018), “Global Wind Statistics 2017”; The Guardian (2008), “Timeline: The history of wind power”

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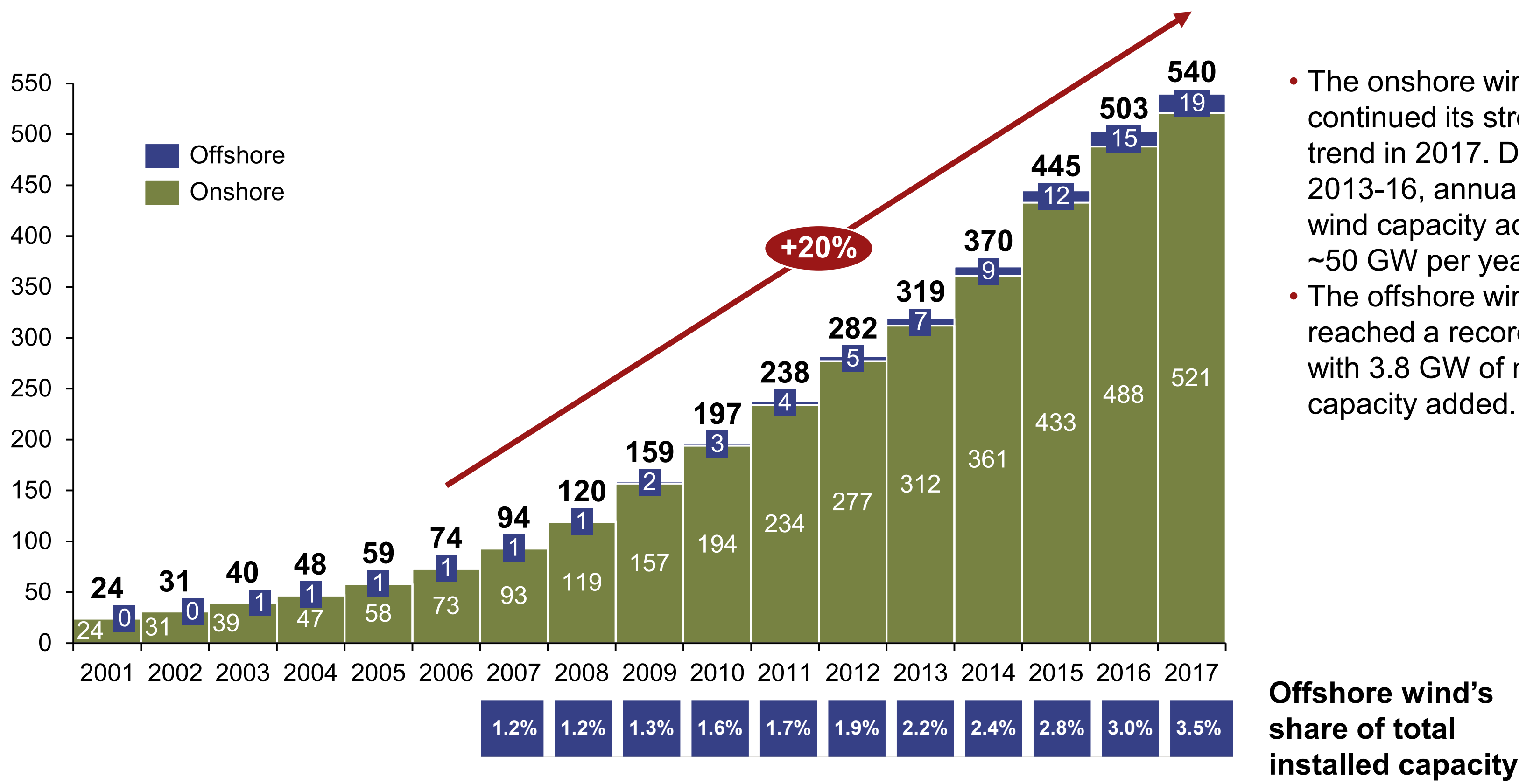
Cumulative installed capacity has grown at an average rate of 20% since 2006, driven by onshore developments

Global installed wind capacity
GW

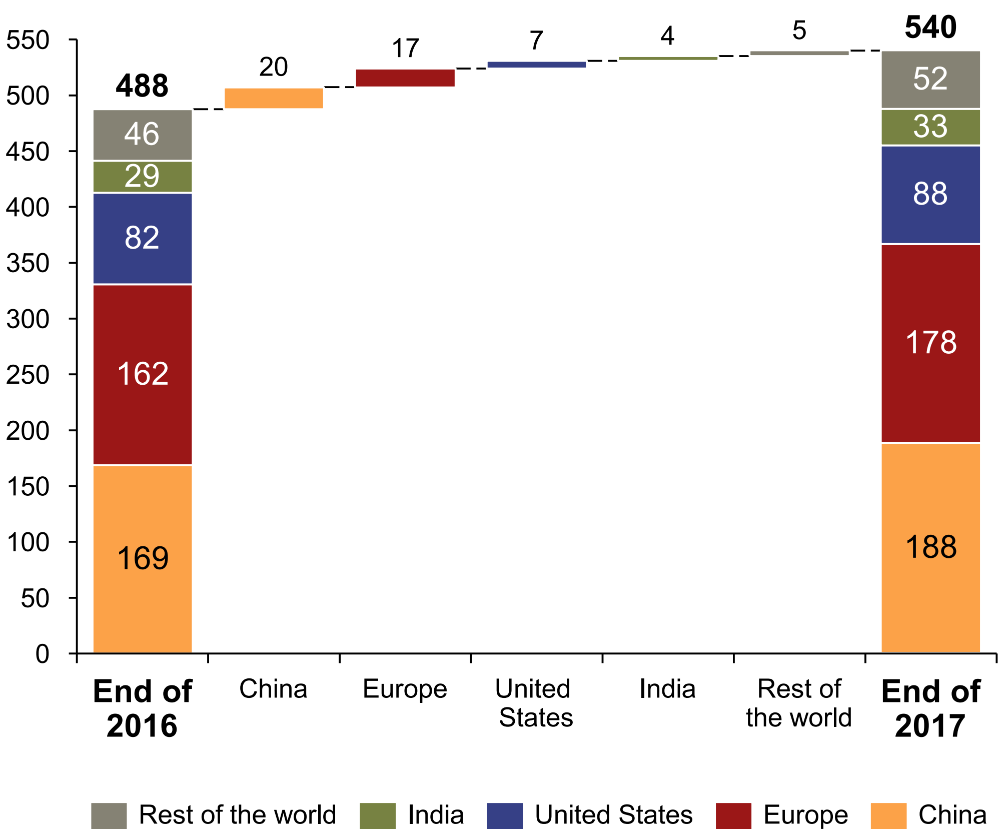


- The onshore wind market continued its strong growth trend in 2017. During 2013-16, annual onshore wind capacity addition was ~50 GW per year.
- The offshore wind market reached a record in 2017 with 3.8 GW of new capacity added.

Sources: Global Wind Energy Council (2018), "Global Wind Report 2017"; A.T. Kearney Energy Transition Institute analysis

China has overtaken the US and Europe as the leader of market growth, accounting for 38% of capacity additions in 2017

Installed wind capacity
GW



- **China was the world's largest market for wind in 2016.** China accounted for almost 35% of installed capacity at the end of 2016 and for 38% of the global capacity additions in 2017.
- **Europe has long been the world leader in terms of installed capacity. At the end of 2017, it still accounted for about 33% of installed capacity and made 32% of the global capacity additions in that year.** The European market is still led by Germany – the third-largest country, after China and the US, for capacity additions in 2017 with 6.6 GW – and to a lesser extent by the UK and France, with 4.3 and 1.7 GW capacity additions in 2017, respectively.
- **The US market continued to develop in 2017, with 7 GW of capacity additions.** The US was the second-largest, after China, for capacity additions. Nevertheless, annual added capacities are still lower than in 2015 and 2016 when approximately 10 and 9 GW of wind capacity was added, respectively.
- In 2017, **648 MW** of capacity has been decommissioned worldwide.

Note: Turkey is treated as Europe in these statistics.
Sources: Global Wind Energy Council (2018), "Annual Market Update 2017; A.T. Kearney Energy Transition Institute analysis

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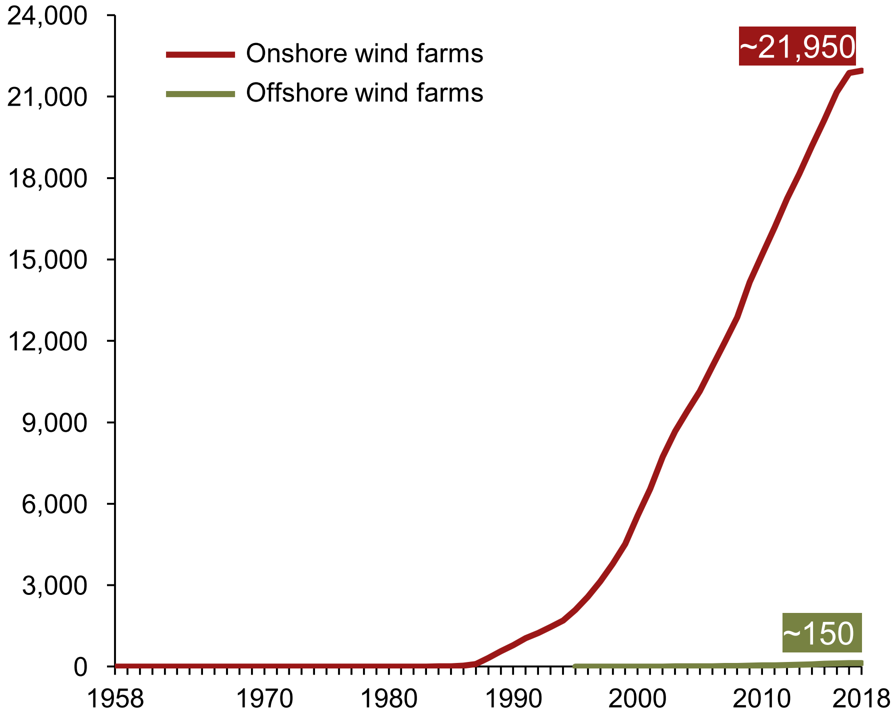
Onshore windfarms development took off in the 90s, while offshore wind is still in its infancy stage

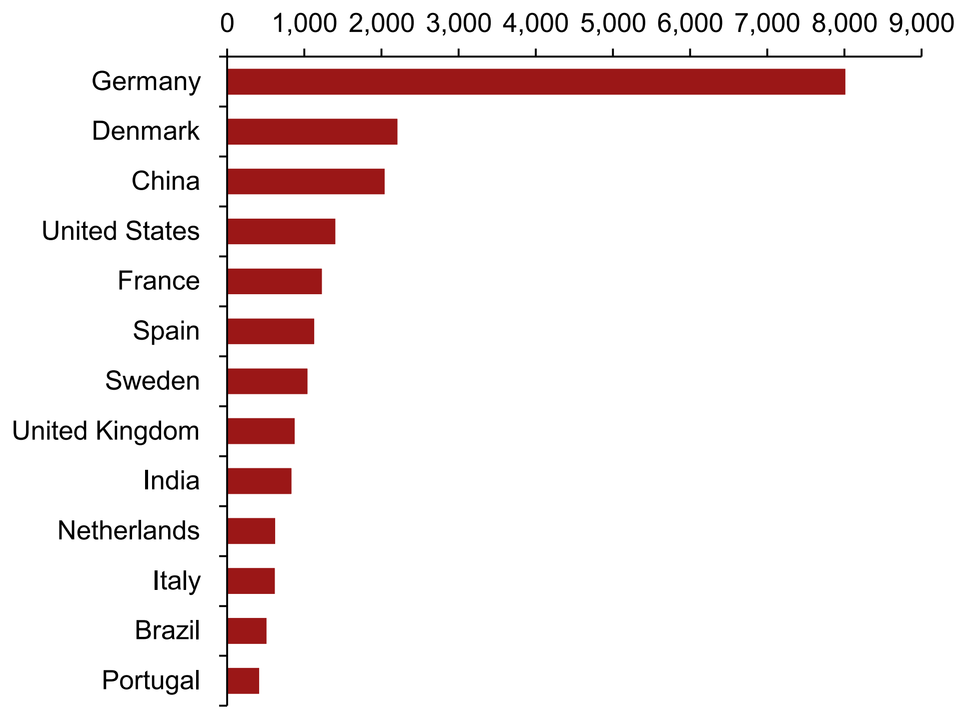
Number of onshore and offshore wind farms

(#, as of July 2018)



Number and location of onshore wind farms[1]

(#, as of July 2018)



1. Average wind farm size varies appreciably on a country to country basis

Sources: The Wind Power (www.windpower.net); A.T. Kearney Energy Transition Institute analysis

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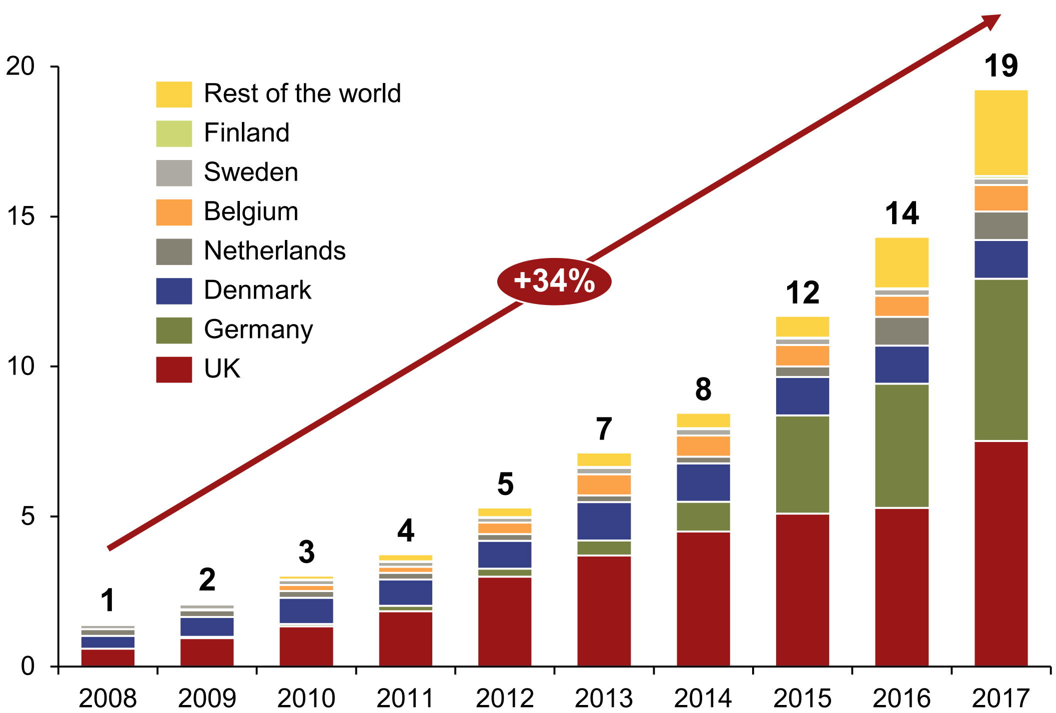
Development of offshore wind installed capacity is accelerating and the UK and Germany are dominating its global market

Global installed offshore wind capacity

GW



- **In 2017, European countries accounted for 85% of the global offshore wind installed capacity,** making offshore wind a relatively concentrated market.
- **The UK and Germany are largely dominating this market, with 67% of global offshore wind capacity in 2017.** Five other European countries – Denmark, the Netherlands, Belgium, Sweden, and Finland – account for 18% of globally installed capacity.
- **The rest of the world only represents 15% of installed capacity, with China representing the largest part (about 13%).** China accounted for almost 35% (in 2016) and 38% (in 2017) of the global capacity additions.
- Since 2008 the offshore wind installed capacity has been growing at a higher rate than the onshore market.

Sources: Irena, “Renewable Capacity Statistics 2018”; A.T. Kearney Energy Transition Institute analysis

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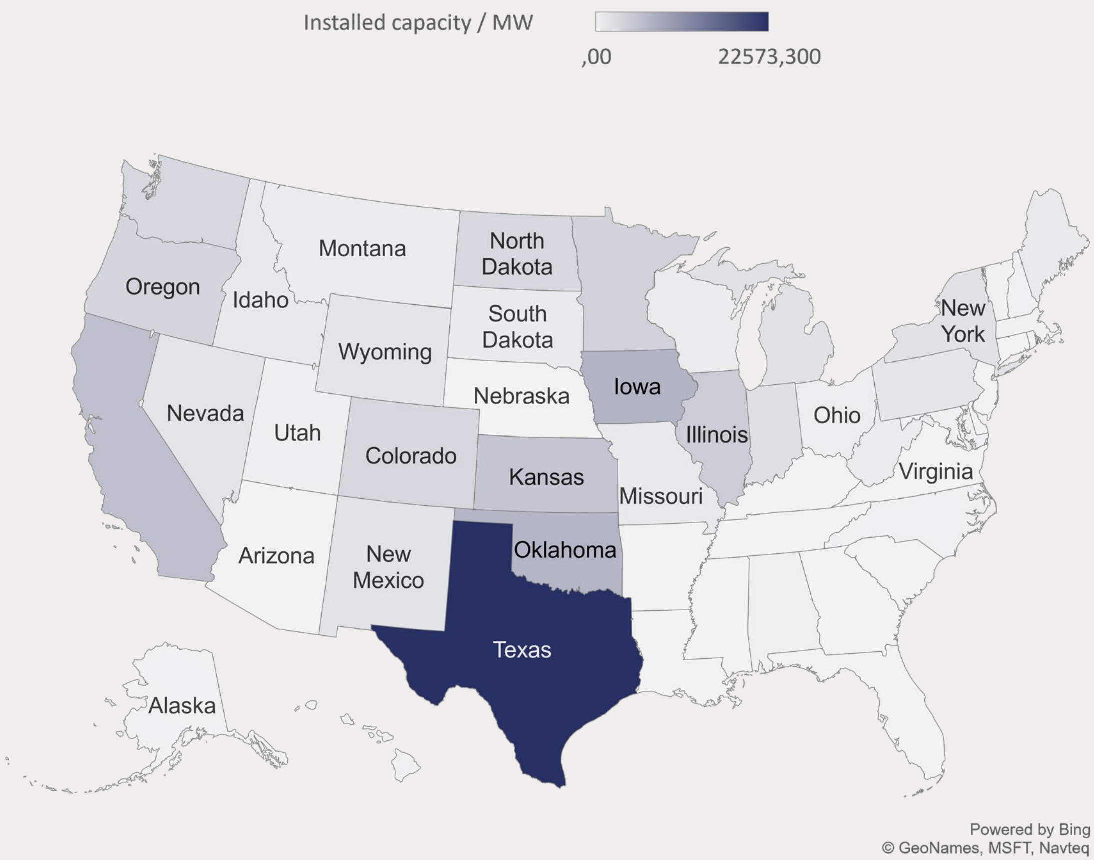
Texas has the largest installed capacity of all states – about one-fourth of the cumulative capacity of the United States

Total installed capacity of US states
(MW)



Why Texas?

- Ranked second-best US state for its wind energy resources (AWEA – onshore).
- The Federal Energy Regulatory Commission has no control over much of Texas (as local grid operator ERCOT has a footprint which falls entirely with-in state borders). This lack of Federal oversight made it easier for ERCOT to build a network of transmission lines to link remote wind sites in West Texas with the more-populated areas of East Texas
- State, county, and local government have no regulatory power over siting, which is left up to the land owner.

Note: Arizona, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, Nebraska, South Carolina, and Virginia have 0 MW capacity.
Sources: https://www.eia.gov/electricity/data/eia860/; A.T. Kearney Energy Transition Institute analysis

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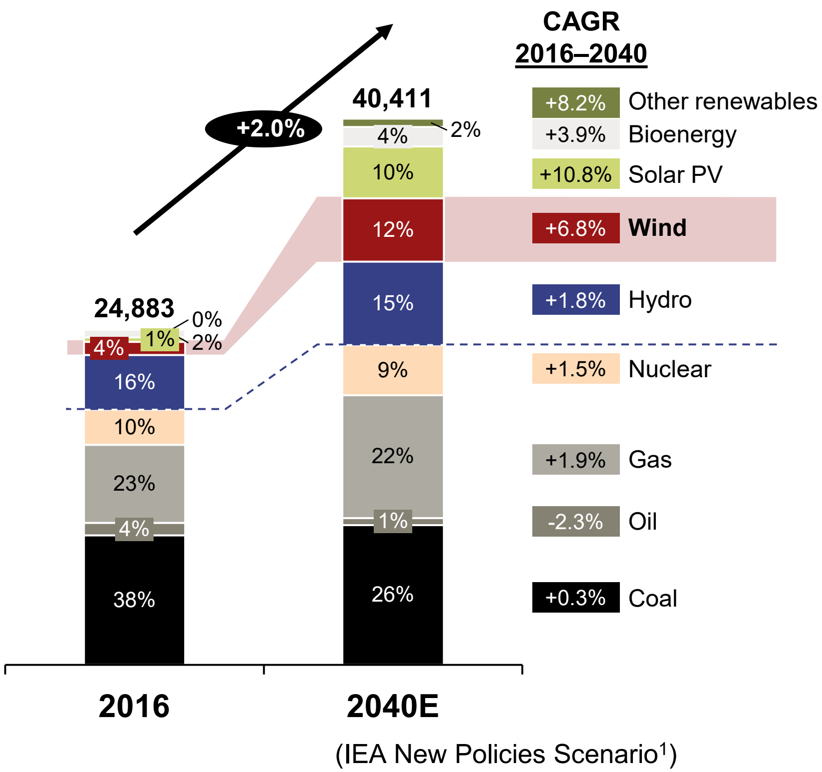
Wind power only produced 4 percent of the global electricity in 2016 but is expected to represent more than 12 percent by 2040

Global electricity generation
TWh, %



- Wind power was the second-largest source of renewable electricity in 2016 behind hydropower and should remain as such at least until 2040 (according to the New Policy Scenario). **Global wind power production should reach 1,085 TWh in 2017**.
- Despite this impressive rate of deployment, **wind supplied just 4% of the world's electricity in 2016**, and accounts for no more than 6.4% of electricity-generation capacity installed globally.
- The strong electrification expected for the coming decades (+2% CAGR) should favor the development of renewable energies. Wind power should benefit from a strong development with an **annual production growth rate around 6.8%** (CAGR).

[1] The New Policies Scenario is IEA's best-case forecast given enacted and proposed government policies as of 2016.
Sources: IEA, "World Energy Outlook 2018"; A.T. Kearney Energy Transition Institute analysis

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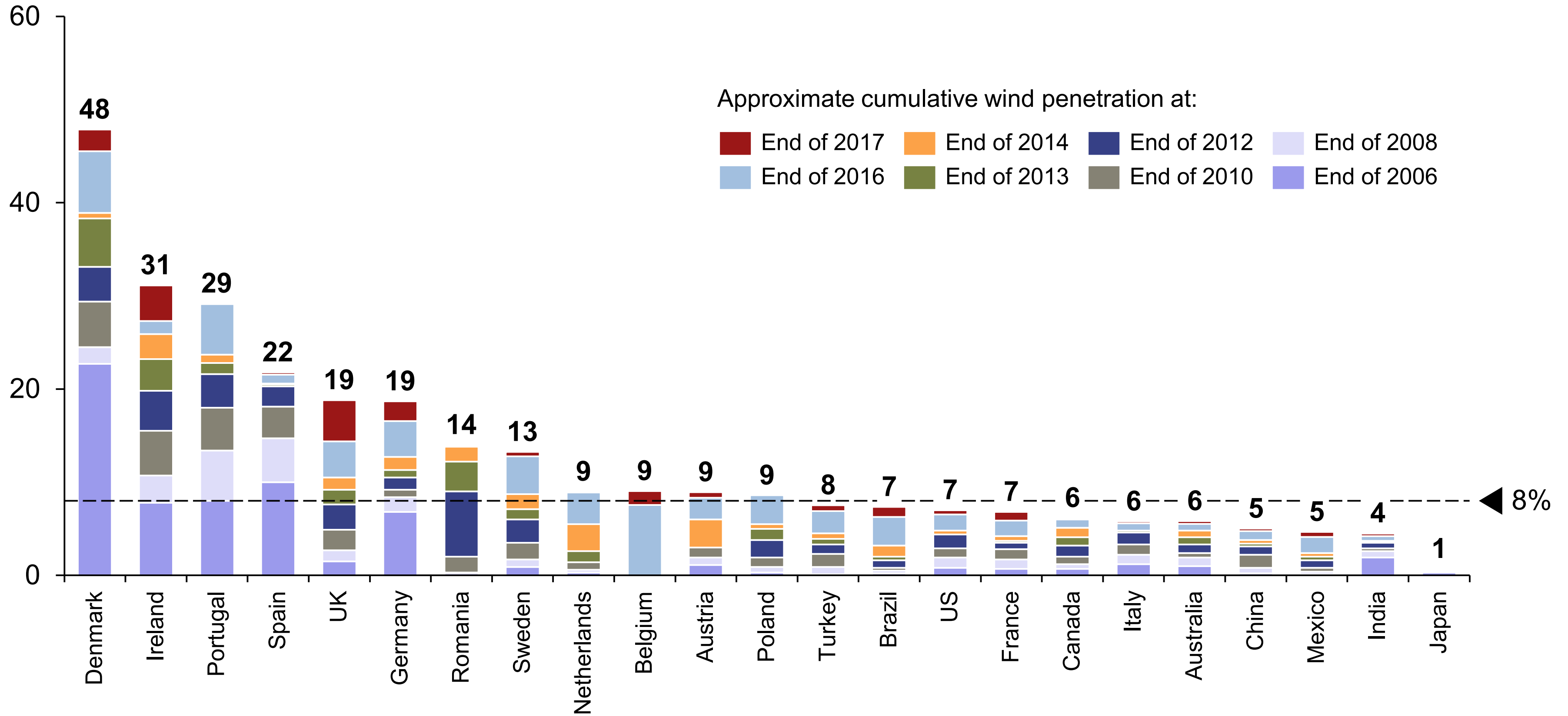
Except in some European countries, wind supplies less than 8 percent of electricity consumed

Annual average wind electricity penetration in top 23 wind countries[1]

2006–2017; % projected wind electricity as a proportion of electricity consumption



[1] Wind penetration corresponds to the share of total electricity consumption supplied by wind power.
Sources: US DoE (2015 and 2018), "2014 Wind Technologies Market Report," "2017 Wind Technology Market Report"; IEA (2013), "Technology Roadmap: Wind Energy – 2013 Edition"; A.T. Kearney Energy Transition Institute analysis

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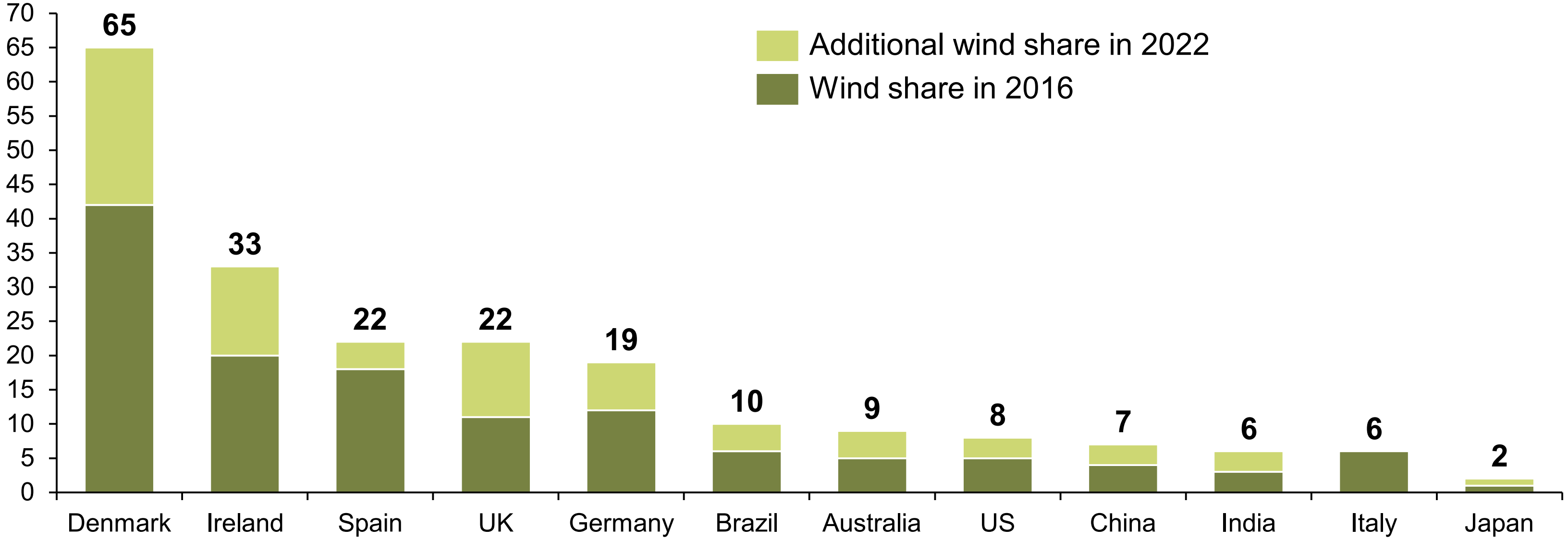
Wind electricity penetration will significantly rise in the next five years which will make system integration issues even more important

Annual average wind electricity penetration in selected countries[1]

2016–2022E; projected wind electricity as a proportion of electricity consumption



- By 2022, Denmark is expected to be the world leader, with **almost 70% of its electricity generation coming from variable renewables (93%from wind)**.
- In some European countries (Ireland, Germany, and the United Kingdom), **the share of total generation represented by wind and solar will exceed 25%.**
- In China, India, and Brazil, **the share of variable generation is expected to double to over 10% in just five years**.

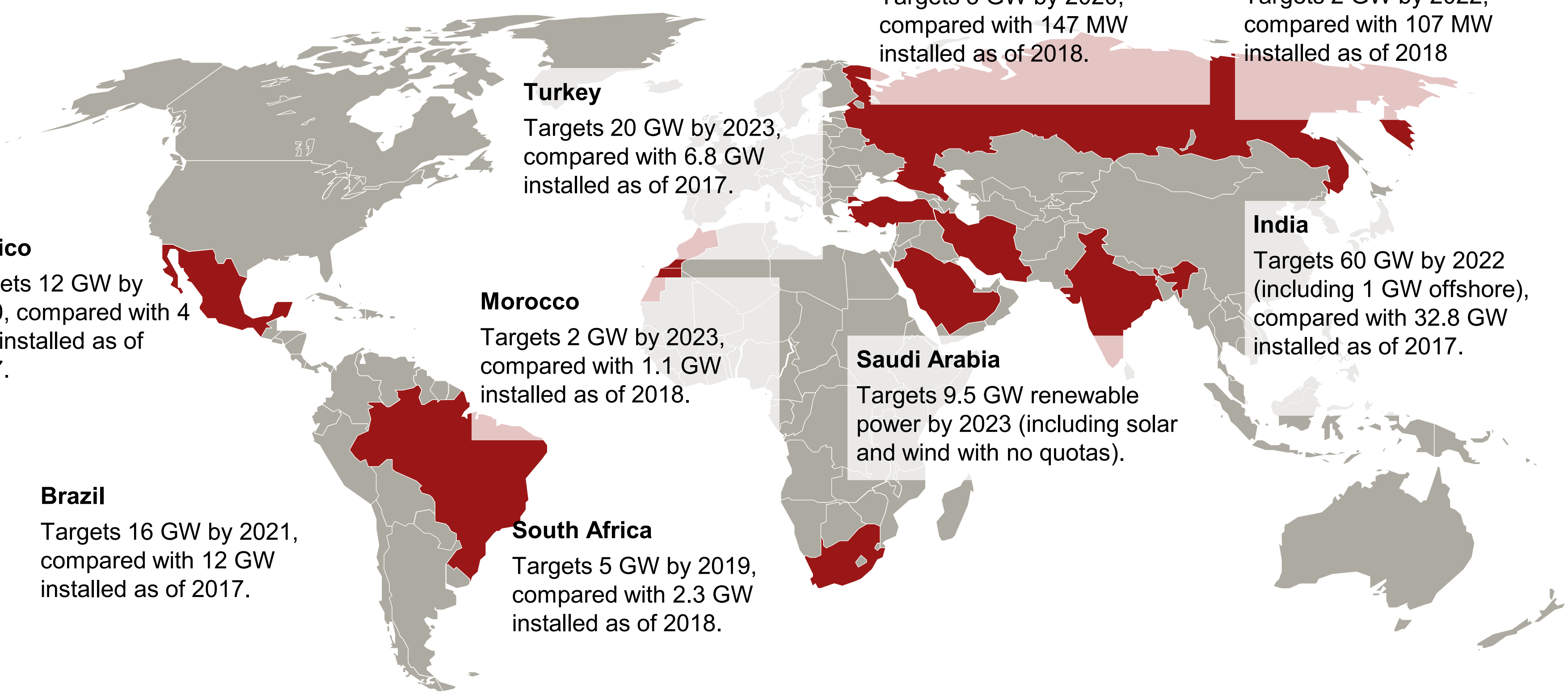
[1] Wind penetration corresponds to the share of total electricity consumption supplied by wind power.
Sources: IEA (2017), "Renewables 2017, Analysis and Forecast 2017-2022"; A.T. Kearney Energy Transition Institute analysis

A.T. Kearney | Energy Transition Institute

Wind power capacity is starting to be deployed outside established markets and could accelerate if announced targets are to be met

Wind power – forecast capacity additions in key emerging markets[1]

GW



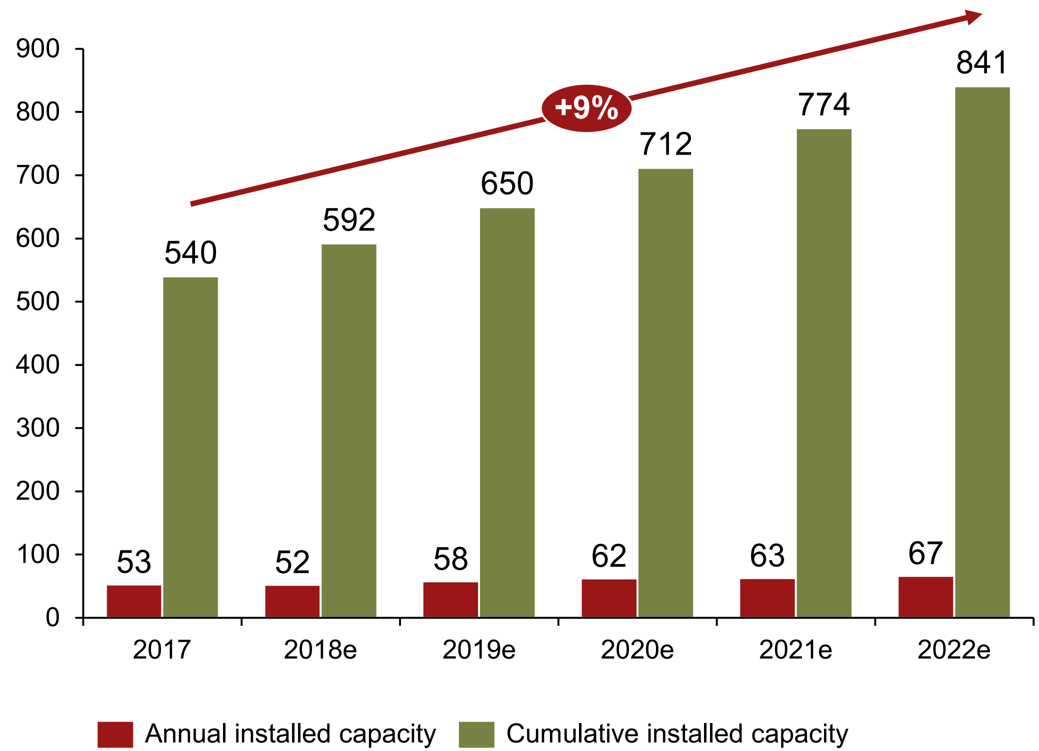
[1] The list is not exhaustive and is for illustrative purpose only.

Sources: A.T. Kearney Energy Transition Institute; Global Wind Energy Council (2018), "Annual Market Update 2017"; Bloomberg (2015), "Turkey Seeks 2,000 Megawatts of Wind Power Earlier Than Planned"; Reegle (link); North American Wind Power (2015), "Mexico Wind Has Bright Horizons, Thanks To Energy Reform"; Renewables International (link), "Russia wind power plans part 1"; Busby (2012), "Wind Power: The Industry Grows Up"; IRENA (2016), "Renewable Energy Market Analysis – The GCC Region" (link); Reuters (2016), "Saudi Arabia targets 9.5 GW of renewable by 2030" (link)

Cumulative installations are expected to reach 840 GW by the end of 2022

Projected global installed wind capacity

GW, cumulative, 2018–2022



- Annual market growth is expected to remain at roughly 2017's level for 2018 due to anticipated decreases in Germany, the UK, and India.
- This will be balanced by increases in North America, the Middle East, Africa, and Latin America. The United States is expected to increase significantly its share in offshore wind development.
- The annual market growth will accelerate in 2019 and 2020 – breaching the 60 GW barrier once again – and continue to grow, albeit at a slower pace, in the beginning of the new decade. We expect to see total cumulative installations reach 840 GW by the end of 2022.

Sources: Global Wind Energy Council (2018), "Annual Market Update 2017", A.T. Kearney Energy Transition Institute analysis

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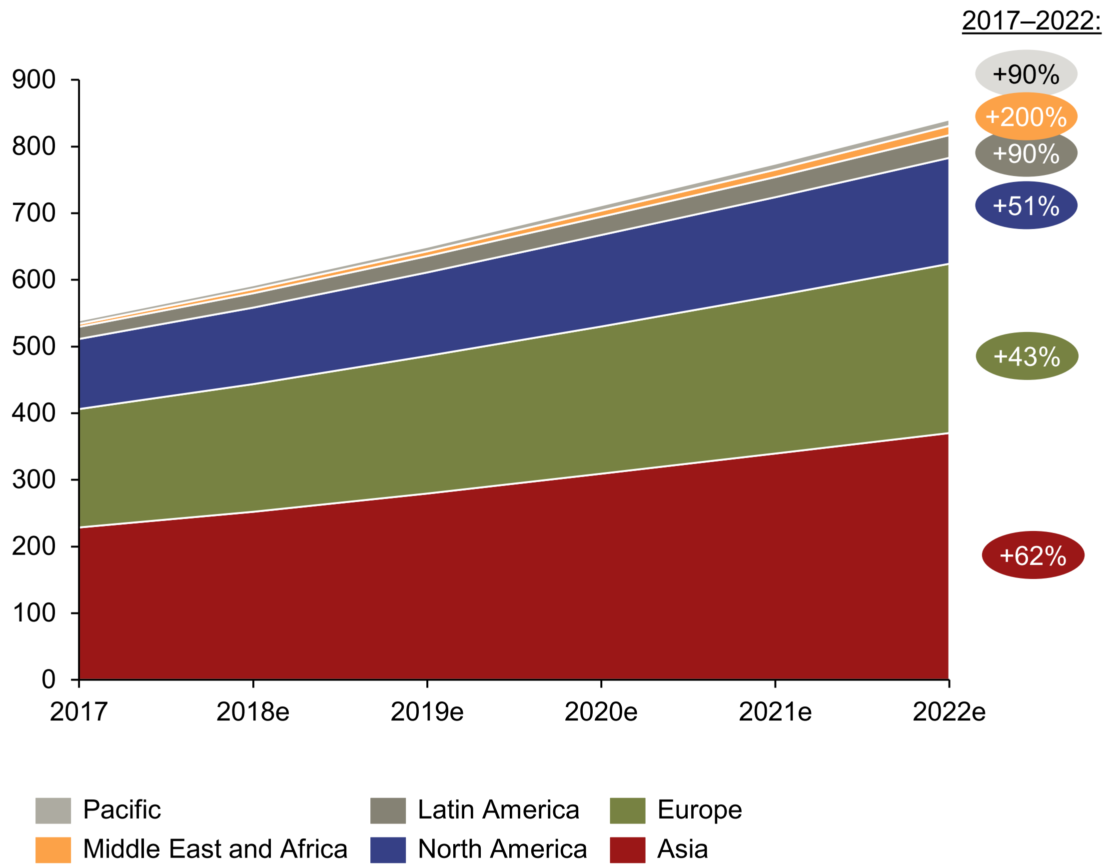
Asia, Europe and North America are likely to remain the main wind markets

Projected installed wind capacities by regions

GW, cumulative, 2017–2022



- **Asia is expected to be leader in wind development in the coming five years,** with 140 GW of capacity additions.
- **North America is expected to grow faster than Europe** -driven by new commissioning of onshore wind parks in the US. In Europe, growth is expected to remain strong, based on projects under construction.
- **Wind capacity in the rest of the world remains negligible in absolute terms,** with forecast installed capacity by 2022 of 58 GW – 8.7% of global wind capacity. However, countries outside North America, Europe, and Asia are increasing their share faster than expected, as a result of growth in emerging wind markets such as Iran, Turkey, and Brazil.

Sources: Global Wind Energy Council (2018), "Annual Market Update 2017"; A.T. Kearney Energy Transition Institute analysis

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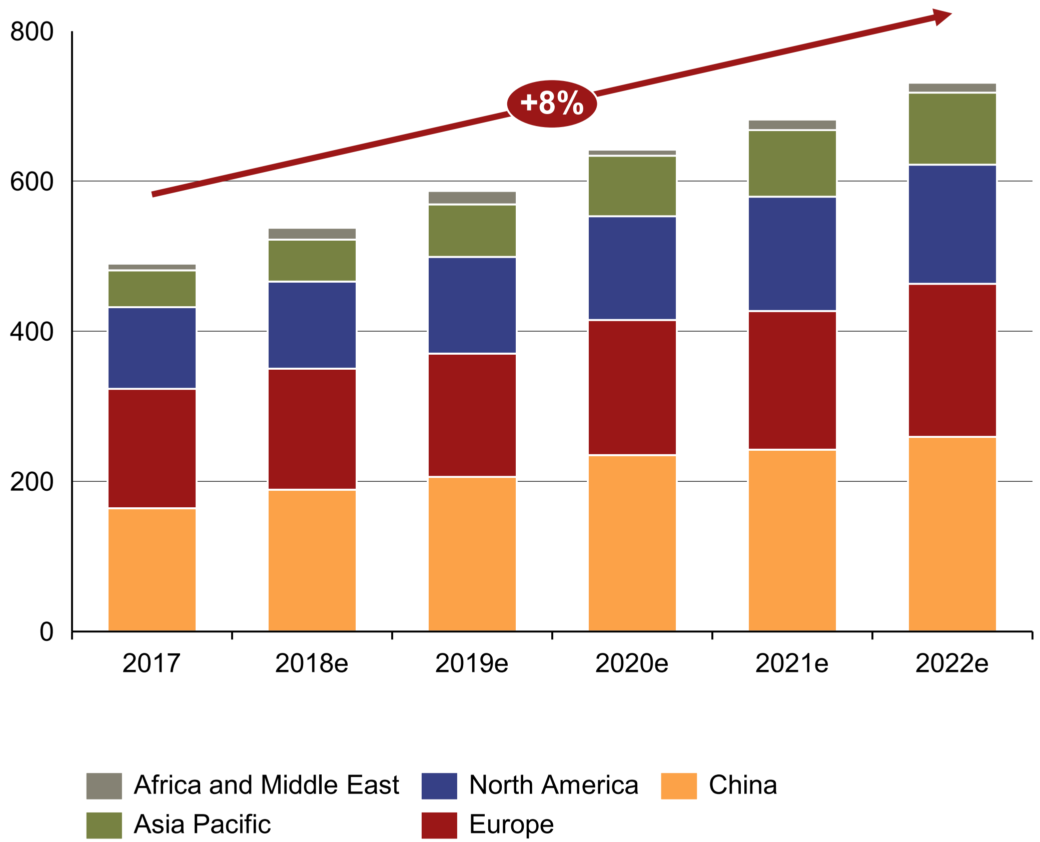
Onshore wind electricity capacity is expected to grow at 8 percent per year until 2022

Projected onshore wind cumulative capacity by region

GW, 2017–2022



- Onshore wind is a proven, mature technology with an extensive global supply chain. Onshore wind turbines are constantly becoming bigger with taller hub heights and larger rotor diameters.
- In 2017, cumulative grid-connected wind capacity reached **540 GW** (521 GW onshore wind and 19 GW offshore wind) and wind power accounted for 4%of global electricity generation.
- Onshore wind capacity is expected to grow by **295 GW** in the next five years and reach almost **750 GW** by 2022 in the main case of the IEA's *Renewables 2017* forecast.
- China leads this growth followed by the United States, Europe, and India. As a result, onshore wind electricity generation would increase by **80%globally** between 2017 and 2022.
- Onshore wind generation is expected to exceed **1500 TWh** per year by 2021 and reach almost **1650 TWh** the following year.

Sources: IEA (2017), "Renewables 2017, Analysis and Forecast 2017–2022"; A.T. Kearney Energy Transition Institute analysis

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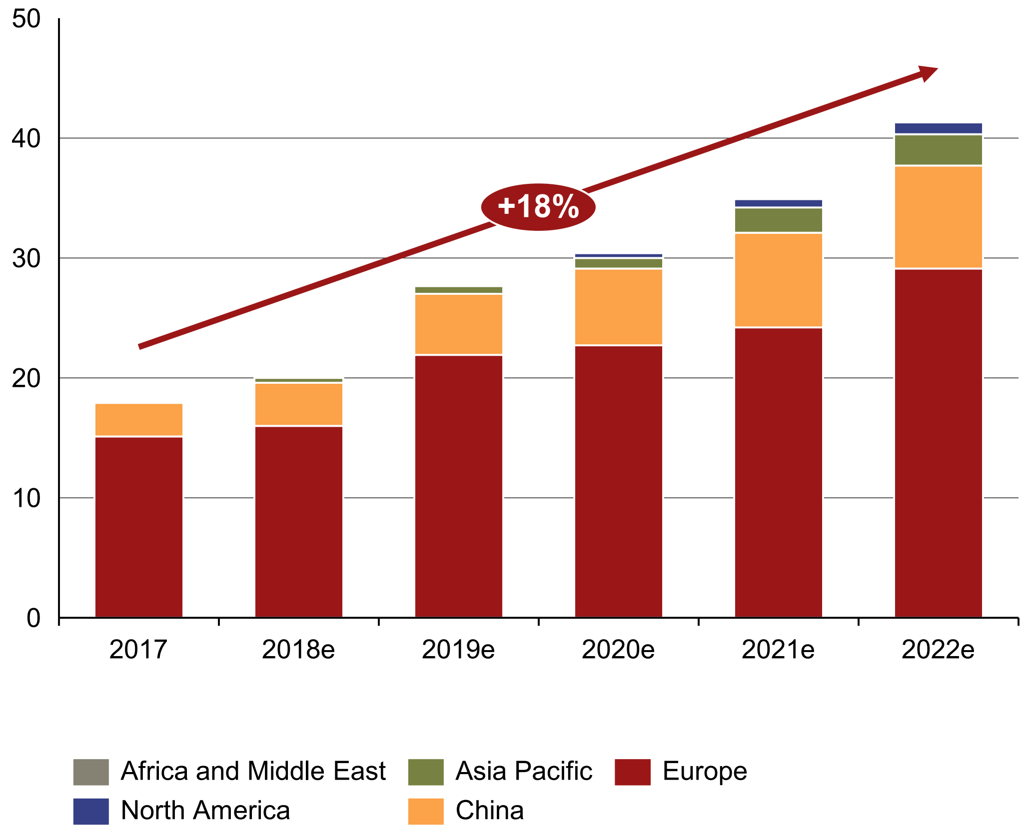
Driven by a predominantly European market, offshore wind capacity is expected to grow at 18 percent annual growth rate until 2022

Projected offshore wind cumulative capacity by region

GW, 2017–2022



- Offshore wind is also expected to grow rapidly. Deploying turbines in the sea takes advantage of better wind resources than at land-based sites and in some geographies (such as US), avoids building expensive infrastructure through densely populated load centers
- Therefore, new offshore turbines are able to achieve significantly more full-load hours, **ranging from 40-55%** depending on resource availability.
- In 2017, global offshore wind generation reached an estimated **55 TWh**, 12% higher than in 2016.
- By 2022, global offshore wind cumulative capacity is expected to reach **41 GW** by 2022, up from 19 GW in 2017. Deployment will be led by the European Union and China. Enhanced policies and faster deployment of projects in the pipeline could result in a further 7 GW.
- In 2021, global wind offshore generation is expected to pass **100 TWh per year** and continue to grow at a steady pace.

Sources: IEA (2017), "Renewables 2017, Analysis and Forecast 2017–2022"; A.T. Kearney Energy Transition Institute analysis

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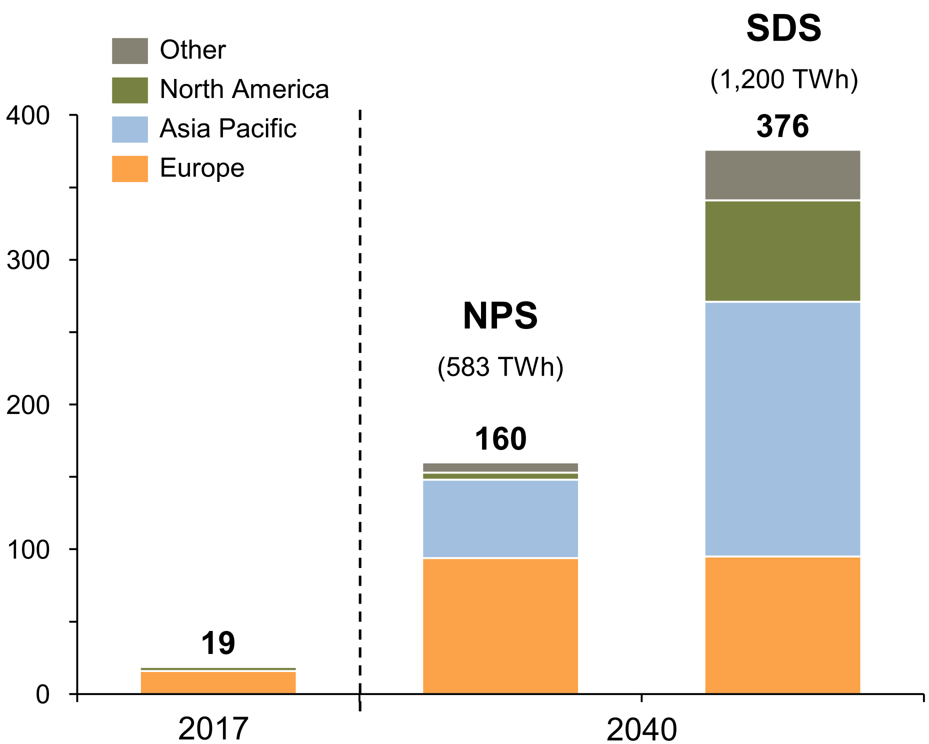
The highest offshore wind penetration rate is expected in the EU – 10–12 percent depending on scenario

Global offshore electricity capacity in the NPS and SDS[1,2]

GW



- In the **New Policies Scenario**, offshore wind capacity growth is dominated by Europe, which accounts for close to 60% of total global additions with 94 GW by 2040. Overall, installed offshore wind capacity grows to around 160 GW in the New Policies Scenario, generating **583 TWh** by 2040. Global offshore wind penetration is 1.5 percent.
- Offshore electricity production in the **Sustainable Development Scenario** gets a major boost as worldwide installed offshore wind capacity rises above **350 GW** in 2040, more than double the level in the New Policies Scenario, and generation increases to **1,200 TWh**. In total, countries in Asia Pacific install almost 180 GW of offshore wind by 2040, compared with less than 60 GW in the New Policies Scenario. However, capacity remains flat in EU in both the scenarios.

Notes: NPS is New Policies Scenario; SDS is Sustainable Development Scenario.
[1] IEA NPS: "In addition to incorporating policies and measures that governments around the world have already put in place, it also takes into account the effects of announced policies, as expressed in official targets and plans (for example, NDC targets, Paris agreement).
[2] IEA SDS: The SDS "builds on the Sustainable Development Goals (SDGs) of the United Nations and aims to provide an energy sector pathway that integrates three closely associated but distinct policy objectives: to ensure universal access to affordable, reliable and modern energy services by 2030 (SDG 7.1); to substantially reduce the air pollution which causes deaths and illness (SDG 3.9); and to take effective action to combat climate change (SDG 13).
Sources: Global Wind Energy Council (2018), "Annual Market Update 2017" (2017 data); IEA (2018), Special Report – Offshore Energy Outlook WEO 2017; A.T. Kearney Energy Transition Institute analysis

3. Research, development and demonstration

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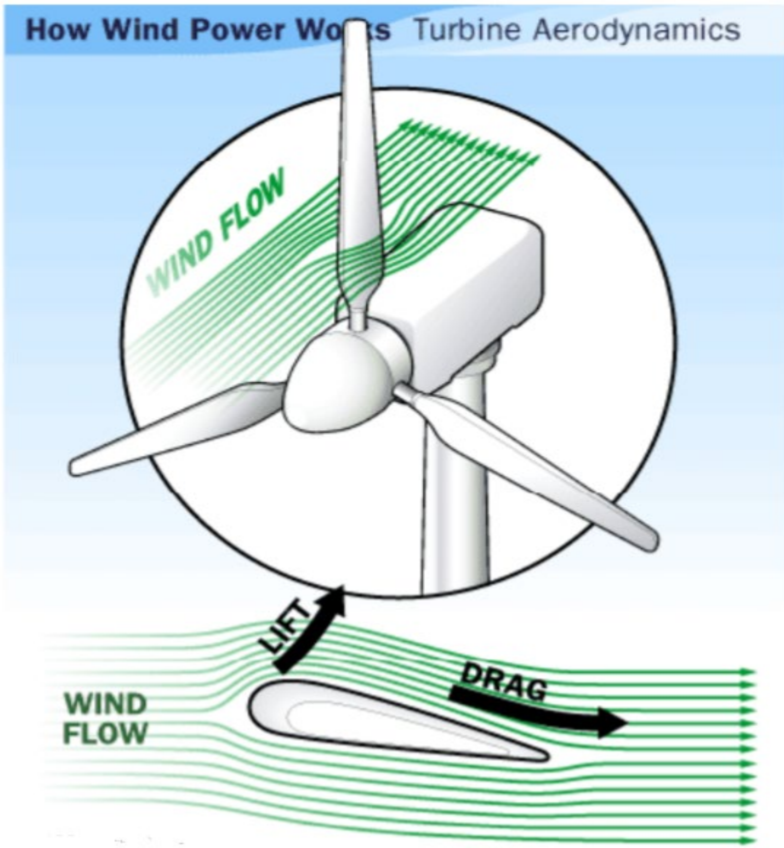
A popular misconception is to consider wind energy as a mature technology where R&D efforts are not necessarily needed

Basic forces acting on a wind turbine



- The concept of a wind-driven rotor is ancient. Nevertheless, making wind turbines is not a simple task. As technology matures, resulting issues require more advanced approaches and solutions.
- Turbine rotors are affected by two different forces: **torque**, which turns the rotors and creates energy, and **thrust**, which pushes against the turbine. Dealing with thrust can be difficult when designing a rotor.
- The energy available to be captured by the turbine blades is proportional (squared relationship) to the **rotor diameter** and proportional (cubic relationship) to the **wind speed**.
- Hence, by definition, longer blades together with higher wind velocity improve **efficiency** and **performance**.
- Wind R&D has **two** main areas:
    - Wind resource assessment and speed forecasting
    - Wind turbine scaling

Picture credit: 2018 HowStuffWorks
Source: A.T. Kearney Energy Transition Institute

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Wind R,D&D aims to maximize energy captured, minimize the cost per unit of capacity, and meet network requirements

Main wind energy improvement levers

1	**Maximize energy capture**	• **Increase capacity (load) factor** • Increase efficiency of wind turbines • Access better wind resources • Exploit lower-quality wind resource sites
2	**Minimize LCOE** (Leverage Cost of Electricity) **through various factors**	• **Reduce initial investment cost** • Reduce operation and maintenance • Increase lifetime
3	**Meet network requirements**	• Contribute to system stability • Contribute to voltage control • **Enhance predictability**

- Wind turbines must meet **specific technical requirements** (voltage, frequency) where each unit will be a stable operating input in the power system, deal with **variability of the wind,** and **compete economically** with other power technology solutions.
- Development of techniques for precise assessment of wind power potential at a site is becoming increasingly important. For instance, wind speed increases with height above ground so taller towers increase available energy.
- On the other hand, as rotor diameters increase, new issues emerge since wind may behave completely different at various elevations. This property of wind is called **wind shear**. Often, increases in scaling bring increases in design costs as well.
- Hence, there are lot of challenges facing the R&D sector.

Note: R,D&D is research, development, and demonstration.
Source: A.T. Kearney Energy Transition Institute based on Global Wind Energy Council (2012)

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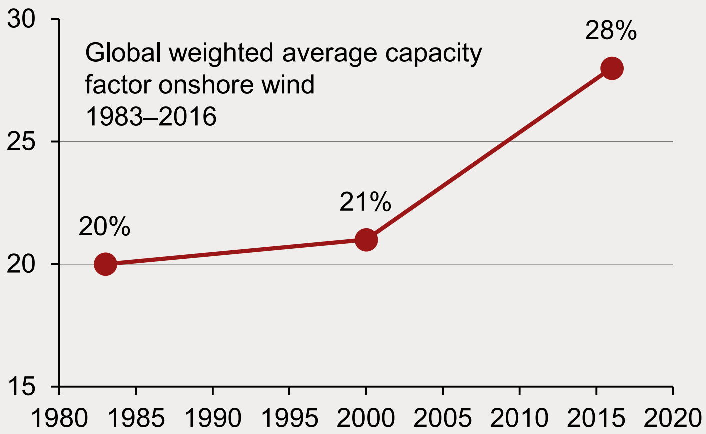
Both onshore and offshore wind technologies are seeking to achieve similar objectives

1) Increase capacity factor



- Main mechanism through which turbine manufacturers can increase capacity factors is by increasing **blade lengths** while keeping the same nominal power of wind turbine.
- **Increasing efficiency and capacity factor** of wind turbines implies increasing efficiency of blades which again implies increasing fluid dynamic efficiency across a range of wind speeds.
- 3D computer modelling is used to simulate real conditions in order to find more **optimal design solutions** and increase **capacity factors**.
- In Brazil, capacity factor of new onshore plant build in **2016 exceeded 45%**. Capacity factor of offshore 12 MW wind turbine is expected to reach **63% in 2021**.

2) **Reduce costs** (production, operation, and maintenance)

- Uncertainties remain regarding the future cost of **raw materials** such as **steel** and **copper,** whose prices, due to high demand, are increasing.
- In order to further decrease wind turbine costs, the R&D sector has to work on finding alternatives and cheaper solutions together with optimizing **operational services** and **component supply (including transportation)**.
- Furthermore, R&D has traditional issues to resolve such as:
  - Fatigue
  - Reliability

3) Address power network requirements

- Voltage control, production predictability, and stability are essential to the integration to the power network.
- Coupling wind and **battery storage** can provide an efficient solution to address power network requirements. The battery helps **maximize utilization** of power produced by wind turbines and contributes to **stabilization** of the system.
- Such a solution potentially brings:
  - Ramp control
  - Predictable power
  - Frequency regulation
  - Safety
  - Environmental Impact

Sources: IRENA 2018, *Renewable Power Generation Costs in 2017*; A.T. Kearney Energy Transition Institute

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A broad set of R,D&D research topics address the various wind power improvement levers

R&D research topics in wind energy

		1 Maximizing energy capture	2 Minimizing cost per unit of capacity	3 Meeting network requirements
Wind conditions	• Improve the understanding of wakes inside wind farms • Offshore meteorology • Extreme wind speeds (resistance to extreme conditions) • Investigate and model the behavior of wind profiles above 100m • Siting of wind turbines in complex terrain and forested areas • Short-term forecasting	✓		
Wind turbine technology	• The wind turbine as: a flow device (larger rotor diameter) • .. a mechanical structure (lighter rotor and hub) • .. an electricity plant • .. a control system (pitch system) • Innovative concepts and integration • Operation and maintenance strategies • Developing standards for wind turbine design	✓	✓	
Wind turbine integration	• Wind power plant capabilities (improved computational tools) • Grid planning and operation • Energy and power management (pitch control, power converter...)	✓		✓
Offshore deployment and operations	• Sub-structures, floating wind • Assembly, installation, and decommissioning • Electrical infrastructure, offshore balance of plant • Larger turbines • Operations and maintenance	✓	✓	✓

Source: A.T. Kearney Energy institute based on: European Wind Energy Council (EWEA), *Wind Energy – The Facts*;

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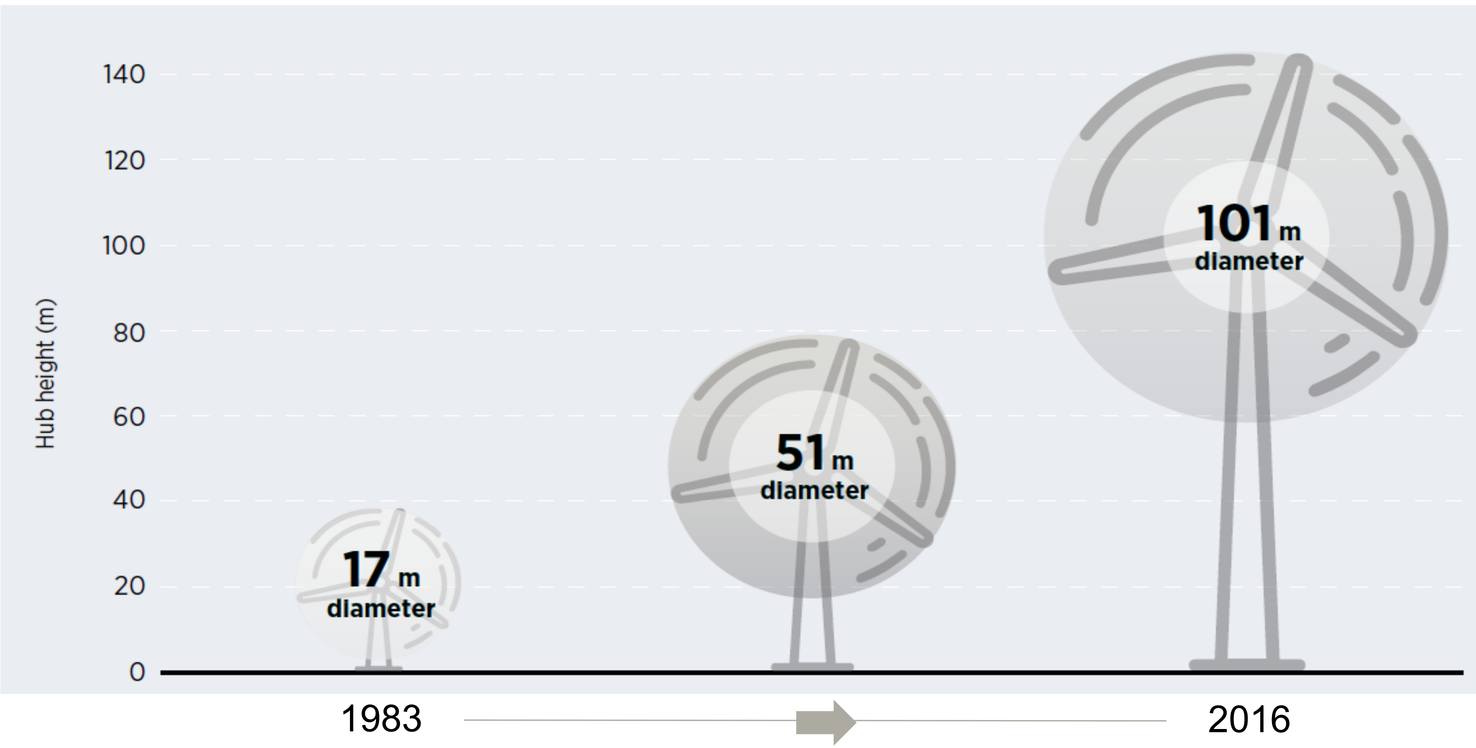
Hubs and rotors of wind turbines are increasingly evolving in height and diameter

Global weighted average hub height and rotor diameter

Onshore wind, 1983–2016



- The energy available to be captured by turbine blades is **proportional** (squared relationship) to the **rotor diameter.** Today, even turbines with smaller nominal power capacity are built with **longer blades** in order to increase overall **capacity factor**.

Sources: IRENA 2018, *Renewable Power Generation Costs in 2017;* A.T. Kearney Energy Transition Institute analysis

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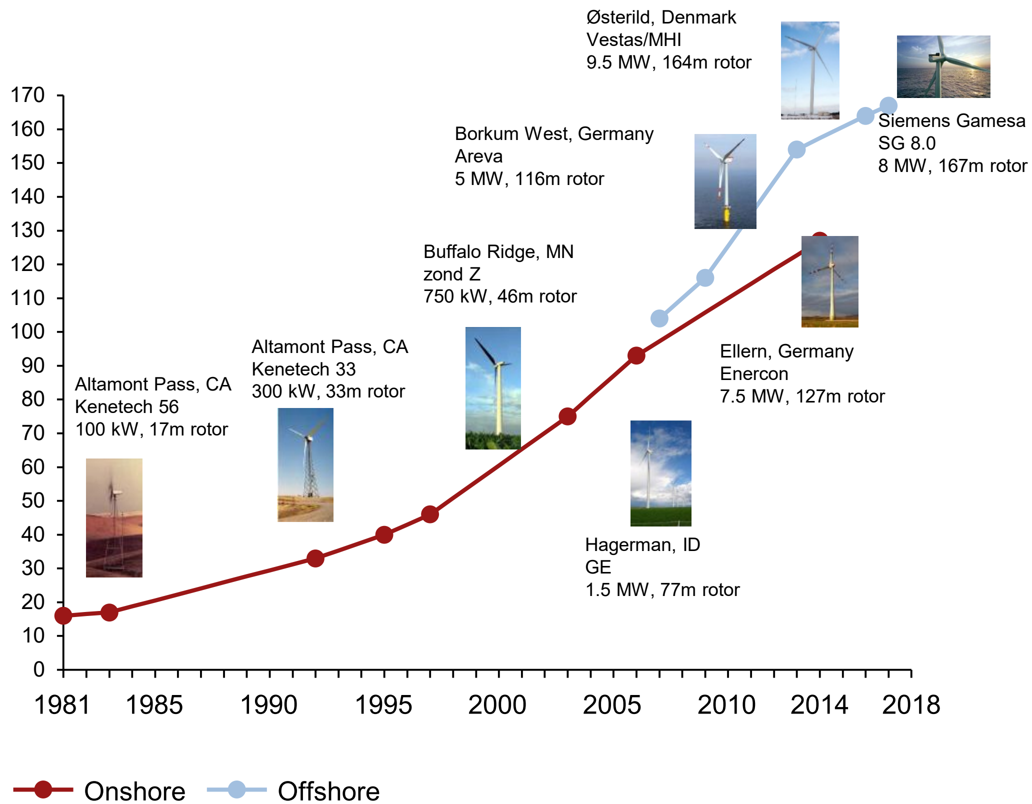
Developing larger and taller turbines remains a major focus of R,D&D and is increasingly being driven by the greater scope for size offshore

Evolution of wind turbine rotors (diameter)

Rotor size in meters in the most advanced turbines[1]



- **The market is dominated by 1.5-3 MW turbines.** However, in the offshore segment, companies are racing to develop very large offshore turbines.
- **Offshore economics requires larger turbines** to (i) limit the proportionally higher costs of infrastructure (for example, building foundations); and (ii) lower the number of units per kW of installed capacity in order to facilitate access and maintenance.
- **The leveling-off in onshore turbine size is due to road-access constraints, and public acceptance** of noise and visual disturbance. In addition, in some cases, larger turbines and taller towers increase the investment cost to an extent that is not balanced by higher capacity factor, hence not reducing the levelized cost of electricity.

[1] This graphic shows prototypical "larger-than-average" turbines created at different stages of the period shown and does not depict growth in average turbine size.
Sources: A.T. Kearney Energy Transition Institute analysis based on US DoE (2015), “2014 Wind Technologies Market Report”; IPCC (2011), “Special report on renewable energy, 2011”; Global Wind Energy Council (2018), “Global Wind Report 2017

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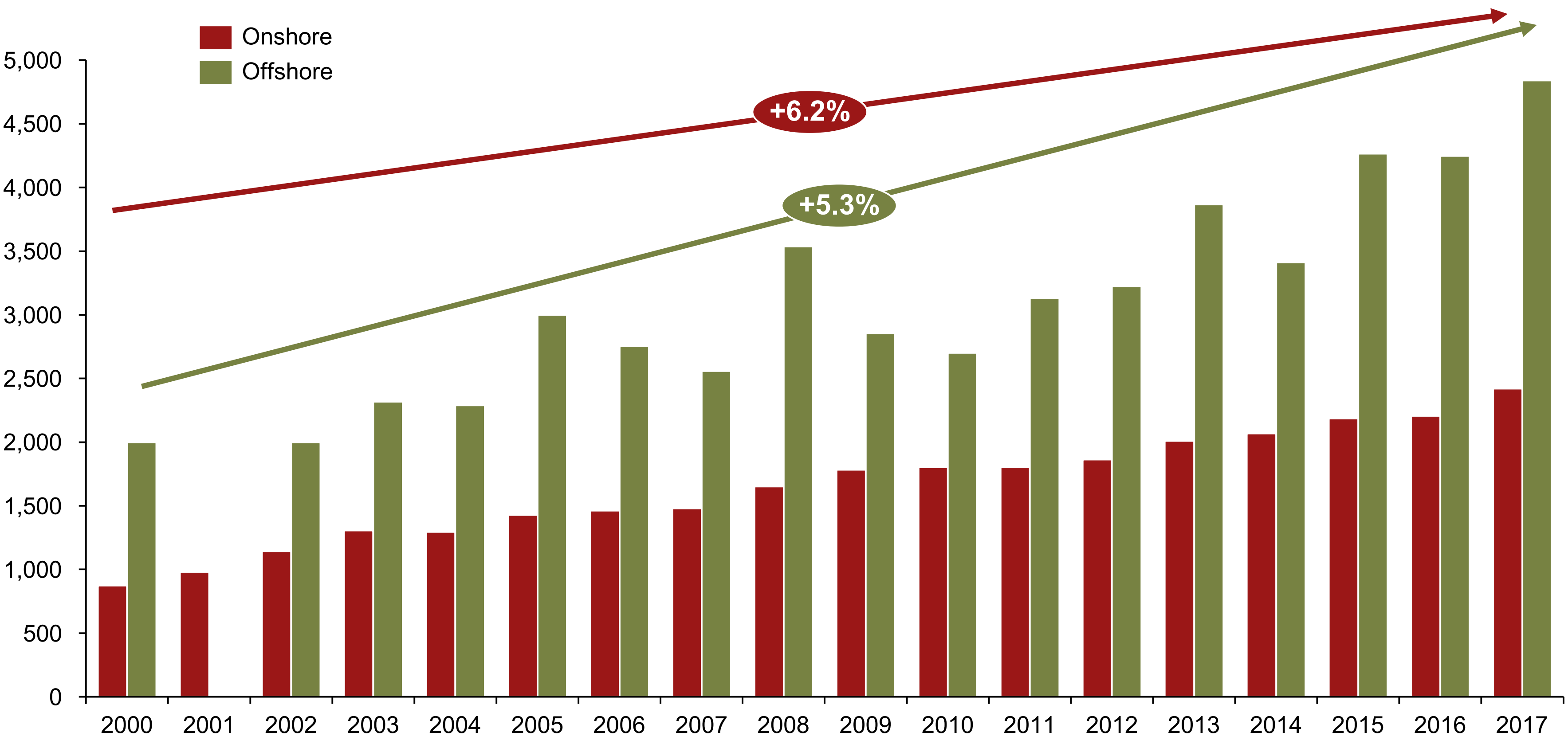
Wind turbine capacity is constantly growing, and offshore units have twice the capacity of onshore turbines

Average turbine capacity used on new projects worldwide
(Kw)



Note: No data for 2001 offshore projects.
Sources: https://www.thewindpower.net; A.T. Kearney Energy Transition Institute

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Unconventional wind turbine designs arouse curiosity, although there is no large-scale pilot plant at this stage

Multirotor and Airborne structure wind energy (AWE) systems[1]

Multirotor concept

Mutirotor concept (pilot) developed by Vestas and Technical University of Denmark, aiming at reducing LCOE

Airborne structure

Heavier than air

- Soft/flexible wing
- Rigid wing

Lighter than air

- Buoyant

Generation system

On ground
Generator stays on ground where an unrolling tether drives a rotating drum

- Soft/flexible wing:

Pumping mode (also known as Yo-Yo mode) with a reel-out phase generating electricity and a reel-in phase (retraction)
(for example, KitePower)

- Rigid wing:

The reel-out phase consists of fast loops, while the reel-in relies on the wing facing the station for minimal tensions
(for example, Ampyx Power)

- Buoyant:

The helium-filled cylinder exploits the Magnus effect during reel-out, and stops rotating when pulled back (reel-in)
(for example, Omnidea)

On board
Generator is mounted on the turbine, which is held by a strong conducting tether

- Soft/flexible wing: No design available

- Rigid wing:

Electrical generator is part of an airplane with one or multiple turbines conducting electricity through the tether
(for example, Makani)

- Buoyant:

The helium-filled balloon is a large rotating drum generating electricity, transmitted back with the conducting tether
(for example, M.A.R.S)

- Unlike in conventional turbine design, where the three-bladed horizontal-axis system predominates, no unconventional system has yet taken the lead. Multiple designs, using different aerodynamic principles (lift, drag, Magnus…), co-exist and are still under development.[2]

[1] In some designs, it may be possible to develop multiple wing systems. The list is not exhaustive and aims to illustrate the classification of airborne structures.
[2] Other unconventional turbines (non-airborne) are under development. These include bladeless designs, which work using resonance frequency.
Sources: A.T. Kearney Energy Transition Institute; Diehl (2013), "Airborne Wind Energy: Basic Concepts and Physical Foundations"; Picture credit to yespolitical (link), awec (link), omnidea (link), European energy review (link), domsweb (link), Vestas (link)

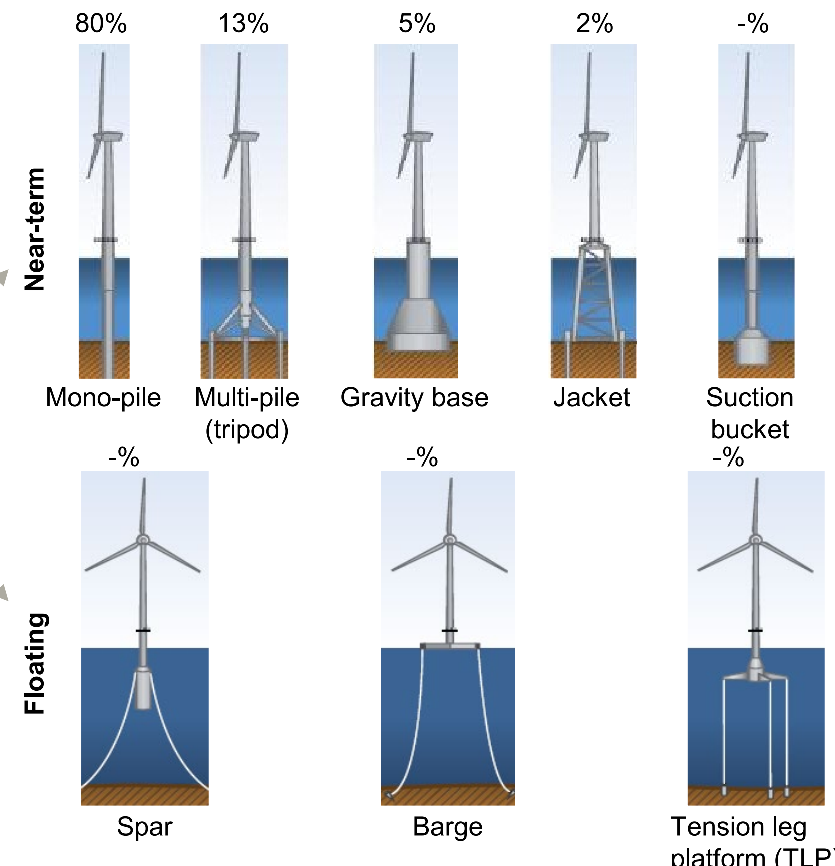
R,D&D in offshore wind is required to optimize high up-front investment, ease maintenance, and improve reliability

Offshore main focus of R,D&D

Group	Focus of R,D&D
Resources assessment	• Wind: the goal is to catch high wind speeds and simultaneously minimize wake losses[1] • Marine conditions: ice, waves, storm prediction
Maintenance	• Favor reliable components to minimize maintenance • Foster remote control and preventive maintenance
Foundations	• New substructure beyond mono-pile and gravity-based (idem) • Floating turbine (avoid heavy foundations and move further offshore)
Logistics	• Purpose-built vessels for installation and maintenance • Compatible harbor installations
Turbines	• Stronger structure to resist harsh marine conditions • Affordable materials with higher strength-to-mass ratios • New blades (for example, carbon fiber, titanium…)

Foundation designs

Global offshore wind substructure market share in 2016 (%)



[1] The wind behind the turbine, in its wake, is less effective at generating energy for a certain distance in the downwind direction due to turbulence created by the upwind machine. Wake losses often account for a large share of overall energy losses and are among the most difficult problems to manage after a turbine is installed.

Sources: A.T. Kearney Energy Transition Institute; Global Wind Energy Council (2012); IEA (2013), "Wind Energy Roadmap 2013"; US DOE, "2016 Offshore Wind Technologies Market Report"

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Resource assessment, control systems, and energy storage are at the forefront of R,D&D to ease integration

Areas of R,D&D for wind integration into the power grid

Mitigate intermittency and variability

Control system

- Originally, controllers had simple sequential control tasks to perform: start-up, controlled shutdown, and the monitoring of temperatures
- More advanced control could reduce the mechanical loads on the turbine and thereby allow mass to be reduced (new algorithms and the implementation of sensors on components) and limit outages/maintenance
- Active power control for turbines would allow them to actively support the grid (for example, frequency regulation)

Resources assessment and forecast

- Resource assessment is crucial to identifying the most suitable locations and developing appropriate technology (offshore is easier as it has a lesser topographical effect)
- Wind prediction models are also an important system for enabling further penetration of wind and reducing forecast error range

Energy storage

- The addition of energy storage could help mitigate the intermittency of wind, helping its penetration grow
- Battery storage and hydrogen production are being investigated (for example, the Utsira Wind and Hydrogen project in Norway)

Note: R,D&D is research, development, and demonstration.
Sources: Chatham House (2011), “Patent Landscapes of Individual Energy Sectors”; A.T. Kearney Energy Transition Institute analysis

With wind turbine size and power quality requirements increasing, there has been a significant trend toward innovative transmission systems

Drive train technology comparison

– Reliability / Investment cost (including rare earth content) +

	High-speed geared system	Low- and medium-speed geared system	Direct-drive system
Stage	Dominant system (~80% market share)	Few turbines installed (mainly Vestas and Areva)	~20% market share (mainly Enercon & Goldwind)
Concept	• Multiple-speed gearbox allows the use of a small generator and reduces initial investment costs. • Complexity and the number of moving parts are likely to create reliability problems and lead to higher maintenance costs.	• Hybrid systems are being developed to combine the reliability of direct-drive systems and the compact size of high-speed geared systems. • A trade-off in costs arises from the choice of the number of speeds, which, on the one hand, affects the complexity of the gearbox and, on the other hand, determines the size, cost, and rare-earth requirements of the generator.	• Direct drive eliminates the need for a gearbox: the generator rotates at the same speed as the rotor. • This increases the reliability of the turbine and is more efficient at low loads. However, it requires a bigger generator and induces higher capital costs, especially with a PMG.
Generator	• First coupled with doubly-fed induction generator, which only requires a small converter, but there is growing use of permanent magnet generators (PMG) to increase efficiency at low loads and to reduce nacelle mass.	• Mainly coupled with PMG, this system minimizes rare earth material requirements, especially in medium-speed designs (greater gearbox complexity allows use of smaller and cheaper generators).	• First developed with classic synchronous generators, direct drive is now using PMGs to increase low-load efficiency. However, it raises a major cost issue due to the rare earth content of the magnet and its quantities needed in large generators.

- **Variable wind power generates electrical energy of varying frequency according to the rotational speed of the rotor.** It is then converted by electronic devices to the frequency of the grid by the transmission system.
- **Several new technologies seek to offer the best mix of capital costs, maintenance requirements, power quality, and efficiency.** The main trade-off is between the use and complexity of the gearbox, and the size of the generator and its associated costs.
- The use of PMGs instead of coils is another important trend.
- Offshore is likely to favor reliability in order to minimize maintenance requirements.

Sources: The Switch (2014), “PMG vs. DFIG – the big generator technology debate” (link); American Superconductor (2009), “Direct Drive Generators” (link); A.T. Kearney Energy Transition Institute analysis

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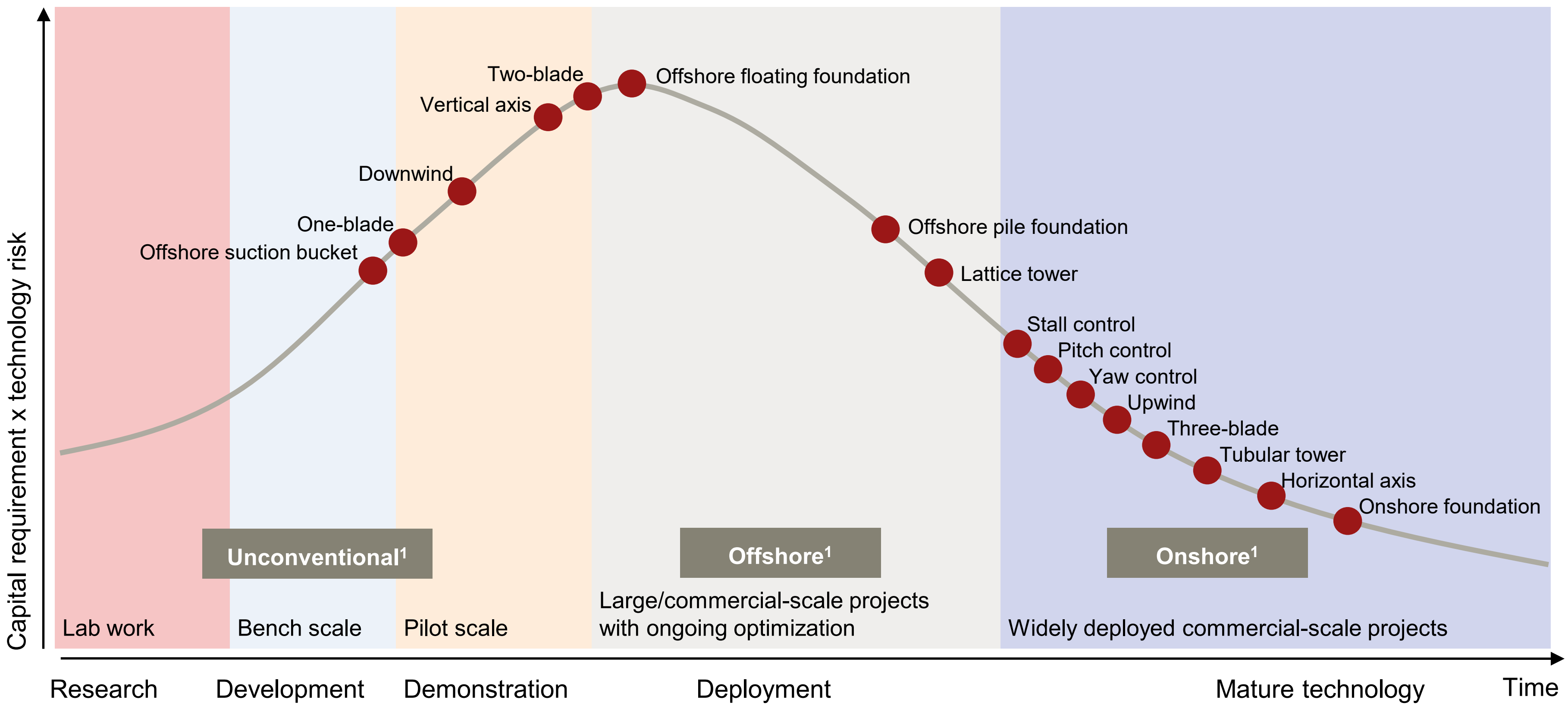
Wind turbine components and systems are at different stages of maturity

Technology maturity curve



[1] Typical position of dominant wind turbine design groups on the maturity curve. Unconventional wind turbines include airborne wind energy technologies, but also others, including bladeless turbines.
Source: A.T. Kearney Energy Transition Institute

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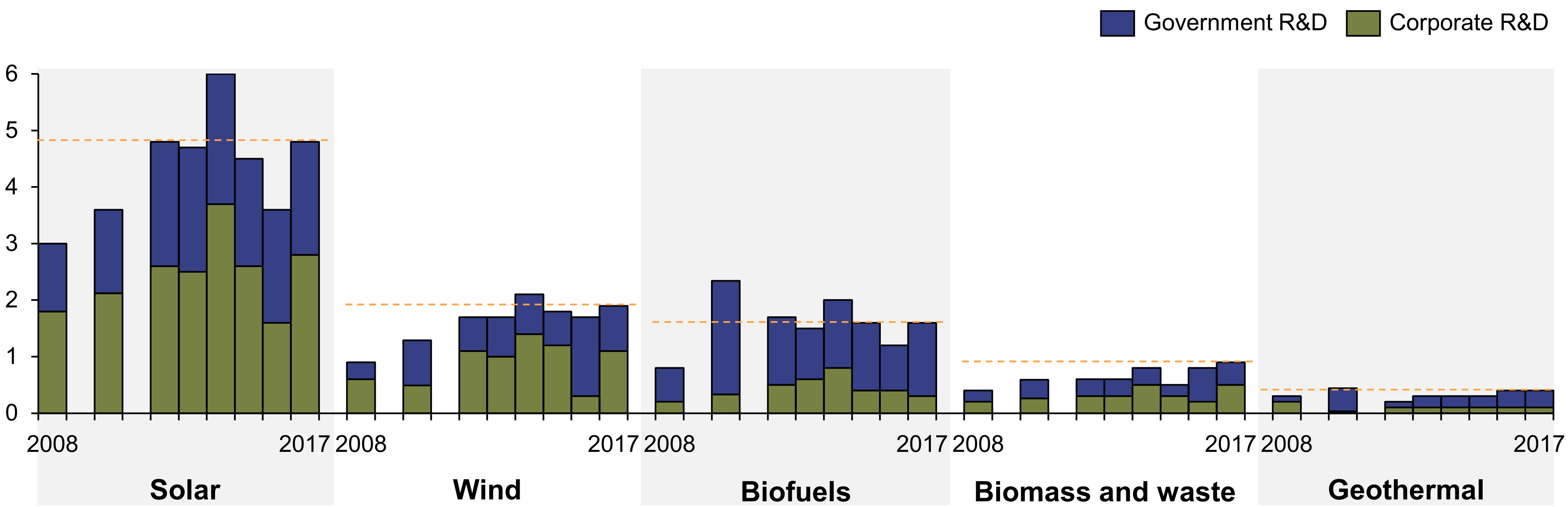
Wind R&D investments are substantially lower than those in solar energy

Global R&D investments in wind and other renewable energy sources (2008–2017)
$ billion



- After an initial period of both corporate and government R&D investment growth, the global investments have somewhat stabilized over the past five years.
- Wind R&D remains relatively low compared to solar R&D, but similar to that of biofuels.

Sources: UNEP (2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011, 2010, 2009), "Global Trend in Renewable Energy Investment". Results based on Bloomberg, Bloomberg New Energy Finance, IEA, IMF, and various government agencies; A.T. Kearney Energy Transition Institute analysis

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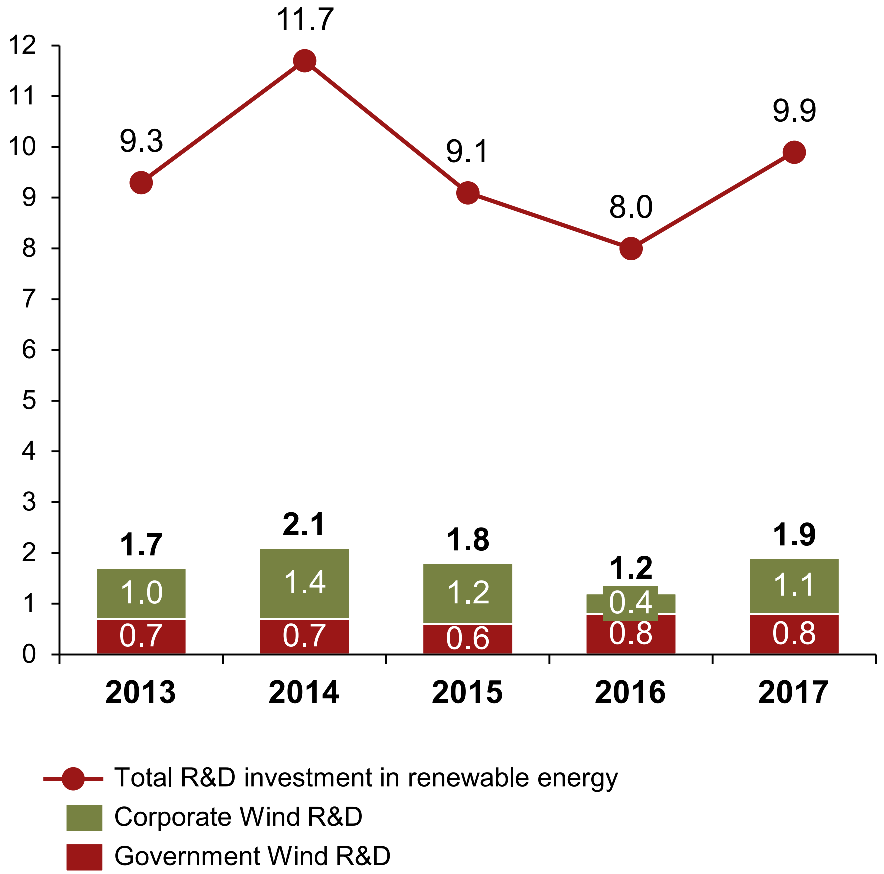
The past five years have seen certain fluctuations in R&D investments in wind energy sector

Global R&D investments in wind energy technology

2013–2017, $ billion



- Annual trends in total research and development investments in **renewable energy** affect investments in **wind R&D** as well.
- Share of investment in wind R&D was predominantly **stable** over the past five years, **between 15 and 20 percent** relative to global R&D investments in renewable energy.
- In absolute terms, **2014** was the top year when investment surpassed the **$2 billion** benchmark (**18 percent** of total renewable energy share).
- On the other hand, share of wind R&D relative to **total investment in renewable energy R&D** was highest in **2015** (19.7 percent).
- Annual fluctuations in both wind and total renewable energy R&D investments were driven by **corporate R&D** while **government R&D** share was stable over the period.

Sources: UNEP 2018, *Global Trends in Renewable Energy Investment*; A.T. Kearney Energy Transition Institute analysis

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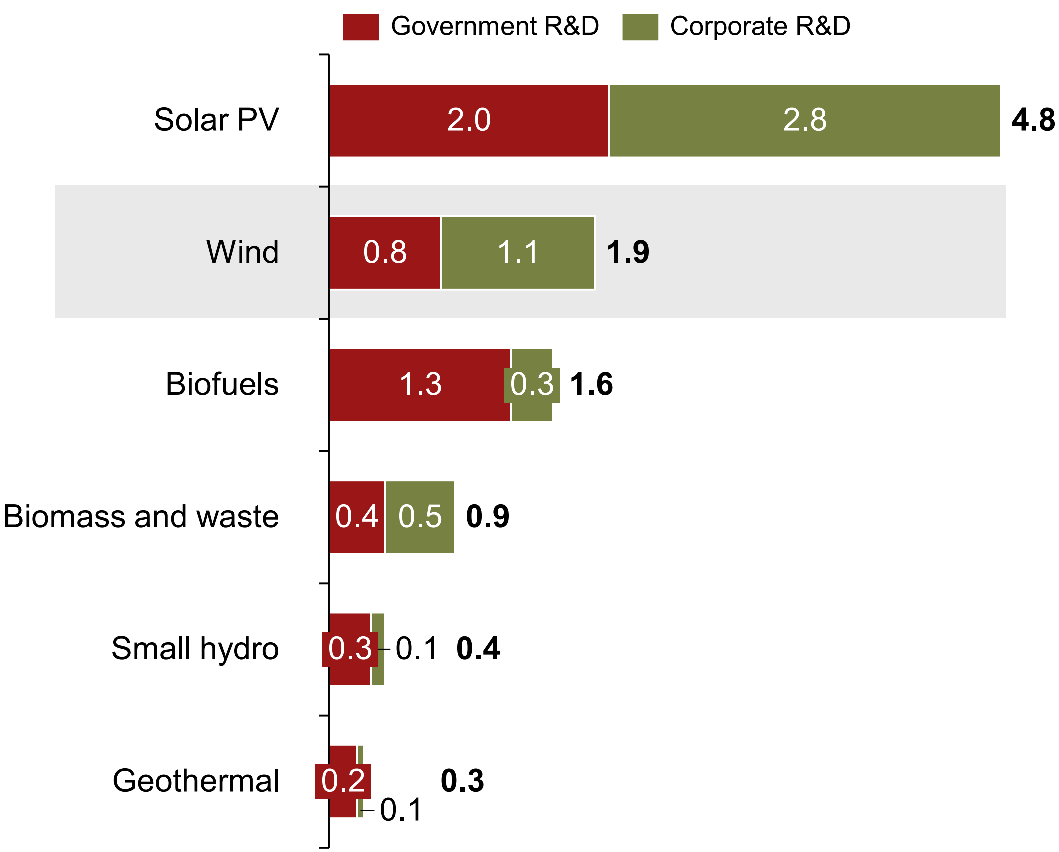
Wind is the second-largest R&D sector among renewable energy technologies after solar PV

Global R&D investments in renewable energy

2017, $ billion



- Investment in research and development in the renewable energy sector set a record in 2017, rising 6% to **$9.9 billion**.
- The increase was entirely driven by corporate R&D, which rose 12% to **$4.8 billion** while government spending remained unchanged at **$5.1 billion**.
- **Solar** remained by far the biggest recipient of overall renewable energy R&D investment, rising 6% to **$4.7 billion.**
- **Wind** was the next-largest sector, setting a new high of **$1.9 billion**, up 6% from 2016.
- Biofuels are behind wind while the biomass and waste sector is close to the $1 billion benchmark.

Sources: UNEP 2018, *Global Trends in Renewable Energy Investment*; A.T. Kearney Energy Transition Institute analysis

4. Economics and ecosystem

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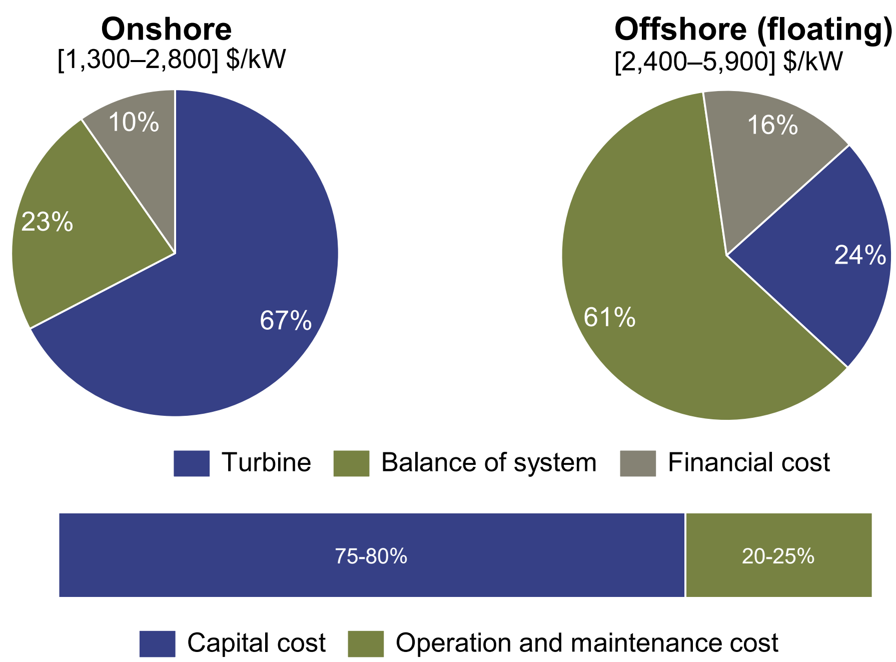
With zero fuel costs, wind is a capital-driven industry

Typical onshore and offshore wind cost breakdown

Capital cost breakdown (top) and share of capital in levelized cost of electricity (bottom)[1,2,3,4]



- **The cost of wind power predominantly consists of up-front investment**. Operation and maintenance typically account for 20% to 25% of the electricity price (can sometimes go up for offshore projects). Financing costs are therefore fundamental to the economic viability of a wind project.
- **Turbine costs account for most of the capital cost in the case of onshore**, where they can account for up to 67% of total installed costs. The main components of turbines are the rotor blades, the tower, and the gearbox, which account for around two-thirds of the overall capital costs.
- **Offshore has significantly more onerous cost components than onshore**, mainly as a result of the harsh marine environment, which requires expensive installations, more robust grid connections, and deeper foundations. The support structure, assembly, transport, and installations represent a major part of the total capital cost of offshore wind systems.

Note: Percentages may not resolve due to rounding.
[1] Turbine costs include rotor, drive train, and tower.
[2] Balance of station costs include foundations, roads and civil work, assembly and installation, electrical interface, development, project management.
[3] Financial costs include contingency, construction, and financing.
[4] Estimate for onshore and offshore combined
Sources: IPCC (2011), “Special report on renewable energy”; IRENA (2012), “Renewable Energy Technologies: Cost Analysis series - Wind Power“; IRENA (2018), “Renewable Power Generation Costs In 2017”; NREL (2017), “2016 Cost of Wind Energy Review”; A.T. Kearney Energy Transition Institute analysis

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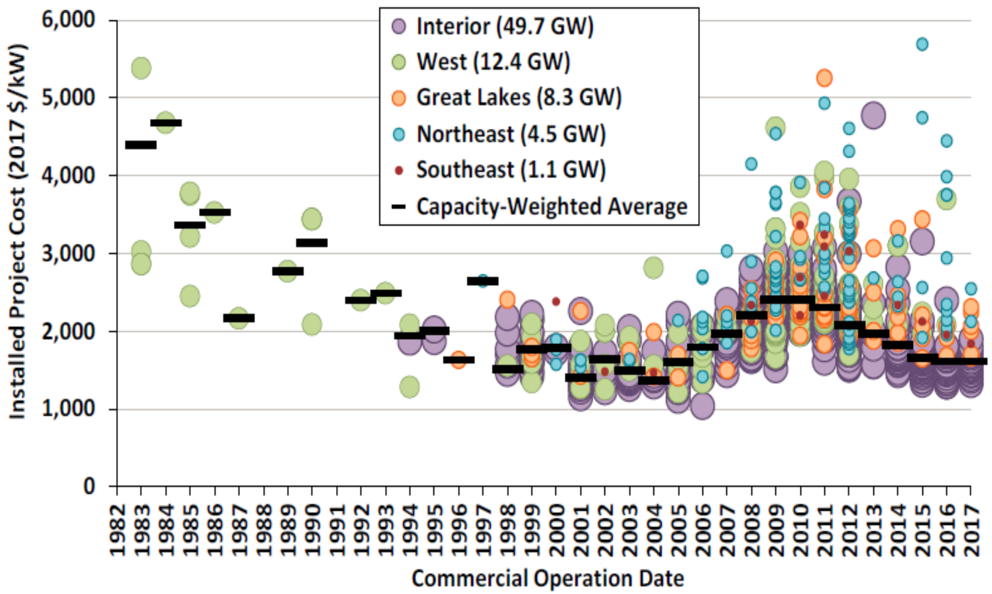
Investment costs have fallen but remain highly sensitive to commodity prices and supply chain bottlenecks

Investment costs of wind power plants in the US

2017 $ /kW



- **There were substantial cost decreases per unit of capacity from the 1980s to the early 2000s** as a result of economies of scale, the learning effect, and improved technology. Historical learning rates for wind power were around 10% from 1980 to 2004.
- **Between the early 2000s and 2010, the US wind industry experienced an increase in turbine prices,** caused by (i) increases in the prices of commodities, mainly steel, copper, and cement; (ii) supply chain bottlenecks caused by rapid market growth; and (iii) increases in turbine price, size, and system sophistication to achieve higher load factors and meet system requirements.[1]
- **Since 2009–2010, there has been a substantial decrease in capacity-weighted average project costs. These appear to have stabilized** as a result of (i) more stable—and even declining—commodity prices (in part due to rising US dollar); (ii) supply chain catch-up with demand; and (iii) increased competition, thanks to the emergence of manufacturers with local content in low-cost manufacturing bases.

[1] Turbine prices peaked in 2008–2009, but project-level installed costs peaked in 2009–2010. This is due to the time difference between agreement and installation.

Sources: US DoE (2018), “2017 Wind Technologies Market Report”; US DoE (2015), “2014 Wind Technologies Market Report”; US DoE (2014), “2013 Wind Technologies Market Report”; A.T. Kearney Energy Transition Institute analysis

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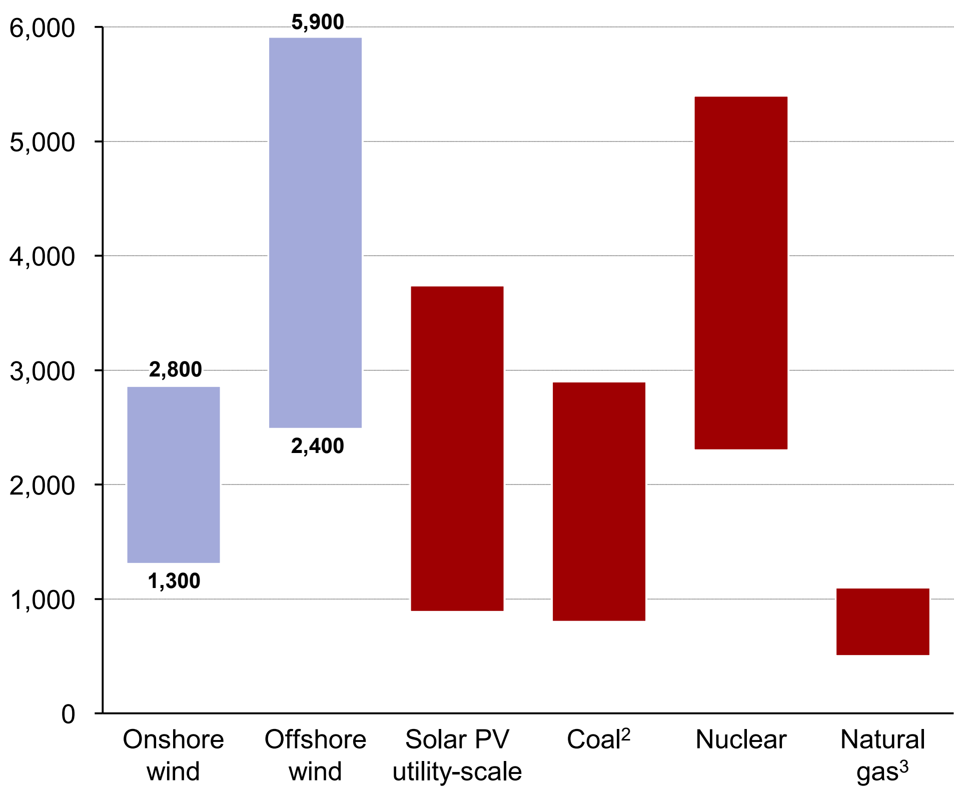
Onshore investment costs are significantly lower than offshore costs

Wind investment costs[1]

2017 $ /kW



- **Wind project costs vary depending on turbine prices, wind farm sizes, and local market conditions** (for example, competitiveness of local industry, labor costs…).
- **Onshore wind is maturing**. Investment costs typically range from $1,300 to $2,800 per kW. Globally, onshore wind total installed costs fell by an average of 20% between 2010 and 2017, notably as deployment in China and India grew, given their relatively low-cost structures.
- Onshore wind now **rivals hydropower, geothermal, and biomass** as a source of low-cost electricity, without financial support. Capacity factors have increased, performance has improved, and installed and O&M costs have fallen, all serving to **drive down the LCOE.**
- **Offshore wind is at the early deployment phase and consequently it is significantly more expensive than onshore** (around twice as expensive). Costs range between $2,400 and 5,900 /kW, depending on turbine size, foundation types and other considerations.

Note: LCOE is levelized cost of electricity.
[1] Comparing investment cost per kW does not reflect the competitiveness of the technologies. It does not take into account the load factor, nor the lifetime or required transmission and distribution costs, which will highly impact the competitiveness of the technologies.
[2] Coal investment costs range includes all technologies from subcritical to integrated gasification combined cycle (IGCC).
[3] Natural gas technologies also include open cycle gas turbine (average around $500 per kW) and combined cycle gas turbine (average $1,000 per kW).
Sources: IRENA (2018), "Renewable power generation costs in 2017"; A.T. Kearney Energy Transition Institute analysis

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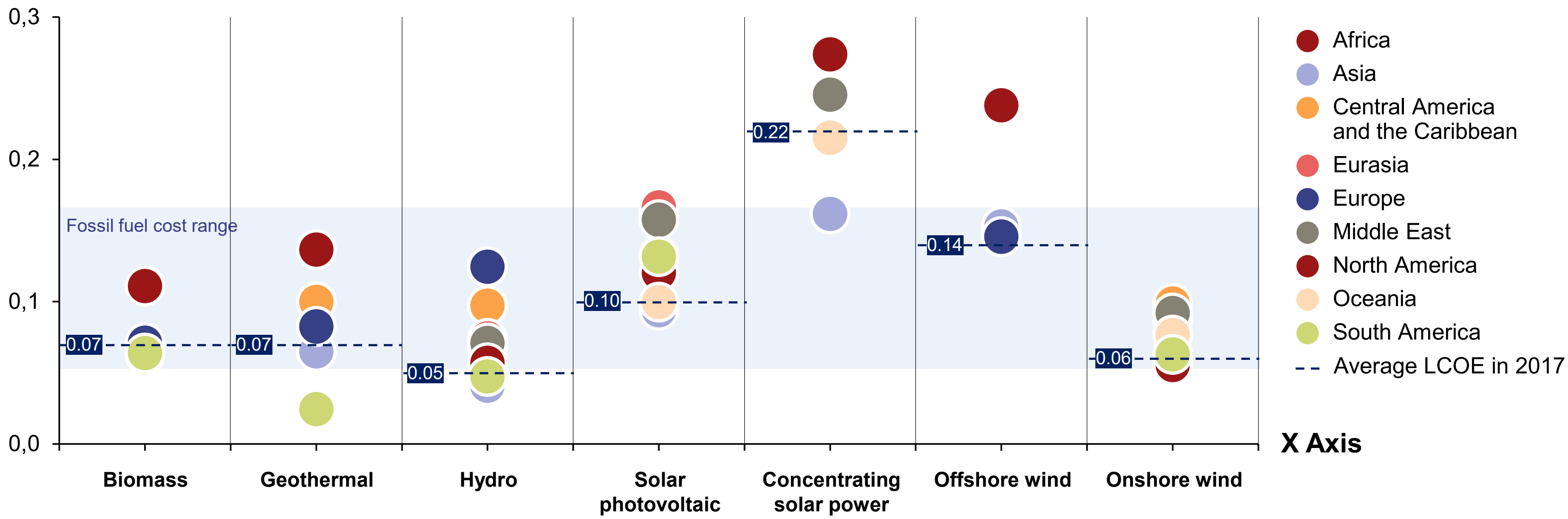
Onshore wind power's LCOE is in the range of that of fossil fuel, but offshore wind development still requires policy support in most regions

Regional weighted average levelized cost of electricity by renewable power generation technology, 2016–2017

2017 $ /kWh



Note: LCOE is levelized cost of electricity, which represents the per-kilowatt-hour cost of building and operating a generating plant over an assumed financial life and duty cycle. Its ranges reflect differences in resources available, local conditions, and choice of sub-technology. Calculations are based on a 7.5% discount rate for OECD countries and China and 10% for the rest of the world. While LCOE allows comparison of costs among technologies, it may be an unreliable metric when comparing technologies at different stages of maturity. LCOE can also be a misleading measure of the value of technologies that perform different roles in an electricity system and that should be assessed in terms of their contribution to system reliability.

Source: A.T. Kearney Energy Transition Institute based on IRENA (2018), "Renewable Power Generation Costs in 2017"

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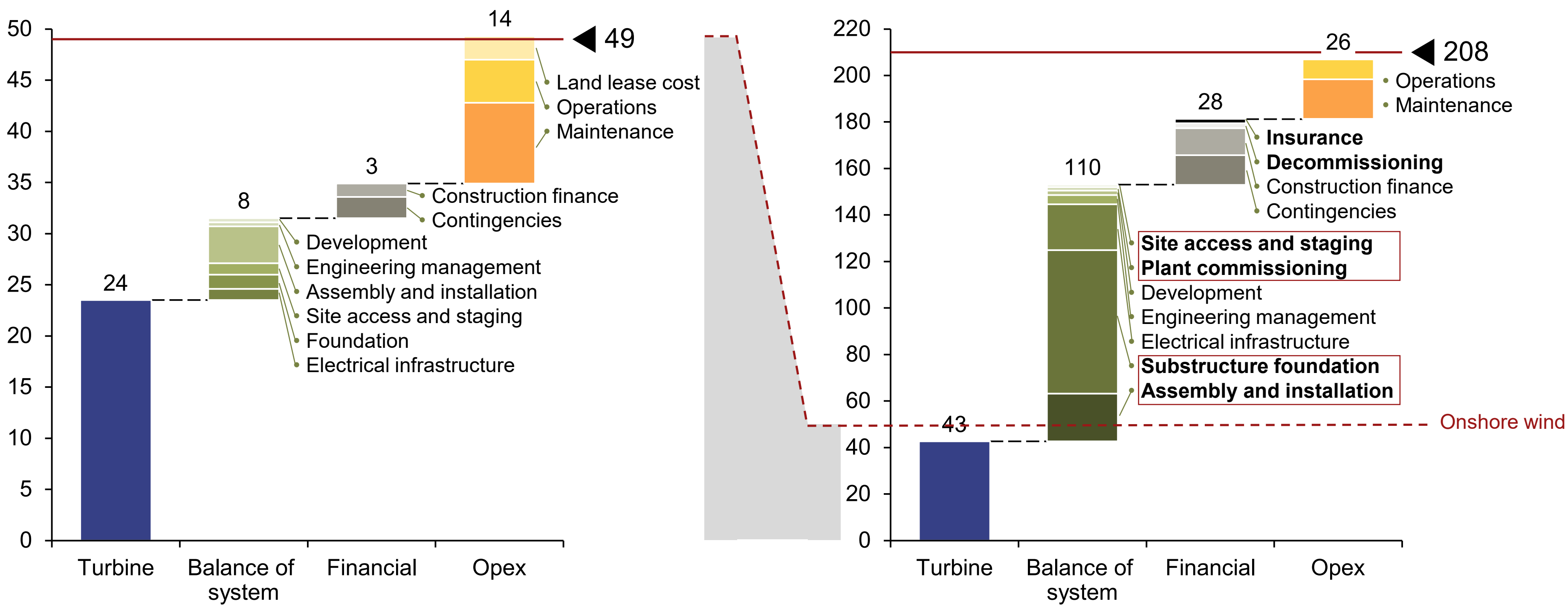
Offshore plants handle additional capital costs related to marine conditions

Indicative LCOE for a land-based wind power plant project in the US
$/MWh

Indicative LCOE for a floating offshore wind power plant project in the US
$/MWh



Notes: LCOE is levelized cost of electricity. Project life is 25 years for onshore, 20 years for offshore.
Sources: NREL (2017), "*2016 Cost of Wind Energy Review*"; A.T. Kearney Energy Transition Institute

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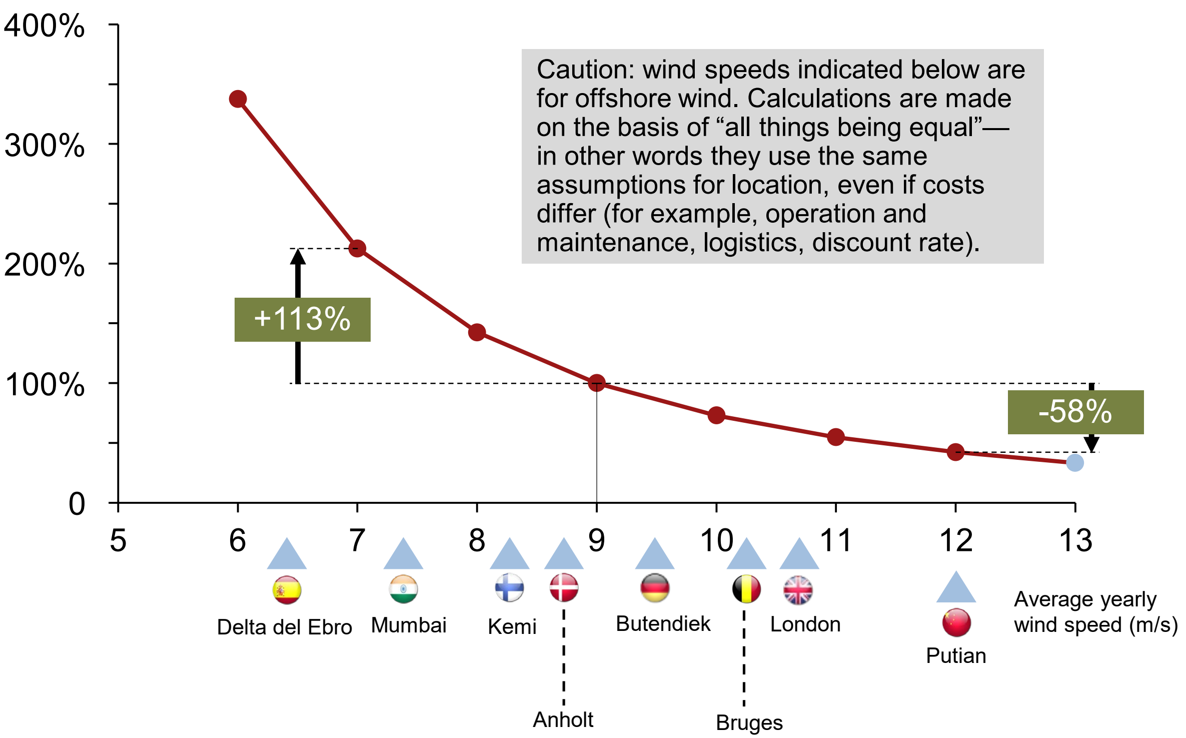
As with other renewables, the quality of a wind resource has an important impact on the economics of the power it produces

Impact of wind speed on the relative LCOE of offshore wind

% compared with a reference plant with an average wind speed of 9 m/s

Illustrative



- **As with any renewable energy, the competitiveness of wind power depends on the quality of the natural resource**. This is generally measured by wind speed (meters per second or km per hour) and will affect the availability of the plant (its load factor).[1]
- **All things being equal, the higher the wind speed, the lower the levelized cost of electricity produced.**[2] Variations in wind speed, depending on geographic location, make the plant's location crucial in determining its economic viability.
- The energy in the wind varies with the third power of the wind speed; hence **a doubling of the wind speed gives an eightfold increase in the wind turbine output.**

Note: LCOE is levelized cost of electricity.
[1] LCOE is calculated for a typical offshore wind turbine of 4.3 MW, assuming investment costs of $5,187 per kW, yearly O&M of $136 per kW, discount rate of 8%, and a lifetime of 20 years. Note that these parameters actually vary between countries.
[2] Wind speed data have been extracted from 4Coffshore.
Sources: A.T. Kearney Energy Transition Institute; 4Coffshore (link), EWEA (2009) "Economics of wind energy"

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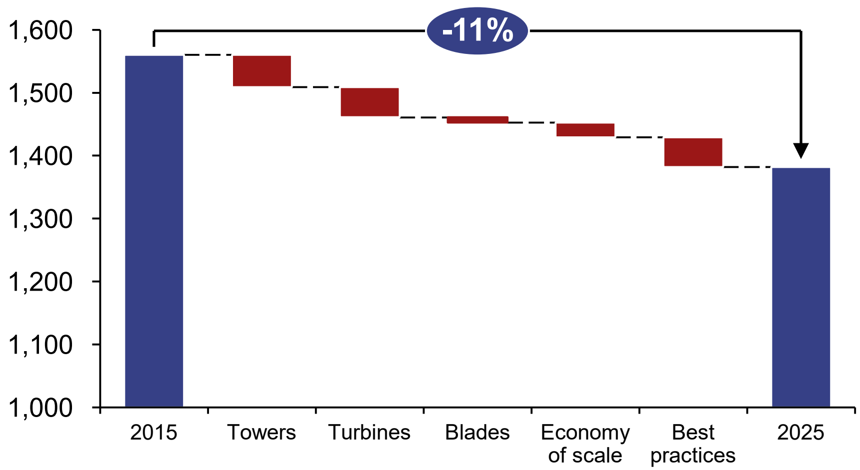
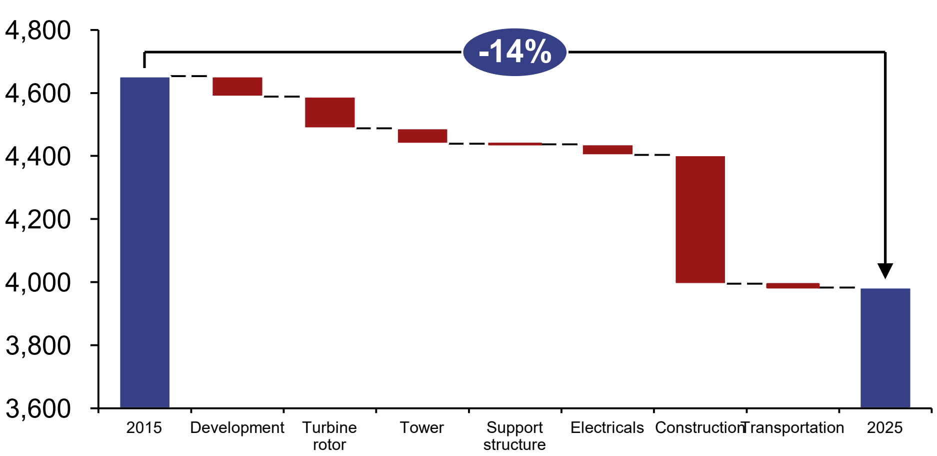
The investment cost reduction of offshore wind projects remains uncertain in the next few years, but is likely to be greater than for onshore

Projected reductions in total installed costs

2015 $ /kW



Onshore wind



Offshore wind

- **Projected reductions of investment costs are greater for offshore than for onshore due to offshore's relative immaturity**, allowing for a greater learning effect, standardization, and economies of scale. Offshore could also benefit from greater reduction in grid connection costs as a result of high-voltage direct current cabling.
- **Decreasing turbine prices continue to flow into onshore wind installed cost reduction**. However, reductions in offshore wind costs are expected to be capped by (i) increases in raw materials prices; (ii) requirements from grid operators regarding power stability and controllability; and (iii) the continued growth of turbine size, including rotor diameter and hub height.
- **Increased competition from emerging market manufacturers is likely to foster a decline in project costs.**

Sources: IRENA Renewable Cost Database and IRENA (2016), "Solar and Wind cost reduction potential to 2025"; A.T. Kearney Energy Transition Institute analysis

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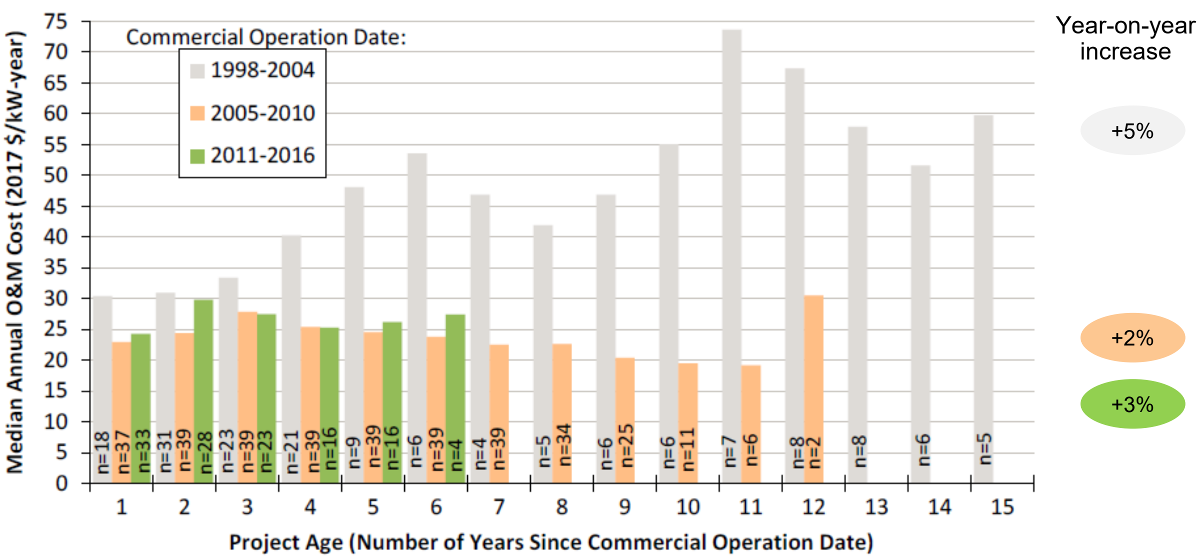
Operation and maintenance costs have been steadily decreasing

Median annual O&M costs by project age and operation date of wind power plants in the US[1,2]

2017 $ /kW-year



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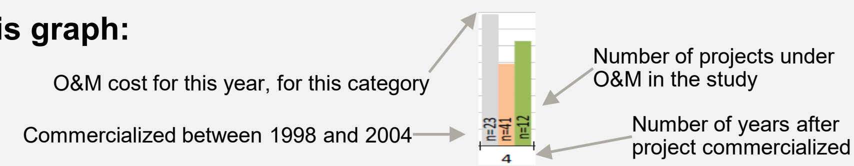

- **Operating costs are a significant component of wind power costs. They are made up of: (i) operation and maintenance (O&M) costs**, including all wages and materials associated with operating and maintaining the facility or rent; and **(ii) other continuing expenses**, such as administrative expenses, taxes, insurance.[3]
- In the US, **O&M costs have, on average, fallen by about 75% since the 1980s, to below $10 per MWh**. The fall in costs is an interplay of two factors – (a) design improvements that reduce the need for O&M on a per MWh basis, (b) O&M costs tend to increase as turbines age[4]. In other words, one should distinguish between two trends: project vintage and project age.
- **Capacity-weighted average 2000–2016 O&M costs were** $36 per MWh for projects in the sample constructed in the 1980s, dropping to $25 per MWh for projects constructed in the 1990s, to $11 per MWh for projects constructed in the 2000s, and to $9 per MWh for projects constructed since 2010.

[1] Operation date means commercial operation date.
[2] Only projects >5 MW are included.
[3] This includes scheduled and unscheduled maintenance.
[4] This is due to component failures becoming more frequent and the potential expiry of warranties.
Sources: US DoE (2018), “2017 Wind Technologies Market Report”; US DoE (2015), “2014 Wind Technologies Market Report”; A.T. Kearney Energy Transition Institute analysis

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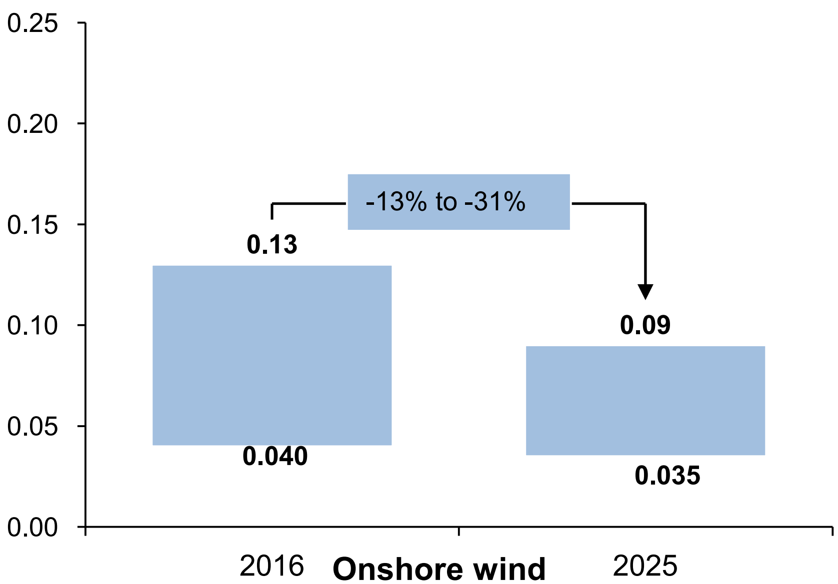
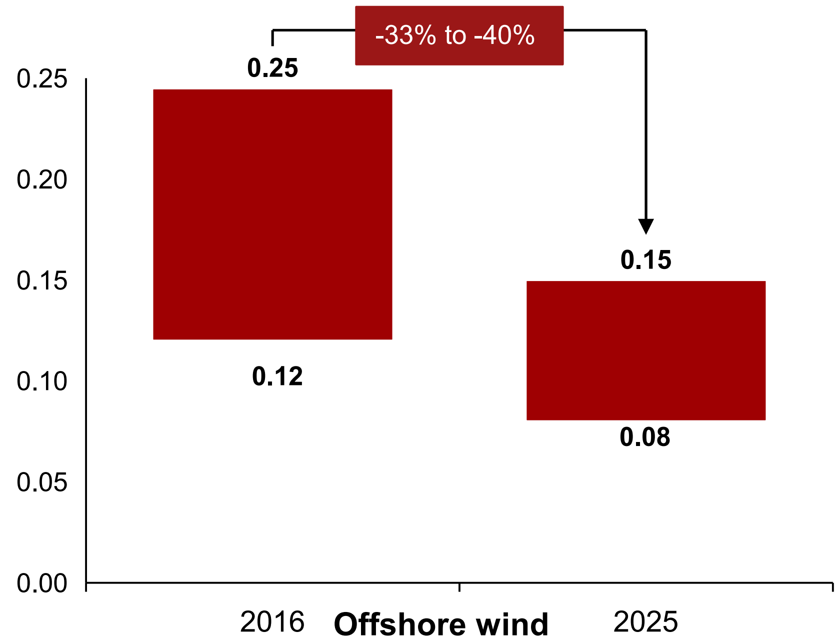
Most stakeholders predict that the LCOE of wind will continue to decrease through 2025

LCOE reduction potential

$ /kWh, global average





- This is due to a combination of levers, such as increased competition among OEMs, larger projects, and improvement in technology/processes.
- Lower prices are a positive for the industry in the long term; rapid declines have put pressure on supply chain participants to reduce costs.
- Decreases in costs are expected to be larger for offshore systems than for onshore because of their relatively low level of maturity.

Note: LCOE is levelized cost of electricity.
Sources: IRENA Renewable Cost Database and IRENA (2016), “Solar and Wind cost reduction potential to 2025”; A.T. Kearney Energy Transition Institute analysis

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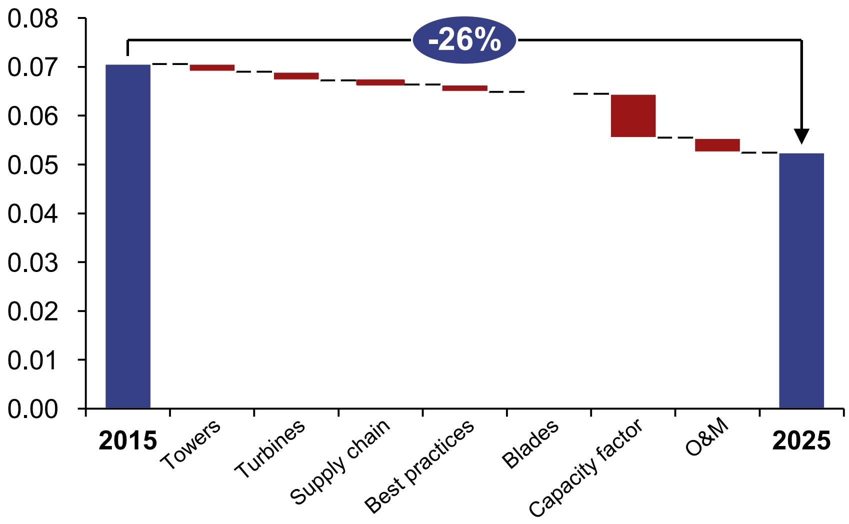
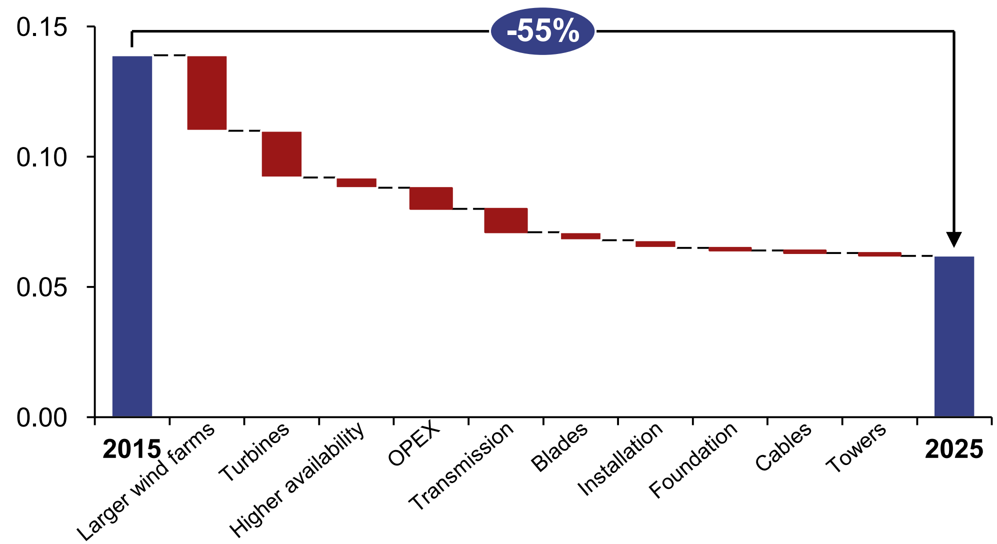
Drivers of LCOE reduction are different for onshore and offshore wind

Breakdown of the reduction in levelized cost of electricity

2015 $ /kW



Onshore wind



Offshore wind

- With low turbine prices and the reduction in total installed costs since 2008–2009, a majority of the future cost reductions in the cost of electricity from onshore wind are increasingly likely to come from **technological improvements that yield higher capacity factors for a given wind resource.**

- Offshore LCOE is projected to fall with **greater developer experience, larger turbines, and improved project development and commissioning practices**. Reduced construction and installation costs (capex) and reduction in unplanned servicing (opex) are expected to be other key contributing factors. WACC will be streamlined as a wider range of financing institutions will acquire experience with offshore wind farm risks and be able to more realistically price them.

Notes: LCOE is levelized cost of electricity; O&M is operations and maintenance; capex is capital expenditure; opex is operational expenditure; WACC is weighted average cost of capital.
Sources: IRENA Renewable Cost Database and IRENA (2016), “Solar and Wind cost reduction potential to 2025”, HSBC (2018) “New giants of the sea by 2021”; A.T. Kearney Energy Transition Institute analysis

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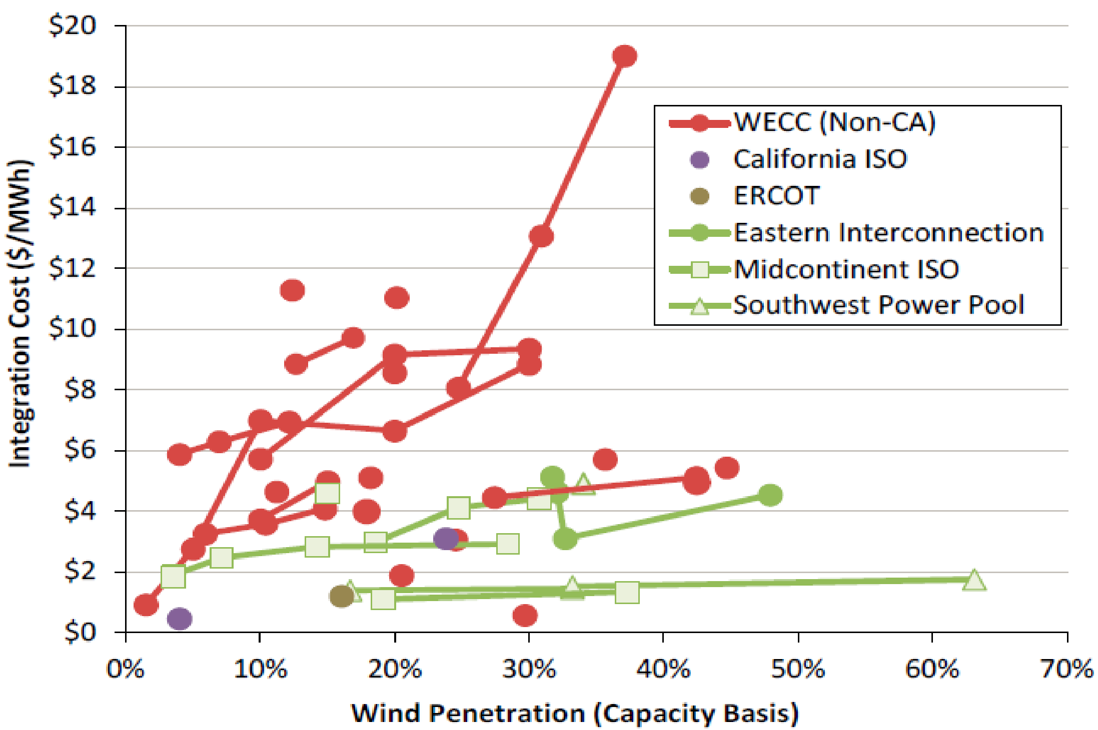
Failure to include rising grid integration costs in the LCOE generated from wind may miss important economic considerations

Increase in balancing costs vs. wind penetration

$/Mwh



- **Wind penetration will generate integration costs due to intermittency.** This will include (i) balancing costs (for example, second-to-hour timescale); (ii) adequacy costs (for example, day-to-year timescale); and (iii) transmission costs – dedicated lines.
- **Grid integration costs resulting from wind are hard to assess and highly system-specific**. They are thus usually not taken into account when calculating the levelized cost of electricity (LCOE).
- **Depending on penetration, integration costs may increase significantly**. There is a lack of research into penetration rates higher than 30%, making wind's ability to account for a larger share of the generation mix highly uncertain.

Sources: US DoE (2018), “2017 Wind Technologies Market Report”; US DoE (2015), “2014 Wind Technologies Market Report”; A.T. Kearney Energy Transition Institute analysis

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Wind support policies take two principal forms: those that mandate a certain quantity of wind power and those that alter the prices to which investors are exposed

Options for policy support[1]

Price-based instruments → Influence wind deployment levels by altering the prices to which investors are exposed (increasing revenues or lowering costs).

Feed-in tariffs (FITs)	Guarantee a certain price per kilowatt hour (kWh) at which electricity is bought during a long period of time (typically 20 years).[2]
Contracts for difference	Long-term PPA under which electricity is directly sold to the market and investors receive or refund the gap between market and predetermined price.[2]
Electricity compensation	Allow self-produced electricity to reduce the electricity bill of the wind system owner through self consumption or net-metering systems.[3]
Market premiums	Complement revenues from the standard electricity market by paying investors based on the quantity of electricity generated or capacity built.
Tax incentives or credits	Reduce the cost of renewable energy projects from the perspective of an investor through direct tax reduction or accelerated depreciation of assets.
Direct cash grants/rebates[4]	Reduce investment costs and improve returns of investors by giving back a percentage of investment costs in cash to developers.

Quantity-based instruments → Mandate a certain quantity of energy or capacity. Prices are thus determined by the costs of projects required to meet this obligation.

Renewable portfolio standards (RPS)	Set a target share or total amount of energy generation from renewable energy sources for electricity producers or suppliers.[5]
Quotas with tradable green certificates	Set a specific amount of electricity to be generated from renewable sources and issue certificates for each unit of green electricity to be traded on a market. This aims at meeting renewable obligations more efficiently.
Centralized procurement	Usually implemented by a government or public body by organizing auctions to contract a predetermined quantity of renewable energy. The price is set in a competitive bidding process.

[1] Policy mechanisms can also be categorized according to how they are financed. Renewable policy support is usually financed by additional charges to electricity consumers' bills, via payments through the general budget or dedicated state funds, or by accepting reduced tax revenues.
[2] A FIT is a standardized, long-term power purchasing agreement (PPA). FIT can also be combined with a tendering process.
[3] For more information on net metering, refer to slide 48.
[4] Also known as direct capital subsidies.
[5] RPS build on the assumption that the obliged producer or supplier has sufficient opportunities to build or purchase renewable energy directly. Where this is not the case, a quantity obligation can be combined with trading of green certificates.
Sources: IEA (2015), "Energy Technology Perspective 2015"; IEA (2014), "Trends 2014 in Photovoltaic Applications"; A.T. Kearney Energy Transition Institute analysis

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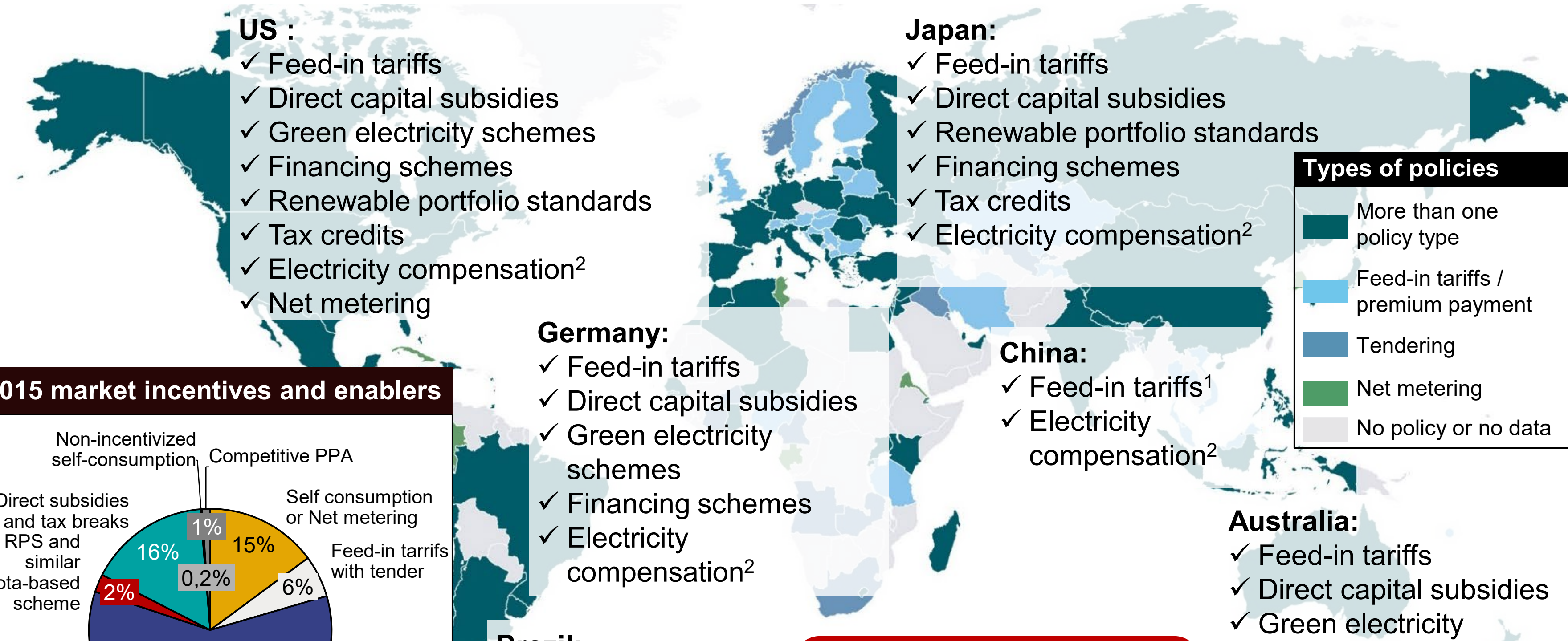
Support policies vary according to regions and are typically combined with each other

Renewable energy policies and policy incentives for selected countries 2015



US :
- ✓ Feed-in tariffs
- ✓ Direct capital subsidies
- ✓ Green electricity schemes
- ✓ Financing schemes
- ✓ Renewable portfolio standards
- ✓ Tax credits
- ✓ Electricity compensation[2]
- ✓ Net metering

Japan:
- ✓ Feed-in tariffs
- ✓ Direct capital subsidies
- ✓ Renewable portfolio standards
- ✓ Financing schemes
- ✓ Tax credits
- ✓ Electricity compensation[2]

Germany:
- ✓ Feed-in tariffs
- ✓ Direct capital subsidies
- ✓ Green electricity schemes
- ✓ Financing schemes
- ✓ Electricity compensation[2]

China:
- ✓ Feed-in tariffs[1]
- ✓ Electricity compensation[2]

Brazil:
- ✓ Net metering
- ✓ Tendering
- ✓ Energy production payments
- ✓ Tax incentives

Australia:
- ✓ Feed-in tariffs
- ✓ Direct capital subsidies
- ✓ Green electricity schemes
- ✓ Renewable portfolio standards
- ✓ Quotas with tradable green certificates
- ✓ Grant schemes

2015 market incentives and enablers

Caution: map and breakdown depict all renewable-support policies, not just support for wind energy.

Note: RPS is renewable portfolio standards.
[1] Three regionally differentiated FIT support schemes with reduced rates for ground-mounted solar PV projects in solar-rich regions.
[2] Can be net energy metering, net billing, or self consumption incentives.
Sources: REN21 (2016), "Global Status Report"; IEA-PVPS (2016), "Trends 2016 in Photovoltaic Applications"; A.T. Kearney Energy Transition Institute (2017), Solar PV Factbook

Many countries are supporting offshore wind development through national policies and targets

Examples of plans and announcements

Country	**Current** 2017A, MW	**Official target** GW	
UK	6,357	14 GW by 2026	A lack of seabed will become an issue by 2030, and offshore wind penetration will reach high levels before then, which may slow down build-out
Germany	5,241	7.7 GW by 2020	Enough seabed for 2030, but like the UK, a lack of seabed will be a limiting factor at some point
Netherlands	1,118	4.5 GW (2023) and 11.5 GW (2030)	Multiple auctions to be announced
Belgium	878	4 GW by 2030	Larger projects expected to come online
France	2	3 GW by 2023	Later start than other European countries and tender prices might be revised
USA	40(1)	8 GW by 2030	Connecticut, Massachusetts, New York, and New Jersey adopt offshore wind. East Coast seabed more suited to wind than West Coast
Taiwan	2	5.5 GW by 2023	High growth market in Asia
China	2,946	5 GW (2020) and 10 GW (2025)	State-driven ramp-up to be expected
India	Nil	5 GW (2022) and 30 GW (2030)	The Ministry of New and Renewable Energy (MNRE) recently invited Expressions of Interest (EoI) for the first 1 GW offshore wind project

(1): according to Irena, US only accounts for 30MW in 2017
Sources: Press search, Credit Suisse equity research May 2018; A.T. Kearney Energy Transition Institute

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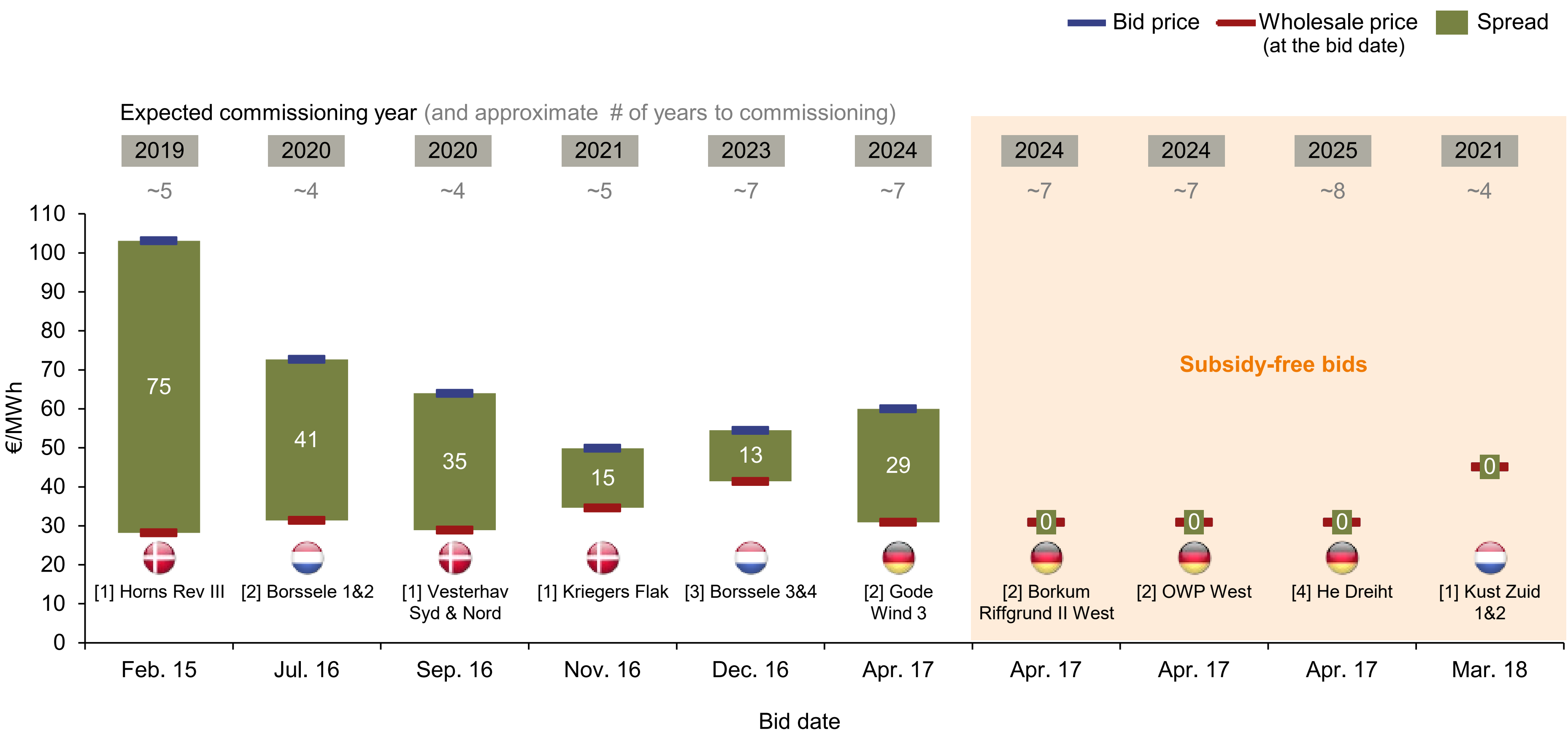
First offshore subsidy-free projects were awarded in 2017, but should be commissioned around 2021–2024, in the Netherlands and in Germany

Bid prices for awarded offshore wind projects in Europe[1]
(€/MWh)



Note: Corresponding developers are: [1] Vattenfall, [2] Orsted, [3] Consortium (Shell, Van Oord, Eneco, Mitsubishi), [4] EnBW.
[1] Excluding grid connection costs
Sources: Press search, Aurora Energy Research, www.offshorewind.biz, European Commission European Electricity Market Reports; A.T. Kearney Energy Transition Institute

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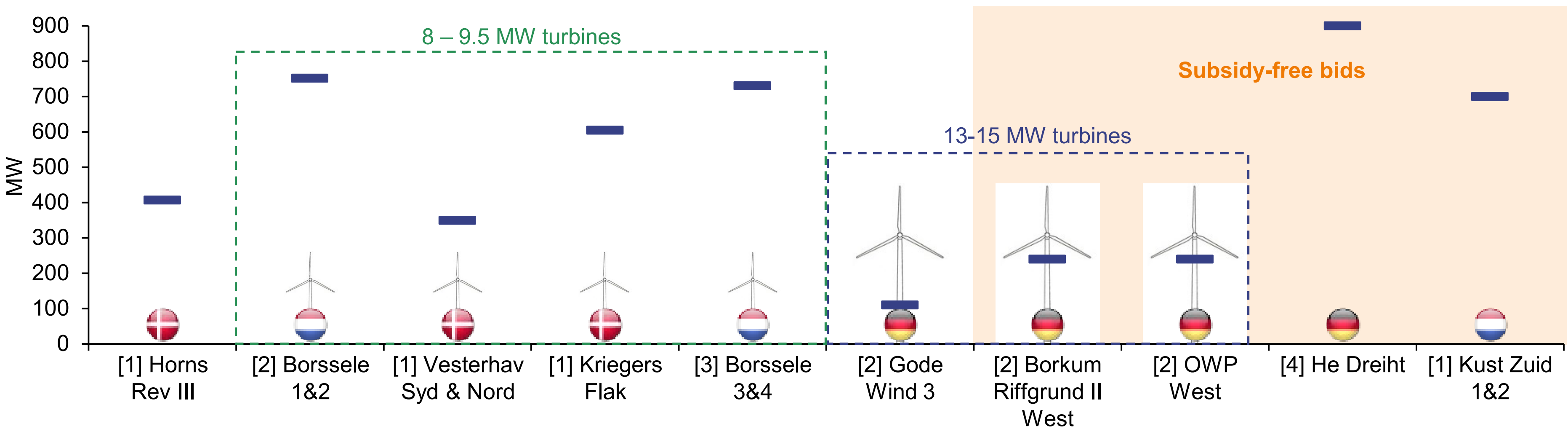
The viability of subsidy-free projects might not be uniform across the markets, and they require technological advances

Expected installed capacity[1]
(MW)



- **Zero subsidy implies different meanings in different markets**. As an example, in Germany and Netherlands (unlike in the UK) the government pays for the grid connection. Hence, developers are able to submit zero-subsidy bids more easily in these markets.
- Bidders **assume wholesale electricity market prices will continue to rise** (as coal and nuclear plants are shut down, introduction of carbon prices) and **offshore wind energy costs will decrease** (due to economies of scale, technological advances such as wind turbine size, and supply chain efficiencies)**.** These key assumptions entail risks which should be managed prudently by the industry players and regulators.
- Accordingly, **project developers have an exit clause (with a penalty) in the contract.** As an example, **Orsted won't make a final investment decision on German offshore projects till 2021** and if the business case doesn't prove attractive, it will pull out paying €59 million penalty.

Note: Corresponding developers are: [1] Vattenfall, [2] Orsted, [3] Consortium (Shell, Van Oord, Eneco, Mitsubishi), [4] EnBW.
[1] Expected wind turbine size data not available for Horns Rev III, He Dreiht, and Kust Zuid 1&2.
Sources: Press search, www.offshorewind.biz, European Commission European Electricity Market Reports, Fraunhofer Wind Monitor; A.T. Kearney energy Transition Institute

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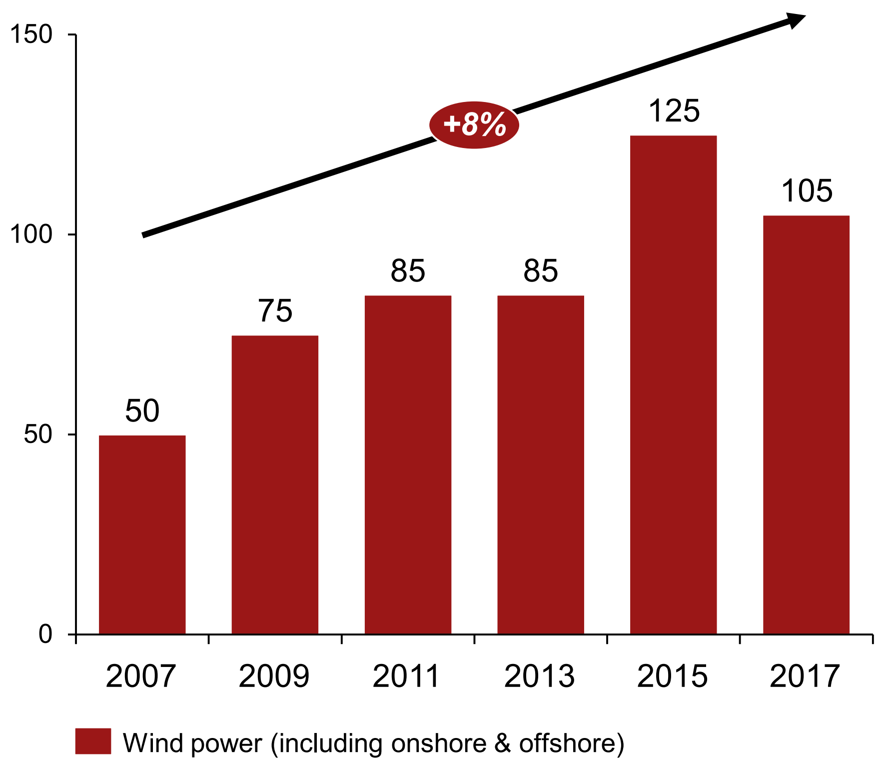
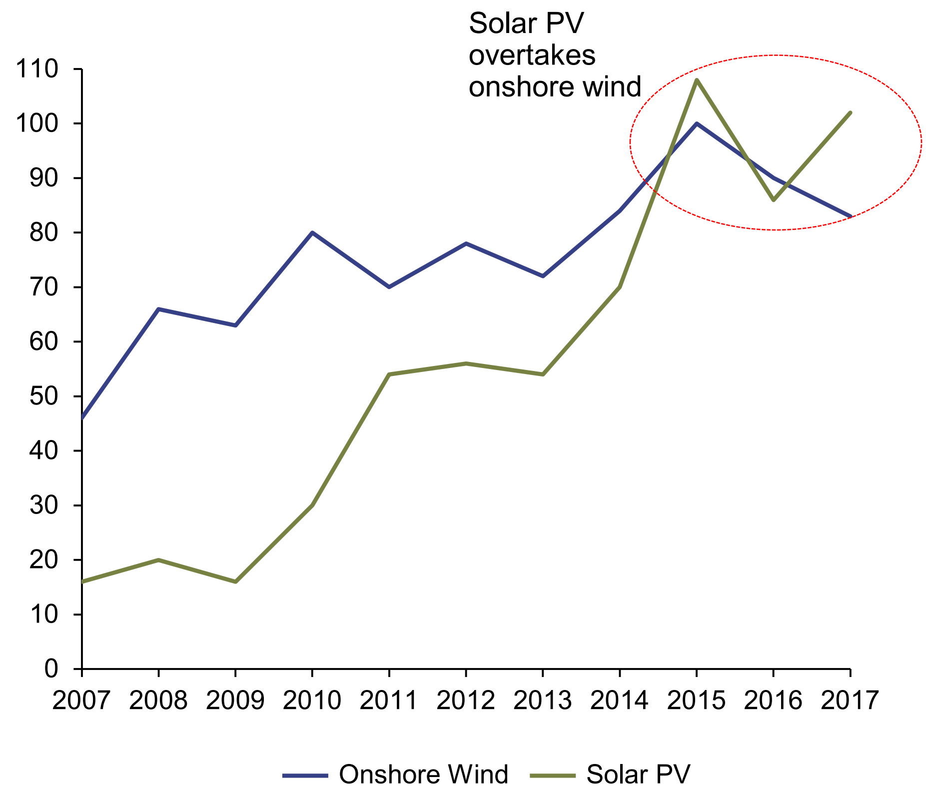
Wind finance experienced strong growth until the end of the past decade, but is now facing growing competition from solar photovoltaic

Asset finance 2007 – 2017[1]
$ billion





1. Total values include estimates for undisclosed deals

Source: UNEP (2018) “Global Trends in renewable energy Investment 2018”, A.T. Kearney Energy Transition Institute analysis

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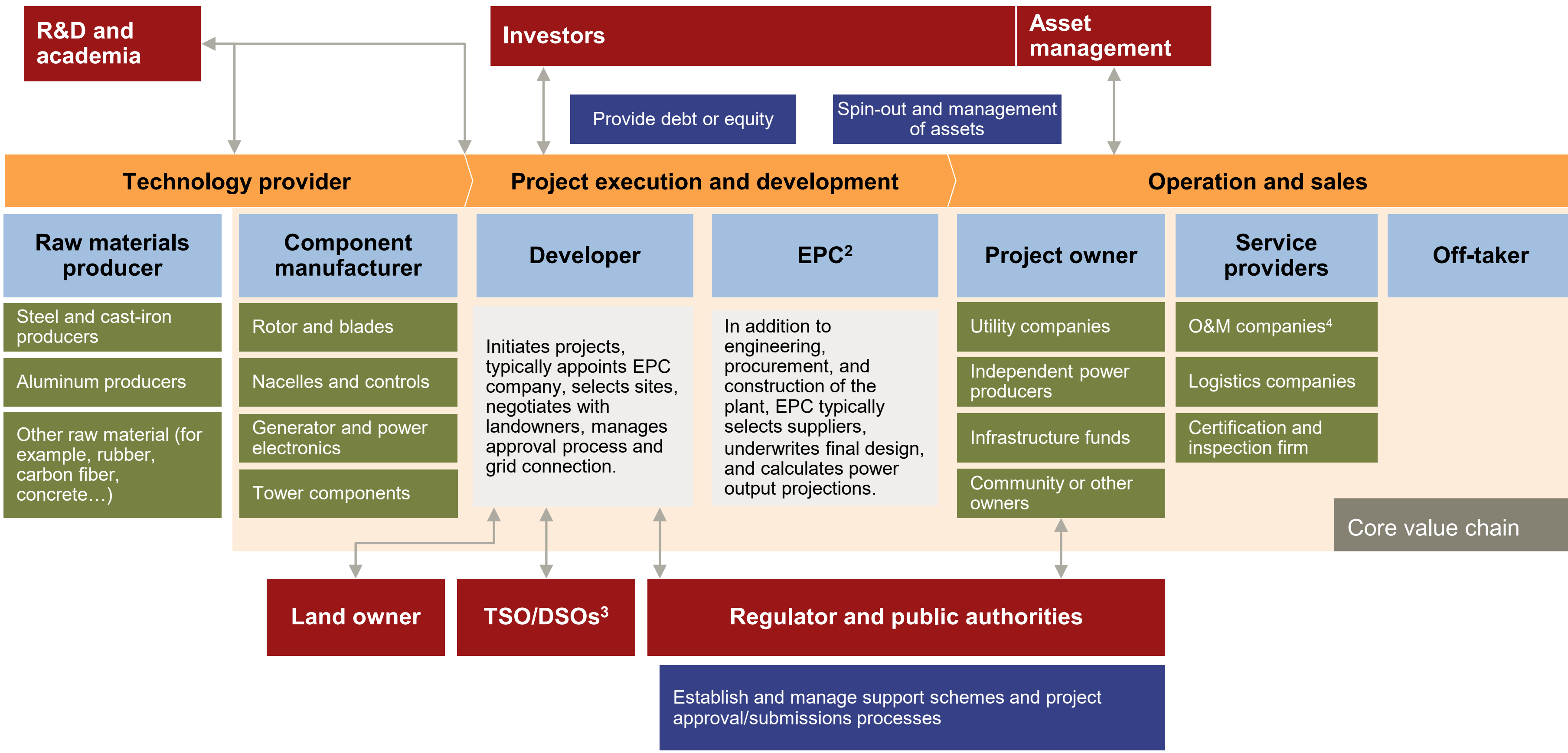
The ecosystem of wind power has developed and matured in recent years, with financiers playing a growing role

Wind power ecosystem[1]



[1] For illustrative purposes only. Note that many wind companies are involved at several stages of the chain (for example, both developing and providing technology, as well as providing EPC services).
[2] EPC is engineering, procurement, and construction.
[3] DSO and TSO are distribution system operator and transmission system operator.
[4] O&M is operation and maintenance.
Source: A.T. Kearney Energy Transition Institute, based on interviews

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There are a wide variety of players in onshore technologies

Value chain players – onshore

Non-exhaustive

Components	Project development	Construction/ installation	Power generation	O&M
• Siemens Gamesa	• Futuren	• Global Energy Services	• Futuren	• Global Energy Services
• Vestas	• Eole Energie	• Skanska AB	• Engie Ineo	• Enercon
• Nordex	• Iberdrola	• GE Alstom	• New Brunswick Power	• Vestas Wind
• Enercon	• Prowind Canada	• Broadwind Energy	• Golders Associates	• Juwi Wind
• Mitsubishi	• Golder Associates	• Prowind Canada	• Youngduk Wind	• GE Alstom
• GE Alstom	• Suzlon	• Ebara Corp	• Green Wind Renewables	• Broadwind Energy
• Goldwind	• New Brunswick Power	• New Brunswick Power	• Parque Eolico La Losilla	• Prowind Canada
• Suzlon	• NextEra Energy Resources		• THUEGA Erneurbare Energien	• Suzlon
• Samyoung m-Tek				
• Nantong Hongbo				
• Timken				

Note: O&M is operation and maintenance.
Sources: Bloomberg New Energy Finance, press search; A.T. Kearney Energy Transition Institute analysis

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Offshore wind firms are mainly based in Northern Europe

Value chain players – offshore specific

Non-exhaustive

Components	Foundations	Cabling	Vessels
• Siemens Gamesa	• PER Aarsleff	• Jdr Cable Systems	• RWE
• Vestas	• Smulders Group	• Js Cable Co	• Ballast Nedam
• WinWinD	• Ramboll Group	• Prysmian	• A2 SEA
• BARD	• GeoSea NV	• Nexans	• GeoSea
• GE Alstom	• Burntisland Fabrications	• NKT Cables	• GMS
• Areva			• IHC Merwede
• Mitsubishi			• McNulty Offshore
• Sinovel			• OWEC Tower
			• Bard Engineering
			• Daiichi Kensetsu
			• Seajacks International

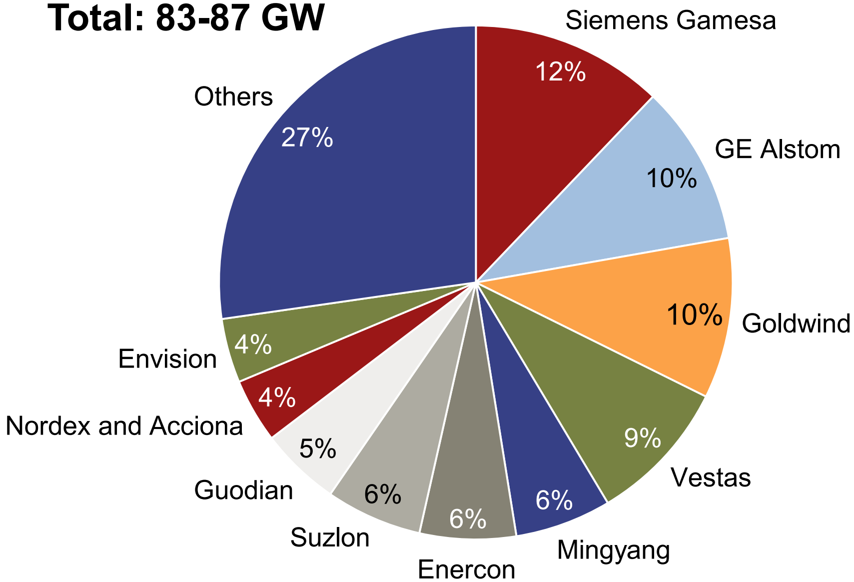
Sources: Bloomberg New Energy Finance, press search; A.T. Kearney Energy Transition Institute analysis

The onshore wind market is maturing and fragmented, while offshore is at an early stage of development but more concentrated

Turbine suppliers' market share

% of global manufacturing capacity in 2016–2017

Total: 83-87 GW

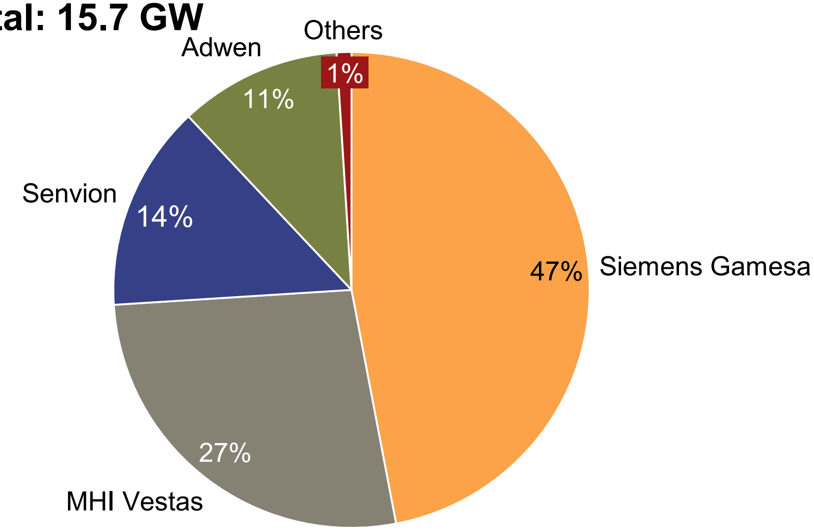


- Despite growing global and local demand, China's turbine market remains oversupplied with limited international expansion.
- Siemens Gamesa occupies the largest share in the wind turbine market followed by GE Alstom and Chinese company Goldwind.

Offshore turbine suppliers' market share

European market in 2017[1]

Total: 15.7 GW



- Europe's offshore wind industry is booming, with a 25% boost in capacity during 2017, with the majority of the installations taking place in the UK and Germany.
- Siemens Gamesa and MHI-Vestas are the leading offshore wind turbine suppliers by market share, followed by Senvion.

Note: Percentages may not resolve due to rounding.
[1] Europe is the largest offshore market with cumulative installations reaching 15.7 GW by the end of 2017, 84% of global offshore wind installations.
Sources: IEA (2016), "Renewable Energy, Medium-term market report"; HSBC (2018) "New giants of the sea by 2021", WindEurope (link): A.T. Kearney Energy Transition Institute analysis

5. Environmental and social impacts

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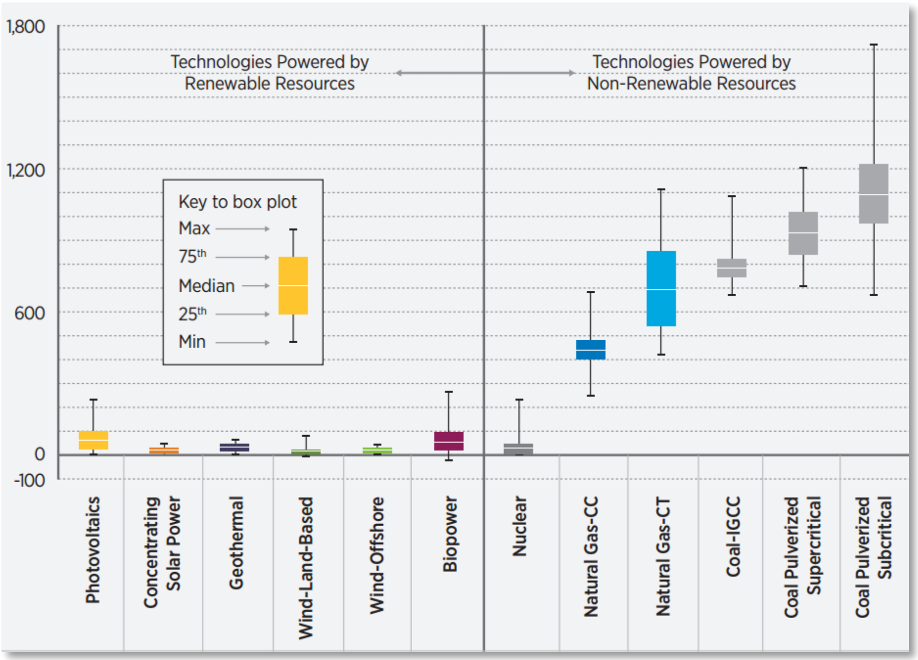
GHG emissions from wind are among the lowest of any renewable-energy technology, but its overall impact depends on power system integration

Life cycle greenhouse gas emissions

gCO_2eq / kWh



- **Wind does not directly emit GHGs or other pollutants.** However, median wind power emissions range between 7 and 52 g of CO_2 equivalent per kWh over a project's lifetime, depending on its location (7-52 and 8-31 gCO_2eq per kWh for onshore and offshore, respectively) and design (for example, type of foundations, type of drive-train).
- **This range is close to that of concentrating solar power, narrower than that of solar PV, and significantly lower than that of fossil alternatives;** the averages for US natural gas and coal-fired power plants are 500 and 1,000 gCO_2eq/kWh, respectively.[1]
- **Replacing fossil-fuel power capacity with wind power may result in an increase in the use of flexible back-up plants.** This could lead to a small reduction (well below 10%; in many cases below 3%) in GHG emissions benefits realized, although the impact would be highly system specific. In general, greater use of wind power will significantly reduce pollutants and GHG emissions, with cycling from fossil plants only modestly reducing those benefits.

Note: GHSs are greenhouse gases.
[1] Figures aim to provide an order of magnitude, as life cycle emissions are inherently specific to location and technology.
Sources: US DoE (2015), "Wind Vision: A New Era for Wind Power in the United States"; A.T. Kearney Energy Transition Institute analysis

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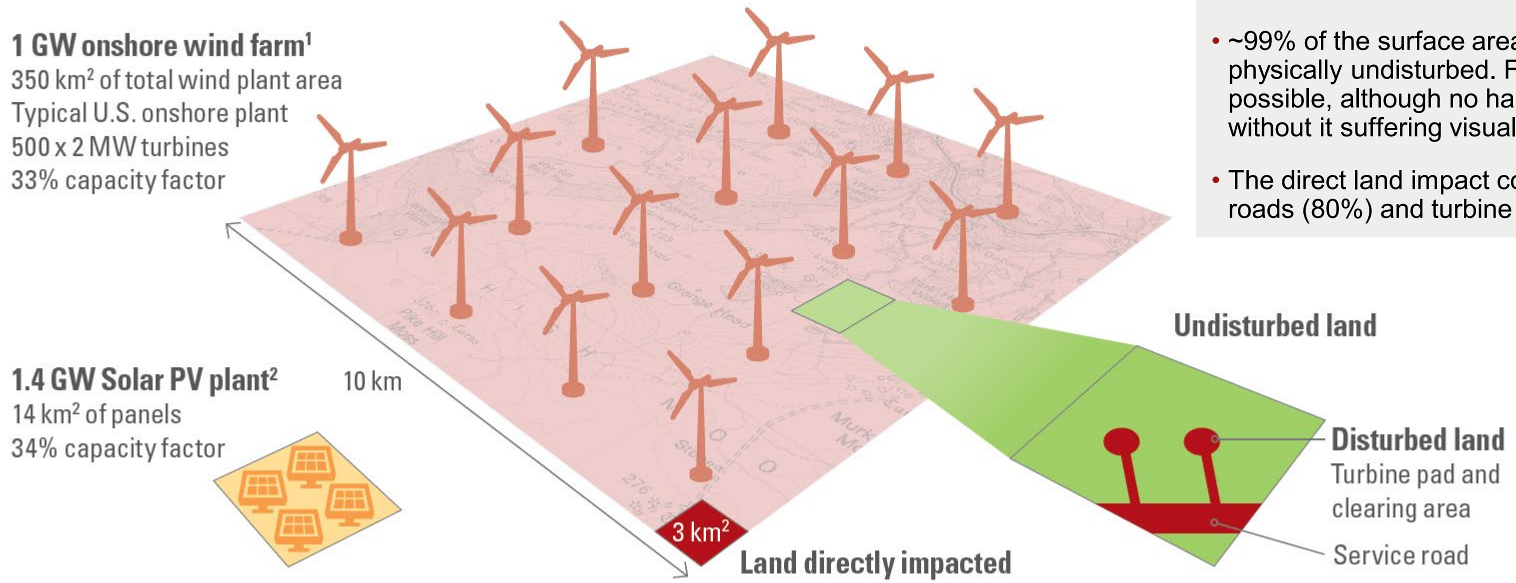
Wind has a lower capacity density than solar, but the footprint of turbines on wind farms is negligible and means the land may be put to other uses

Land-use comparison for two 330 MW-equivalent renewable-power plants



- The total plant area (defined as the convex hull containing all turbines) is very large because wind turbines must be erected at a minimum distance to each other in order to avoid the drop-in wind speed in the shadow of upwind turbines.[3]
- ~99% of the surface area of a wind farm is physically undisturbed. Farming or fishing is possible, although no habitation can be built without it suffering visual disturbance.
- The direct land impact consists mainly of service roads (80%) and turbine pads (10%).

[1] The weighted average capacity density of 172 existing US onshore wind farms is 35 ± 22 hectare/MW, whereas land directly impacted averaged 0.3 ± 0.3 ha/MW according to NREL (2009) “Land-Use Requirements of Modern Wind Power Plants in the United States.” Such a plant would meet the need of roughly 2.2, 6, and 0.8 million households in China, Brazil, and Germany, respectively.
[2] According to the US DoE, modern solar PV plants require 10 to 20 km² per GW of capacity installed, depending on the latitude. 10km² /GW in this example.
[3] Refer to appendix for more information.
Sources: NREL (2009) “Land-Use Requirements of Modern Wind Power Plants in the United States”; IPCC (2014), “Technology-specific cost and performance parameters”; NREL(2013), “Land-Use Requirements for Solar Power Plants in the United States”; A.T. Kearney Energy Transition Institute analysis

Currently wind incurs few social and environmental challenges except aesthetic and noise impacts

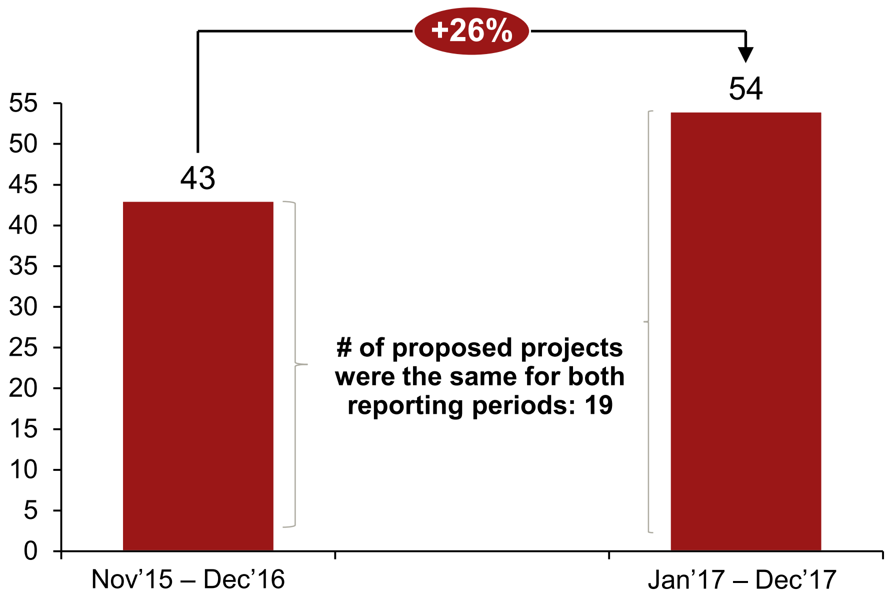
Main social and environmental impacts of wind

- The principal social issues for wind power are its aesthetic and noise impacts:
  - **Visual:** not in my backyard (NIMBY) syndrome raises major social acceptance challenges and may have negative impact in tourist areas.
  - **Noise:** generally restricted to 35 to 45 decibels at 300 meters and not of concern to humans after 800 meters.[1]
- Wind projects may also have minor detrimental impacts on wildlife and land use:
  - **Wildlife:** wind may result in habitat destruction and involve collisions with bats and birds (even though wind is thought to represent only 0.003% of anthropogenic bird death).
  - **Marine ecosystems:** wind farms may disturb mammals, notably due to the noise during construction. The long-term impact is yet under debate, as it could also attract new species thanks to artificial reefs where marine species can thrive.
  - **Wealth:** property value and recreational impact.
- Technology advances and siting wind farms offshore should avoid some of these impacts:
  - **Technology advances:** wind turbine manufacturers have worked on designs and aerodynamics that limit noise and the impact on wildlife.
  - **Offshore:** wind farms are being located further and further from shores, which should negate many of the public concerns relating to the visual and noise impact of turbines on coastal areas.
- **Public acceptance:** social impact studies indicate that public concern about wind energy is greatest directly after the announcement of a wind farm, while acceptance increases after construction, when the actual impacts can be assessed. People living closest to existing wind plants are sometimes more accepting than those who live further away and are less familiar with the technology.
- **Maintenance and Decommissioning**: Estimated lifespan of offshore and onshore wind turbines are 10 years and 25 years respectively. Sustaining a global fleet of >340,000 wind turbines will require major effort and disposal of heavy equipment can pose a significant environment challenge.
- **Mineral scarcity**: Copper (3 tonnes/MW) and silver are two of the critical minerals used to fabricate wind turbines. Huge ramp up in wind turbine installation can lead to shortage of these minerals.

[1] Wind turbines have to be built at least 300 meters from houses. At that distance, noise would be around 45 decibels, equivalent to the noise of an average air conditioner.
Sources: IPCC (2011), "Special report on renewable energy"; Mike Conley and Tim Maloney (2017), "Roadmap to nowhere"; A.T. Kearney Energy Transition Institute analysis

Onshore and offshore wind projects are increasingly facing resistance from the population in some countries

Increase in complaints and legal activity



- **In Australia**, the national wind farm commissioner and an independent scientific panel were instituted to investigate, monitor, and progress on the public complaints (Nov’15)
- In the last reporting year, complaints against the proposed wind farms jumped by 26% compared to the previous time frame (14 months) under observation

- Reasons often involved aesthetics (landscape footprint, viewshed); ecosystem (birds/bats, habitat); sound and health (audible sound, infrasound); annoyance and welfare (quality of life, property value).
- **In France:** Opposition to wind power is increasing, as shown by the evolution of the **percentage of appeals lodged** against wind projects: **70% in 2018 vs. 50% in 2013**. If 80% of actions are rejected, legal procedures were responsible for long project duration: it took on average 8 years to complete a wind project (compared to 3 to 4 years in Germany).
- **In Scotland:** Of the 436 wind turbine-related planning appeals since May 2007, 246 (56%) were refused and 191 (44%) were allowed. More than 44,000 objections to wind farm applications in the past 5 years have been recorded.
- **In the US:** In 2015, roughly 1.4 million households were estimated to be within five miles of an existing utility-scale wind turbine; this number is estimated to increase as wind capacity grows. As per Lawrence Berkeley National Laboratory (LBNL) survey of this population:
  - 8% of the population had negative attitudes within five miles
  - 25% of the population had negative attitudes within a half mile

Sources: Scottish Government - Wind turbine appeal decisions statistics (https://beta.gov.scot/publications/wind-turbine-appeal-decisions-statistics/), Lawrence Berkeley National Laboratory (2018) - National Survey of Attitudes of Wind Power Project Neighbors, Australian government National Wind Farm Commissioner annual reports (2017, 2016); A.T. Kearney Energy Transition Institute analysis

Both onshore and offshore wind projects face increasing protests in every part of the world

Recent quotes from the press

Onshore Offshore

***The Guardian**, May 2018*

Isle of Lewis residents protest against windfarm plan to raise turbine height to 200 metres – **"Detrimental effect on tourism"**

***Le Monde**, May 2018*

Everything is "under attack": Farm projects as well as the regulatory texts that organize the sector at national or even European level.

***Esmerk Danish News**, Oct 2018*

Planned offshore Jammerland Bugt project in Denmark is being opposed by Swedish Environmental Protection Agency as wind turbines **may affect birdlife on the Swedish coastline**

***Derry Journal**, Oct 2018*

*Anti-windfarm campaigner has called on **legislators to revisit the laws regarding the development of turbines** to prevent the saturation of the North West with the renewable energy*

***MPR**, Sept 2018*

.. ramping up turbine size for efficiency but **the skyscraper-sized machines are also attracting more public opposition**….turbines are an "intrusion," interrupt views, and produce noise

***Esmerk Danish News**, Feb 2018*

Mayor in the municipality of Assen in Denmark, argued in favour of a **change in Danish legislation which will prevent offshore wind turbines within 20 kms (from 4 kms now) of the coast**

***The Canadian Press**, July 2018*

Ontario government cancelled 758 renewable projects including a wind project. **More than 80 per cent of voters in a community referendum had rejected wind turbines**

***The Australian**, Sept 2018*

Despite being compliant with state laws an independent review accepted complaints that noise from a Gippsland wind farm was causing harm…**findings have implications for the industry**

***The Press and Journal**, May 2018*

Sandend residents have opposed offshore wind farm cables at the village beach. **Sands are seen as a "jewel in the crown" for surfers and villagers fear infrastructure would destroy them**

Sources: Press review; A.T. Kearney Energy Transition Institute analysis

6. Grid integration

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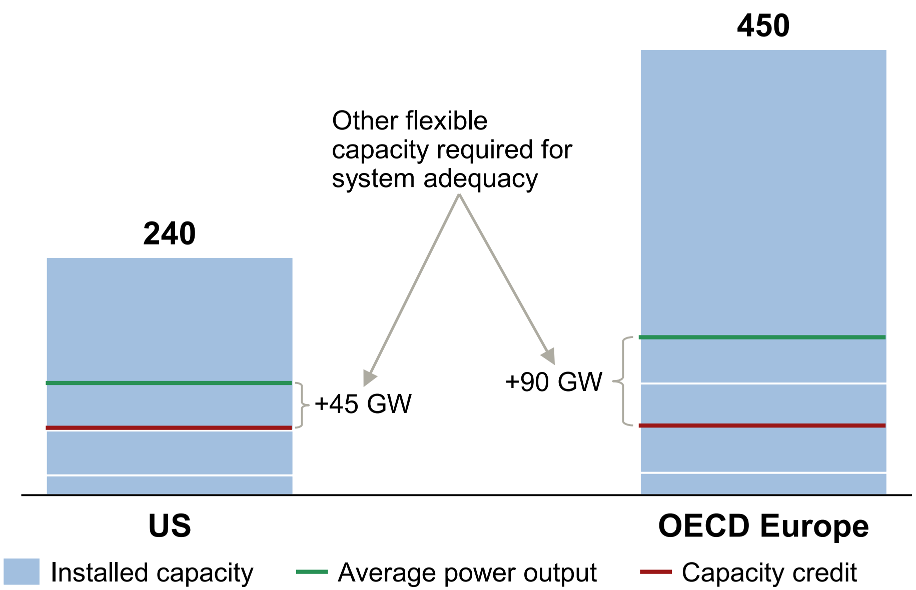
Wind power increases flexibility needs without contributing significantly to the pool of resources that can adjust to just-in-time requirements

Installed vs. reliable capacity of additional renewables in 2035

GW



How to read this graph:

- For OECD Europe, this means that out of the 450 GW of installed capacity expected in 2035, only 22.5 GW can be relied on to meet peak demand, according to capacity credits granted by system operators, while average annual output is around 112 GW. From this, it can be estimated that ~90 GW of additional flexibility capacity (in other words, the difference between average annual output and capacity credit) must be found elsewhere to ensure system adequacy.

- **Wind power intermittency makes power demand–supply matching more difficult. Wind power tends to increase flexibility needs.** The latter are often divided into three groups, depending on time scale: (i) grid stability, which mainly refers to the control of frequency and voltage in order to comply with the grid's technical limits over periods of seconds; (ii) grid balancing, which refers to load changes over minutes or days that must be balanced; and (iii) grid adequacy, which refers to capacity needed to meet peak demand even under the most extreme conditions in the long term (months to years). The increasing need for flexibility is apparent by observing the residual load (that is, demand minus wind and solar generation).[1]
- **Wind power makes a limited contribution to the flexibility pool of resources,** as it cannot be relied upon to produce energy at a given time with any certainty. This is mirrored by the low capacity credits that are granted by system operators.
- **To mitigate the integration costs of growing variable renewables, system operators will have to draw upon flexibility resources.** Flexibility management can be optimized by perfecting models for forecasting output from wind plants, fine-tuning market regulations, and refining the design of power systems. But additional flexibility will be needed in the form of demand-side participation, better connections between markets, greater flexibility in base-load power supply, and electricity storage.[1,2]

[1] This corresponds in most cases to fossil-fuel back-up.
[2] For more information, refer to A.T. Kearney Energy Transition Institute Hydrogen-based energy storage FactBook (link).
Sources: IEA (2014), "Renewable Energy, Medium Term Market Report 2014"; NREL (2012), "Renewable Electricity Futures Study"; IEA (2012), "World Energy Outlook 2012"; A.T. Kearney Energy Transition Institute analysis

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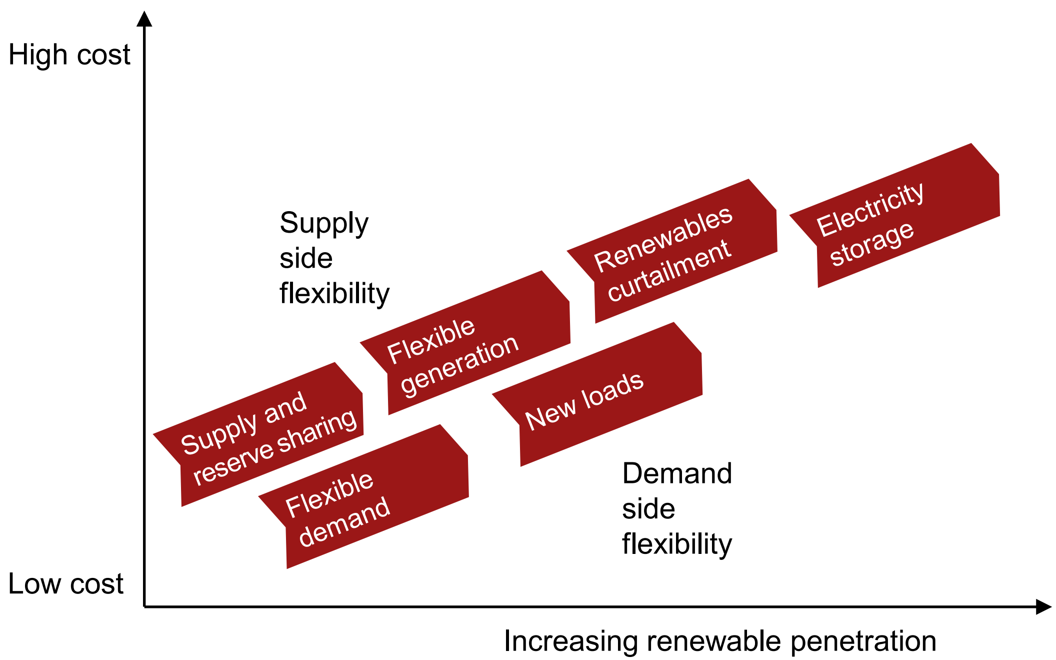
Increasing wind penetration requires flexibility sources, which vary in costs

The flexible curve

Illustrative, relative order is conceptual



- **Wind power—**and solar photovoltaic**—increase the need for flexibility by** introducing variability and uncertainty to the supply side of the power system. Up to a certain penetration rate, the integration of wind and solar into the power mix can usually be managed with existing flexibility sources. The threshold depends on the system's location and characteristics, and ranges roughly between 15% and 25%.
- **To mitigate the increasing integration costs resulting from growth in variable renewables, system operators will have to draw upon alternative flexibility resources.** Given that it is normal practice to utilize the cheapest flexibility options first (for example, flexible demand), this is likely to incur increasing costs.
- **Alternative resources (see graph) are known and are already being used to some extent** (for example, dispatchable power plants, demand response from industry, better market interconnections, electricity storage), but their role is expected to grow in importance, and their task should be made easier by improved market rules and processes for system management.

Sources: NREL (2010), "The Role of Energy Storage with Renewable Electricity Generation"; A.T. Kearney Energy Transition Institute (2015), "Introduction to Smart Grids FactBook"

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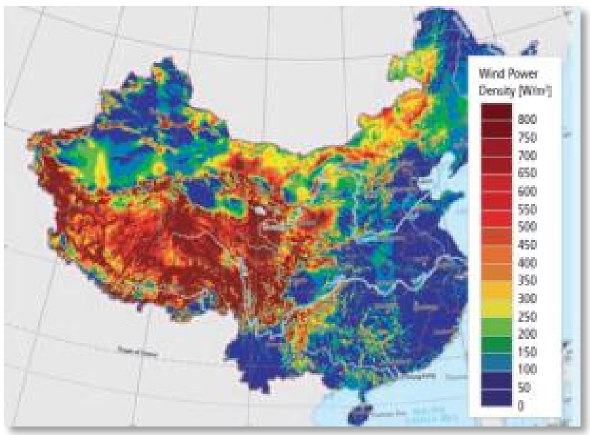
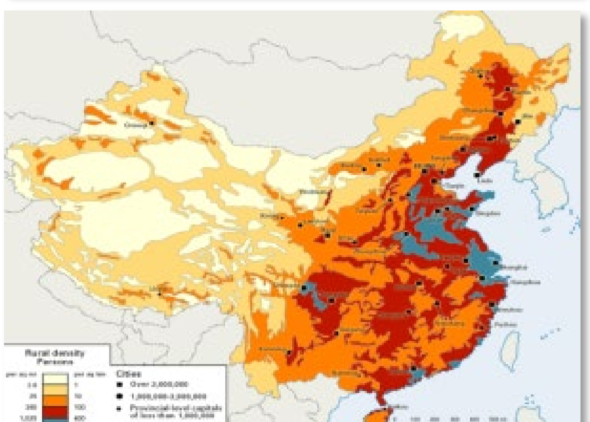
The quality of wind resources is location specific, with the best locations often found far from the load center

Wind resources and population misalignment – illustration for China

W/m²; *people /km²*



Wind resources
W /m²



Population density
people /km²

- **Wind resource locations tend to be misaligned with large demand centers,** requiring the construction of new long-distance transmission lines.
- **Due to the impact of wind quality on economics, additional transmission infrastructure is sometimes economically justified.**
- **However, additional long-distance transmission lines face multiple challenges** including (i) technical challenges due to thermal, voltage, and transient constraints on long lines; (ii) time scale challenges due to a longer development time than wind generation (8 to 15 years vs. ~3 years, respectively); (iii) economic challenges, as transmission and distribution (T&D) costs are supported by end-consumers and already account for a large proportion of electricity prices; and (iv) institutional barriers to siting and paying for transmission systems.

Sources: IPCC (2011), "Special report on renewable energy"; A.T. Kearney Energy Transition Institute analysis

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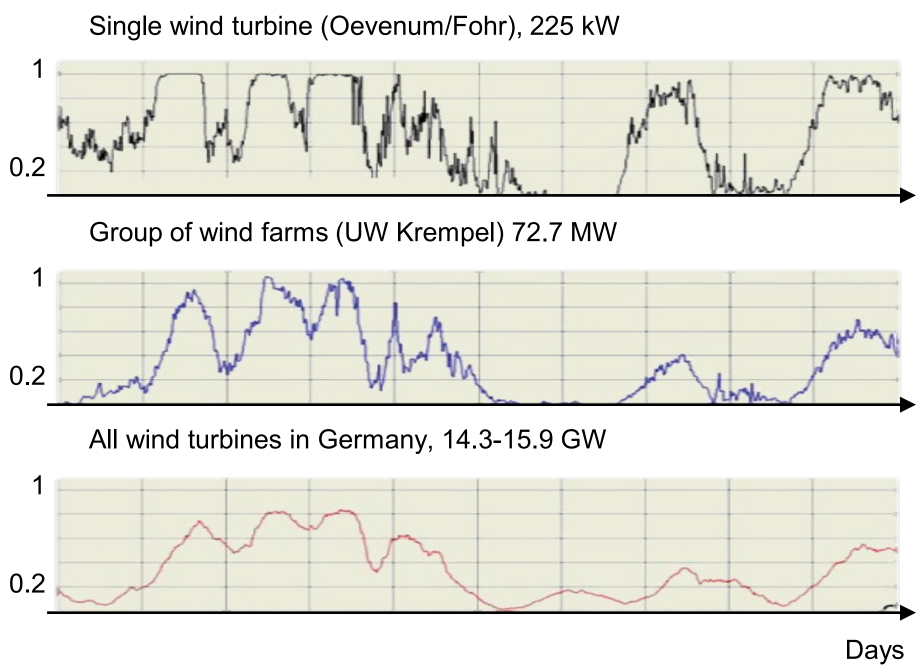
Wind power can be smoothed out geographically to reduce unpredictability but may in some instances require expensive interconnection lines

Single wind turbine variable production and geographic smoothing across Germany

Nominalized power, 2004

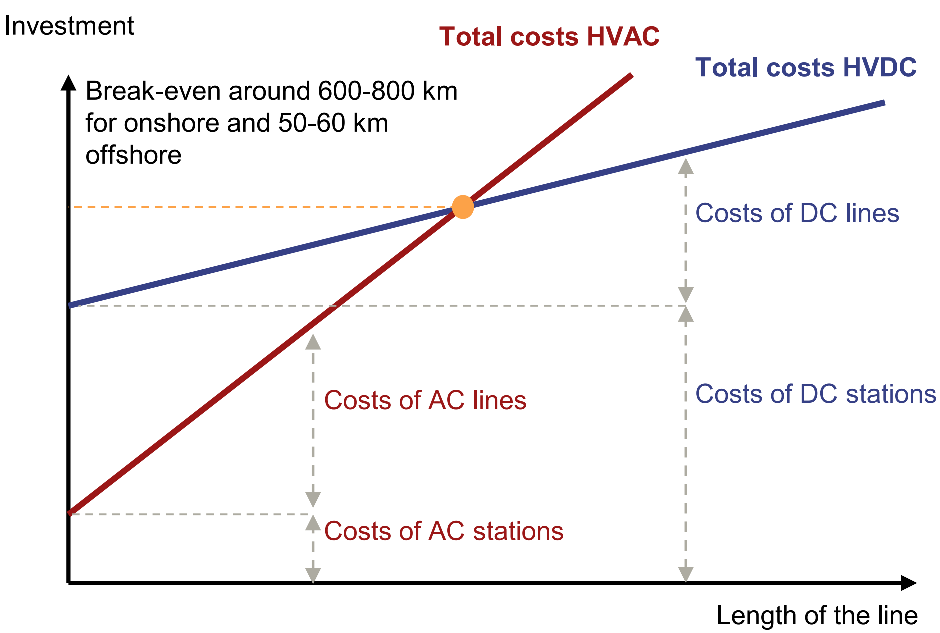


- Geographic dispersion of wind farms can smooth out output over a large area that may contain more than one prevailing weather system (for example, Atlantic and Baltic Sea in Europe), balancing out local events, such as storms.

Sources: IPCC (2011), "Special report on renewable energy", TradeWind (2009), "Integrating Wind - Developing Europe's power market for the large-scale integration of wind power"; A.T. Kearney Energy Transition Institute analysis

Direct current and high-voltage transmission technologies are playing a crucial role in helping the development of offshore wind

Illustrative arbitrage between HVDC and HVAC transmission lines



- **The best wind resources are not necessarily close to the main consumption centers. In the early stage of onshore wind's development,** wind-produced electricity was usually consumed in the region where it was produced. However, the development of larger, centralized onshore wind farms, and—more significantly—of offshore wind projects in deep waters further from shore, could be enhanced by long-distance and submarine electricity transmission systems.
- **Over long distances, high-voltage direct current (HVDC) has lower capital costs than AC technology.** Above a certain distance, the relatively high fixed-station costs associated with HVDC are offset by savings in conductor cables—HVDC requires fewer and thinner cables than AC. HVDC also tends to have lower distribution losses than conventional AC.
- **In addition, HVDC can connect asynchronous grids and is virtually the only solution for long submarine cables.** AC is usually limited to a few tens of kilometers (~60-80 km) and DC is believed to be cheaper for any project above 50 km. In addition to requiring more modest and cheaper subsea infrastructure, DC has the ability to isolate farms from faults in the grid and to reduce visual impact on land, with one cable instead of two.

Notes: AC is alternating current; DC is direct current.
Sources: A.T. Kearney Energy Transition Institute (2015), "Introduction to Smart Grids FactBook"; MIT (2011), "The Future of Electric Grid"; ABB (2011), "MITEI Symposium, Grid integration of Renewables: Challenges & Technologies"

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High-voltage direct current transmission projects are helping drive integration of large-scale wind and solar power generation

Examples of HVDC offshore wind projects

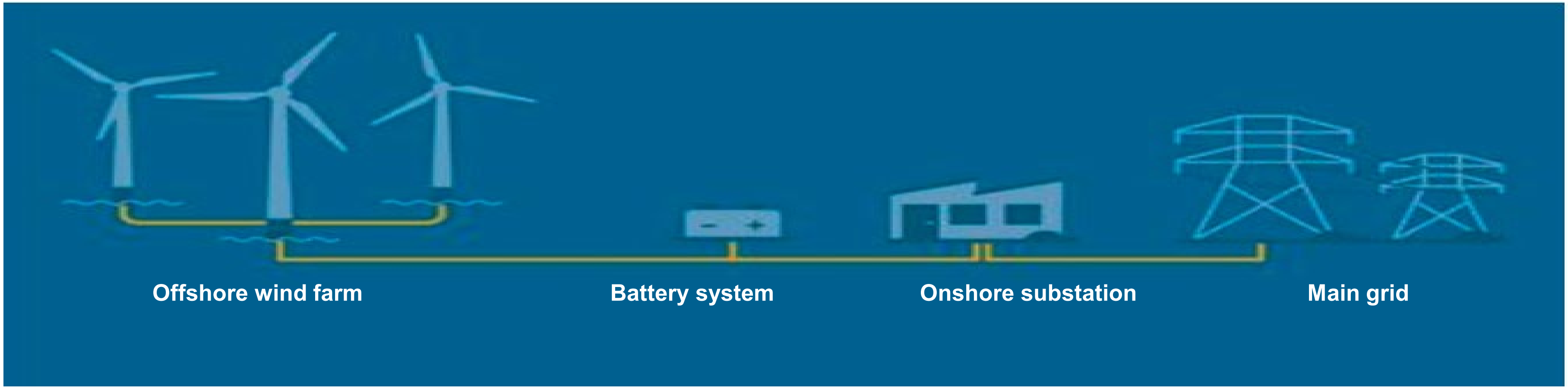
Fig: Atlantic Wind Connection

- Europe is leading the way in interconnecting offshore wind via HVDC, with a few operational projects in the North Sea. The**. DolWin beta is the world's most powerful offshore converter station in the North Sea.** The 320-kilovolt converter station, housed on an offshore platform, has a 916 MW power transmission capacity, making it the world's most powerful installation of its kind, enough to power around 1,000,000 households with clean energy. The wind farms are connected with AC cables to an HVDC converter station installed on an offshore platform in the North Sea. The power they generate is transmitted through a 45-km-long DC sea cable system and a further 90-km-long land cable to an HVDC onshore station at the grid connection point of Dörpen West.
- **HVDC technology will form an essential part of integrated European offshore grid solutions.** North Sea Countries Offshore Grid Initiative (NSCOGI) is currently being developed by the energy ministries of Belgium, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands, Norway, Sweden, and the UK with support from ENSTO-E, ACER, European Commission, and national regulators.
- **The Atlantic Wind Connection** is a proposed offshore, undersea transmission line that will span the mid-Atlantic region and will support 8000 MW by 2030 offshore wind targets set out by Massachusetts, Rhode Island, New York, New Jersey and Maryland. Partners include Google, Bregal Energy, Marubeni Corporation, and Elia System Operator NV. However, high cost of transmission lines are key challenges to the immediate implementation of the project.

Notes: HVDC is high-voltage direct current; DC is direct current; AC is alternating current.
Sources: EPRI journal (2016), "HVDC on the rise"; Atlantic Wind Connection website, https://new.abb.com/systems/hvdc/references/dolwin2, https://www.eenews.net/stories/1060109405, https://www.forbes.com/sites/kensilverstein/2018/11/14/despite-hurdles-offshore-wind-energy-potential-is-generating-hype-in-the-u-s/#6965d8108422, A.T. Kearney Energy Transition Institute

Wind farms are now being developed with electricity storage capacities to address intermittency

Integrating battery storage into offshore wind farms



- Wind still lags far behind solar when it comes to storage adoption. However, an interest in combining storage with wind has been gaining momentum recently. **Orsted (through Bay State Wind partnership with Eversource)** has announced a collaboration with NEC Energy Solutions to develop an energy storage solution for its 800 MW wind / 55 MW – 110 MWh energy storage combined offshore project in Massachusetts. In November 2017, **Toshiba** installed a 2 MW lithium-ion battery system near NRG Yield's Elbow Creek Wind Farm in Howard County, Texas. The system is intended to correct short-term grid imbalances from intermittent wind generation on the Electric Reliability Council of Texas (ERCOT) grid.
- **Equinor (in partnership with Masdar – Abu Dhabi Future Energy Company)** has installed, and will soon begin testing, a new 1 MW battery system designed to store electricity generated by Hywind Scotland, the world's first commercial-scale floating wind farm.
- **KK Wind Solutions**, a Danish wind systems developer, is planning to use turbine-based batteries to reduce output fluctuations by 90 percent through storage levels amounting to about 8 percent of total wind farm capacity. The purpose of the project is to develop a new modular battery storage solution, which is integrated into the wind turbine itself. **Vestas, PowerCon, and Aalborg University** are other project partners.
- **Siemens Gamesa plans to commission its 30 MWh electric thermal energy storage facility (ETES)** in Hamburg-Altenwerder in 2019. The facility converts wind power output to heat and then stores the surplus energy in stones. ETES facilities have reduced construction and operations costs compared to the usual level for battery storage and it is stated that in commercial use, energy can be produced at below €0.10/kWh.

Sources: Press search; A.T. Kearney Energy Transition Institute

Appendix & bibliography

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Acronyms

AC: Alternating current
AWE: Airborne wind energy
CAGR: Compound annual growth rate
CAPEX: Capital expenditure
c-Si: Crystalline silicon
DC: Direct current
DSO: Distribution system operator
EPC: Engineering, procurement, and construction
EJ: Exajoules (10^{18} joules)
EOI: Expression of interest
EU: European Union
FIT: Feed-in tariff
gCO_{2eq}: Gram of CO_2 equivalent
GHG: Greenhouse gas
GW: Gigawatt
GWEC: Global Wind Energy Council
HVAC: High-voltage alternating current
HVDC: High-voltage direct current
Hz: Hertz
IEA: International Energy Agency
IRENA: International Renewable Energy Agency
KW: Kilowatt
KWh: Kilowatt-hour
LCOE: Levelized cost of electricity
m/s: Meter per second
MW: Megawatt
MWh: Megawatt-hour
NREL: National Renewable Energy Laboratory
NIMBY: Not in my backyard
NREL: National Renewable Energy Laboratory
O&G: Oil and gas
O&M: Operation and maintenance
OECD: Organisation for Economic Co-operation and Development
OPEX: Operational expenditure
PBL: Planetary boundary layer
PMG: Permanent magnet generator
PPA: Power purchase agreement
PTC: Production tax credit
P2G: Power-to-gas
PV: Photovoltaic
R&D: Research and development
R,D&D: Research, development, and demonstration
ROW: Rest of the world
RPS: Renewable portfolio standard
T&D: Transmission and distribution
TSO: Transmission system operator
TSR: Tip speed ratio
UK: United Kingdom
US DoE: United States Department of Energy
UNEP: United Nations Environmental Programme
US: United States
WACC: Weighted average cost of capital
WIPO: World Intellectual Property Organization

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Slide 11: CNET (link). Global atlas of wind speed over land and over water, in meters per second.
Slide 15: Robert W. Righter (1996), "Wind Energy in America: A History“ (link). The first wind turbine generating electricity was built in Ohio in 1888. It was an 18 m tall structure rated at 12 kW.
Slide 23: Bestweb, Shutterstock (link). Photo of wind power installation on a sunny day.
Slide 39: Bestweb, Shutterstock (link). Gearbox of a wind turbine - room arrangement.
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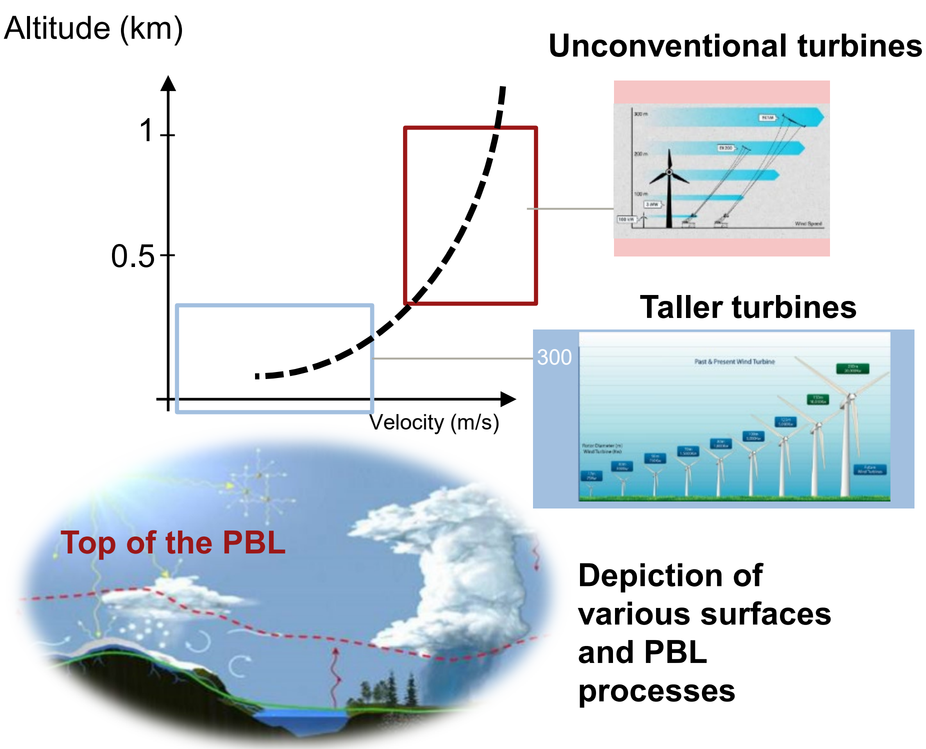
Appendix 1
Interest in high-elevation and airborne wind turbines is strong because of the influence of the Earth's surface on the planetary boundary layer

Illustration of the impact of the planetary boundary layer on wind velocity



- **The troposphere—the lowest zone of the atmosphere—can be divided into two parts: the free troposphere and the planetary boundary layer** (PBL).[1] The latter extends upward from the surface to a height that ranges anywhere from a few hundred to 3,000 meters, depending on the location. The PBL is characterized by the fact that it is directly influenced by the presence of the Earth's surface, responding to forces such as solar heating or evapotranspiration.
- **Within the PBL, forces generate turbulence that have an impact on the wind industry.** In addition to wind turbulence (for example, changes in wind speed and wind direction), which affects power generation, the PBL makes weather prediction more complex since it involves complex calculations relating to surface conditions.[2]
- **To mitigate or circumvent the impact of PBL, the wind industry has explored the use of taller or airborne wind turbines, capable of** harnessing faster and more regular winds, with enhanced predictability.[3]

[1] The planetary boundary layer (PBL) is also known as atmospheric boundary layer.
[2] Power production increases with wind speed. For more information, refer to slide 72.
[3] For more information on unconventional wind turbines, refer to slides 32 and 76.
Sources: A.T. Kearney Energy Transition Institute; MET, "The Planetary Boundary Layer: a Definition" (link); picture credit, National Oceanic & Atmospheric Administration (link)

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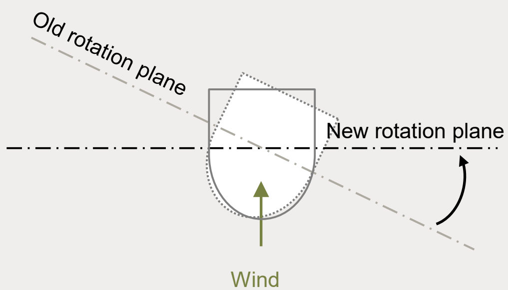
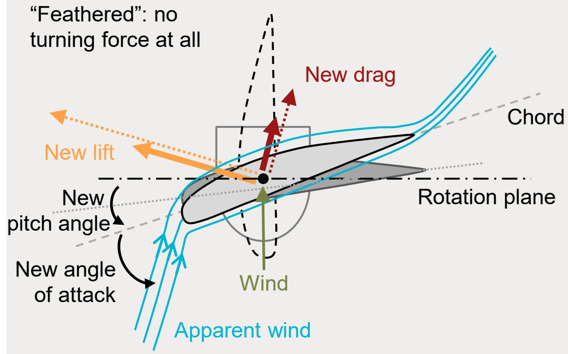
Appendix 2
There are three main ways to regulate power output and to optimize power production: yaw, pitch, and stall control

Yaw control



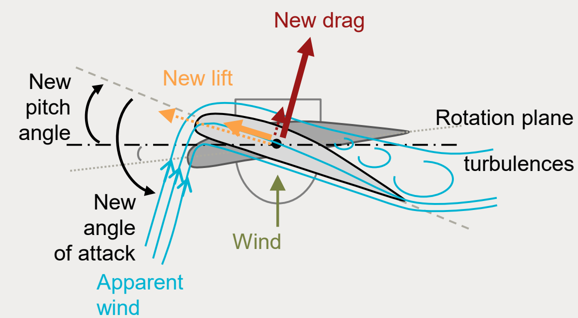
- Yaw angle corresponds to the rotation of the nacelle around its vertical axis (along the tower).
- Therefore, controlling yaw angle enables turbines to always face the wind, for optimum power production.
- Small nacelles can be oriented with a wind vane (weathercock). For large nacelles, anemometers calculate the orientation of the wind and the turbine is accurately aligned with the gearbox.

Pitch control



- The pitch angle is the angle between the rotation plane and the chord of the blade.
- Controlling the pitch angle enables the power output to be regulated.[1] This is because lift and drag are a function of the angle of attack, which itself depends on the pitch angle.
- This angle is controlled by gearboxes that dynamically orient the turbine blades. Feathering the blade (facing wind = parallel to flow) minimizes drag and prevents rotation.

Stall control



- The angle of attack can also be oriented to create a phenomenon known as stall: engineered turbulence removes the low pressure on the upper surface of the wind blade.
- Stall control can be passive (the blade is designed so that turbulence occurs when wind speeds are too high) or active (as in pitch control, blades are oriented to create this stall effect). Stall is less accurate and less effective than pitch control, due to its turbulent nature.

[1] Controlling the angle of pitch enables wind turbines to produce more than their rated power, hence providing the option of having both negative and positive reverses—to shut down the turbine if there is an excess of power injected into the grid or to increase power supply to its maximum rated level if there is a shortage of electricity, assuming suitable wind conditions.

Sources: A.T. Kearney Energy Transition Institute; Danish Wind Industry Association (link); Energy Plus (link); Gurit "Wind Turbine Blade Aerodynamics" (link)

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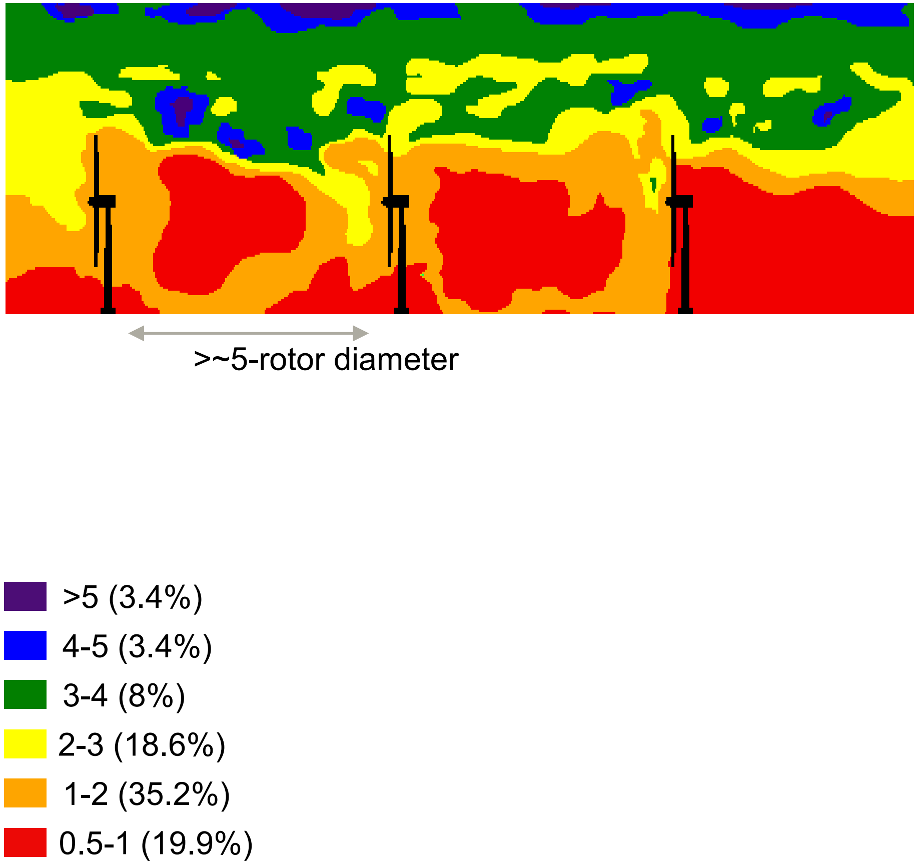
Appendix 3
Wind turbines must be spaced at suitable intervals to ensure the optimal harnessing of wind energy

Distance between wind turbines required in wind farms

Wind speed (m/s)



- **Wind turbines harness the power of the wind energy, and therefore slow the wind down.** Since the power is proportional to the cube of the velocity, reduced speed leads to reduced power. Therefore, wind turbines must be installed at suitable distances to ensure maximum power optimization. This distance is generally considered to be a minimum of the diameter of at least five rotors (5-9).
- **The design of wind farms can be optimized by assessing the prevailing wind** and finding the best possible orientation. Thanks to yaw control, wind turbine hubs can be oriented toward the wind, thus reducing the average minimum distance required between wind turbines from five to roughly three rotor diameters (3 to 5).

Sources: A.T. Kearney Energy Transition Institute; University of Ottawa, “Wind Energy Technology” and “Wind Turbine Generators for Wind Power Plants”; UPPSALA Universitet, Ivanell (link)

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Appendix 4
Several technologies can be used to convert mechanical energy into electricity, depending on grid requirements

Classification of turbine components according to rotation speed

		Blades	Generator[1]
Rotation speed	Fixed	**Mechanically fixed blades** • Power control is not possible (except by disconnecting the turbine) and optimization options are limited: the rotor speed is directly proportional to the wind speed.	**Fixed-speed generators**[2] • Fixed-speed generators, such as type 1, have a frequency proportional to their rotational speed.[2] Thus, the rotor speed must be controlled in order to meet the grid's frequency requirements.
	Variable	**Mechanically orientated blades** • Power production/energy harnessing can be adjusted because of, for example, pitch-angle control: the rotor speed can be adjusted to optimize the output of a wind turbine, depending on wind velocity.	**Variable-speed generators** • Variable speed generators, such as type 2, are equipped with variable resistors and electronics.[2] Variation in resistance directly impacts the current. Thus, controlling resistance allows for rapid power control to ease integration under gusting conditions or in the event of grid perturbations.

[1] In order to maintain a 50 Hz frequency while preserving a good tip speed ratio (function of the invert of the wind speed, critical for efficiency), induction generators with dual windings generate electricity through either 4 or 6 poles at rotating speeds of 1,500 or 1,000 rpm, respectively. For a 60 Hz frequency (for example, in the US), the nominal rotation speeds are 1,800 and 1,200 rpm for faster and slower wind speeds, respectively.
[2] There are five types of wind generators. Types 1 and 2 are the most common.
Sources: A.T. Kearney Energy Transition Institute; Paul Gipe (2004), "Wind Power: Renewable Energy for Home, Farm, and Business"; NREL (2013), "Fixed-Speed and Variable-Slip Wind Turbines Providing Spinning Reserves to the Grid"; University of Ottawa, "Wind Energy Technology" and "Wind Turbine Generators for Wind Power Plants"

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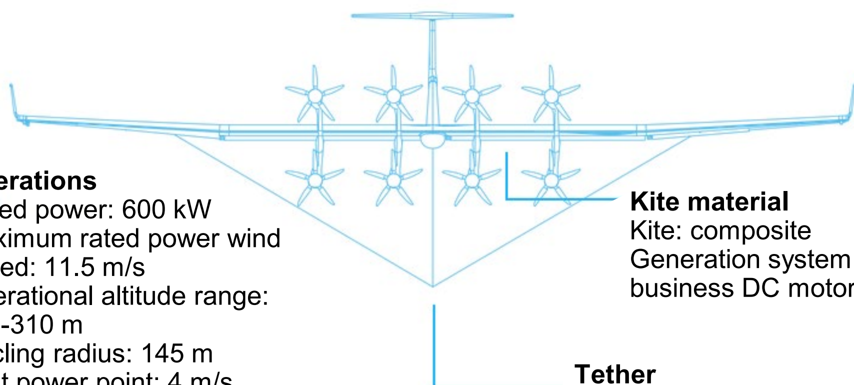
Appendix 5
Makani's energy kites are rigid, airborne turbines with onboard generation, which aim to extract faster wind speeds and lower investment costs

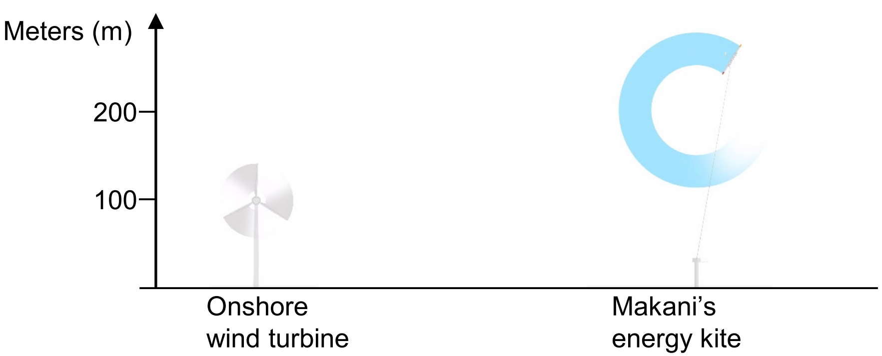
Makani 600 kw energy kite



Operations
Rated power: 600 kW
Maximum rated power wind speed: 11.5 m/s
Operational altitude range: 140-310 m
Circling radius: 145 m
First power point: 4 m/s

Kite material
Kite: composite
Generation system: 8 business DC motors

Tether
Structure: carbon fiber
Conductor: aluminum



- **How does it work?** Makani's kite simulates the tip of a wind turbine's blade. Rotors on the kite act like propellers on a helicopter, launching it from the ground station. The tether connects the kite to the ground station, and transfers power and communications between the kite and ground station in both directions. The ground station holds onto the tether and is used as a resting place for the energy kite when not in flight. The ground station occupies less ground space than conventional wind turbines and is significantly smaller. The computer system uses GPS and other sensors to guide the kite to the flight path with the strongest and steadiest winds for maximum energy generation.
- **Rationale.** The Makani system aims to eliminate most of the materials required in conventional wind turbines in order to reduce costs; harness higher wind speeds because of the greater altitude; and produce more power than conventional turbines at any given speed. Makani can bring electricity to locations where access to energy is limited (by exploiting energy at higher altitudes) and is viewed as one of the options that might alleviate energy poverty.

Sources: Makani – Google (link) [last access on August 2015]; A.T. Kearney Energy Transition Institute analysis

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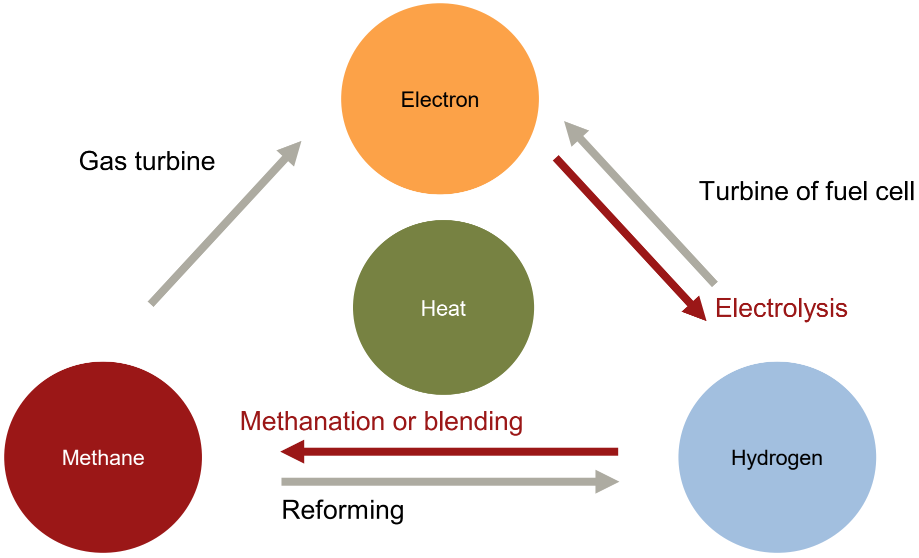
Appendix 6
The increasing penetration of wind power has led to a growing interest in the power-to-gas concept in Europe

Power-to-gas concept



- **The increasing use of wind and solar PV is bringing the potential and limitations of existing storage applications into sharper focus.**[1] Hydrogen-based storage technologies may be an effective way of absorbing peaks in renewable electricity supply and avoiding the wastage of large quantities of renewable power. Hydrogen is versatile and its volumetric energy density is superior to that of alternative methods of energy storage, especially when natural sites for pumped hydro storage are not available or are already occupied.[2]
- **In addition to hydrogen's use as a fuel or as a chemical feedstock, there is a growing interest in power-to-gas** (P2G), which was conceived as a way of using the gas grid to store renewable electricity.[1] But, in practice, P2G does more than this. Its benefits include the "greening" of end uses of natural gas, such as heat generation. It also improves the flexibility of the energy system by pooling gas and power infrastructure. Power and gas grids can be linked in two ways: blending, which involves injecting hydrogen into the gas grid, and methanation, which is the conversion of hydrogen and CO_2 into methane, also known as synthetic natural gas. There are currently several large-scale demonstration projects, especially in Germany (such as Audi in Werlte).
- **Even if power-to-gas elegantly binds networks and energy sources together, its economics remain highly uncertain.** Hydrogen produced from electrolysis is currently too expensive, ranging from $120-500 per MWh, depending on the utilization rate and electricity prices. However, it should be investigated as a solution for decarbonizing heating and mobility, and several countries are considering this option.

[1] For more information, refer to A.T. Kearney Energy Transition Institute Hydrogen FactBook (link).
[2] Although the volumetric energy density of hydrogen is inferior to those of hydrocarbons, hydrogen-based energy storage is one of the only technologies capable of compensating for several weeks of windless conditions.
Source: A.T. Kearney Energy Transition Institute

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Appendix 7
The wind industry could capitalize on oil and gas best practices to ensure efficient and safe offshore operations

Oil and gas best practices

- The offshore wind industry is facing greater technical challenges as larger turbines are sited in deeper, more hostile waters further from the coast. Financial investments are becoming more onerous too.
- The oil and gas industry has undergone a similar process, moving from onshore operation to shallow waters and deep waters—developing a profound knowledge of the requirements and peculiarities of the offshore environment.
- Not everything is transferable, but synergies do exist and lessons can be learned.
- Oil and gas offshore facilities, especially in their late life, could also be used to host wind turbines and wind substations.

Oil and gas best practices transferable to offshore wind		
	Safety	• Fit for purpose equipment (for example, lifesaving appliances and firefighting equipment) • Safety processes and tools (for example, emergency response plan, audits, risk-assessment methods)
	Investment arbitrage	• Remote control (for example, remote or on-site maintenance) • Access (for example, air or marine access)
	Operating performance	• Production performance (for example, shutdown management) • Marine logistics (for example, vessels fleet management) • Inspection (for example, diving, remote operating vehicle)

Sources: DNV (2010), “Access to offshore wind facilities - What can we learn from other industries?”; Equinor Hywind Demo website (link); A.T. Kearney Energy Transition Institute analysis

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