LEADING THE ENERGY TRANSITION

FACTBOOK

Wind Power

SBC Energy Institute

May 2013

Schlumberger | SBC Energy Institute

Compiled by the SBC Energy Institute

About SBC Energy Institute

The SBC Energy Institute, a non-profit organization founded in 2011 at the initiative of Schlumberger Business Consulting (SBC), is a center of excellence for scientific and technological research into issues pertaining to the energy industry in the 21st century. Through its unique capability to leverage both Schlumberger's technological expertise and SBC's global network of energy leaders, the SBC Energy Institute is at the forefront of the search for solutions to today's energy supply challenges. It is overseen by a scientific committee comprised of highly experienced individuals in the areas of natural and applied sciences, business, and petroleum engineering.

About *Leading the Energy Transition* series

"Leading the energy transition" is a series of publicly available studies on low-carbon energy technologies conducted by the SBC Energy Institute that aim to providing a comprehensive overview of their development status through a technological and scientific prism.

About the Wind Power factbook

This factbook seeks to summarize the status of the wind industry and its prospects, list the main technological hurdles and principal areas for research and development, and to analyze the economics of this technology.

This factbook has been reviewed by Dr. Fort Felker, Director of the National Wind Technology Center from the National Renewable Energy Laboratory (United States).

For further information about SBC Energy Institute and to download the report, please visit **http://www.sbc.slb.com/sbcinstitute.aspx**, or contact us at **sbcenergyinstitute@slb.com**

Wind power capacity has accelerated rapidly over the last decade in the OECD, China & India

Global wind-power capacity has increased by an average of 24% a year for the last 10 years to reach 282 GW at the end of 2012. Growth has been driven by onshore technology, which accounts for 98.1% of capacity. China and the US each accounted for 29% of capacity additions in 2012, overtaking Germany and Spain as the principal driver of market growth.

Despite this impressive deployment, wind is accounting globally for no more than 4.4% of total installed capacity, supplying less than 2% of global electricity.

Going forward, wind growth is yet expected to continue, doubling capacity to about 500 GW by 2017. Mainly as a result of improvements in grid-connection delays in China, growth in wind generation should exceed capacity growth because of increasing load factors. Despite European and Chinese interest, offshore should not account for more than 5.3% of global wind capacity in 2017.

The IEA estimates that in order to create an energy system capable of limiting the average global temperature increase to 2°C, wind will need to be meeting 15% to 18% of global electricity demand by 2050. Even in the most conservative forecast (6°C increase, business-as-usual case), wind is expected to play a greater role in the power mix, meeting at least 5.2% of electricity demand in four decades' time.

Onshore wind is nearing competitiveness, while the economics of offshore projects will depend on cost reductions once the present demonstration phase is complete

As with most other renewables, upfront investment accounts for the bulk of the full cost of wind power, although operation & maintenance costs are more significant in offshore projects. Investment costs are significantly lower for onshore than for offshore, ranging respectively from $1300-$2500/kW and from $3200-$6000/kW.

This gap can be explained by offshore wind's relative lack of maturity, as well as the marine environment's need for expensive foundations and costly grid connections. However, a limited 8% decrease is expected for onshore investment costs by 2020, while offshore should benefit from a 43% drop in investment costs.

If wind conditions are favorable, onshore projects are becoming competitive, with a levelized cost of electricity (LCOE) of $50-150/MWh. Offshore wind is not yet competitive, with an LCOE of $100-300/MWh, varying according to the load factor. In addition, because of the cost structure of offshore wind, the technology's economics are highly sensitive to project delays. Grid-integration costs have not been taken into account in either case. Cost estimates are system specific and dependent on the wind resources available, but, in general, the higher the wind penetration, the higher the integration costs.

In parallel with the expansion in capacity, wind finance took off during the 2000s. The onshore wind value chain is fragmented, with a significant presence of non-OECD players. Offshore is dominated by northern European companies.

Wind Research, Development & Demonstration (RD&D) efforts are focused on maximizing energy capture, promoting the use of offshore wind power and solving network-integration difficulties arising from wind's intermittency

After years of growth in turbine size, a new trend is emerging: the size of offshore turbines is continuing to increase, while the size of onshore turbines is stabilizing. The need to ensure wind power meets network requirements has resulted in a significant effort to create innovative transmission systems. Research, Development & Demonstration is now essential for offshore to improve components and reduce technology costs. Large-scale demonstration activities are under way in Europe.

Public R&D funding peaked in 1981, driven by the EU. Investment in wind R&D is now substantially lower than investment in other renewables, such as solar or biofuels.

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 is subject to sudden changes in rate. In addition, wind output tends to be poorly correlated with demand, and the best wind resources are often far from large consumption centers, requiring long-distance transmission lines.

Despite the output smoothing resulting from geographic dispersion, 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 specific.

Wind is not facing any major environmental and social hurdles

Wind power is one of the lowest greenhouse-gas-emitting energy technologies, with median emissions of 12 grams of CO_2 equivalent per kWh over its full lifecycle. 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.

Despite the reluctance of the public to accept wind power because of the noise of turbines and their aesthetic impact, and relatively high space requirements, wind is not facing significant social or environmental hurdles.

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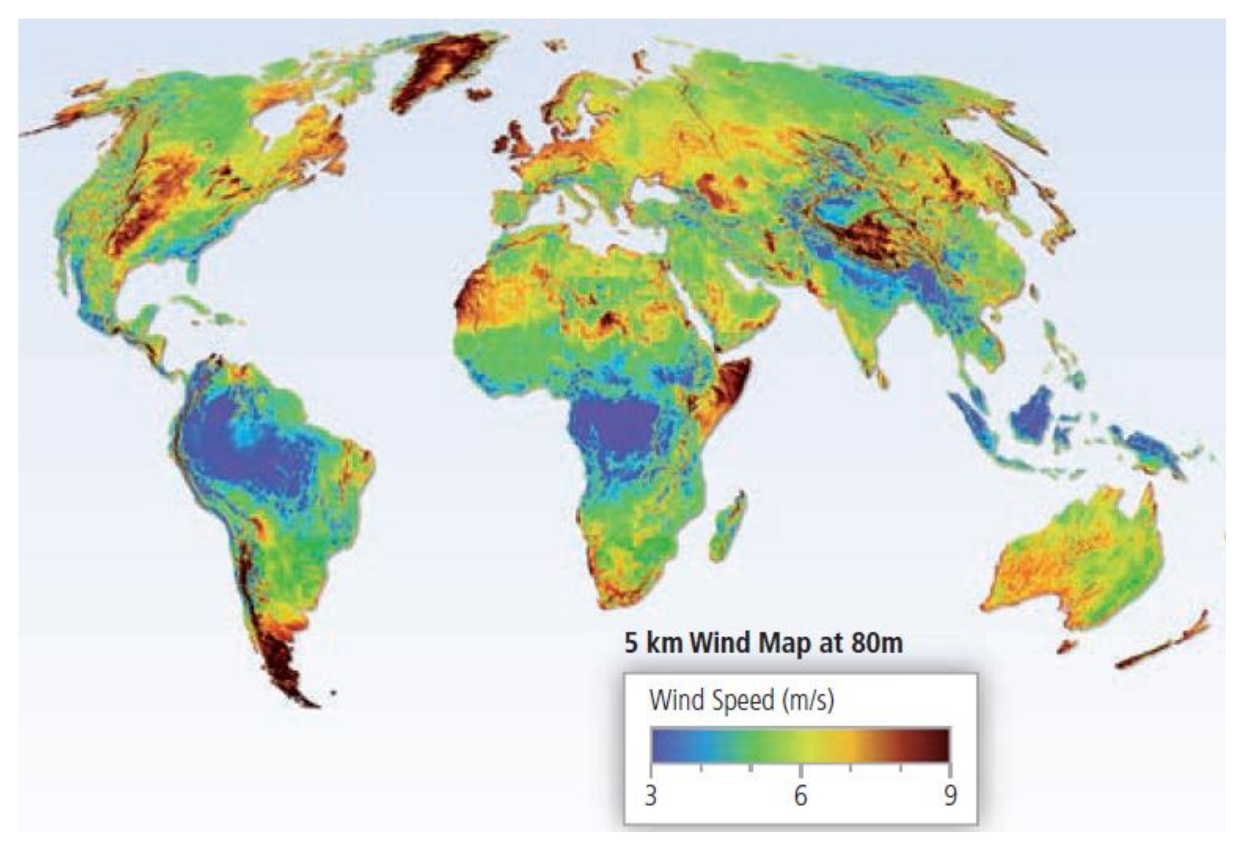
1. Key Concepts of Wind Power

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

GLOBAL WIND RESOURCE MAP
2009, 5 km x 5 km resolution



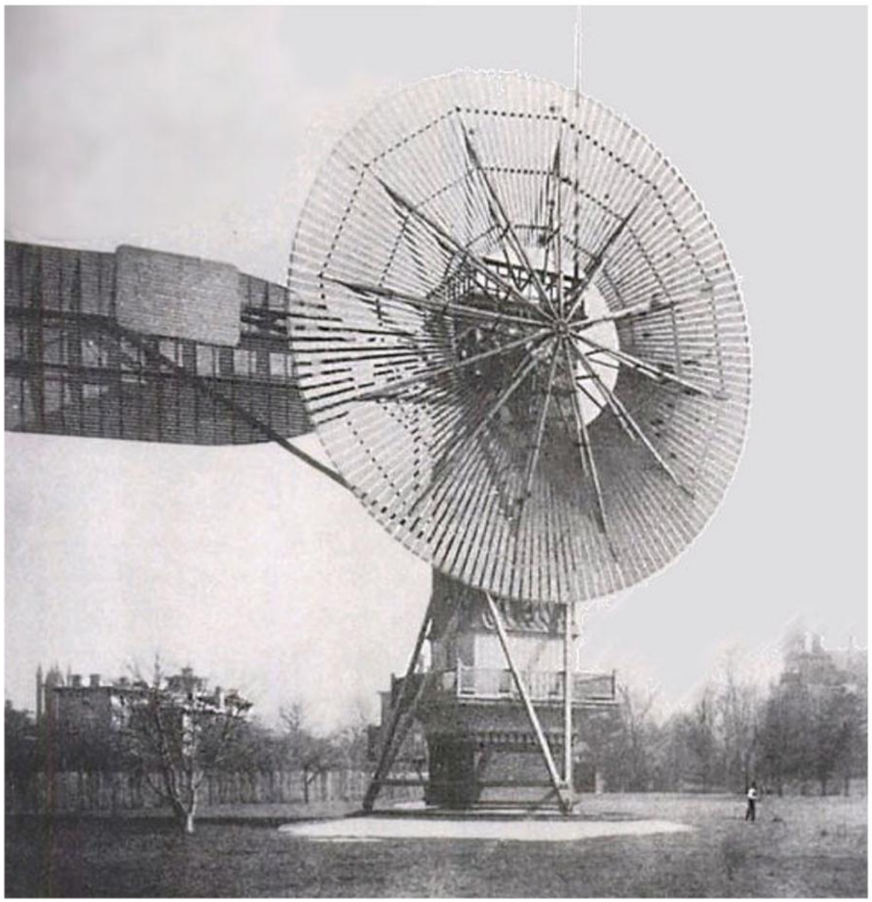
- **The technical potential of wind exceeds current global electricity production.** Estimates range from 70-450 EJ/year, while the global electricity production is of 60 EJ/year[1].
- **Wind is location and weather dependent.** Though wind speeds vary considerably by location, ample technical potential exists in most regions to enable significant wind energy deployment.

Note: *EJ: Exajoules (10^{18} Joules). According to the IEA, 189 EJ are transformed every year in the Heat & Power (co-)generation plants, generating 60 EJ of electricity, 11 EJ of commercial heat and 118 EJ of losses

Source: IPCC (2011), "Special report on renewable energy"; IEA (2012), "Energy Technology Perspectives"

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

US: THE FIRST WIND TURBINE TO GENERATE ELECTRICITY
Cleveland, Ohio, 1888



- **Wind energy has been used for millennia** (*e.g.* windmills to pump water), with the first successful electricity production observed in the late 19th century.
- **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**.

Source: IPCC (2011), "Special report on renewable energy"

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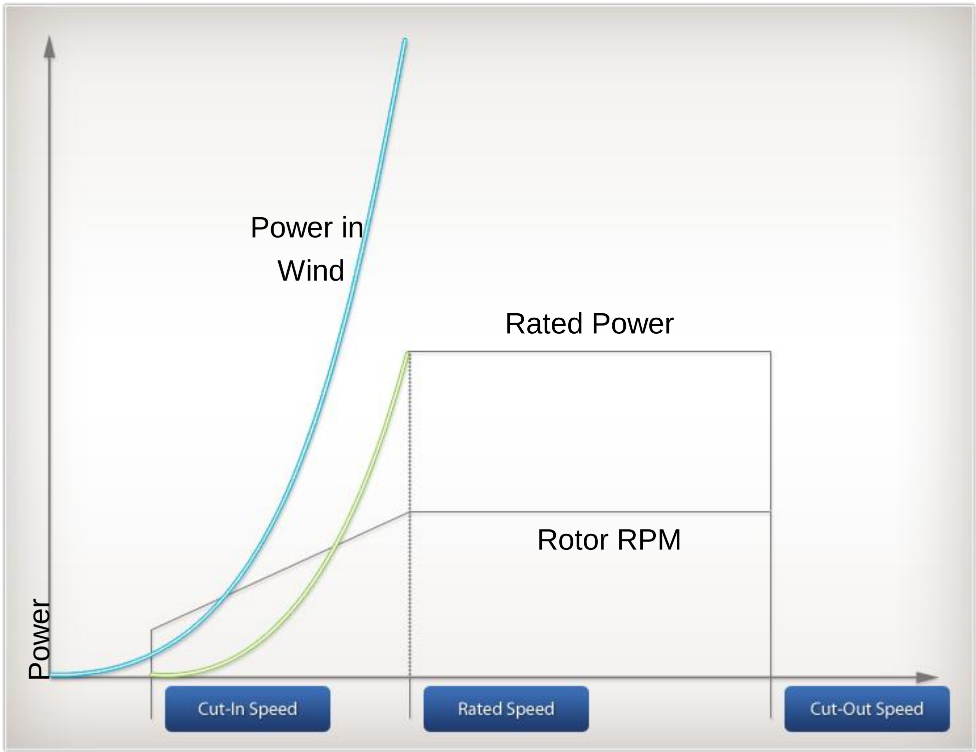
The kinetic energy theoretically available for extraction increases with wind speed but is controlled to protect the turbine

CONCEPTUAL POWER CURVE
2008 modern wind turbine



- **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).
- **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.
- **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).

Note: m/s: meters per second
Source: IPCC (2011), "Special report on renewable energy"

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

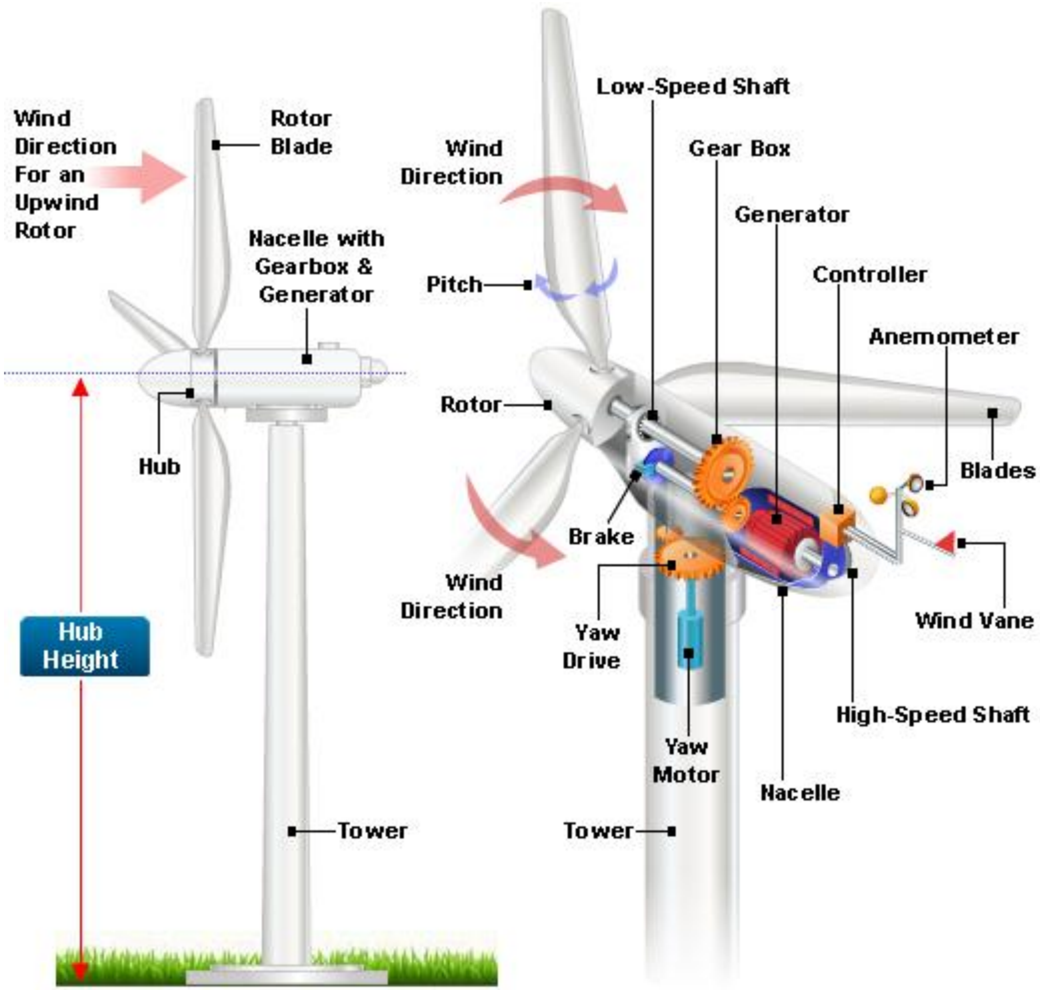
TURBINE DESIGN OPTIONS

- **Several design options have been investigated**:
  - Horizontal *vs* vertical axis;
  - Upwind *vs* downwind;
  - Three blades *vs* two-blades;
  - Stall regulation *vs* pitch regulation;
  - Fixed *vs* variable speed machines.
- **A dominant design has emerged for large wind turbines:**
  - Horizontal axis;
  - Upwind;
  - Three evenly spaced blades;
  - Pitch regulation (pitching the blade);
  - Variable speed.

Source: IPCC (2011), "Special report on renewable energy"; Global Wind Energy Council (2012), "Wind Energy Technology"

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

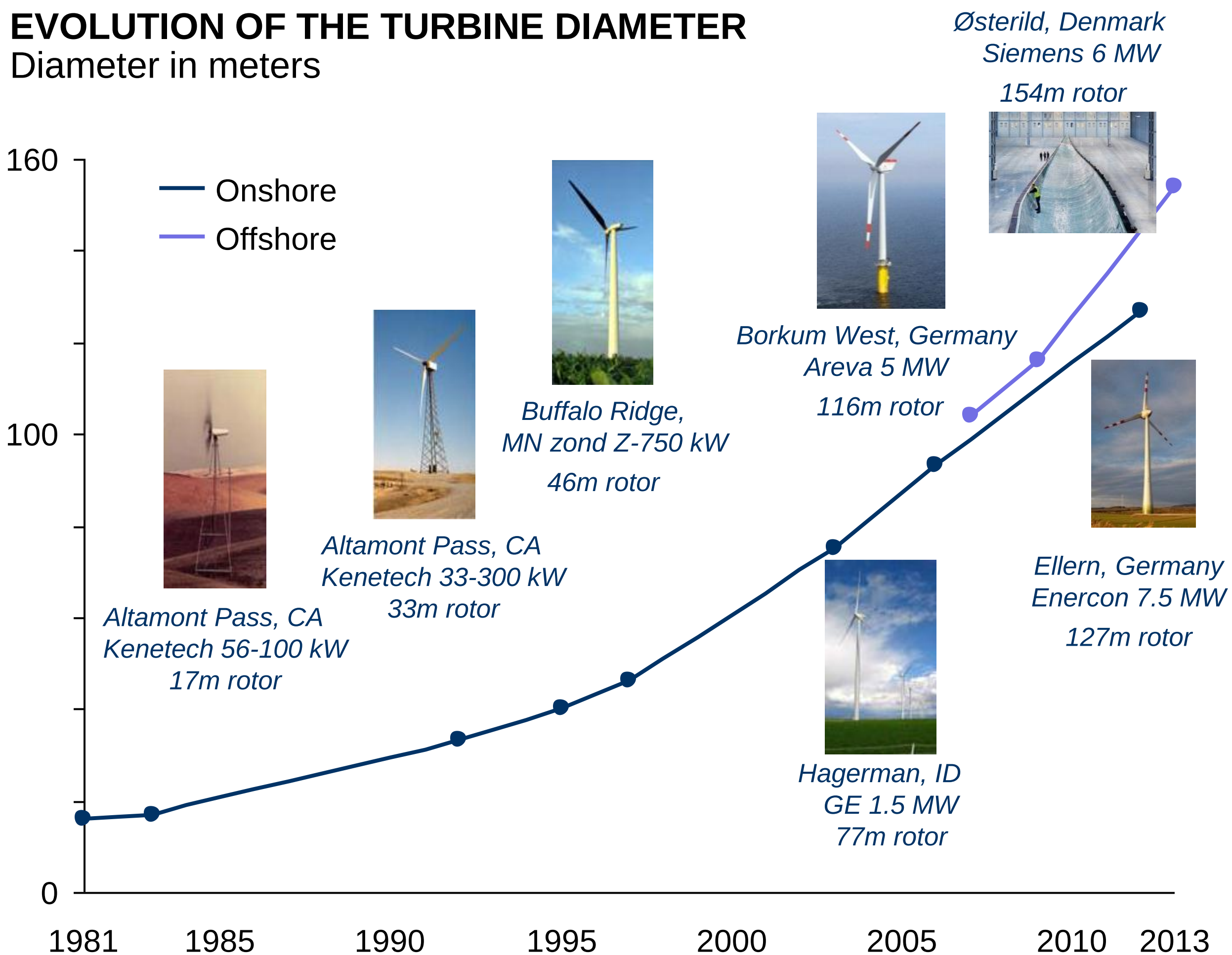


- Most turbines have an **upwind rotor** with a **yaw motor** to turn the rotor and preserve alignment with wind direction.
- **Blades** are attached to the hub, from which power is transferred through a **gearbox** to a **generator**.
- There are several **designs** for the layout of the rotor support, 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 (*e.g*. in metal wall thickness and in diameter).
- Tower height is site specific.

Source: IPCC (2011), "Special report on renewable energy"

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

EVOLUTION OF THE TURBINE DIAMETER
Diameter in meters



- **Potential weight increases have been negated** by advances in materials and aerodynamics.
- **Today's installed towers are typically 80-100 meter tall** and occasionally up to 135 meters tall (Ellern 7.5 MW Enercon Turbine).
- **Onshore turbines have grown but their size may be limited by constraints in the construction process*.** These limitations may be circumvented if efforts to develop self-erecting and telescopic towers are successful.
- **Offshore sitting allows larger turbines.** Larger turbines can be constructed offshore. Areva, Siemens, Repower or CSIS have announced plans for turbines with rotor diameters exceeding 130 m (up to 154 m). These are likely to become the standard.
- **Improved blade efficiency** should help to capture more energy at lower wind speeds.

Note: *Such as transporting components by road and finding large enough cranes
Source: US DOE LBNL (2012), "2011 Wind Technologies Market Report"
IPCC (2011), "Special report on renewable energy", 2011; Global Wind Energy Council (2011)

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

TYPICAL ONSHORE & OFFSHORE TECHNOLOGY FEATURES

	ONSHORE	OFFSHORE
Resources	- ~2000 full load hours per year average to date - ~3000 full load hours per year average for new installations	- ~3500 full load hours per year average to date - ~4300 full load hours per year average for new installations
Dimensions	- 1 - 3 MW turbine size - 20 - 200 MW wind farm - 40 - 450 M$ investment	- 3 - 7 MW turbine size - 100 - 1000 MW wind farm - 450 - 4500 M$ investment
Environment	- Land-based conditions - Unrestricted access - Land constraints for large turbines (roads)	- Rough marine conditions - Distant from shores (~23 km in 2011) - 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 & soil consistency

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

Source: E.ON (2011), "Offshore Wind Energy Factbook"; European Wind Energy Association (2012), "Key 2011 trends and statistics"; IEA (2012), "Renewable Energy , Medium-term market report"

Wind industry could capitalize on oil & gas best practices to ensure efficient and safe offshore operations

OIL & 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 & 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 learnt.
- Oil & Gas offshore facilities, especially in their late life, could also be used to host wind turbines and wind substations.

Oil & Gas best practices transferable to Offshore Wind	Safety	- Fit for purpose equipment (*e.g.* lifesaving appliances and fire fighting equipment) - Safety processes and tools (*e.g.* emergency response plan, audits, risk-assessment methods)
	Investment arbitrage	- Remote control (*e.g.* remote or on-site maintenance) - Access (*e.g.* air or marine access)
	Operating Performance	- Production performance (*e.g.* shutdown management) - Marine logistics (*e.g.* vessels fleet management) - Inspection (*e.g.* diving, remote operating vehicle)

Source: DNV (2010), "Access to offshore wind facilities - What can we learn from other industries?"

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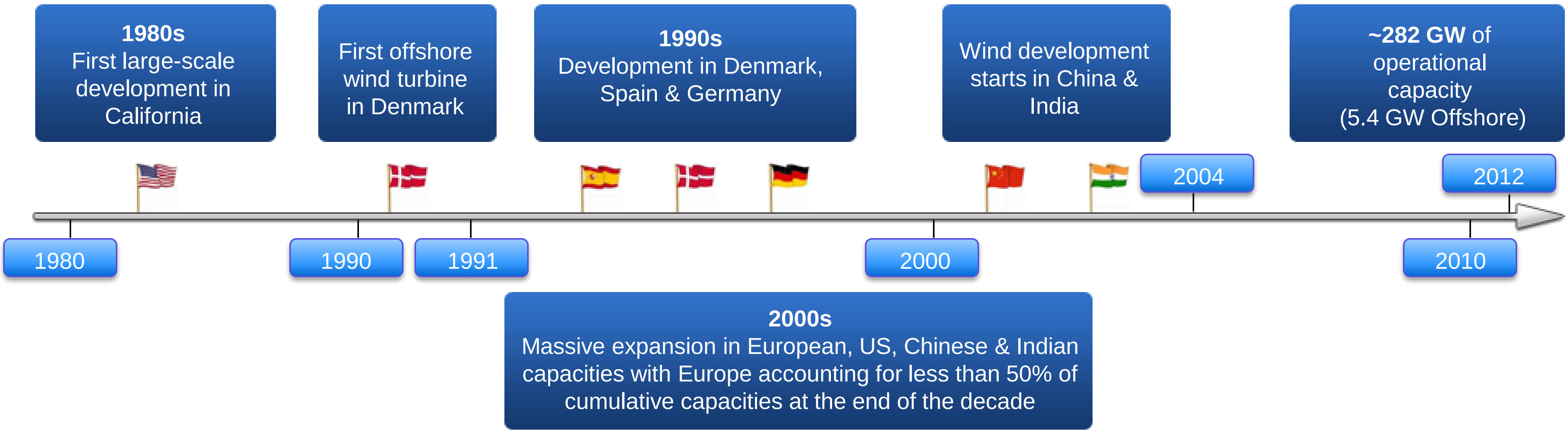
2. Status & Future Development

Wind capacity has spread worldwide over the last three decades

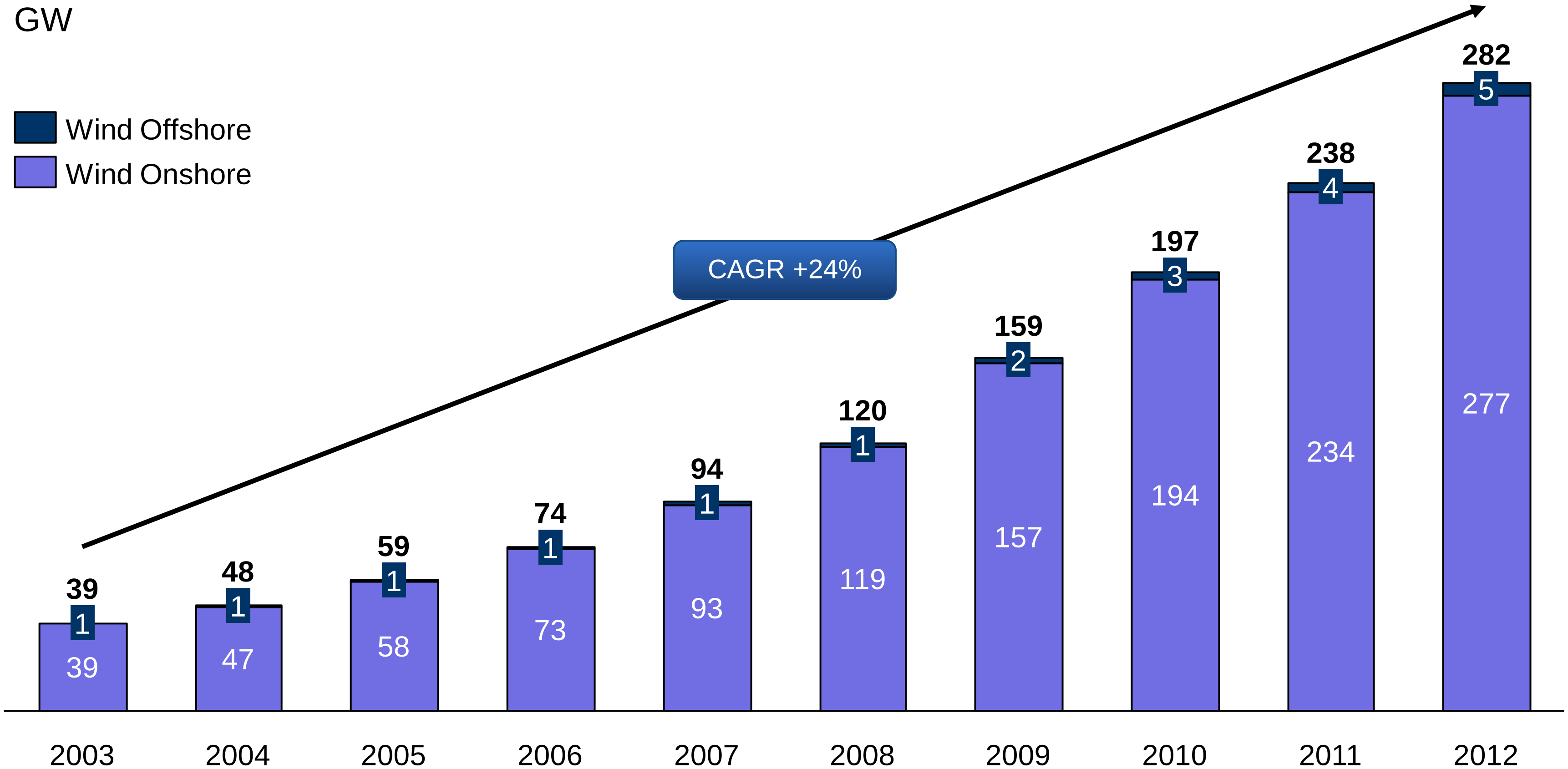
WIND DEVELOPMENT TIMELINE



Source: SBC Energy Institute Analysis, Global Wind Energy Council (2013), “Global Wind Statistics 2012”

Cumulative installed capacities have grown at a steady annual rate of 24% over the past 10 years, driven by onshore technology

GLOBAL INSTALLED WIND CAPACITY
GW



1.3%	1.3%	1.2%	1.1%	1.2%	1.2%	1.3%	1.6%	1.7%	1.9%	***Offshore wind's share of total installed capacity***

Source: Global Wind Energy Council (2013), "Global Wind Statistics 2012"

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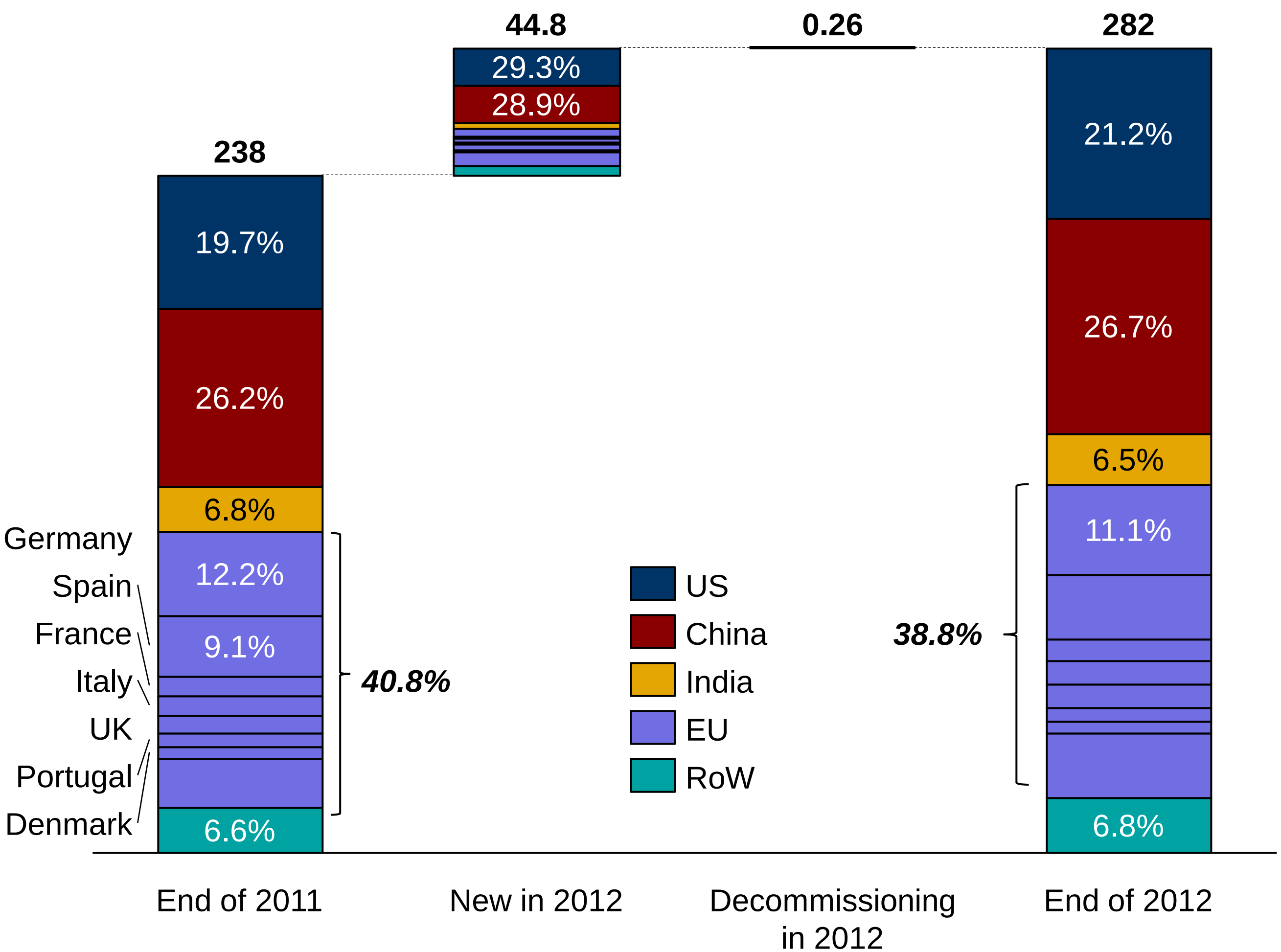
China and the US have overtaken Germany and Spain as the principal drivers of market growth, each accounting for 29% of capacity additions in 2012

INSTALLED WIND CAPACITY
GW



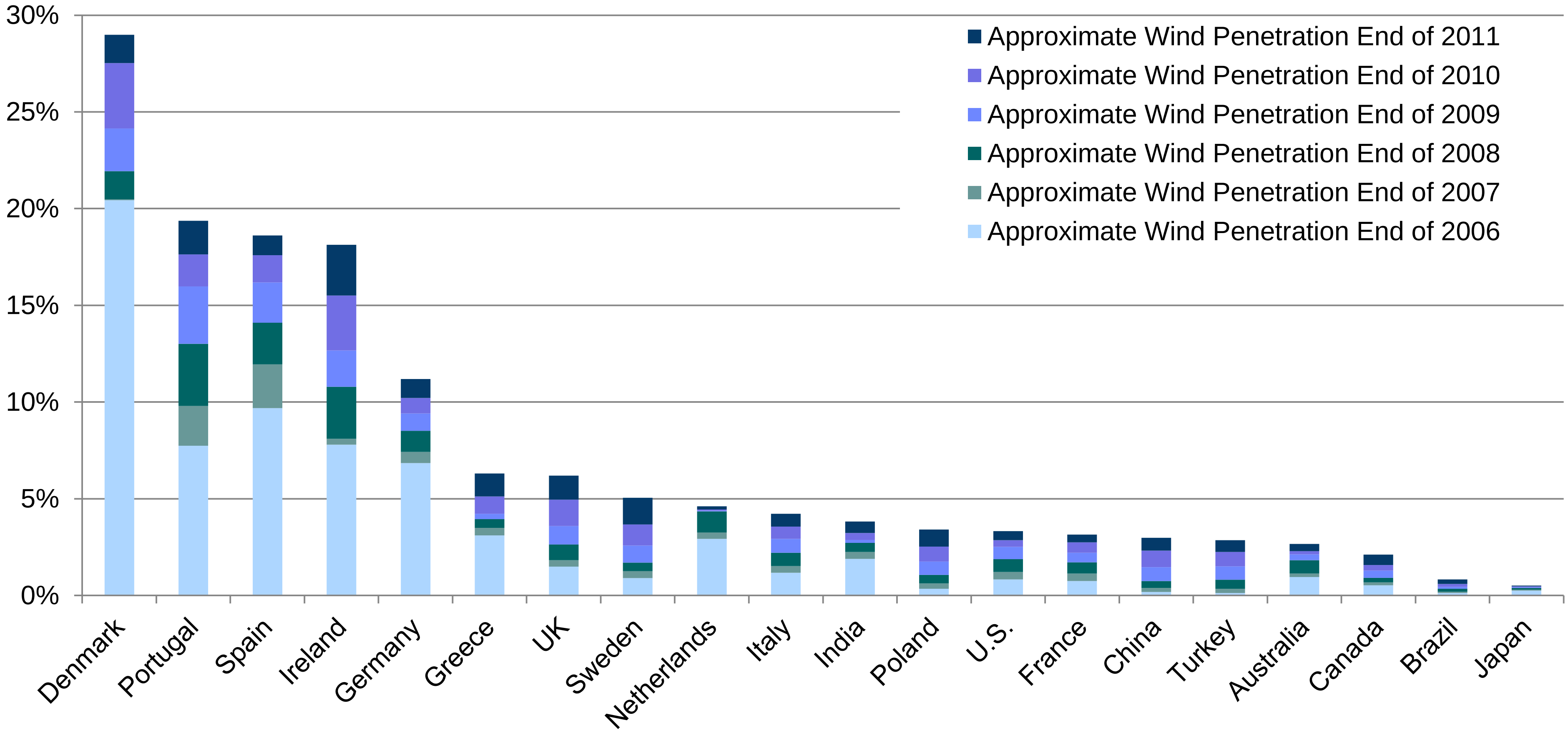
- Europe has long been the main market for wind and still accounted for ~40% of installed capacity at the end of 2012 and 28.4% of capacity additions in 2012.
- In the US, uncertain federal policies have led to a record of 13 GW in additions. Developers rushed to finish projects before the expected expiration of the US Renewable Electricity Production Tax Credit, which was finally been extended for a year.
- With this 2012 US exception, China remains the world's biggest market. It accounted for 29% of global installed capacity in 2012 and 26.7% of cumulative capacity at the end of 2012.
- Europe accounted for 78% of decommissioning in 2012, with most occurring in Germany.

Note: RoW: rest of the world
Source: Global Wind Energy Council (2013), "Annual Market Update 2012"

Except in seven European countries, wind supplies less than 5% of electricity consumed

ANNUAL AVERAGE WIND ELECTRICITY PENETRATION IN TOP-20 WIND COUNTRIES*

% projected wind electricity as a proportion of electricity consumption

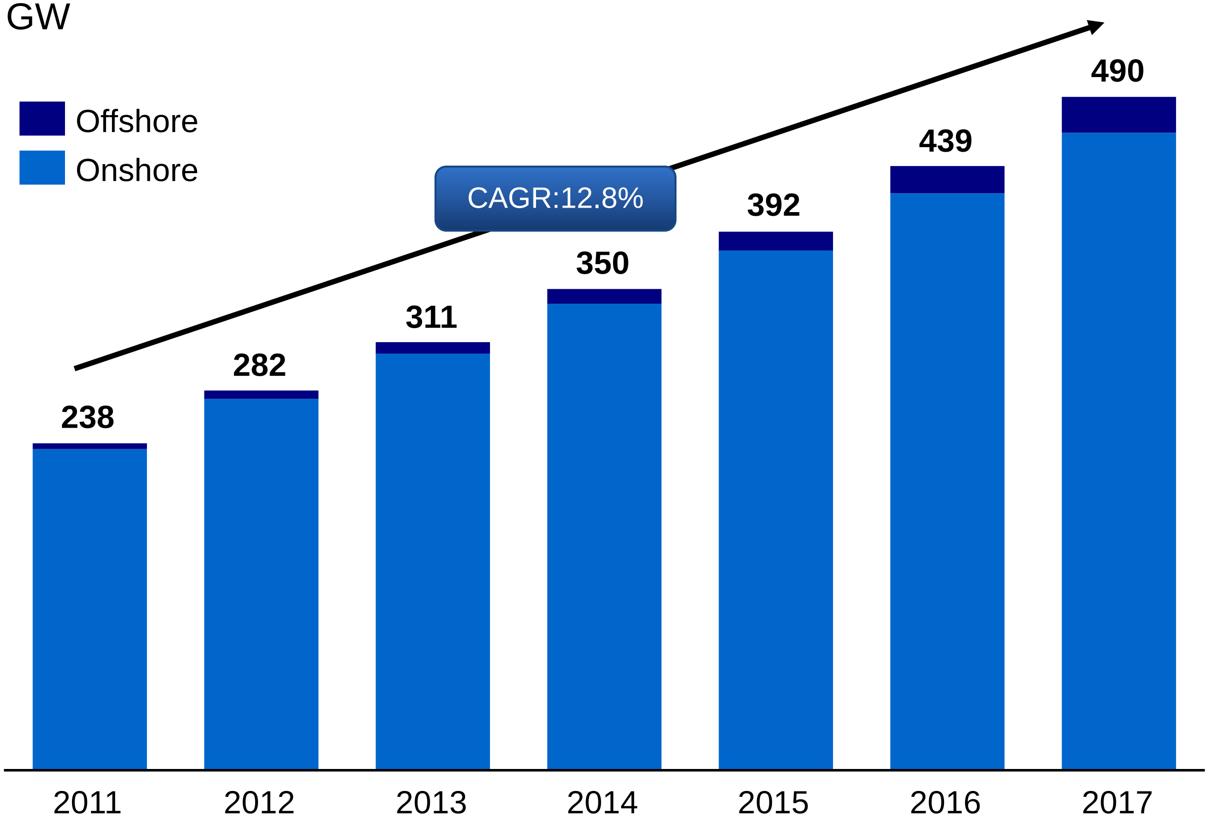


Note: *Top-20 countries with the most wind capacity/production.

Source: US DoE (2012), "2011 Wind Technologies Market Report"

Wind growth is expected to continue over the next five years, doubling installed capacity to about 500 GW

PROJECTED INSTALLED WIND CAPACITIES (2011-2017)
GW



39.6	43.5	25.4	36.4	38.6	41.8	44.0	***Annual onshore additions***
0.9	1.3	2.3	2.2	3.2	5.8	6.3	***Annual offshore additions***

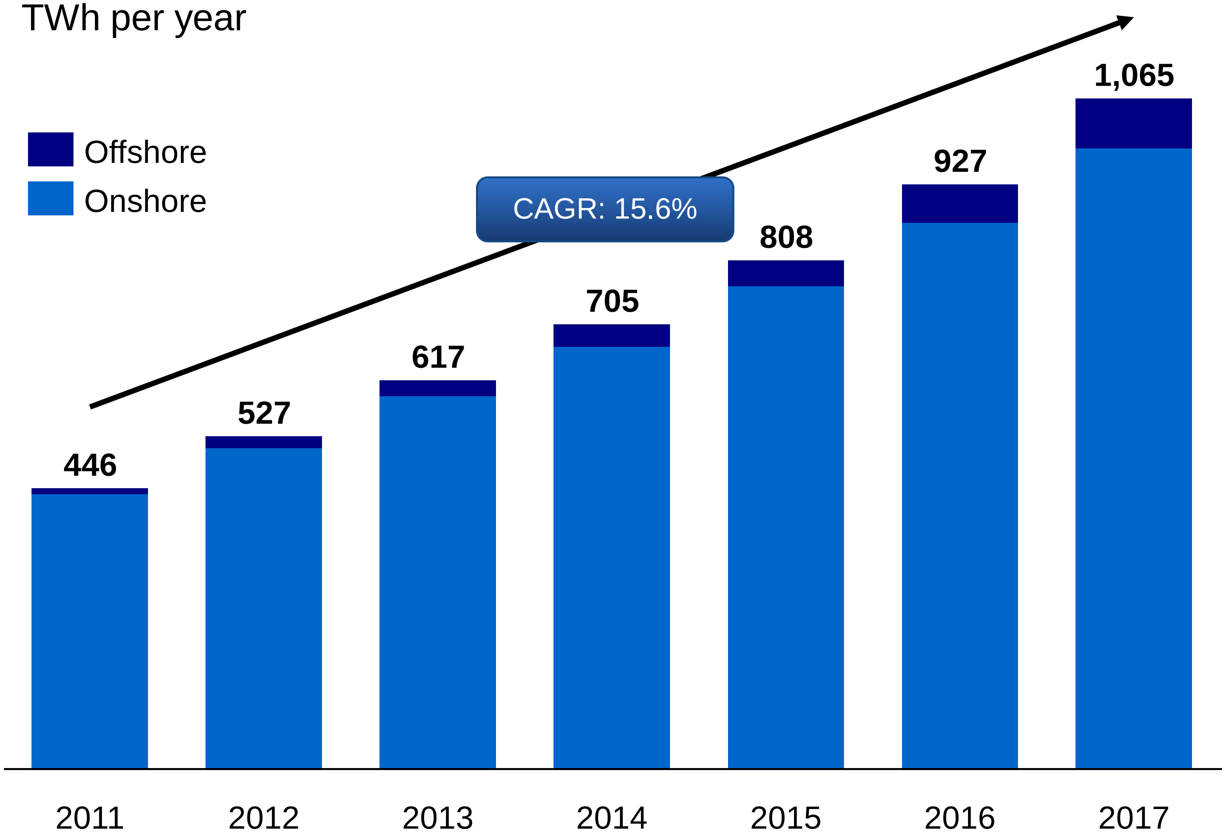
- Even if the growth rate remains lower than in the 2000s, installed wind capacity growth is expected to continue, doubling capacity between 2011 and 2017 to about 500 GW.
- Offshore growth is expected to accelerate after 2015.

Note: The drop in capacity additions in 2013 can be explained by the fact that in the US, developers rushed to finish projects before expected expiration of the US Renewable Electricity Production Tax Credit

Source: IEA (2012), "Renewable Energy , Medium-term market report", SBC Energy Institute Analysis

As a result of offshore penetration and a reduction in grid-connection delays in China, wind generation should grow at a higher rate than capacity

PROJECTED WIND ENERGY GENERATION (2011-2017)
TWh per year



	2011	2012	2013	2014	2015	2016	2017
Onshore load factor	21.6%	21.5%	22.3%	22.6%	23.1%	23.6%	24.2%
Offshore load factor	34.5%	33.7%	34.7%	35.9%	35.2%	34.1%	35.1%

- Wind electricity generation will grow faster than installed wind capacity.
- The reason for this is an increase in the average load factor* of wind turbines.
- An increase in the average load factor is expected to result from growth in deployment of offshore wind, improvements in onshore turbine technology and better integration of wind farms into the electricity grid, especially in China:
  - The average load factor of China's wind farms should increase from 13.4% in 2011 to 18.8% by 2017
  - US load factor was 29.2% in 2011
  - Germany and Spain are expected to progress slightly, from 18.2% and 22.1% to 20% and 25.1%, respectively, by 2017.

Note: *Load factors are derived from generation supplied to the grid / capacity. They are therefore affected by grid-connection delays and curtailment.
Source: IEA (2012), "Renewable Energy, Medium-term market report", SBC Energy Institute Analysis (2012)

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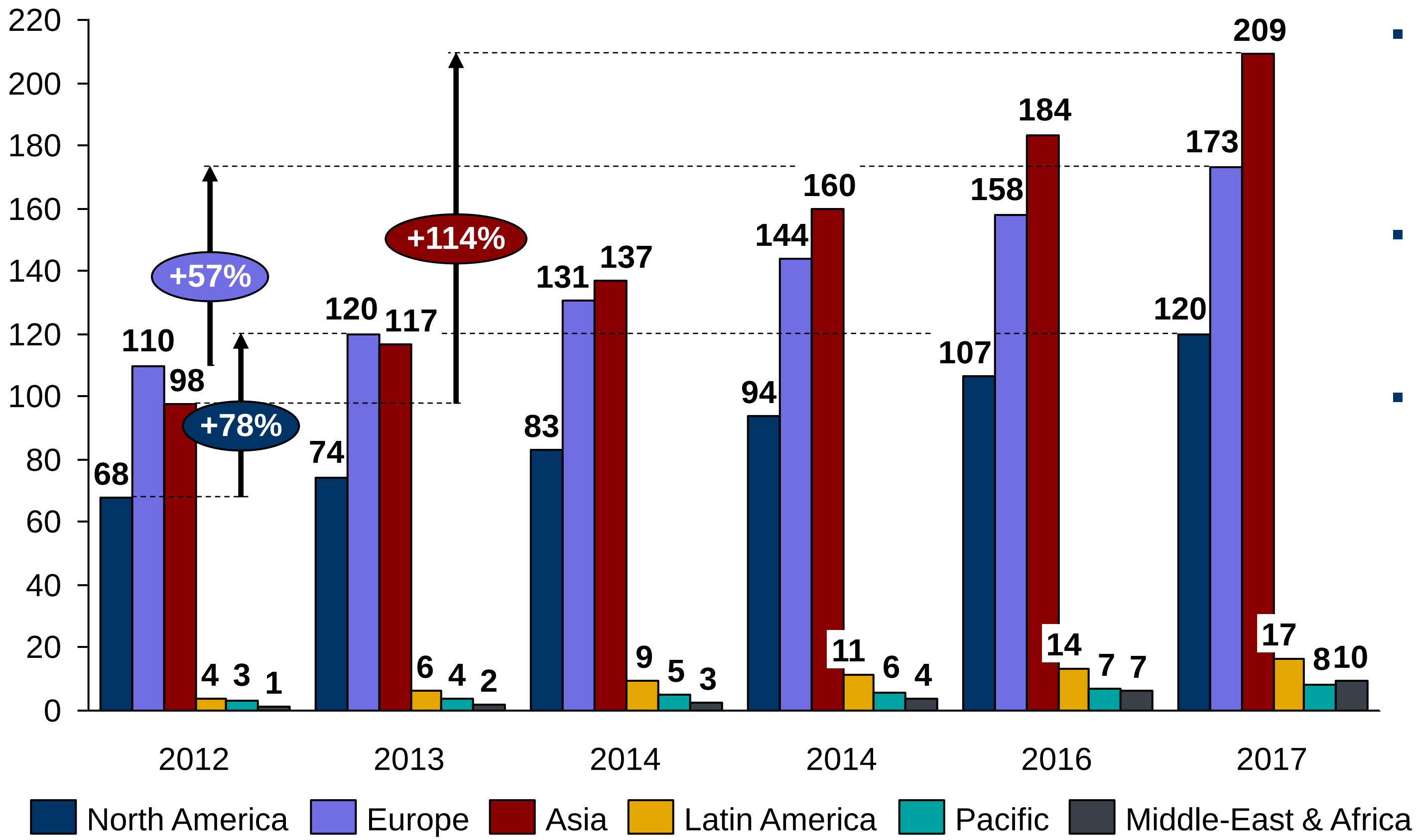
Asia is likely to become the largest area for installed wind capacity in 2014, overtaking Europe

PROJECTED INSTALLED WIND CAPACITIES BY REGIONS (2012-2017)
GW

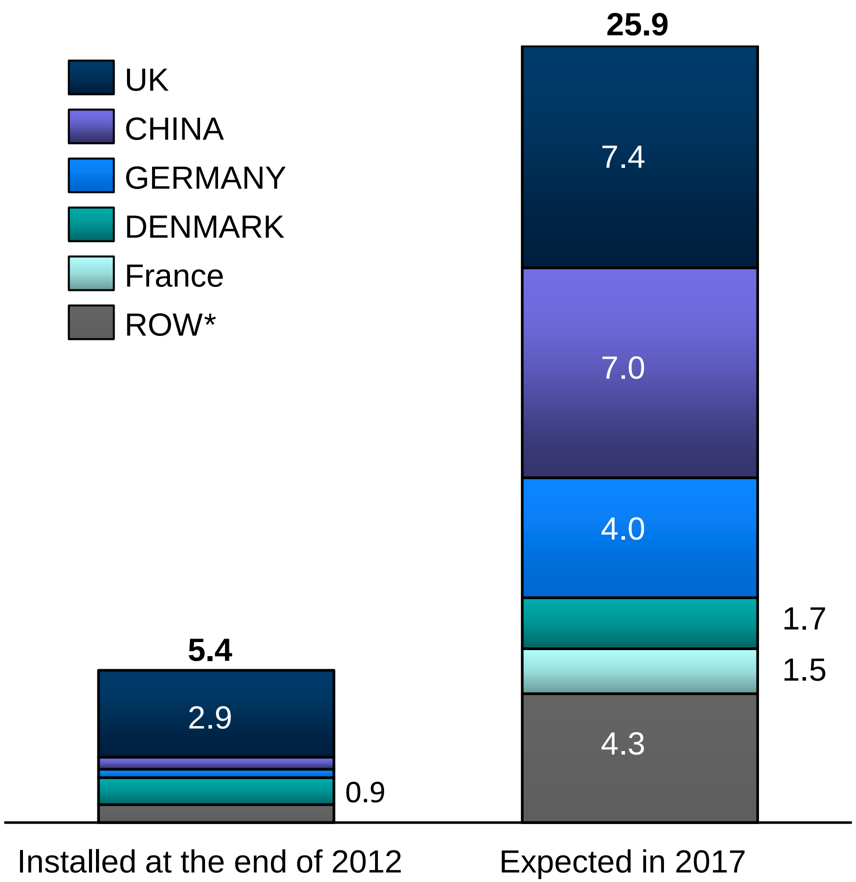


- Asia is expected to be the main driver of wind development in the coming five years, with 111 GW of capacity additions.
- North America is expected to grow faster than Europe, despite being behind in absolute terms.
- Wind capacity in the rest of the world remains negligible, with forecasted installed capacity by 2017 of 34 GW – 6.3% of global capacity.

Note: Projections are more optimistic in this scenario that forecasts 536 GW by 2017 compared to 490 GW for the IEA
Source: Global Wind Energy Council (2013), "Annual Market Update 2012"

Despite progress in Europe and rising interest from China and Japan, offshore wind is yet to overcome deployment-phase challenges

INSTALLED OFFSHORE CAPACITIES IN 2012 AND 2017
GW



- Northern Europe is leading offshore development, with 90% of installed capacity at the end of 2012 and 57% of capacity additions by 2017:
  - The UK has taken the lead, accounting for half of installed capacity at the end of 2012 and 22% of capacity additions by 2017;
  - Germany and France are also planning to invest significantly, despite delays in and reductions of expected tenders.
- China is the main non-European investor in offshore wind and may challenge the UK as market leader by the end of the decade. Despite this, its ambitious targets of 5 GW offshore by 2015 and 30 GW by 2020 seem yet difficult to achieve.
- Japan and South Korea have also expressed a strong interest in offshore wind. The US, meanwhile, seems to be lagging behind.
- Investment plans in Europe have generally been scaled back because of:
  - Financial challenges of high up-front costs of offshore projects – a burden for heavily indebted countries;
  - Technical constraints caused by the harsh marine environment.

Note: *Rest of the World includes 1.4% in European countries (Norway, Portugal, Finland, Belgium, Netherlands) and 0.6% in Japan
Source: IEA (2012), “Renewable Energy, Medium-term market report”, Bloomberg New Energy Finance database

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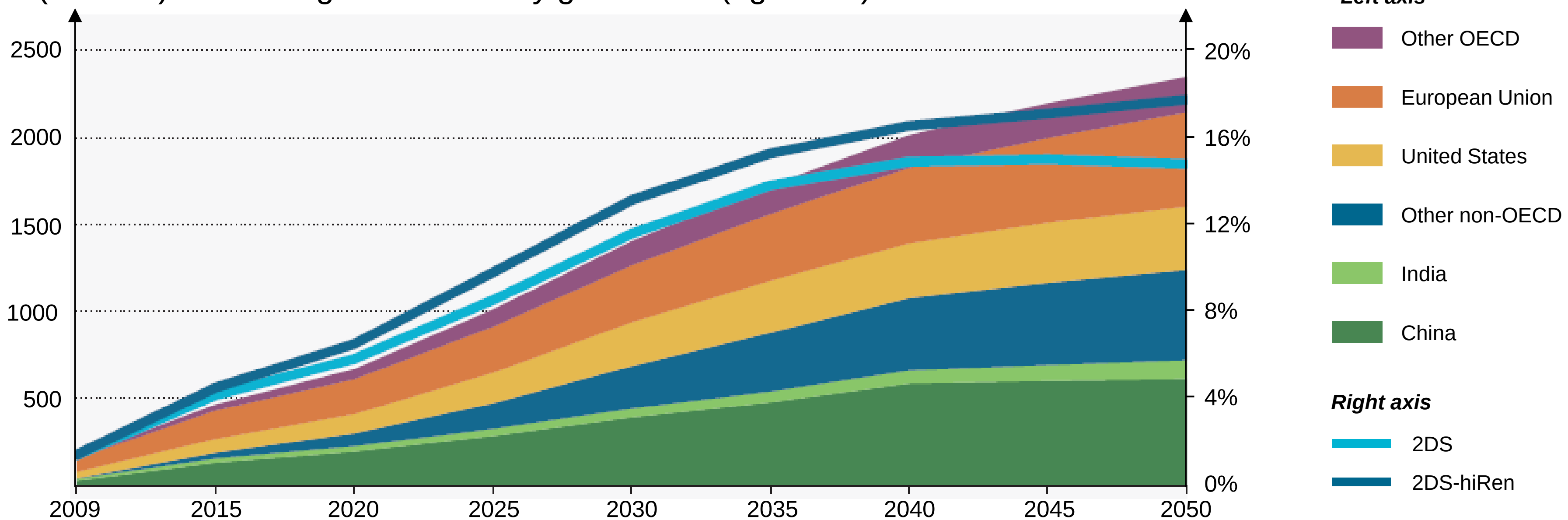
In its most ambitious climate change mitigation scenario, the IEA estimates that wind would need to account for 15% to 18% of global electricity generation

IEA *2DS SCENARIO* FOR WIND

GW (left axis) and % of global electricity generation (right axis)



- Wind's share of global electricity consumption would need to rise to 15%-18%, compared to around 1.5% in 2010, in order for the IEA's 2DS Scenario* to be achievable. Even in less stringent scenarios, wind is expected to make a significant contribution to the electricity mix, accounting in 2050 for 5% of demand in the 6DS (business-as-usual case) and 10% in the 4DS (which takes current governmental pledges into account).
- For wind to attain an 18% share of global electricity consumption, an additional 2000 GW of installed capacity would be required – a ninefold increase in capacity from the end-2011 level.

Note: * The 2DS Scenario corresponds to the lowest cost pathway to an energy system consistent with an emissions trajectory that recent climate science research indicates would give an 80% chance of limiting the average global temperature increase to 2°C
The 2DS-hiRen scenario is a variant of the 2DS, with less nuclear or carbon capture and storage, and more renewables

Source: IEA (2012), "Energy Technology Perspectives"

3. Research, Development & Demonstration

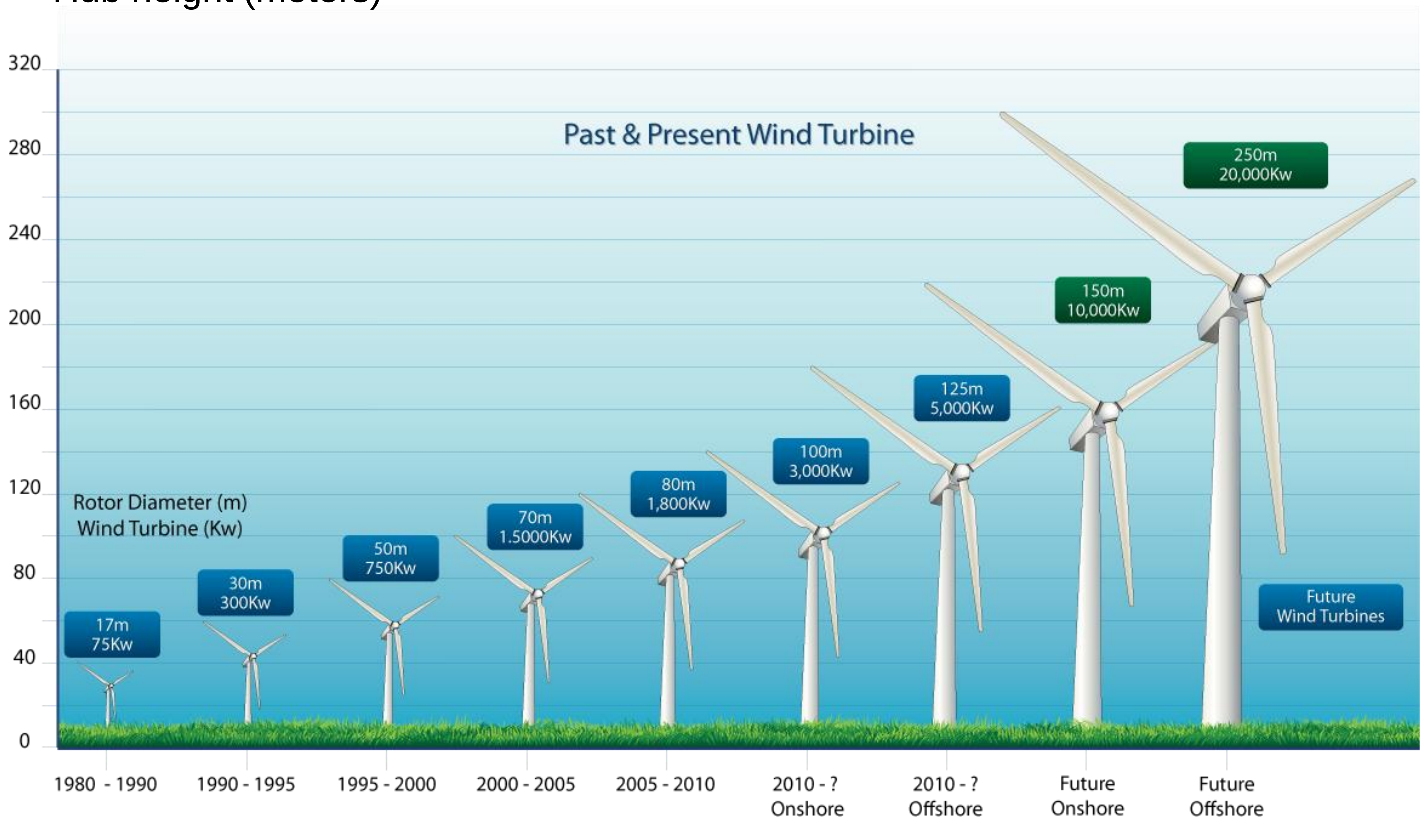
Wind RD&D has three principal objectives: maximizing energy captured, minimizing the cost per unit of capacity and meeting network requirements

OBJECTIVES	DRIVERS	AXIS OF RD&D
1 MAXIMIZING ENERGY CAPTURE	– Access to better wind resources – Exploit lower-quality wind resource sites – Increase load factor	- Larger rotor diameter / turbine size - Variable speed turbine - Extreme conditions resistance
2 MINIMIZING COST PER UNIT OF CAPACITY	– Reduce investment cost – Reduce operation & maintenance – Maximize land-use value	– Lighter rotor and nacelle, drive train layout – Pitch system, control system to avoid fatigue – Second-hand market
3 MEETING NETWORK REQUIREMENTS	– Contribute to system stability – Contribute to voltage control – Enhance predictability	– Pitch control, power converter, drive train – Variable speed, fast response & communication, converters – Computational tools & new projection methodology

Source: SBC Energy Institute Analysis based on Global Wind Energy Council (2012)

After a period of growth in turbine size driven by offshore economics, growth in onshore turbine size is starting to level off

GROWTH IN SIZE OF TYPICAL COMMERCIAL WIND TURBINES
Hub height (meters)



- The market is dominated by 1.5-2 MW turbines but there is:
  - a resurgence of interest in 800 kW size for onshore;
  - an emerging race towards very large offshore turbines.
- Offshore economics requires larger turbines to:
  - Limit the proportionally higher costs of infrastructure (*e.g.* building foundations);
  - Lower the number of units per kW of installed capacity in order to facilitate access and maintenance.
- The levelling-off in onshore turbine size is due to:
  - Road access constraints;
  - Public acceptance of noise and visual disturbance.

Source: IPCC (2011), "Special report on renewable energy"

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

DRIVE TRAIN TECHNOLOGY COMPARISON

– → + Reliability / *Investment Cost (inc. rare earth content)*

	High Speed geared system	Low & 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 Permanent Magnet Generator (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 & cheaper generators).	First developed with classic synchronous generators, direct drive is now using PMG 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 Permanent Magnet synchronous Generators instead of coils is another important trend.
- Offshore is likely to favor reliability in order to minimize maintenance requirements.

Source: Anders Troedson (2009), PMG & FPC, the new drive train standard; American Superconductor, Direct Drive Generators presentation

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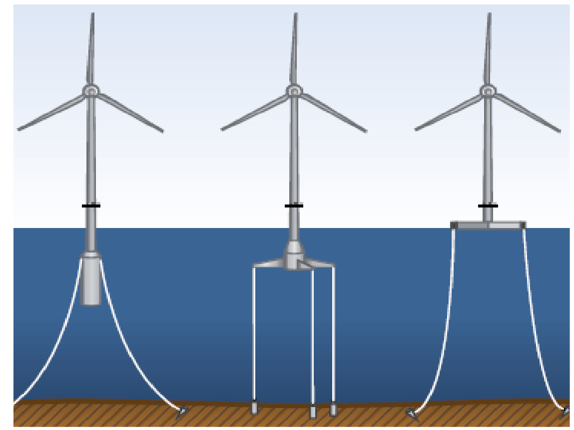
RD&D in offshore wind is required to optimize high up-front investment, ease maintenance and improve reliability

OFFSHORE MAIN AXIS OF RD&D

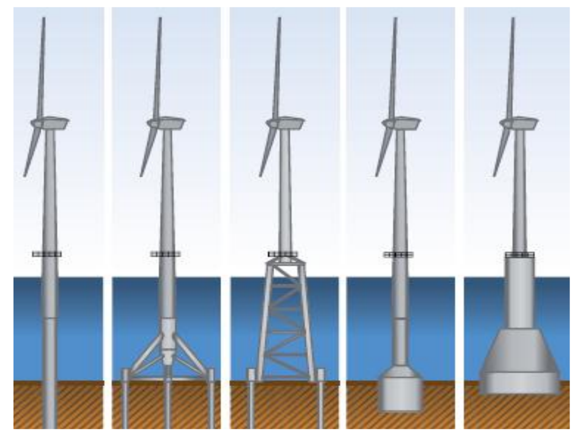
Group	Axis of RD&D
Resources assessment	− Wind: more desirable to catch high wind speeds due to large turbine size − Marine conditions: ice, waves, storm prediction
Maintenance	− Favor reliable components to minimize maintenance − Foster remote control − Lightning protection
Foundations	− Floating turbine (avoid heavy foundations & move further offshore) − New substructure beyond monopile & gravity-based (idem)
Logistics	− Purpose-built vessels − Self-erecting & telescopic towers − Compatible harbor installations
Turbines	− Stronger structure to resist harsh marine conditions − Affordable materials with higher strength-to-mass ratios − New blades (*e.g.* carbon fibre, titanium…)

FOUNDATION DESIGNS

FLOATTING



NEAR-TERM



Source: SBC Energy Institute Analysis based on Global Wind Energy Council (2012)

Schlumberger SBC Energy Institute

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

AREAS OF RD&D FOR WIND INTEGRATION INTO THE POWER GRID

Mitigate Intermittency & 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 & the implementation of sensors on components) and limit outages/maintenance
- Active power control for turbines would allow them to actively support the grid (*e.g.* frequency regulation)

Resources assessment & forecast

- Resource assessment is critical 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 (*e.g.* Utsira Wind & Hydrogen project in Norway)

Source: Chatham House (2011), "Patent Landscapes of Individual Energy Sectors"

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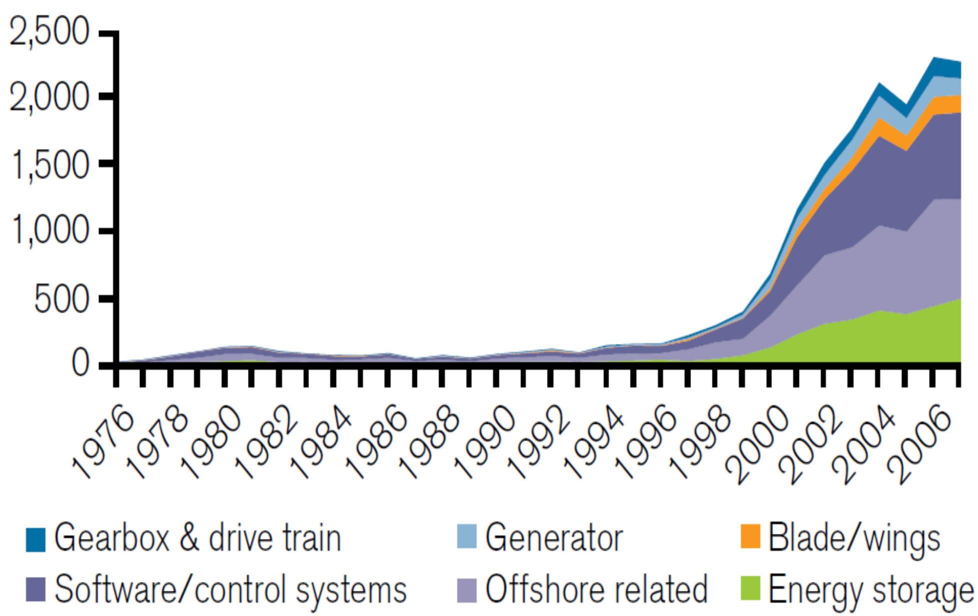
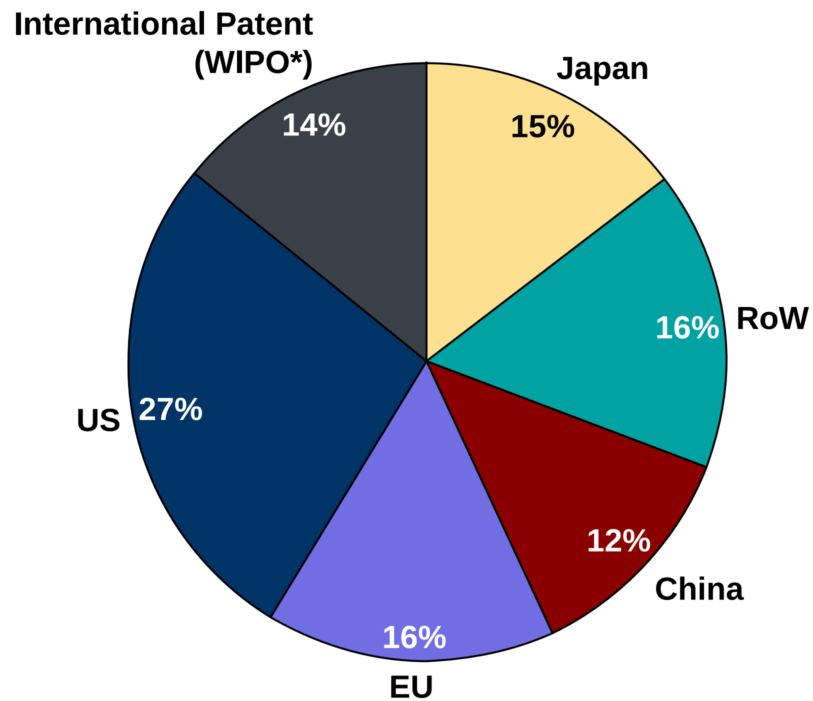
Offshore and network integration accounted for the largest share of wind-related patents between 2000 and 2010

PATENTING RATES BY WIND SUBSECTOR
Annual patent filings registered, 1976-2006



PATENT FILING LOCATION
Cumulative patent filings registered, 1976-2006



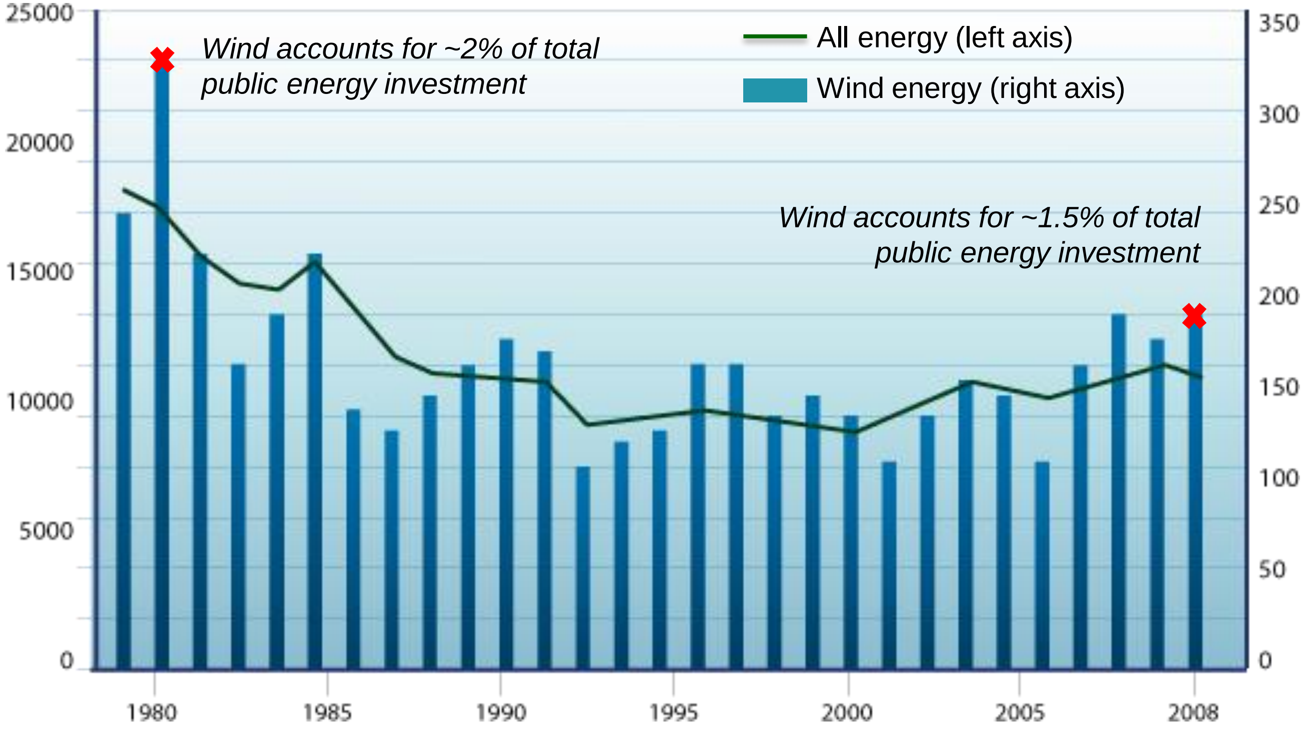
- Software/control systems and offshore related patents formed the bulk of patent filing and have driven wind patents filing growth since 2000.

- The US is the leading location for patents filing, followed by Europe, Japan and China.

Note: * WIPO: World Intellectual Property Organization
Source: Chatham House (2011), "Patent Landscapes of Individual Energy Sectors"

The public funding of wind energy R&D has a long history, peaking in 1981 in OECD countries

OECD PUBLIC FUNDING FOR WIND ENERGY
USD Million, 1979-2008



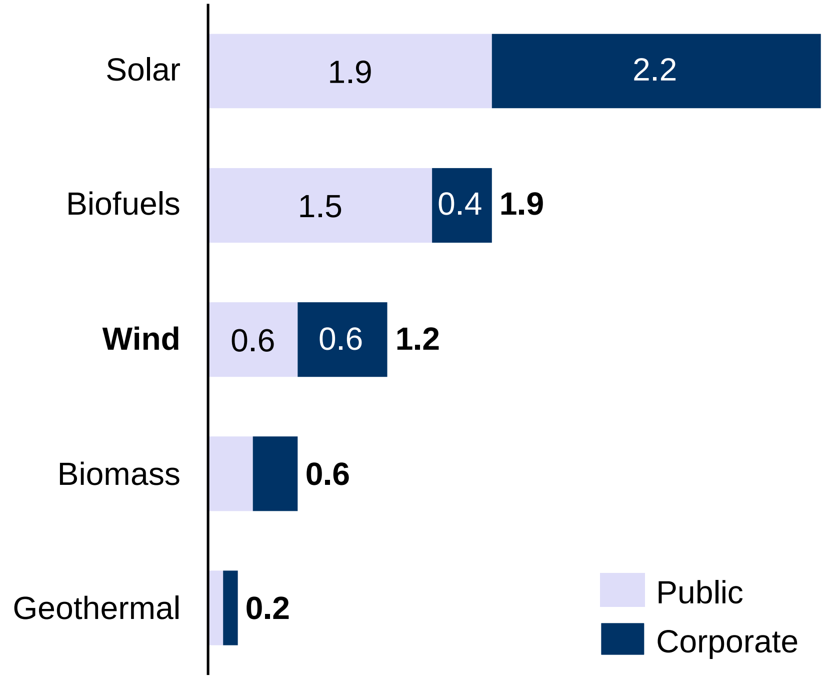
- Public R&D funding for wind energy peaked in 1981, while installed capacity started emerging on a large scale in the late 1990s.
- In the last 30 years, public R&D funding in the OECD for wind power has accounted for only 1% to 2% of all energy-related R&D, fluctuating between 100 and 200 million USD a year.

Source: IEA (2009), "Wind Energy Roadmap"; IEA (2012), "Tracking Clean Energy Progress"; EC Joint Research Centre (2011), "Capacities Map 2011"

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

GLOBAL R&D INVESTMENTS IN WIND (2008-2011)
USD Billion

GLOBAL R&D INVESTMENTS IN RENEWABLES (2011)
USD Billion



- Corporate R&D has been stable over the last four years.
- Public R&D increase in 2009 is the result of a push towards offshore in the late 2000s.

- Wind R&D is very low compared with investments in other renewables, especially solar.

Source: UNEP (2012, 2011, 2010, 2009) "Global Trend in Renewable Energy Investment". Results based on Bloomberg, Bloomberg New Energy Finance, IEA, IMF, and various government agencies

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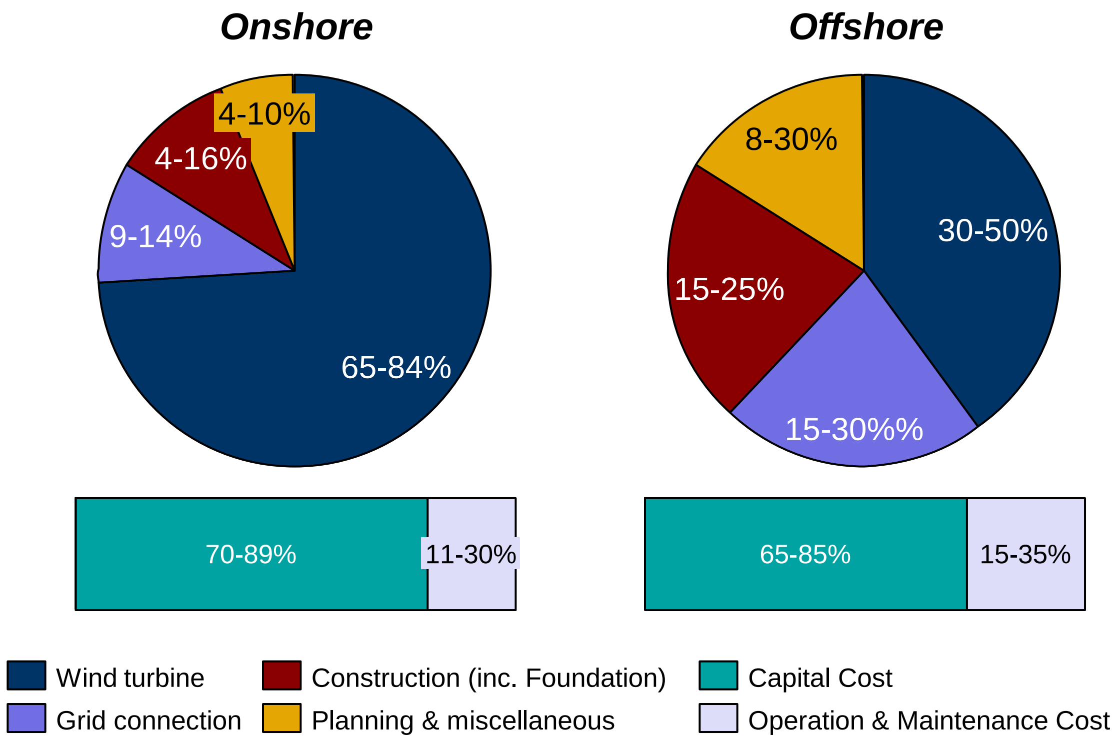
4. Economics, financing & key players

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

TYPICAL ONSHORE & OFFSHORE WIND COST BREAKDOWN

Capital cost breakdown (top) & share of capital in levelized cost of electricity (bottom)



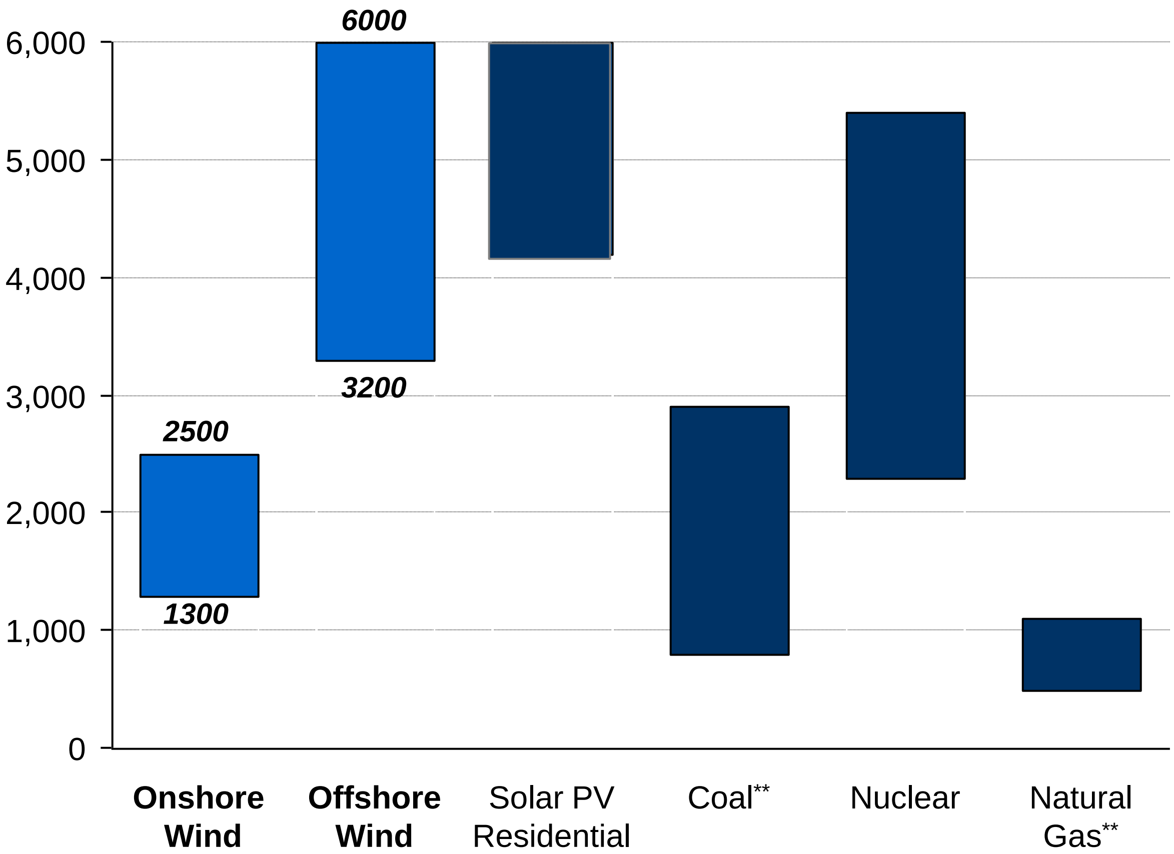
- The cost of wind power predominantly consist of up-front investment. Operation & Maintenance typically account for 20% to 25% of the electricity price (as low as 11% for onshore in the US, up to 35% for some offshore projects). Financing costs are therefore fundamental to the economic viability of a wind project.
- Turbine costs account for most of the capital cost, especially in the case of onshore, where they can account for up to 84% of total installed costs. The main components of turbines are the rotor blades, the tower and the gearbox, which account for around 50% of its costs.
- Offshore has significantly more onerous cost components than onshore, mainly as a result of the harsh marine environment, which requires deeper foundations, expensive installations and more robust grid connections.

Note: Grid connection costs include cables, substation and installations. Construction costs include foundations and road improvements. Planning and miscellaneous relate to Engineering, Permitting and licensing. Operation & Maintenance (O&M) costs correspond to fixed O&M such as insurance, management, taxes, lease, maintenance contracts, and to variable O&M such as repair, maintenance or spare parts

Source: IPCC (2011), “Special report on renewable energy”; IRENA (2012), “Renewable Energy Technologies: Cost Analysis series - Wind Power”

Onshore investment costs are significantly lower than offshore costs

WIND INVESTMENT COSTS*
USD / kW



- Wind project costs vary, depending on turbine prices, wind farm sizes and local market conditions (e.g. competitiveness of local industry, labor costs…).
- Onshore wind is maturing. Investment costs typically range from 1500 to 2500 USD/kW. They are as low as 1300 USD/kW in China or India, and averaged around 2000 USD/kW in 2011 in the US. The cost of onshore wind is highly correlated with the cost of turbines.
- Offshore wind is at the early deployment phase and consequently it is significantly more expensive than onshore (around twice as expensive). Costs range between 3300 and 6000 USD/kW, depending on turbine size and floating design. The average for shallow water and semi-near shore conditions is around 4 500 USD/kW in the UK.

Note: * 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
** Coal investment costs range include all technologies from subcritical to Integrated Gasification Combined Cycle (IGCC). Natural Gas technologies also include open cycle gas turbine (average around 500 USD / kW) & Combined Cycle Gas Turbine (average 1000 USD / kW).

Source: IEA (2012), "Tracking Clean Energy Progress"

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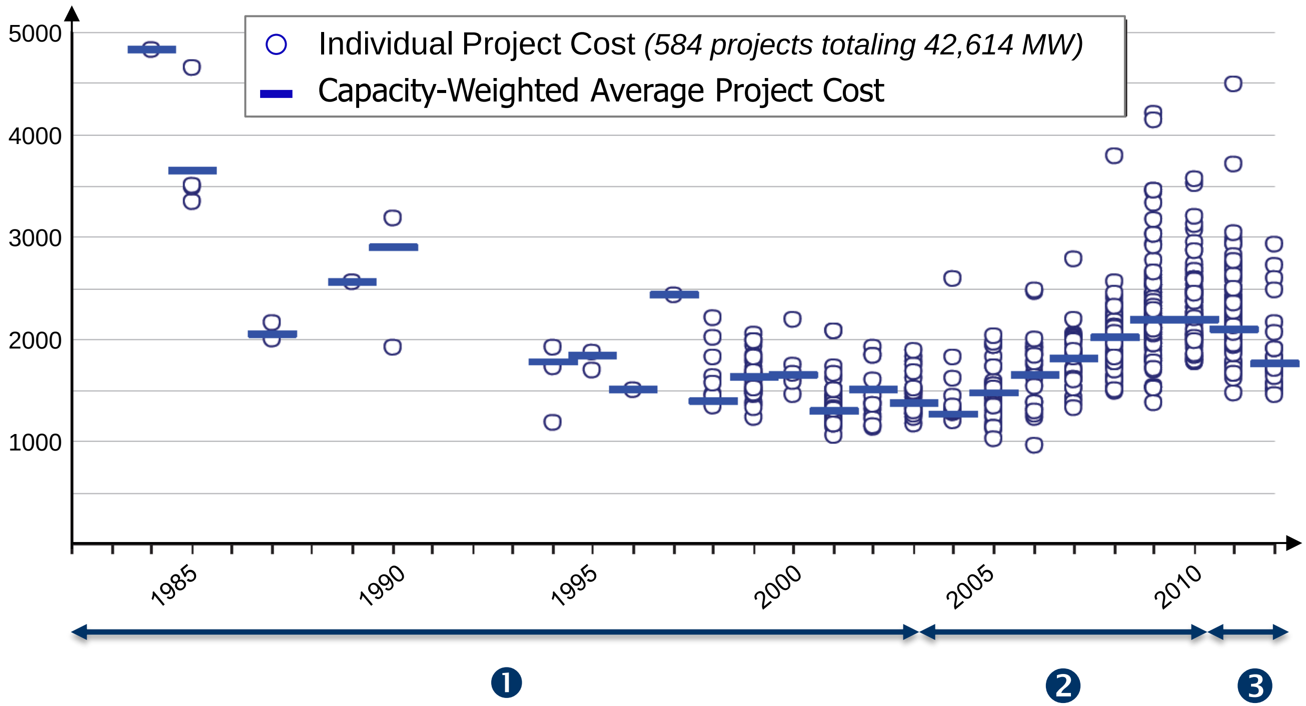
Investment costs have fallen but remain highly sensitive to commodity prices and supply-chain bottlenecks

INVESTMENT COSTS OF WIND POWER PLANTS IN THE US (ONSHORE)

USD_{2011} / kW



❶ There have been substantial cost decreases per unit of capacity as a result of economies of scale, the learning effect and improved capacity factors. Historical learning rates for wind power were around 10% from 1980 to 2004.

❷ Increase in turbine price caused by:

- Increases in the prices of commodities, mainly steel, copper and cement;
- Supply-chain bottlenecks caused by rapid market growth;
- Increases in turbine size and system sophistication to achieve higher load factors and meet system requirements.

❸ Plateau and decrease in wind turbine prices due to:

- More stable – and even declining – commodity prices;
- Supply chain catch-up with demand;
- Increased competition, following the emergence of manufacturers with local content in low-cost manufacturing bases.

Source: US DOE LBNL (2012), "2011 Wind Technologies Market Report"

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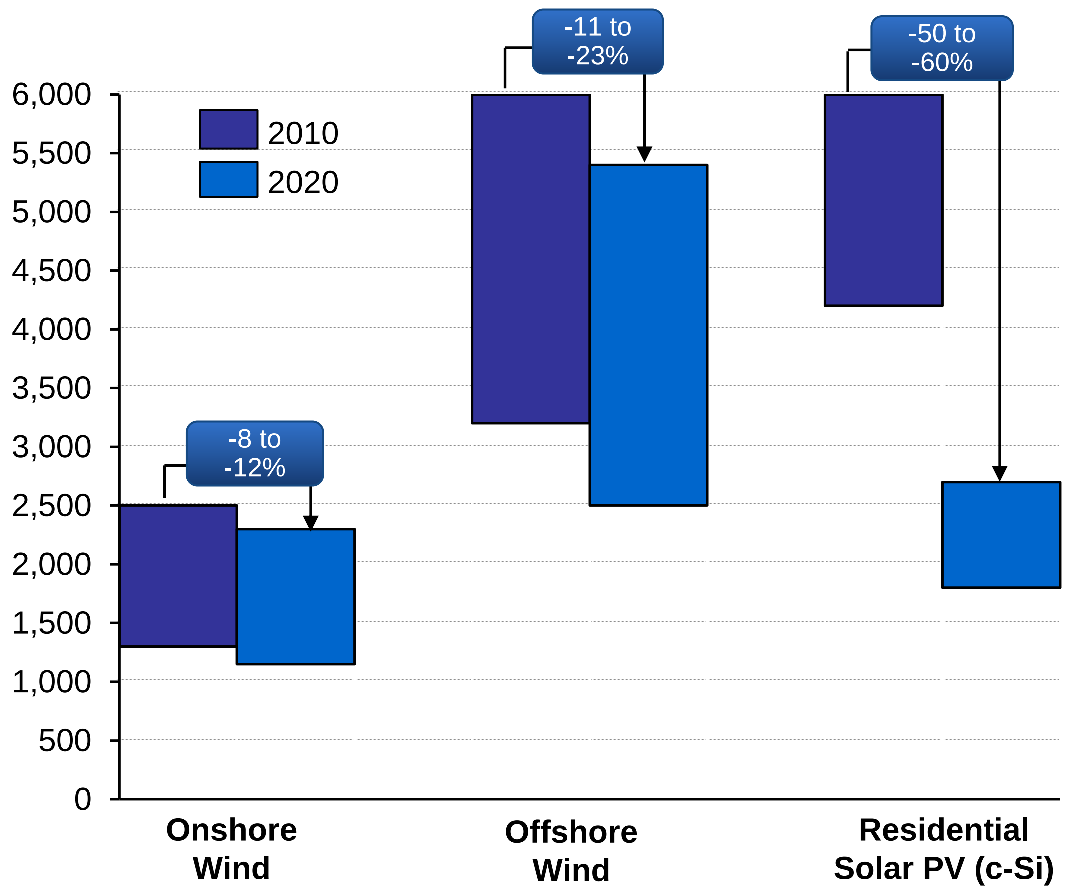
The investment cost reduction of offshore wind projects remains uncertain in the next few years, but is likely to be greater than for onshore

PROJECTED INVESTMENT COSTS
USD / kW



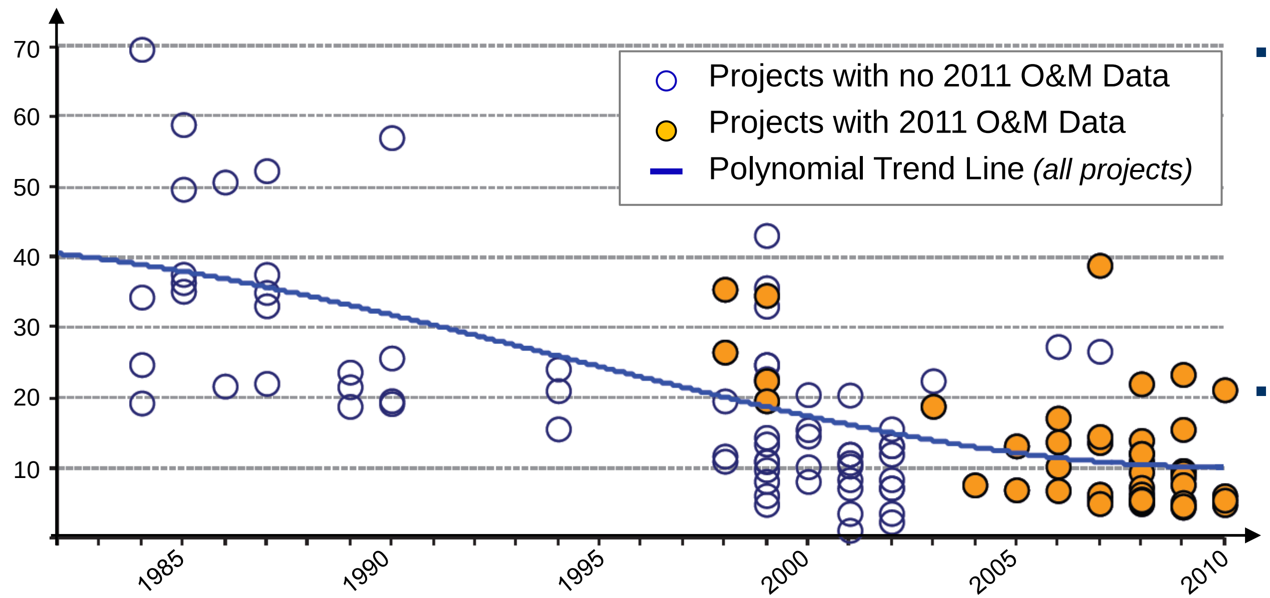
- Projected reductions are greater for offshore than for onshore due to offshore's relative immaturity, allowing for a greater learning effect, standardization and economies of scale. Offshore could also benefit from greater reduction in grid connection costs as a result of high voltage direct current cabling.
- Having diverged from its historical learning rate because of increasing turbine prices, onshore wind is now expected to return to its historical learning rate. However, its learning rate is expected to be capped by:
  - Increases in raw-materials prices;
  - Requirements from grid operators regarding power stability and controllability.
- Increased competition from emerging market manufacturers is likely to foster a decline in project costs.

Source: IRENA (2012), "Renewable Energy Technologies: Cost Analysis series - Wind Power"

Operation and maintenance costs have been steadily decreasing

ANNUAL OPERATION & MAINTENANCE (O&M) COSTS OF WIND POWER PLANTS IN THE US (ONSHORE)

USD_{2011} / MWh

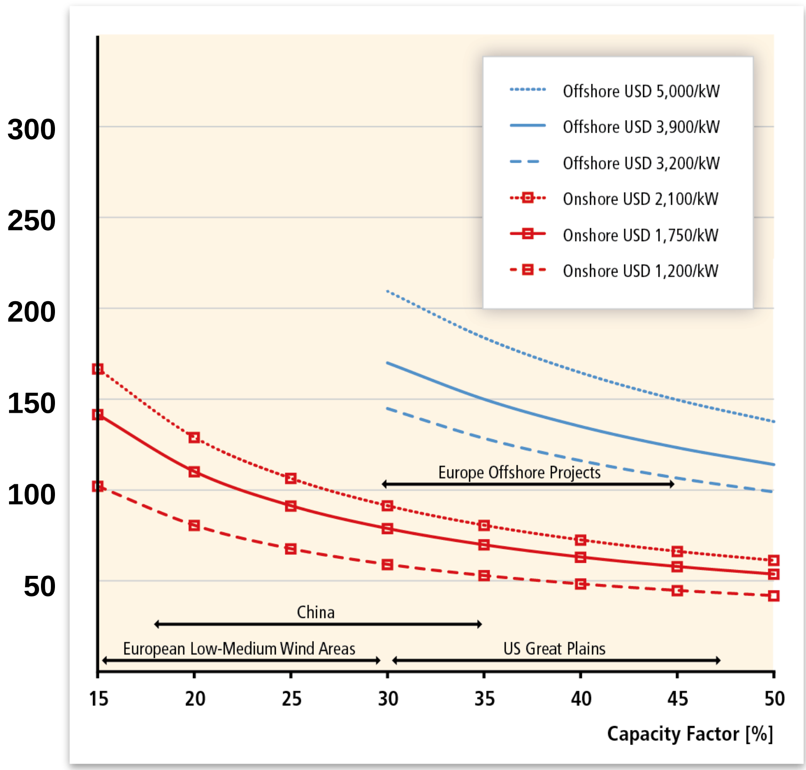


- Operation & Maintenance (O&M) costs are a significant component of wind power costs. They include:
  - Fixed O&M such as insurance, administration, grid access fees;
  - Variable O&M, mainly scheduled and unscheduled maintenance.
- Despite a lack of data and marked regional differences, there is a clear trend of decreasing costs. In the US, O&M costs have, on average, fallen by 75% since the 1980s, to 10 USD/MWh.
- Average onshore O&M costs are typically around 10 USD/MWh in the US and 20 USD/MWh in Europe.
- Offshore O&M costs are expected to be significantly higher, ranging from 27 to 54 USD/MWh.

Source: US DOE LBNL (2012), "2011 Wind Technologies Market Report"

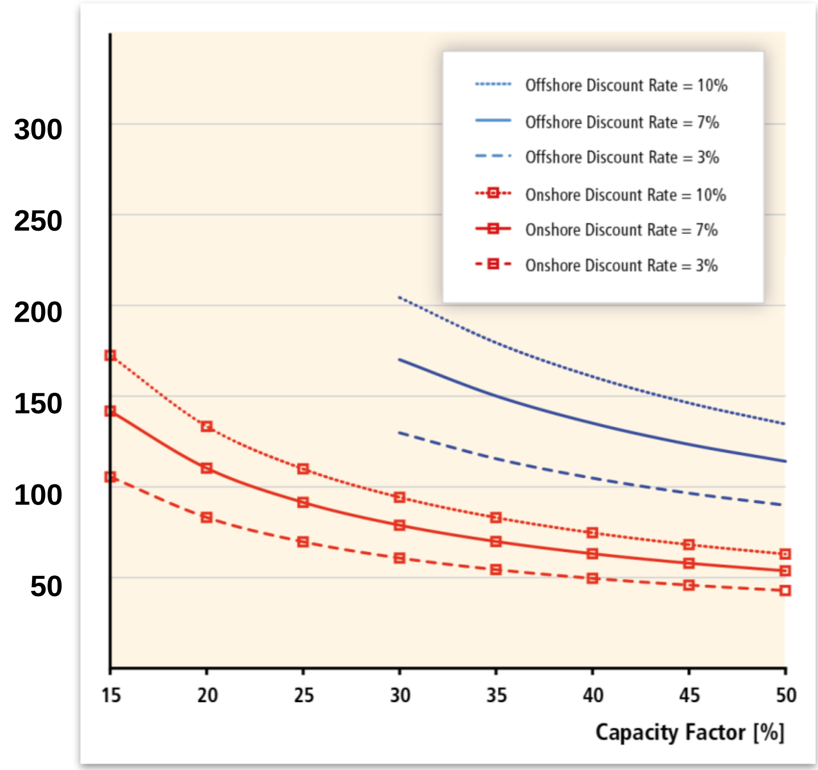
Depending largely on capacity factors, current wind electricity prices range from 50 to 150 USD/MWh for onshore and from 100 to 300 USD/MWh for offshore

LCOE VS. INVESTMENT COSTS & CAPACITY FACTOR
USD / MWh, with a 7% discount rate



- Onshore wind is nearing competitiveness in some regions. LCOE may be as low as 50 USD/MWh when local conditions allow for load factors higher than 25%.

LCOE VS. DISCOUNT FACTOR & CAPACITY FACTOR
USD / MWh, capital costs of 1750 USD/kW onshore, and 3900 USD/kW offshore

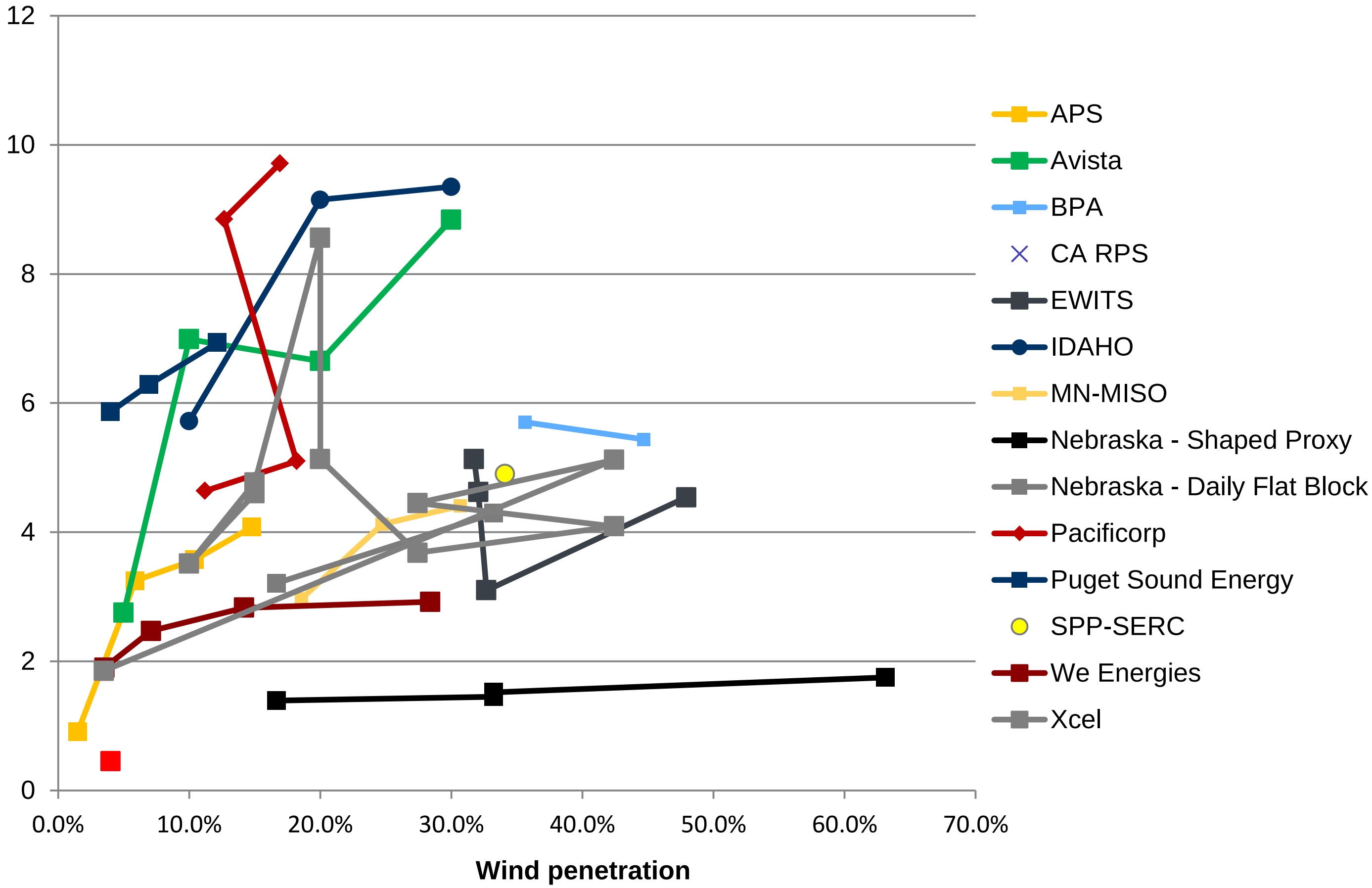


- Offshore wind has not reached ‘commerciality’ at this stage. Offshore’s LCOE is higher than 100 USD/MWh even for very favorable load factors. It is very sensitive to financing costs and thus to any project delays (discount rate, investment costs).

Note: LCOE for Levelized Cost of Electricity
Source: IPCC (2011), “Special report on renewable energy”

Failure to include rising grid-integration costs in the levelized cost of electricity generated from wind may result in a significant increase in end-user costs

INCREASE IN BALANCING COSTS VS. WIND PENETRATION
USD / MWh



- Wind penetration will generate integration costs due to intermittency :
  - Balancing costs (*i.e.* second-to-hour timescale);
  - Adequacy costs (*i.e.* day-to-year timescale);
  - 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 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 large share of the generation mix highly uncertain.

Source: US DOE LBNL (2012), "2011 Wind Technologies Market Report"

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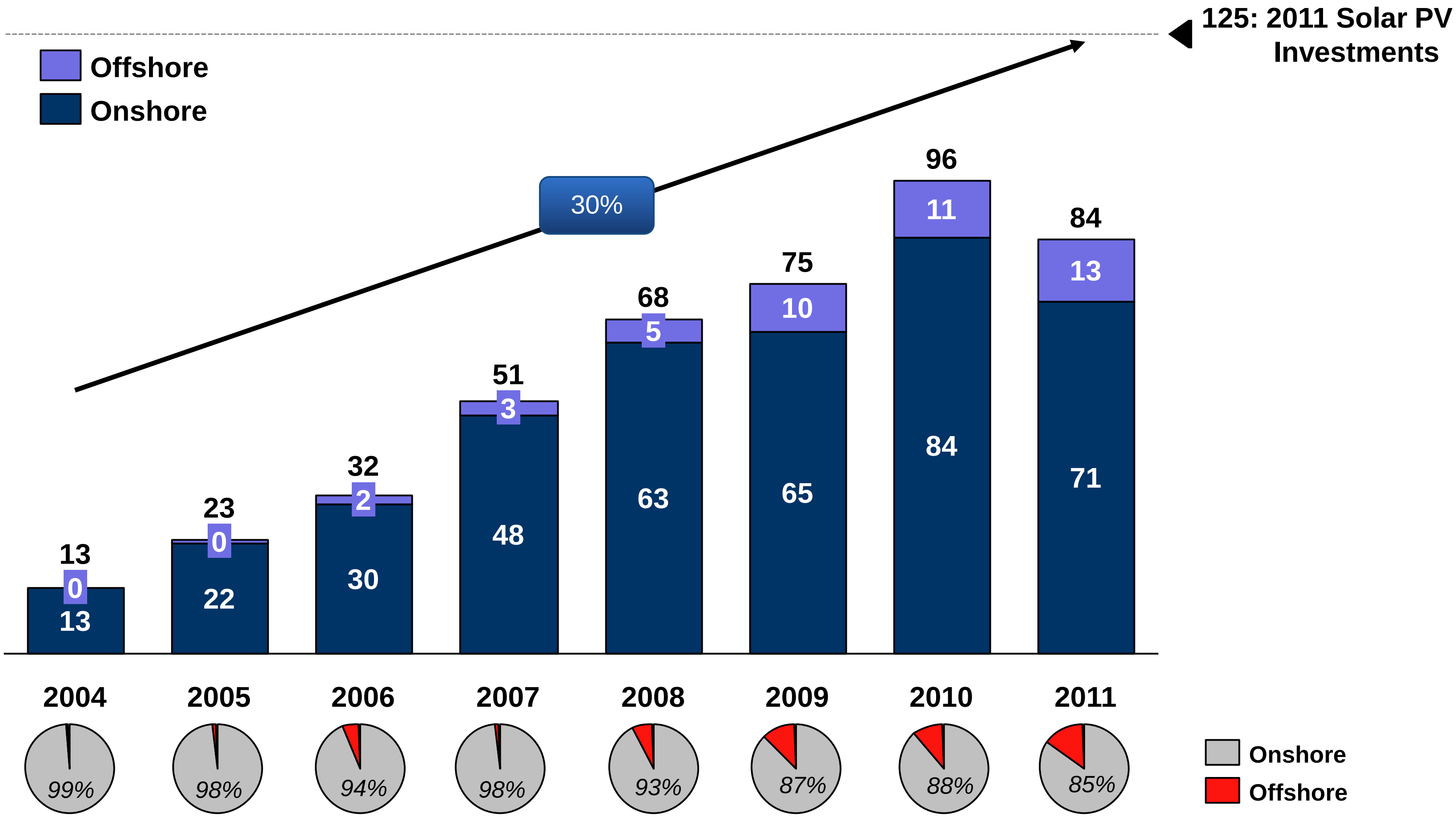
Wind finance experienced strong growth until the end of the past decade, but is now facing growing competition from solar photovoltaic

WIND INVESTMENTS 2004 - 2011
USD Billion



Note: Investments includes project financing, equipment manufacturing scale-up, and R&D
Source: UNEP (2012) “Global Trends in renewable Investment”; Bloomberg New Energy Finance database (accessed in July 2012)

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There is a wide variety of players in onshore technologies

VALUE CHAIN AND MAIN PLAYERS: ONSHORE

Components	Project Development	Construction / Installation	Power Generation	O&M
- Siemens	- Theolia	- Global Energy	- Theolia	- Eaton Power
- Vestas	- Eole Energie	- Skanska AB	- Eole Generation	- Global Energy
- Eole Generation	- Eno Energy	- enXco	- New Brunswick Power	- Eno Energy
- EGT	- Iberdrola	- GE Energy	- Golders Associates	- Enercon
- Enercon	- enXco Inc	- Upwind Capital	- Jantus	- Vestas Wind
- Winergy	- Prowind Canada	- Broadwind Energy	- ReNew Power	- enXco
- Mitsubishi	- Golder Associates	- Prowind Canada	- Youngduk Wind	- Juwi Wind
- Timken	- Jantus	- Ebara	- Green Wind Renewables	- GE Energy
- GE Energy	- ReNew Power	- New Brunswick Power	- Parque Eolico La Losilla	- Upwind Energy
- Samyou m-Tek	- Suzlon Energy		- THUEGA Erneurbare Energien	- Broadwind Energy
- Nantong Hongbo	- New Brunswick Power			- Prowind Canada
- Golden Concord				- Suzlon Energy
- Renobrax Energias Renovaveis				

Source: Bloomberg New Energy Finance, extract of Database April 2013

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Offshore wind firms are mainly based in Northern Europe

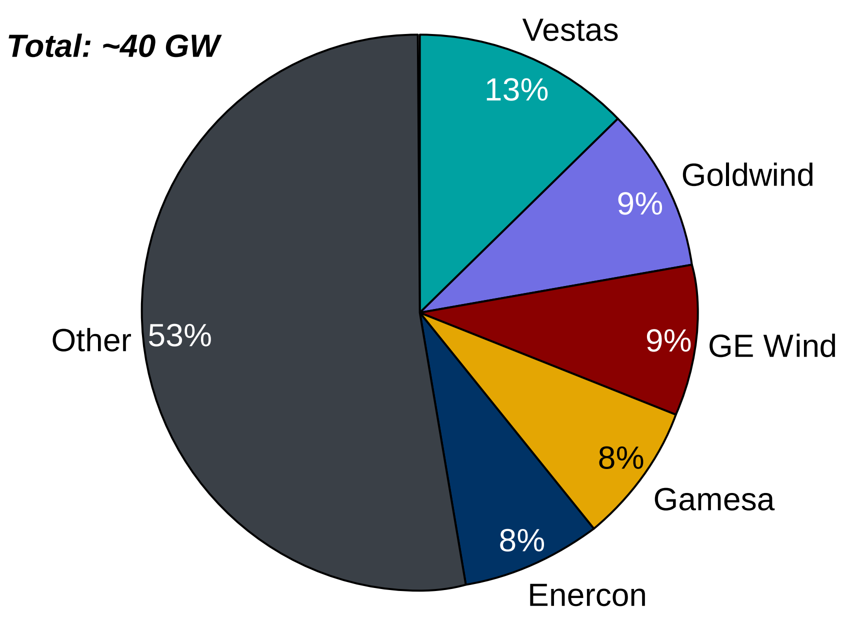
VALUE CHAIN AND MAIN PLAYERS: OFFSHORE SPECIFIC

Components	Foundations	Cabling	Vessels
- Siemens	- PER Aarsleff	- Jdr Cable Systems	- RWE Innogy
- Vestas	- Smulders Group	- Js Cable Co	- Ballast Nedam
- Repower	- Ramboll Group	- NSW	- A2 SEA
- WinWind	- GeoSea NV	- Prysmian	- MPI
- BARD	- Burntisland Fabrication	- Nexans	- GeoSea
- GE		- NKT Cables	- Gulf Marine
- Areva			- IHC Merwede
			- McNulty Offshore
			- OWEC Tower
			- Bard Engineering
			- Daiichi Kensetsu
			- Seajacks International

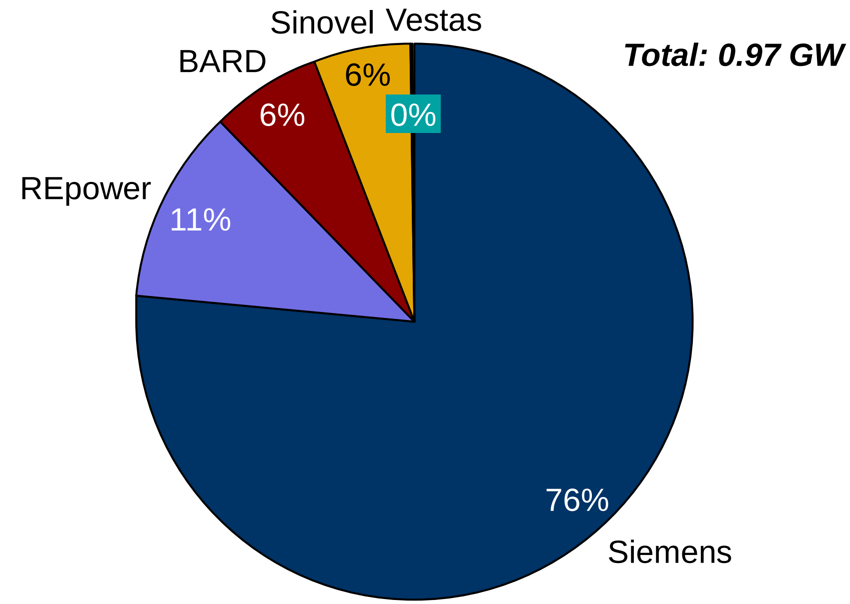
Source: Bloomberg New Energy Finance, extract of Database April 2013

Onshore wind market is maturing and fragmented, while offshore is at an early stage of development

ONSHORE TURBINE SUPPLIERS' MARKET SHARE
% of turbines supplied in 2011



OFFSHORE TURBINE SUPPLIERS' MARKET SHARE
% of turbines supplied in 2011



- Onshore market is maturing, with Chinese suppliers increasing their market shares.
- Suppliers tend to have to position themselves in a specific market segment to preserve their competitive advantages and meet local requirements.
- Offshore market is still at an early stage of development, with five manufacturers accounting for all turbines.
- The offshore market is largely driven by German manufacturers Siemens, Repower and BARD.

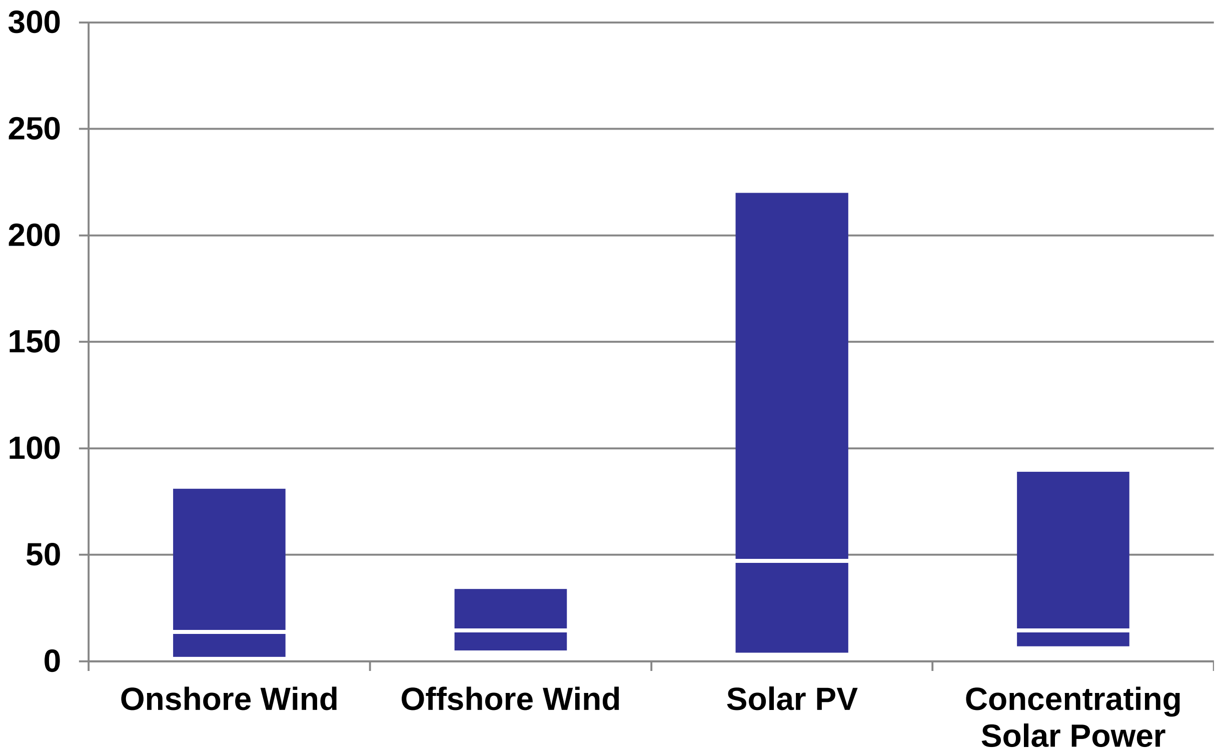
Source: IEA (2012), "Renewable Energy, Medium-term market report"

5. Environmental & Social Impacts

Horns Rev 1 owned by Vattenfall. Photographer Christian Steiness

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

LIFECYCLE GREENHOUSE GAS EMISSIONS
g CO_2 eq / kWh



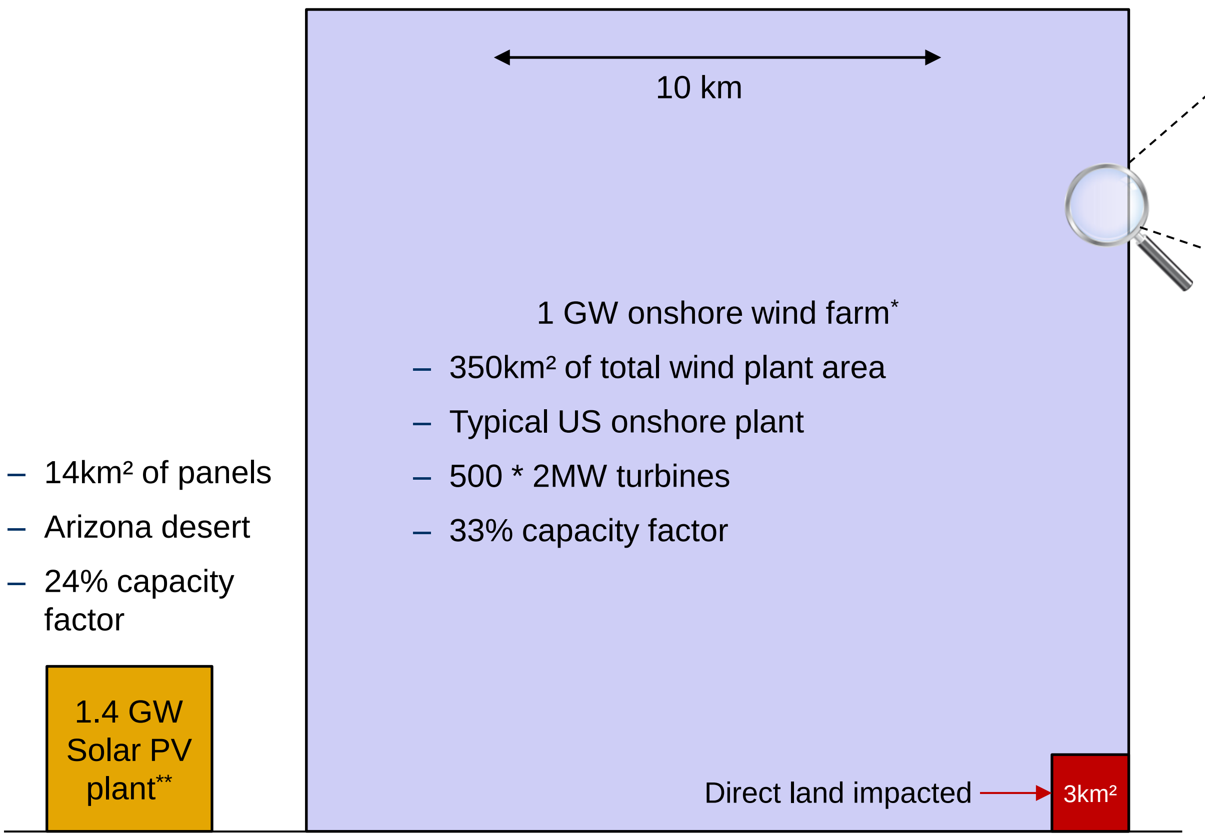
Median g CO2 eq / kWh	12	13	48	13

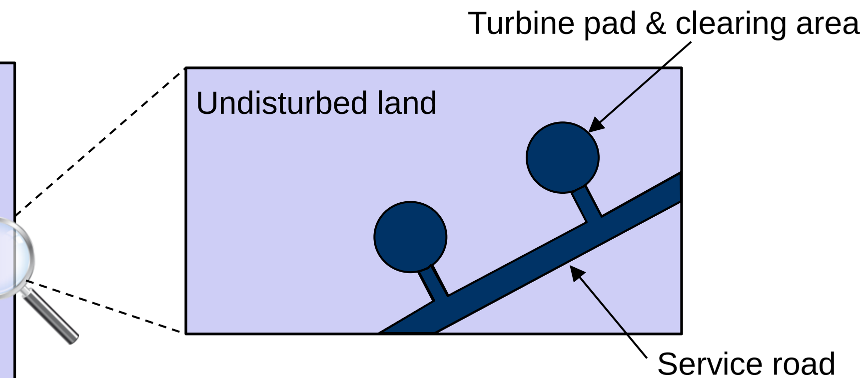
- Wind does not directly emit GHGs or other pollutants.
- On average, wind emits 12g CO_2 equivalent per kWh over its full lifecycle:
  - ~ 22 for concentrating solar power;
  - ~ 48 for solar PV;
  - ~ 500 for natural gas power plants;
  - ~ 1000 for coal power plants.
- If wind displaces fossil-fuel power plants, it may result in greater use of flexible peak & intermediate plants emitting more GHGs.
- Impact is thus highly system specific, but nonetheless clear that it reduces air pollutants & GHG emissions.

Source: IPCC (2011), "Special report on renewable energy"

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 TO PRODUCE AN ANNUAL AVERAGE OF 330MW OF RENEWABLE ELECTRICITY





- 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 wind turbulence.
- ~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%).

Source: *The weighted average capacity density of 172 US existing onshore wind farms is 35 ± 22 hectare/MW, whereas direct land impacted averaged 0.3 ± 0.3 ha/MW according to NREL (2009) "Land-Use Requirements of Modern Wind Power Plants in the United States"
**According to the USDOE, modern solar PV plants require 10 to 20 km² per GW of capacity installed, depending on the latitude. 10km² /GW in this example

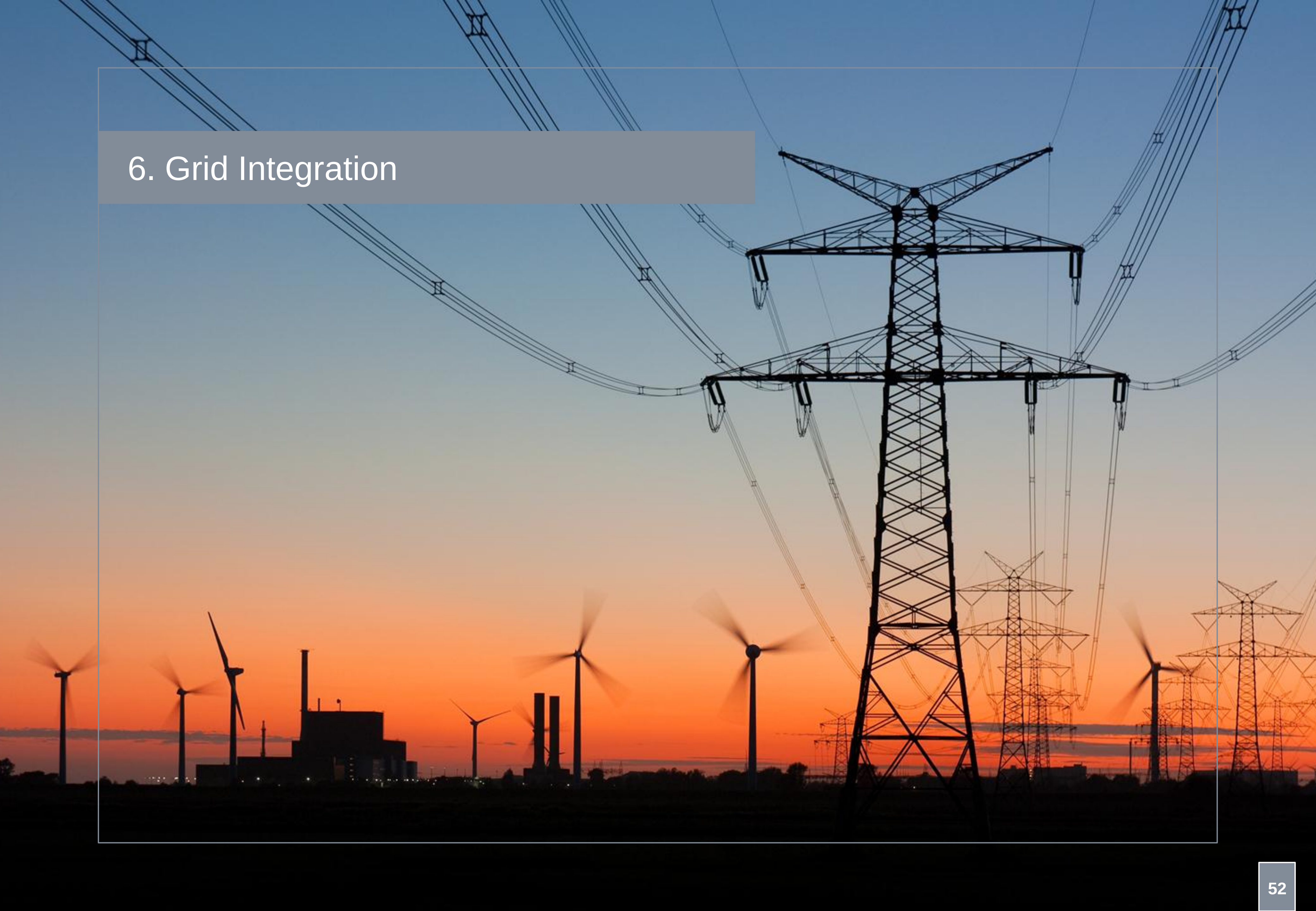
Wind incurs few social challenges except aesthetic and noise impacts

MAIN SOCIAL IMPACTS OF WIND AND MEANS OF MITIGATING THEM

- Principal social issues for wind power are its aesthetic and noise impacts:
  - *Visual*: Not In My Backyard syndrome (NIMBY) raises major social acceptance challenge and may have negative impact in touristic areas;
  - *Noise*: generally restricted to 35 to 45 decibels at 300 meters and not of concern to humans after 800 meters.
- 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 if 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 & recreational impact.
- Technology advances and siting wind farms offshore should largely avoid 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: the more, the easier. 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 tend to be more accepting than those who live further away and are less familiar with the technology.

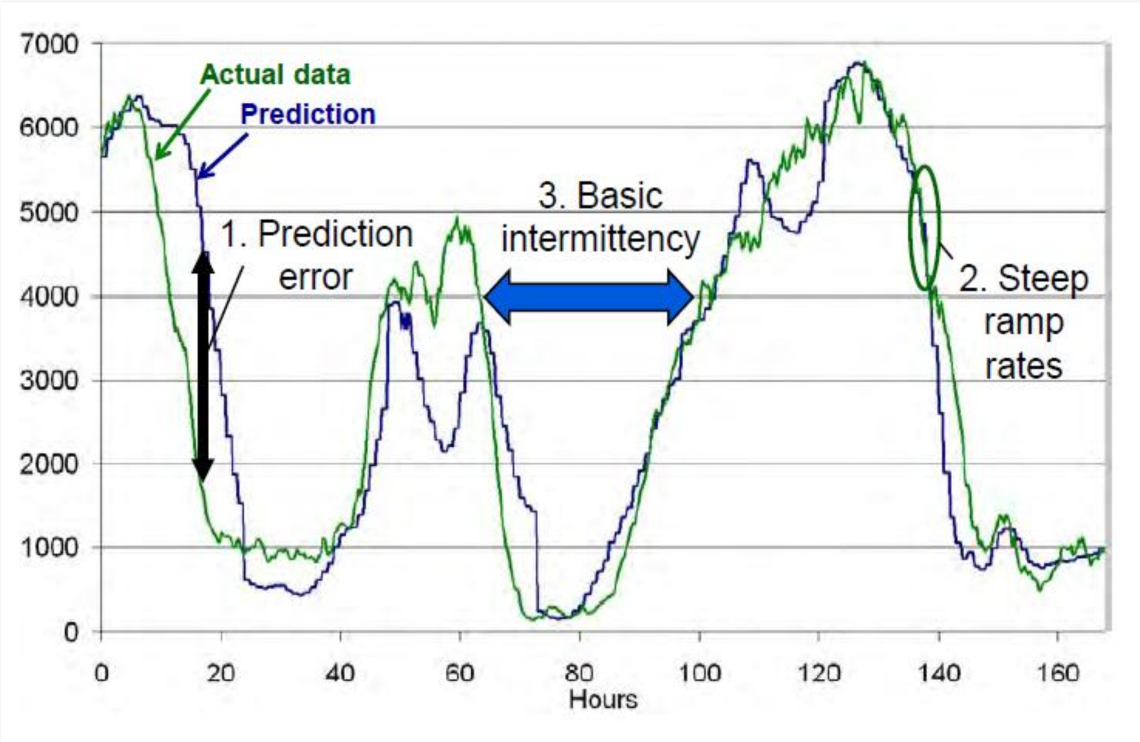
Source: IPCC (2011), "Special report on renewable energy"

6. Grid Integration



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:
  - Lower level of predictability than fossil-fired power plants;
  - Forecast less accurate 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.
- Wind output is variable and imperfectly controllable over several timescales:
  - Wind output depends on weather;
  - Variations can occur on multiple time scales, from sub-hourly to inter-annual.
- Intermittency is a crucial challenge for grid stability and to match demand & supply.

Source: IPCC (2011), “Special report on renewable energy”

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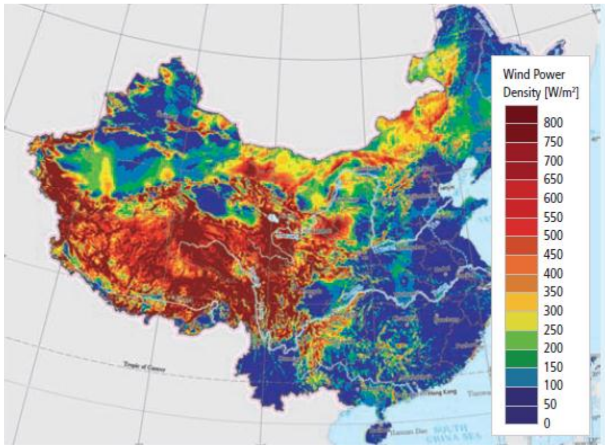
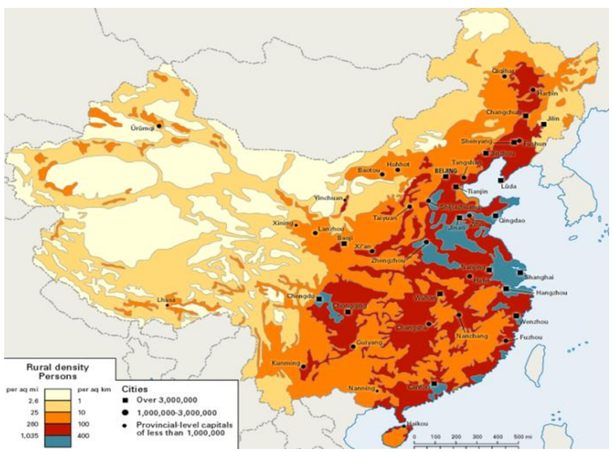
The quality of wind resources is location specific, with the best locations often found far from the load center

WIND RESOURCES & POPULATION MISALIGNMENT

Illustration for China



Wind resources
W / km²



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:
  - Technical challenges due to thermal, voltage and transient constraints on long lines;
  - Timescale challenges due to a longer development time than wind generation (8 to 15 years *vs* ~3 years respectively);
  - Economic challenges, as transmission and distribution (T&D) costs are supported by end-consumers and already account for a large proportion electricity prices.

Source: IPCC (2011), "Special report on renewable energy"

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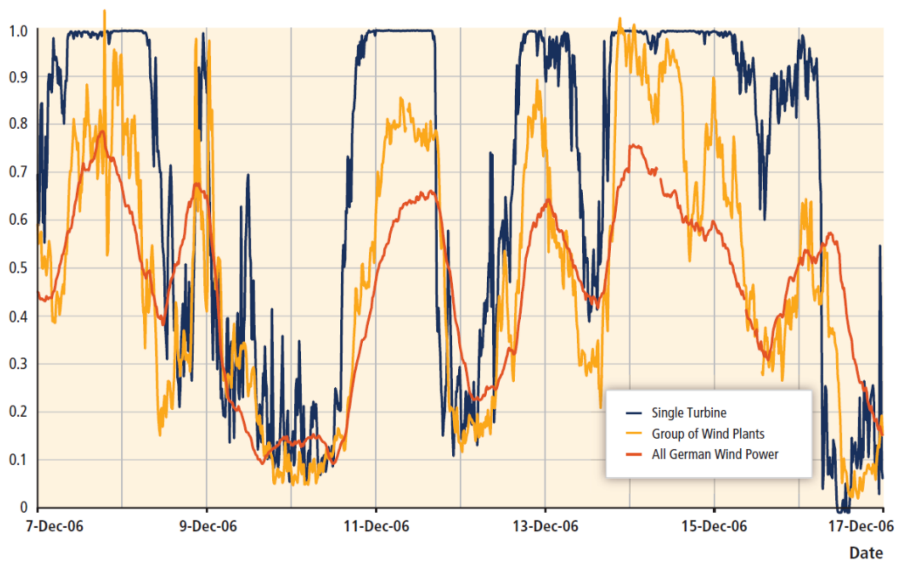
Wind power can be smoothed out geographically to reduce unpredictability but this requires expensive interconnection lines

WIND GEOGRAPHIC SMOOTHING ILLUSTRATION IN GERMANY OVER A 10-DAY PERIOD IN 2006

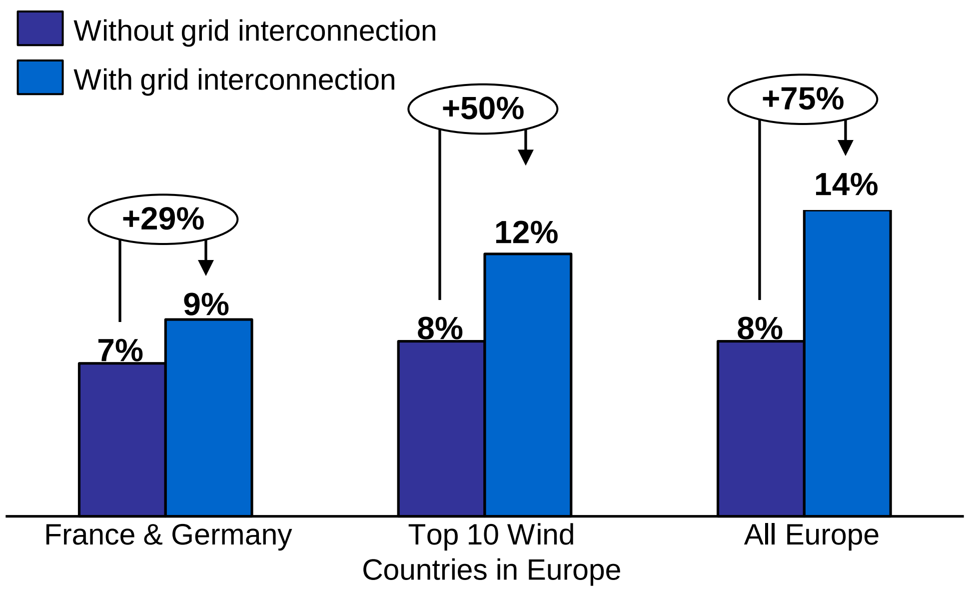
Effective load factor



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

CAPACITY CREDIT* OF EUROPEAN WIND FARMS IN 2020 (200GW WIND CAPACITY SCENARIO)

Capacity credit* in % of total wind capacity



- The wider the area, the higher the wind capacity credit*, *i.e.* the level of wind's output that can be relied on during times of peak demand. However, even at the European scale, capacity credit is still limited to 14%, meaning that additional flexible capacity will be needed.

Note: * The capacity credit is the amount of capacity that contributes to system adequacy, i.e. can be relied upon at times of peak demand.

Source: IPCC (2011), "Special report on renewable energy", TradeWind (2009), "Integrating Wind - Developing Europe's power market for the large-scale integration of wind power"

Appendix & Bibliography

Acronyms

- **CAGR**: compound annual growth rate
- **g CO_2 eq**: gram of CO_2 equivalent
- **EJ**: Exajoules (10^{18} joules)
- **GHG**: Greenhouse Gas
- **GW**: Gigawatt
- **m/s**: meters per second
- **LCOE**: levelized cost of electricity
- **MW**: Megawatt
- **MWh**: Megawatt hour
- **NIMBY**: Not In My Backyard
- **OECD**: Organisation for Economic Co-operation and Development
- **O&M**: Operation & Maintenance
- **PMG:** Permanent Magnet Generator
- **PV**: Photovoltaic
- **R&D**: Research & Development
- **RD&D**: Research, Development & Demonstration
- **UK**: United Kingdom
- **USD**: United States Dollar

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