ENE425 Sustainable Energy and App Development

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Contents

Chapter 5

Sustainable energy. Wind

5.1 Introduction

In this chapter, we will study the **main characteristics of wind energy from a technological perspective**, and we will connect that analysis with the **economic development of that technology**. The chapter is organized as follows:

1. Watch a video to **discuss** some important aspects of wind energy
2. Review the **history** and evolution of wind energy
3. Wind **technology** and its impact in wind production
4. Wind energy. **Key trends**: **Onshore** wind energy and **offshore** wind energy
5. **Questions** to summarize the chapter

5.2 Discussion

To motivate the chapter, we start by watching the video How Big Can Wind Turbines Get?

Based on that video, we discuss the next questions:

1. Which have been the evolution of **wind installed capacity** in the next 20 years?
2. Which is the **share energy production that come from wind energy** in Denmark in one year? And in a windy day?
3. Which has been the evolution of the **size of windmills** in the last years?
4. Which is the mathematical formula to work out **kinetic energy**? And **power** from that kinetic energy?
5. Based on those mathematical formulas, **why have increased the size of windmills**?
6. Which are the main **problems to continue increasing the size of windmills**?

5.3 Introduction

Wind power is one of the fastest-growing renewable energy technologies. Usage is on the rise worldwide, in part because costs are falling. Global installed wind-generation capacity onshore and offshore has increased by a factor of almost 75 in the past two decades, jumping from 7.5 gigawatts (GW) in 1997 to some 564 GW by 2018, according to IRENA's latest data (link). Production of wind electricity doubled between 2009 and 2013, and in 2016 wind energy accounted for 16% of the electricity generated by renewables. Many parts of the world have strong wind speeds, but the best locations for generating wind power are sometimes remote ones. Offshore wind power offers tremendous potential.

Wind-turbine capacity has increased over time. In 1985, typical turbines had a rated capacity of 0.05 megawatts (MW) and a rotor diameter of 15 metres. Today's new wind power projects have turbine capacities of about 2 MW onshore and 3–5 MW offshore.

Commercially available wind turbines have reached 8 MW capacity, with rotor diameters of up to 164 metres. The average capacity of wind turbines increased from 1.6 MW in 2009 to 2 MW in 2014.

5.4 History

Wind turbines first emerged more than a century ago. Following the invention of the electric generator in the 1830s, engineers started attempting to harness wind energy to produce electricity. Wind power generation took place in the United Kingdom and the United States in 1887 and 1888, but modern wind power is considered to have been first developed in Denmark, where horizontal-axis wind turbines were built in 1891 and a 22.8-metre wind turbine began operation in 1897.

People have been using wind energy for thousands of years.

People used wind energy to propel boats along the Nile River as early as 5,000 BC. By 200 BC, simple wind-powered water pumps were used in China, and windmills with woven-reed blades were grinding grain in Persia and the Middle East.

New ways to use wind energy eventually spread around the world. By the 11th century, people in the Middle East were using wind pumps and windmills extensively for food production. Merchants and the Crusaders brought wind technology to Europe. The Dutch developed large windpumps to drain lakes and marshes in the Rhine River Delta. Immigrants from Europe eventually took wind energy technology to the Western Hemisphere.

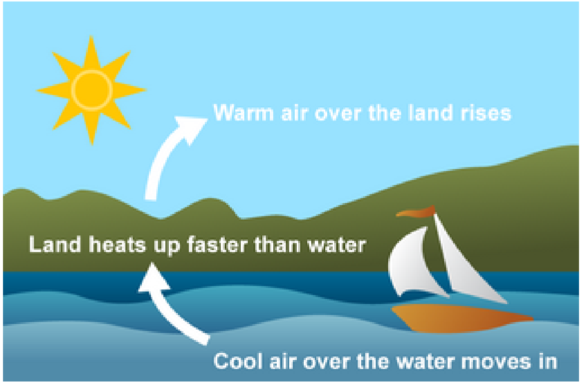
American colonists used windmills to grind grain, to pump water, and to cut wood at sawmills. Homesteaders and ranchers installed thousands of wind pumps as they settled the western United States. In the late 1800s and early 1900s, small wind-electric generators (wind turbines) were also widely used.

The number of wind pumps and wind turbines declined as rural electrification programs in the 1930's extended power lines to most farms and ranches across the country. However, some ranches still use wind pumps to supply water for livestock. Small wind turbines are becoming more common again, mainly to supply electricity in remote and rural areas.

Wind energy use expanded in the wake of oil shortages and environmental concerns.

The oil shortages of the 1970s changed the energy environment for the United States and the world. The oil shortages created an interest in developing ways to use alternative energy sources, such as wind energy, to generate electricity. The U.S. federal government supported research and development of large wind turbines. In the early 1980s, thousands of wind turbines were

Figure 5.1: How uneven heating of water and land causes wind



Source: EIA webpage

installed in California, largely because of federal and state policies that encouraged the use of renewable energy sources.

In the 1990s and 2000s, the U.S. federal government established incentives to use renewable energy sources in response to a renewed concern for the environment. The federal government also provided research and development funding to help reduce the cost of wind turbines and offered tax and investment incentives for wind power projects. In addition, state governments enacted new requirements for electricity generation from renewable sources, and electric power marketers and utilities began to offer electricity generated from wind and other renewable energy sources (sometimes called green power) to their customers. These policies and programs resulted in an increase in the number of wind turbines and in the amount of electricity generated from wind energy.

The share of U.S. electricity generation from wind grew from less than 1% in 1990 to about 7.3% in 2019. Incentives in Europe have resulted in a large expansion of wind energy use there. China has invested heavily in wind energy and is now the world's largest wind electricity generator. In 1990, 16 countries generated a total of about 3.6 billion kWh of wind electricity. In 2017, 129 countries generated a total of about 1.13 trillion kWh of wind electricity.

5.5 Technology

5.5.1 How wind turbines work.

Wind turbines use blades to collect the wind's kinetic energy. Wind flows over the blades creating lift (similar to the effect on airplane wings), which causes the blades to turn. The blades are connected to a drive shaft that turns an electric generator, which produces (generates) electricity.

5.5.2 Energy from moving air

Wind is caused by uneven heating of the earth's surface by the sun. Because the earth's surface is made up of different types of land and water, it absorbs the sun's heat at different rates. One example of this uneven heating is the daily wind cycle (figure 5.1).

The daily wind cycle

During the day, air above the land heats up faster than air over water. Warm air over land expands and rises, and heavier, cooler air rushes in to take its place, creating wind. At night, the winds are reversed because air cools more rapidly over land than it does over water.

In the same way, the atmospheric winds that circle the earth are created because the land near the earth's equator is hotter than the land near the North Pole and the South Pole. The global wind kinetic energy averaged approximately 1.50 MJ/m2 over the period from 1979 to 2010, 1.31 MJ/m2 in the Northern Hemisphere with 1.70 MJ/m2 in the Southern Hemisphere. The atmosphere acts as a thermal engine, absorbing heat at higher temperatures, releasing heat at lower temperatures. The process is responsible for the production of wind kinetic energy at a rate of 2.46 W/m2 sustaining thus the circulation of the atmosphere against frictional dissipation.

Wind is used to produce electricity using the kinetic energy created by air in motion. This is transformed into electrical energy using wind turbines or wind energy conversion systems. Wind first hits a turbine's blades, causing them to rotate and turn the turbine connected to them. That changes the kinetic energy to rotational energy, by moving a shaft which is connected to a generator, and thereby producing electrical energy through electromagnetism.

The amount of power that can be harvested from wind depends on the size of the turbine and the length of its blades. The output is proportional to the dimensions of the rotor and to the cube of the wind speed. Theoretically, when wind speed doubles, wind power potential increases by a factor of eight.

Mathematically, total **wind energy** flowing through an imaginary surface with area A during the time t is:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}(Avt\rho)v^2 = \frac{1}{2}At\rho v^3 \tag{5.1}$$

where ρ is the density of air; v is the wind speed; Avt is the volume of air passing through A (which is considered perpendicular to the direction of the wind); $Avt\rho$ is therefore the mass m passing through A. $\frac{1}{2}\rho v^2$ is the kinetic energy of the moving air per unit volume.

Power is energy per unit time, so the wind power incident on A (e.g. equal to the rotor area of a wind turbine) is:

$$P = \frac{E}{t} = \frac{1}{2}A\rho v^3 \tag{5.2}$$

Energy:

As energy is defined via work, the International System of Units unit of energy is the same as the unit of work – the **joule (J)**, named in honor of James Prescott Joule and his experiments on the mechanical equivalenta of heat. In slightly more fundamental terms, **1 joule is equal to 1 newton metre** and, in terms of International System of Units base units:

$$1J = \left(1kg\frac{m}{s^2}\right) m = 1kg \left(\frac{m}{s}\right)^2 = 1\frac{kg \cdot m^2}{s^2} \tag{5.3}$$

Electricity is measured in Watts and kilowatts:

Electricity is measured in units of power called Watts, named to honor James Watt, the inventor of the steam engine. A Watt is the unit of electrical power equal to **one ampere under the pressure of one volt**.

One Watt is a small amount of power. Some devices require only a few Watts to operate, and other devices require larger amounts. The power consumption of small devices is usually measured in Watts, and the power consumption of larger devices is measured in kilowatts (kW), or 1,000 Watts.

Electricity generation capacity is often measured in multiples of kilowatts, such as megawatts (MW) and gigawatts (GW). One MW is 1,000 kW (or 1,000,000 Watts), and one GW is 1,000 MW (or 1,000,000,000 Watts).

Electricity use over time is measured in Watthours:

A Watthour (Wh) is equal to the energy of one Watt steadily supplied to, or taken from, an electric circuit for one hour. **The amount of electricity that a power plant generates or an electric utility customer uses is typically measured in kilowatthours (kWh)**. One kWh is one kilowatt generated or consumed for one hour. For example, if you use a 40-Watt (0.04 kW) light bulb for five hours, you have used 200 Wh, or 0.2 kWh, of electrical energy.

For more information about energy measures visit:

- Energy Information Administration (link).
- Wikipedia, wind power (link); wikipedia, units of energy (link); wikipedia, electric power (link).

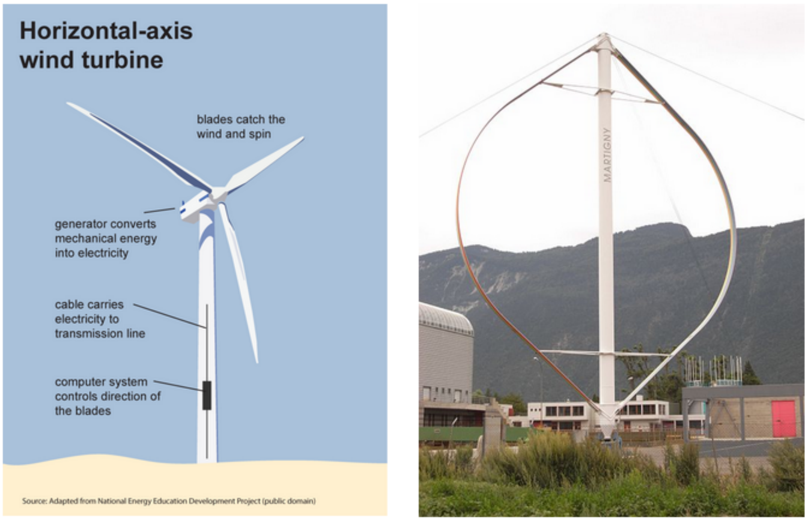
5.5.3 Types of wind turbines.

There are two basic types of wind turbines (figure 5.2):

- Horizontal-axis turbines
- Vertical-axis turbines

The size of wind turbines varies widely. The length of the blades is the biggest factor in determining the amount of electricity a wind turbine can generate. Small wind turbines that can power a single home may have an electricity generating capacity of 10 kilowatts (kW). The largest wind turbines in operation have electricity generating capacities of up to kilowatts (10

Figure 5.2: Types of wind turbines



Source: EIA webpage

megawatts), and larger turbines are in development. Large turbines are often grouped together to create wind power plants, or wind farms, that provide power to electricity grids.

Horizontal-axis turbines are similar to propeller airplane engines.

Horizontal-axis turbines have blades like airplane propellers, and they commonly have three blades. The largest horizontal-axis turbines are as tall as 20-story buildings and have blades more than 100 feet long. Taller turbines with longer blades generate more electricity. Nearly all of the wind turbines currently in use are horizontal-axis turbines.

Vertical-axis turbines look like egg beaters.

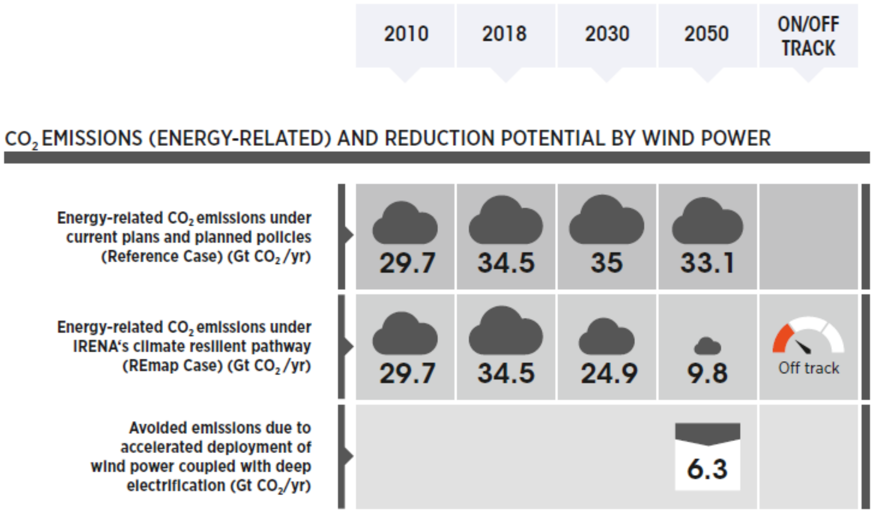
Vertical-axis turbines have blades that are attached to the top and the bottom of a vertical rotor. The most common type of vertical-axis turbine—the Darrieus wind turbine, named after the French engineer Georges Darrieus who patented the design in 1931—looks like a giant, two-bladed egg beater. Some versions of the vertical-axis turbine are 100 feet tall and 50 feet wide. Very few vertical-axis wind turbines are in use today because they do not perform as well as horizontal-axis turbines.

Two very useful videos to know more about **wind turbines**:

- How do wind turbines work: (link).
- Why Do Wind Turbines Have Three Blades? (link).

More information about **wind turbine generators** can be found in the Alternative Energy Tutorials webpage (link).

Figure 5.3: CO2 emissions (energy-related) and reduction potential by wind power



Source: IRENA (2019a)

The **Global Wind Atlas** is a web-based application developed to help policymakers and investors identify potential high-wind areas for wind power generation virtually anywhere in the world, and perform preliminary calculations.

It provides **free access to data on wind power density and wind speed at multiple heights** using the latest historical weather data and modeling, at an output resolution of 250 meters.

It was developed and is maintained by the **Wind Energy Department of the Technical University of Denmark (DTU Wind Energy)** in partnership with the **World Bank**, with funding provided by the Energy Sector Management Assistance Program (ESMAP).

For more information about the Global Wind Atlas visit (link).

5.6 Future of wind. Deployment, investment, technology, grid integration and socio-economic aspects

This section is based on IRENA (2019a).

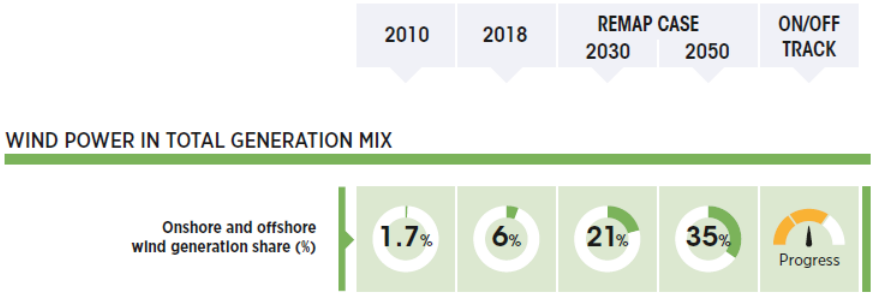
5.6.1 Key findings

1. Accelerated deployment of renewables, combined with deep electrification an increased energy efficiency, can achieve over 90% of the energy-related CO2 emissions reductions needed by 2050 to set the world on an energy patway towards meeting the **Paris climate targets**.

   Among all low-carbon technology options, accelerated deployment of wind power when coupled with deep electrification would contribute to more than one-quarter of the total emissions reductions needed **(nearly 6.3 gigatonnes of carbon dioxide (Gt CO2) annually) in 2050** (figure 5.3).[1].

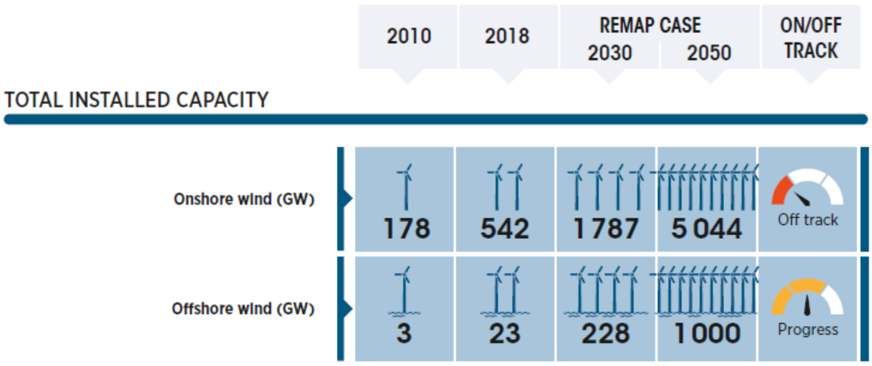
[1]For more information about CO2 emission visit section ??

Figure 5.4: Wind power in total generation mix



Source: IRENA (2019a)

Figure 5.5: Wind total installed capacity



Source: IRENA (2019a)

2. The achievement of the Paris climate targets is only possible by greatly **scaling up wind capacity installations** in the next three decades.

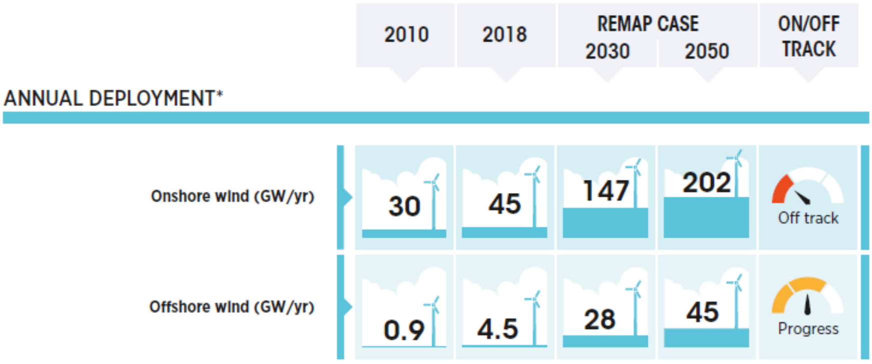
   This entails increasing the global cumulative installed capacity of **onshore wind power** more than three fold by 2030 (to 1 787 gigawatts (GW)) and nine-fold by 2050 (to 5 044 GW) compared to installed capacity in 2018 (542 GW). For **offshore wind power**, the global cumulative installed capacity would increase almost ten-fold by 2030 (to 228 GW) and substantially towards 2050, with total offshore installation nearing 1 000 GW by 2050 (figures 5.4 and 5.5).

3. **Annual capacity additions for onshore wind** would increase more than four-fold, to more than 200 GW per year in the next 20 years, compared to 45 GW added in 2018. Even higher growth would be required in **annual offshore wind capacity additions** – around a ten-fold increase, to 45 GW per year by 2050 from 4.5 GW added in 2018 (figure 5.6).

4. At a regional level, Asia would largely drive the pace of wind capacity installations, becoming the world leader in wind energy.

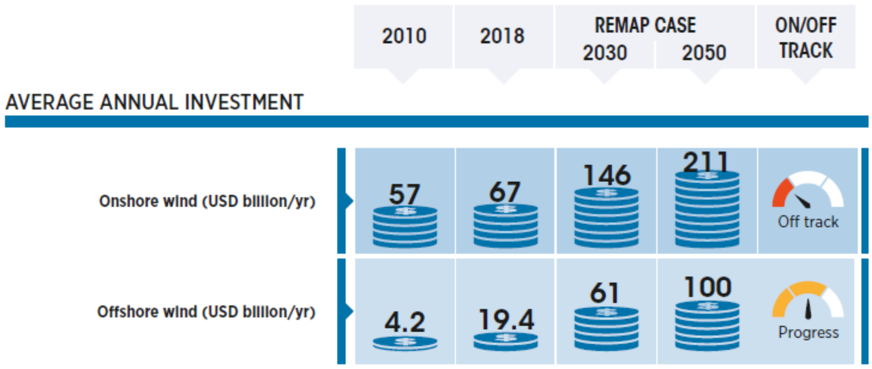
   - Asia (mostly China) would continue to dominate the **onshore wind** power industry, with more than 50% of global installations by 2050, followed by North America (23%) and Europe (10%).
   - For **offshore wind**, Asia would take the lead in the coming decades with more than 60% of global installations by 2050, followed by Europe (22%) and North America

Figure 5.6: Wind annual deployment



Source: IRENA (2019a)

Figure 5.7: Wind average annual investment



Source: IRENA (2019a)

(16%).

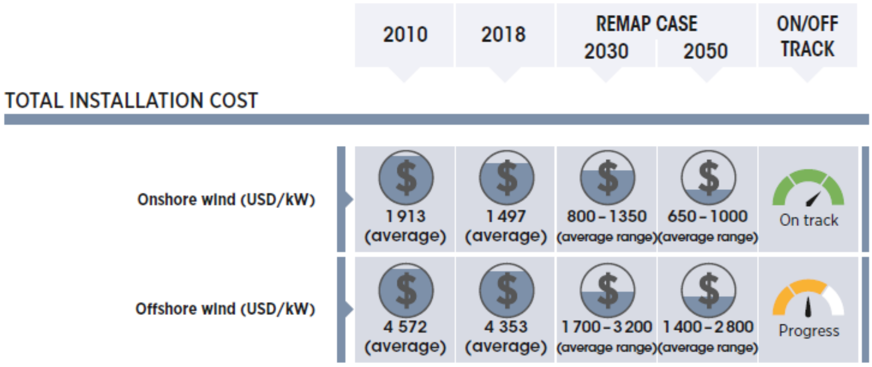
5. **Scaling up wind energy investments** is key to accelerating the growth of global wind power installations over the coming decades.

   - This would imply increasing global average annual **onshore wind** power investments by more than two-fold from now until 2030 (USD 146 billion/year) and more than three-fold over the remaining period to 2050 (USD 211 billion/year) compared to 2018 investments (USD 67 billion/year).
   - For **offshore wind**, global average annual investments would need to increase three-fold from now until 2030 (USD 61 billion/year) and more than five-fold over the remaining period to 2050 (USD 100 billion/year) compared to 2018 investments (USD 19 billion/year).

6. Increasing economies of scale, more competitive supply chains and further technological improvements will continue to reduce the **costs of wind power**.

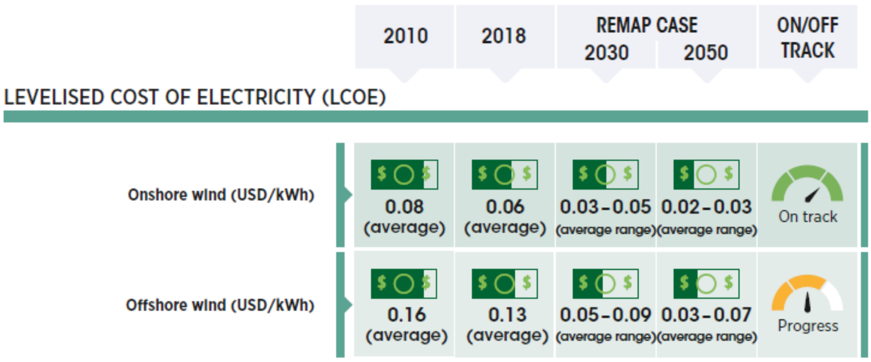
   (a) The **total installation cost** of **onshore wind projects** would continue to decline in the next three decades with the average cost falling in the range of USD 800 to 1 350 per kilowatt (kW) by 2030 and USD 650 to 1 000/ kW by 2050, compared to the global-weighted average of USD 1 497/kW in 2018. For **offshore wind projects**, the

Figure 5.8: Wind total installation cost



Source: IRENA (2019a)

Figure 5.9: Wind levelised cost of electricity (LCOE)



Source: IRENA (2019a)

average total installation cost would further drop in coming decades to between USD 1 700 and 3 200/kW by 2030 and between USD 1 400 and 2 800/kW by 2050.

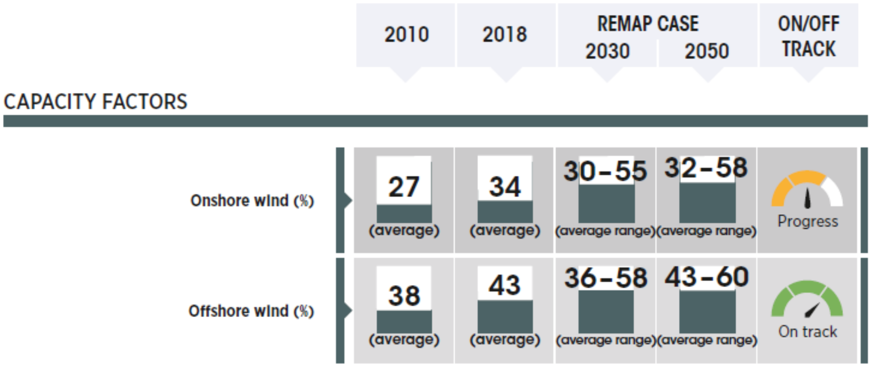
(b) The **levelised cost of electricity (LCOE)** for **onshore wind** will continue to fall from an average of USD 0.06 per kilowatt-hour (kWh) in 2018 to between USD 0.03 to 0.05/kWh by 2030 and between USD 0.02 to 0.03/kWh by 2050. The LCOE of offshore wind would drop from an average of USD 0.13/kWh in 2018 to an average between USD 0.05 to 0.09/kWh by 2030 and USD 0.03 to 0.07/kWh by 2050.

7. Ongoing **innovations** and **technology enhancements** towards larger capacity turbines as well as increased hub heights and rotor diameters help improve yields for the same location.

   - For **onshore wind plants**, global weighted average capacity factors would increase from 34% in 2018 to a range of 30% to 55% in 2030 and 32% to 58% in 2050.
   - For **offshore wind farms**, even higher progress would be achieved, with capacity factors in the range of 36% to 58% in 2030 and 43% to 60% in 2050, compared to an average of 43% in 2018.

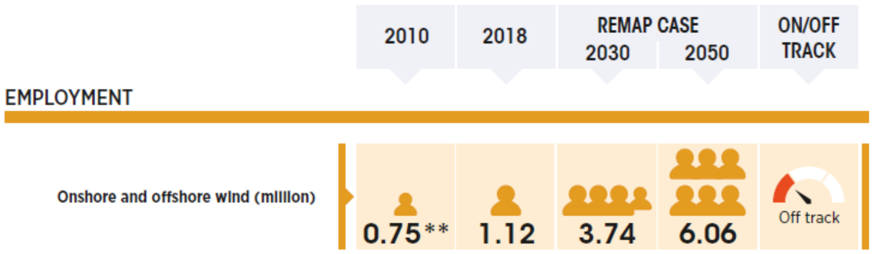
8. Technological developments in **wind turbine foundations** are a key factor enabling the accelerated deployment of offshore wind permitting access to better wind resources. By 2030, industry experts estimate that around 5 GW to 30 GW of floating offshore capacity

Figure 5.10: Wind capacity factors



Source: IRENA (2019a)

Figure 5.11: Wind employment



Source: IRENA (2019a)

could be installed worldwide and that, based on the pace of developments across various regions, floating wind farms could cover around 5% to 15% of the global offshore wind installed capacity (almost 1 000 GW) by 2050.

9. The wind industry can employ 3.74 million people by 2030 and more than 6 million people by 2050, a figure nearly three times higher and five times higher respectively than the 1.16 million jobs in 2018.

The levelized cost of energy (LCOE), or levelized cost of electricity, is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. The LCOE is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered. The LCOE is used to compare different methods of electricity generation on a consistent basis. The LCOE "represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle." Inputs to LCOE are chosen by the estimator. They can include cost of capital, "fuel costs, fixed and variable operations and maintenance costs, financing costs, and an assumed utilization rate.

The LCOE is calculated as:

$$LCOE = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where,

- I_t: Investment expenditure in the year t.
- M_t: Operations and maintenance expenditures in the year t.
- F_t: Fuel expenditures in the year t.
- E_t: electrical energy generated in the year t.
- r: Discount rate
- n: Expected lifetime of system or power station.

For more information about the levelized cost of energy (LCOE) visit:

- Wikipedia (link).
- Energy Information Administration (link).

The **net capacity factor** is the unitless ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period. The capacity factor is defined for any electricity producing installation, such as a fuel consuming power plant or one using renewable energy, such as wind or the sun. The average capacity factor can also be defined for any class of such installations, and can be used to compare different types of electricity production.

The Danish offshore wind farm Horns Rev 2 has a nameplate capacity of 209.3 MW. As of January 2017 it has produced 6416 GWh since its commissioning 7 years ago, i.e. an average annual production of 875 GWh/year and a **capacity factor of**:

$$\frac{875.000 MW \cdot h}{(365\text{days })(24\text{hours/day})(209.3\text{MW})} = 0.477 = 47.7\% \tag{5.4}$$

Sites with lower capacity factors may be deemed feasible for wind farms, for example the onshore 1 GW Fosen Vind which as of 2017 is under construction in Norway has a projected capacity factor of 39%. Feasibility calculations may be affected by seasonality. For example in Finland, capacity factor during the cold winter months is more than double compared to July. While the annual average in Finland is 29.5%, the high demand for heating energy correlates with the higher capacity factor during the winter.

For more information about the capacity factor visit wikipedia (link).

The capacity factor of a wind turbine measures actual production relative to possible production, it is unrelated to **Betz's coefficient** of $16/27 \simeq 59.3\%$, which limits production vs. energy available in the wind.

Betz's law indicates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow. It was published in 1919 by the German physicist Albert Betz. The law is derived from the principles of conservation of mass and momentum of the air stream flowing through an idealized "actuator disk" that extracts energy from the wind stream. According to Betz's law, no turbine can capture more than $16/27 \simeq 59.3\%$ of the kinetic energy in wind. The factor 16/27 (0.593) is known as Betz's coefficient. Practical utility-scale wind turbines achieve at peak $75 - 80\%$ of the Betz limit.

For more information about the capacity factor visit wikipedia (link).

5.6.2 Onshore wind outlook to 2050

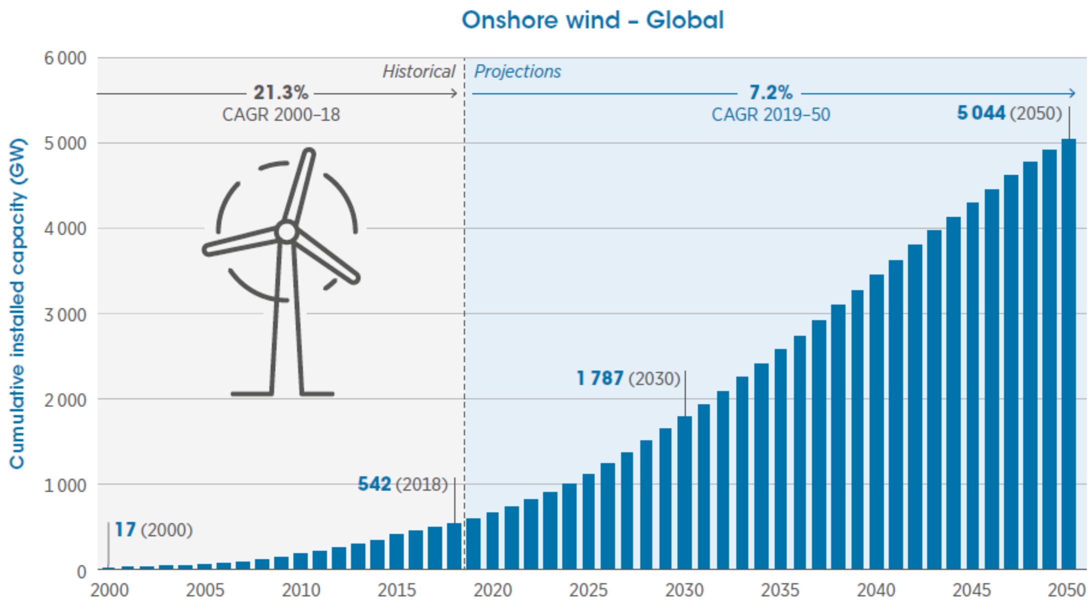
The global installed capacity of onshore wind power would increase three-fold by 2030 (to 1 787 GW) and ten-fold by 2050 (to 5 044 GW) compared to installations in 2018 (542 GW) (figure 5.12).

Deployment strategies by regions (countries)

Asia – mainly China (at more than 2 000 GW) and India (at more than 300 GW) – would continue to lead global onshore wind power installations, with the region accounting for more than half (2 656 GW) of the total global capacity by 2050 (figure 5.13).

After Asia, significant onshore wind power deployments would occur in **North America** (mainly the US, at more than 850 GW), where the installed capacity would grow more than ten-fold from 2018 levels, reaching around 1 150 GW by 2050 (figure 5.13).

Figure 5.12: Onshore wind - Global



Source: IRENA (2019a)

Africa would be a key market for rapid onshore wind deployment in the next three decades installing onshore wind capacity of more than 500 GW by 2050 (figure 5.13).

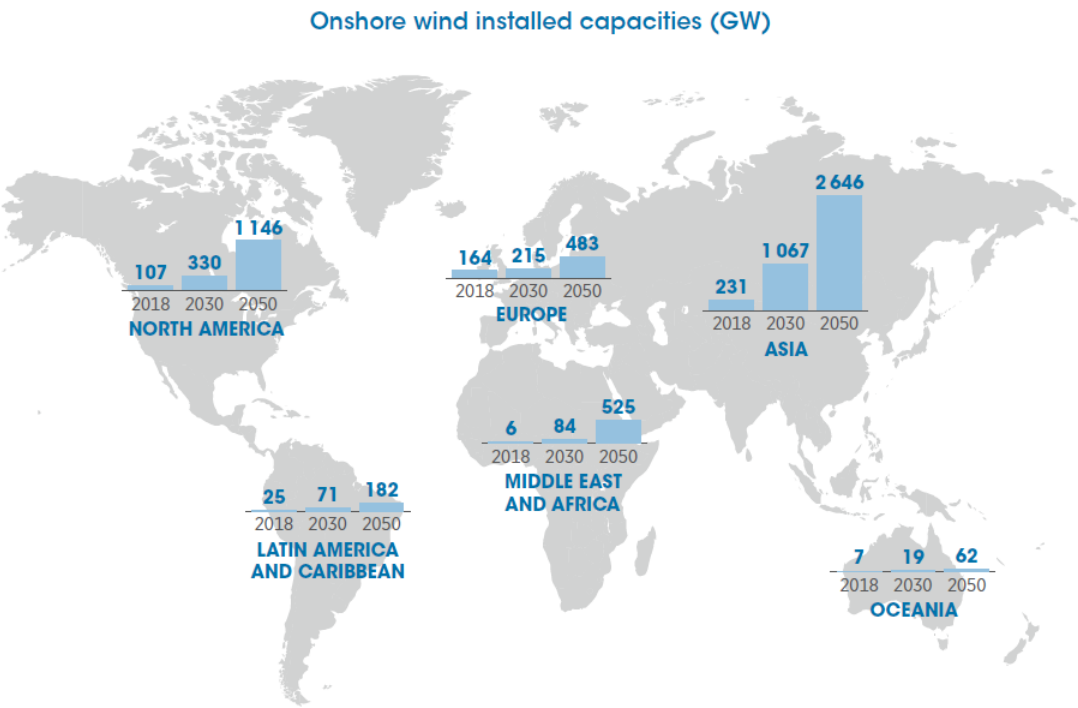
A detail analysis by regions (countries).

China: China's onshore wind installed capacity would grow from 205 GW in 2018 (CWEA, 2019) to almost 2 150 GW in 2050. This represents nearly a quarter of China's total land-based wind potential, which is estimated at around 8 800 GW considering an average wind turbine height of 80 metres (figure 5.14). In particular, China's northern regions have abundant onshore wind potential. The provinces of Qinghai, Xinjiang and Inner Mongolia, and the country's north east, have the highest power density (average values between 400 and 600 watts per square metre (W/ m^2)),

The onshore wind installed capacity in the 3.5 million km^2 of land excluding protected areas, **US** would grow from 94 GW in 2018 to almost cities and water This massive potential is mostly 857 GW by 2050 (figure 5.15). According to the National concentrated in a central area of the country Renewable Energy Laboratory (NREL), the total land-based wind potential in the country is more than 10 000 GW, equivalent to almost 3.5 million km^2 of land excluding protected areas, cities and water This massive potential is mostly concentrated in a central area of the country from Minnesota/North-Dakota to Texas, which is likely to see the most deployment of future in land wind installations (NREL, 2018).

After China and the US, **Europe** is the third largest market for onshore wind in the coming three decades. The installed onshore capacity is expected to increase more than two-fold by 2050 compared to the 161 GW installed as of the end of 2018 (figure 5.16). The region's total land-based wind potential is an estimated 13 900 GW (EEA, 2009). The best sites for onshore installations are in northern and central continental Europe as well as in the UK (EEA, 2009).

Figure 5.13: Onshore world wind installed capacities (GW)



Source: IRENA (2019a)

Figure 5.14: Onshore wind China

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

Source: IRENA (2019a)

Figure 5.15: Onshore wind US

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

Source: IRENA (2019a)

Figure 5.16: Onshore wind Europe

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

Source: IRENA (2019a)

Cost reductions and capacity factore improvement

The breakthrough in renewable capacity additions over the past few years has been achieved largely because of the significant cost reductions in renewables driven by technology improvements, specialisation and standardisation, broader and more competitive supply chains, economies of scale, competitive procurement and a wide base of experienced, internationally active project developers. In particular, in production, a combination of improved **wind turbine technologies**, deployment of **higher hub heights** and **longer blades** with larger swept areas has led to increased capacity factors for a given wind resource. As a consequence, the total installation cost and the levelised cost of wind energy will decrease during the next three decades (figures 5.8 and 5.9).

Investment needs

Scaling up onshore wind investments is key to facilitate the uptake of the onshore wind market. In particular, global average annual onshore wind power investment needs to scaled up a factor of more than two until 2030 (USD 146 billion/year) and more than three over the remaining period to 2050 (USD 211 billion/year), compared to 2018 investment (USD 67 billion/year) (figure 5.7).

Ongoing and future innovations

1. **Wind turbine technology:** The key parameters that denote the improvements in wind turbine technologies are the rotor diameter and the hub height to access more power from wind turbines, even in areas with lower wind speeds. Larger rotors aid in decreasing specific power, which eventually boosts capacity factors and opens up low-wind areas to more wind. The maximum size of turbines added in 2018 was 4.3 MW, up from 3.3 MW in 2015 (figure 5.17). GE Renewable Energy is now offering improved onshore turbine technologies rated at 4.8 MW and 5.3 MW, respectively (Wind Power Monthly, 2018). Siemens-Gamesa presented its 5.8 MW, 170-metre rotor diameter model, which is larger than the largest offshore turbine currently available in the market (Vestas's V164 10 MW) (Wind Power Monthly, 2019).

2. **Optimised power electronics:** Optimising the power inverters reliability and dimensions could reduce turbine installation and operation costs.

3. **"Smart/Intelligent" wind turbines:** The digital revolution is affecting wind energy with new technologies for turbine monitoring and controls.

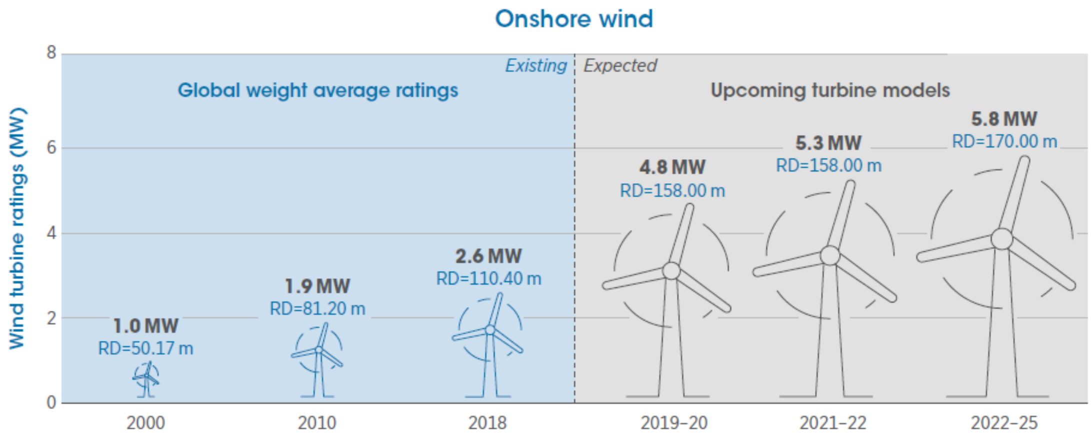
4. Recycling of materials: Currently, nearly 2.5 million tonnes of composite materials are in use in the wind energy sector (RECYCLING, 2019). In Europe alone, almost 12 000 wind turbines are expected to be decommissioned in the next five years (RECYCLING, 2019).

For more information about market developments, legislation, technical issues, new products and technologies, management knowledge in the recycling sector visit the webpage of the RECYCLING Magazine (link).

5.6.3 Offshore wind outlook to 2050

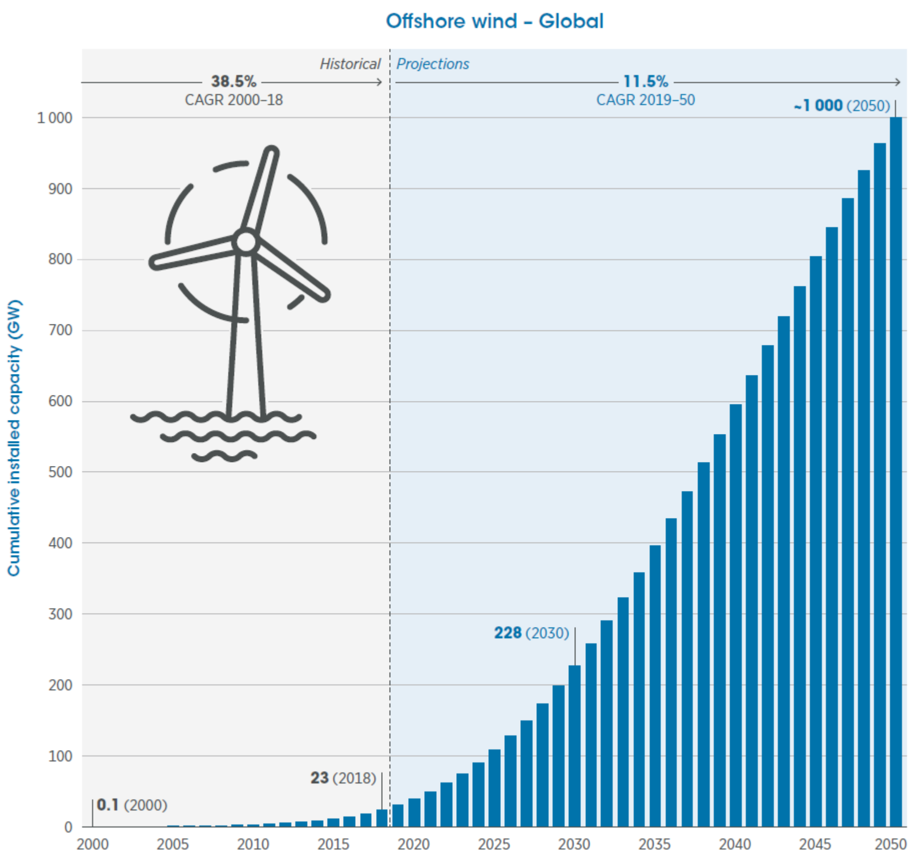
Global cumulative offshore wind capacity would increase almost ten-fold by 2030 (to 228 GW) and even more towards 2050, with total offshore installation nearing 1 000 GW by 2050 (figure 5.18).

Figure 5.17: Onshore wind turbines improvements



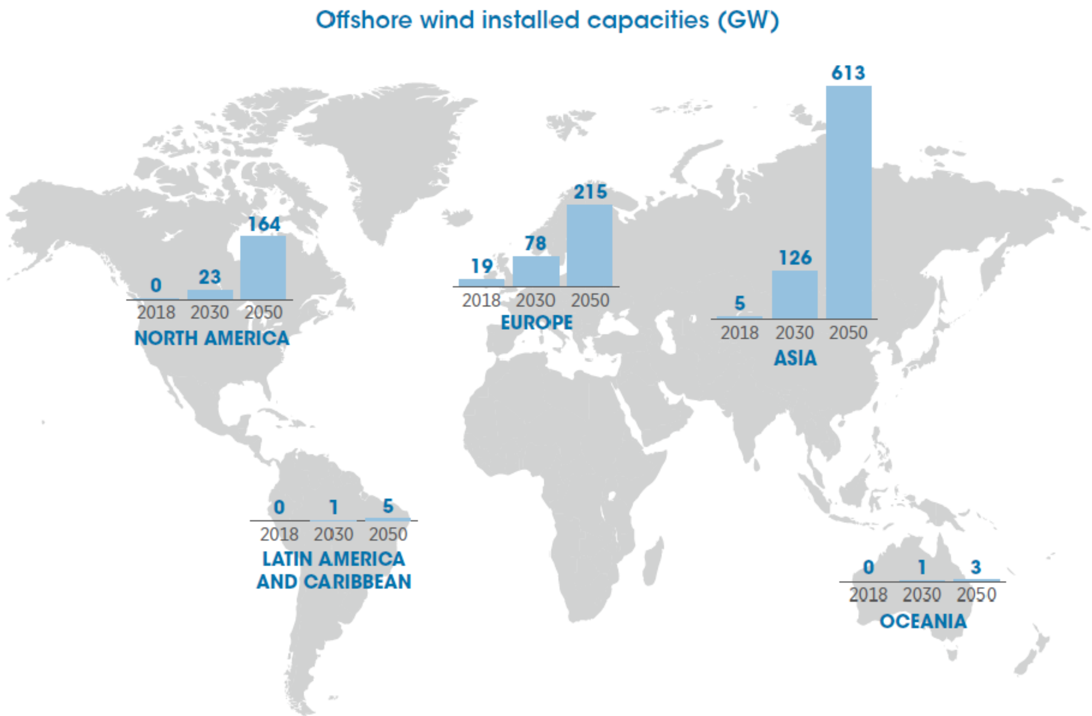
Source: IRENA (2019a)

Figure 5.18: Offshore wind - Global



Source: IRENA (2019a)

Figure 5.19: Offshore world wind installed capacities (GW)



Source: IRENA (2019a)

Deployment strategies by regions (countries)

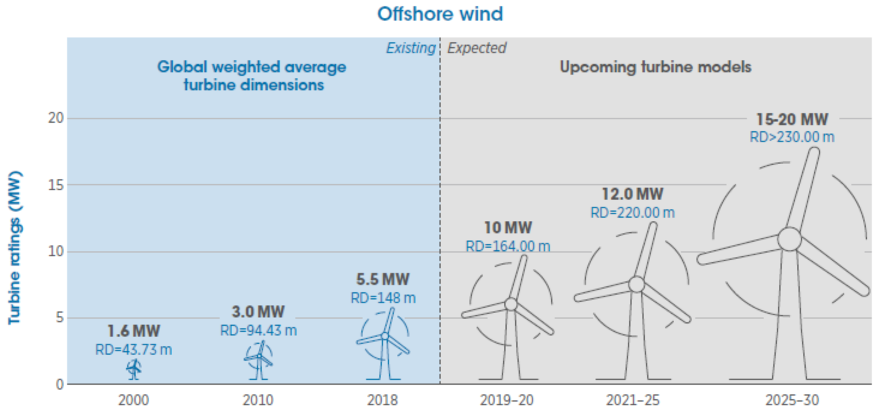
Moving forward, a prominent shift in deployment would happen in Asian waters (mostly in China, India, Chinese Taipei, the Republic of Korea, Japan, Indonesia, the Philippines and Viet Nam) in the next three decades. **Asia** would eventually dominate global offshore wind power installations with a total capacity exceeding 100 GW by 2030 and 600 GW by 2050 (figure 5.19). Within Asia, significant offshore wind deployment would occur in China, where the installed capacity would reach around 56 GW by 2030 and 382 GW by 2050.

China would dominate offshore wind installations, outpacing Europe in less than two decades from now. **Europe** would continue to dominate offshore wind installations for a decade or so, with total offshore wind capacity growing four-fold to 78 GW by 2030 and more than eleven-fold to 215 GW by 2050, compared to 19 GW in 2018 (figure 5.19). After Asia and Europe, **North America** would be another emerging offshore wind market. In the US, offshore wind installed capacity would grow more strongly, from less than 1 GW today to almost 23 GW by 2030 and 164 GW by 2050 (figure 5.19).

Cost reductions and capacity factors

The growth in turbine size helps to increase wind farm output. Larger turbines with greater swept areas yield higher capacity factors for the same resource quality. The cost reductions for offshore wind farms have been driven by technology improvements that have raised capacity factors, as well as by declines in total installed costs, operation and management costs and the cost of capital as project risk has declined. As a consequence, the total installation cost and the levelised cost of wind energy will decrease during the next three decades (figures 5.8 and 5.9).

Figure 5.20: Offshore wind turbines improvements



Source: IRENA (2019a)

Investment needs

Globally, investment in offshore wind would need to grow substantially over the next three decades, with overall cumulative investment of over USD 2 750 billion from now until 2050. In annual terms, global average annual offshore wind investment would need to increase more than three-fold from now until 2030 (USD 61 billion/year) and five-fold during the last two decades to 2050 (USD 100 billion/year) compared to investment in 2018 (USD 19.4 billion/year) (figure 5.7).

Ongoing and future innovations

Future generation turbines.

Developments in blade, drivetrain and control technologies, in particular, would enable the development of larger, more reliable turbines with higher capacity ratings. Turbine sizes have increased rapidly in recent decades and the technological changes make that the turbine size will increase even more in the next years (figure 5.20).

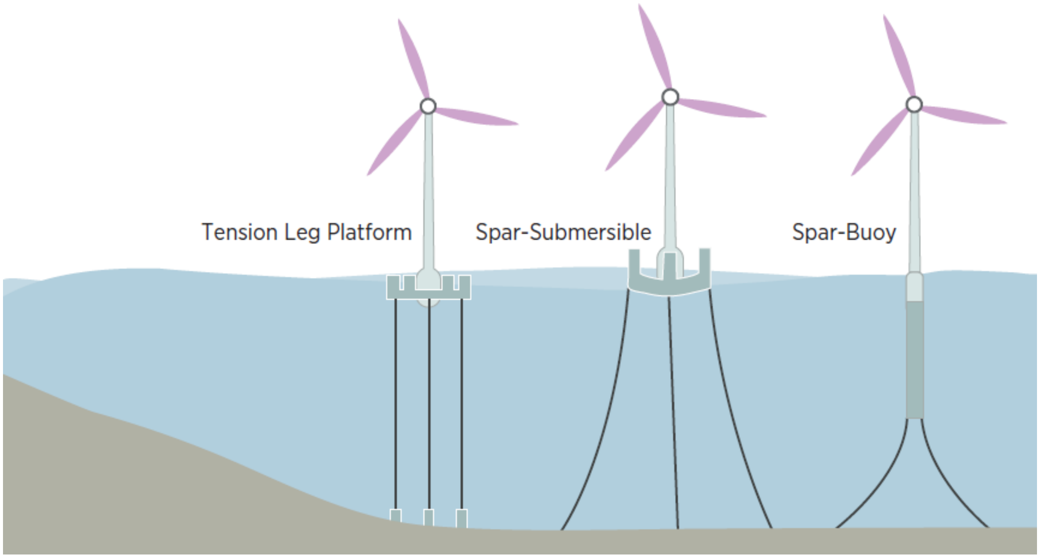
Floating foundations.

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

In such cases, floating foundations may be a better choice. Floating wind farms are one of the most exciting developments in ocean energy technologies. Floating foundations offer the offshore wind industry **three important opportunities**:

1. They allow access to sites with water deeper than 60 metres.
2. They ease turbine set-up, even for mid-depth conditions (30–50 metres) and may in time offer a lower-cost alternative to fixed foundations.

Figure 5.21: Offshore wind turbine foundation technologies



Source: IRENA (2019a)

3. Floating foundations generally offer environmental benefits compared with fixed-bottom designs due to less-invasive activity on the seabed during installation.

Three main designs are under development and have been tested: spar-buoys, spar-submersibles and tension-leg platforms (figure 5.21).

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

Integrated turbine and foundation installation.

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

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

HVDC technology.

For projects far offshore, high-voltage direct current (HVDC) transmission is preferable to high-voltage alternating current (HVAC) transmission in order to overcome the reactive resistance (capacitance) caused by the export cables in a long grid connection (offshore and onshore).

Today, HVDC infrastructure is used to connect two points, but it cannot be used to create a multi-nodal network. However, commercialisation of HVDC infrastructure for wind farms is under way, with point-to-point grid connections used on a few projects in European waters.

Direct current (DC).

Direct current (DC) is the one directional or unidirectional flow of electric charge. An electrochemical cell is a prime example of DC power. Direct current may flow through a conductor such as a wire, but can also flow through semiconductors, insulators, or even through a vacuum as in electron or ion beams. The electric current flows in a constant direction, distinguishing it from alternating current (AC).

Alternating current (AC).

Alternating current (AC) is an electric current which periodically reverses direction and changes its magnitude continuously with time in contrast to direct current (DC) which flows only in one direction. Alternating current is the form in which electric power is delivered to businesses and residences.

Transmission, distribution, and domestic power supply.

Electrical energy is distributed as alternating current because AC voltage may be increased or decreased with a transformer. This allows the power to be transmitted through power lines efficiently at high voltage, which reduces the energy lost as heat due to resistance of the wire, and transformed to a lower, safer, voltage for use. Use of a higher voltage leads to significantly more efficient transmission of power. The power losses (P_w) in the wire are a product of the square of the current (I) and the resistance (R) of the wire, described by the formula:

$$P_w = I^2 R$$

This means that when transmitting a fixed power on a given wire, if the current is halved (i.e. the voltage is doubled), the power loss due to the wire's resistance will be reduced to one quarter.

The power transmitted is equal to the product of the current and the voltage (assuming no phase difference); that is,

$$P_t = IV$$

Consequently, power transmitted at a higher voltage requires less loss-producing current than for the same power at a lower voltage. Power is often transmitted at hundreds of kilovolts on pylons, and transformed down to tens of kilovolts to be transmitted on lower level lines, and finally transformed down to 100 V – 240 V for domestic use.

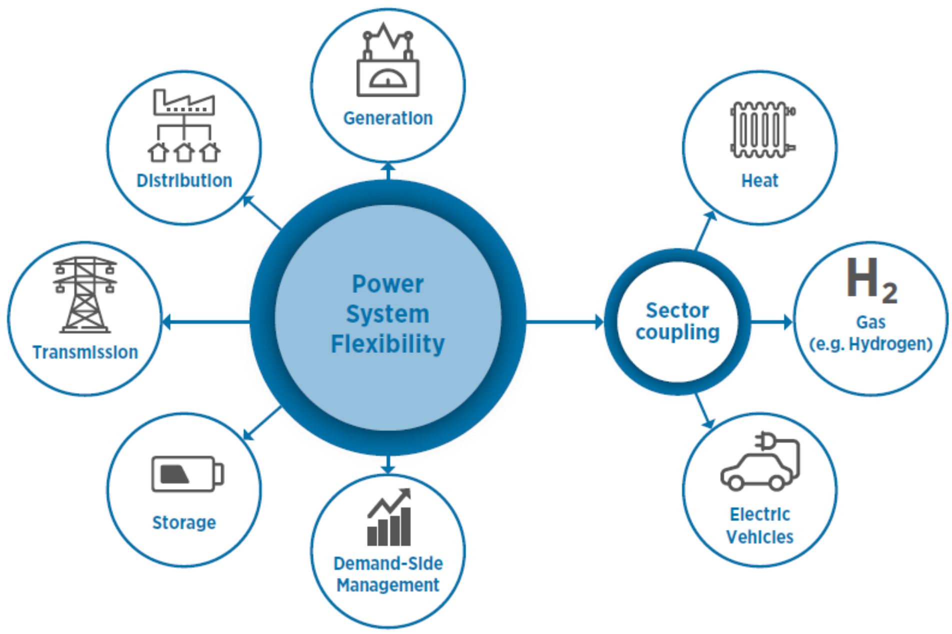
High-Voltage Direct Current (HVDC).

A **high-voltage, direct current (HVDC)** electric power transmission system (also called a power superhighway or an electrical superhighway) uses direct current (DC) for the bulk transmission of electrical power, in contrast with the more common alternating current (AC) systems.

Most HVDC links use voltages between 100 kV and 800 kV. A 1,100 kV link in China was completed in 2019 over a distance of 3,300 km with a power of 12 GW. With this dimension, intercontinental connections become possible which could help to deal with the fluctuations of wind power and photovoltaics.

For more information about power electronics visit EEPOWER textbook (link), or the Wikipedia.

Figure 5.22: Power system flexibility enablers in the energy sector



Source: IRENA (2019a)

5.6.4 Power system flexibility to integrate rising shares of variable renewable energy

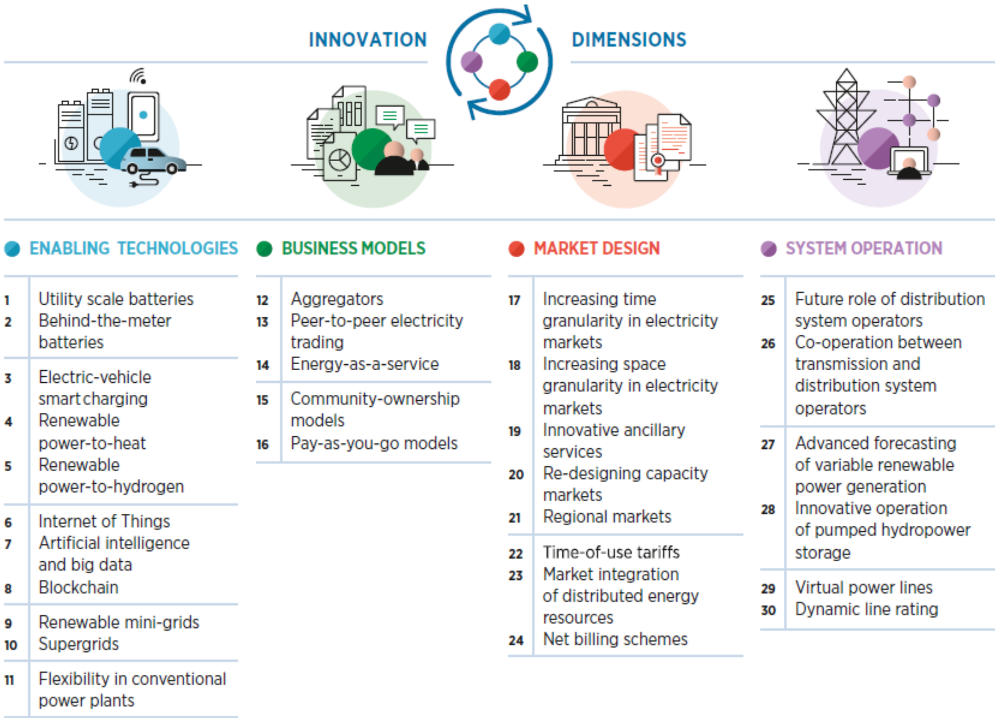
To effectively manage large-scale variable renewable electricity (VRE), flexibility must be harnessed in all sectors of the energy system, from power generation to transmission and distribution systems, storage (both electrical and thermal) and, increasingly, flexible demand (**demand-side management** and **sector coupling**) (IRENA, 2018) (figure 5.22).

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

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

Hydrogen contributes to “Sector Coupling” between the electricity system and industry, buildings and transport, increasing the level of flexibility while facilitating the integration of VRE into the power system. The gas grid can also be decarbonised via renewable hydrogen by taking advantage of low electricity prices, providing seasonal storage for solar and wind, and

Figure 5.23: The four dimensions of innovation



Source: IRENA (2019a)

providing grid services from electrolysers. The deployment of hydrogen requires specific efforts such as targeted applications, dedicated supply system and conversion pathways (IRENA, 2019d).

For more information about power system flexibility enablers and clustering with other low-carbon technologies hybrid systems visit the experience of the Danish island of Bornholm (link).

5.6.5 Innovation landscape to integrate high shares of variable renewable energy

IRENA's work confirms that there is no single game-changing innovation. No innovation, in isolation, may have a significant impact, but rather it needs to be accompanied by innovations in all segments of the power sector. IRENA has investigated the landscape of abundant innovations that can facilitate the integration of high shares of VRE into the power system, identifying and clustering 30 transformative innovations across four dimensions: enabling technologies, business models, market design and system operation (IRENA, 2019c) (figure 5.23).

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

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

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

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

5.7 Some questions to summarize the chapter

1. Can you explain briefly how the wind turbines **transform wind into electricity**?

Wind first hits a turbine's blades, causing them to rotate and turn the turbine connected to them. That changes the **kinetic energy to rotational energy**, by moving a shaft which is connected to a generator, and thereby producing electrical energy through **electromagnetism**.

The amount of power that can be harvested from wind depends on the **size of the turbine** and the **length of its blades**.

The output is proportional to the **dimensions of the rotor** and to the **cube of the wind speed**.

Theoretically, when **wind speed doubles**, wind **power potential increases by a factor of eight**.

An useful video to know more about **wind turbines**: How do wind turbines work: (link)
More information about **wind turbine generators** can be found in the Alternative Energy Tutorials webpage (link).

2. Can you formulate **mathematically** the concept of wind energy?

Mathematically, total **wind energy** flowing through an imaginary surface with area A during the time t is:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}(Avt\rho)v^2 = \frac{1}{2}At\rho v^3$$

where ρ is the density of air;
v is the wind speed; Avt is the volume of air passing through A (which is considered perpendicular to the direction of the wind);
$Avt\rho$ **is therefore the mass** m **passing through** A

$\frac{1}{2}\rho v^2$ is the kinetic energy of the moving air per unit volume

3. Can you formulate **mathematically** the concept of power from wind energy?

Power is energy per unit time, so the wind power incident on A (e.g. equal to the rotor area of a wind turbine) is:

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

4. Can you formulate **mathematically** the concept of energy?

Energy:

As energy is defined via work, the International System of Units unit of energy is the same as the unit of work – the **joule (J)**, named in honor of James Prescott Joule and his experiments on the mechanical equivalenta of heat. In slightly more fundamental terms, **1 joule is equal to 1 newton metre** and, in terms of International System of Units base units:

$$1J = \left(1kg\frac{m}{s^2}\right) m = 1kg \left(\frac{m}{s}\right)^2 = 1\frac{kg \cdot m^2}{s^2}$$

5. Can you formulate **mathematically** the concept of power in electricity?

Electricity is measured in Watts and kilowatts:

Electricity is measured in **units of power** called Watts, named to honor James Watt, the inventor of the steam engine. A Watt is the unit of electrical power equal to **one ampere under the pressure of one volt**.

6. In which amount **carbon emissions** will decrease due to wind energy?

Wind power when coupled with deep electrification would contribute to more than one-quarter of the total emissions reductions needed **(nearly 6.3 gigatonnes of carbon dioxide (Gt CO2) annually) in 2050**

7. Which should be the **share of wind production in 2050** to satisfy the Paris Agreement?

35% of the electricity needs to be produced with wind energy

8. Which should be the **wind production capacity** in 2050 to satisfy the Paris Agreement?

The global cumulative installed capacity of **onshore wind power** should increase more than three fold by 2030 (to 1 787 gigawatts (GW)) and nine-fold by 2050 (to 5 044 GW) compared to installed capacity in 2018 (542 GW)

For **offshore wind power**, the global cumulative installed capacity would increase almost ten-fold by 2030 (to 228 GW) and substantially towards 2050, with total offshore installation nearing 1 000 GW by 2050

9. Which should be the **wind capacity additions** in 2050 to satisfy the Paris Agreement?

Annual capacity additions for onshore wind would increase more than four-fold, to more than 200 GW per year in the next 20 years, compared to 45 GW added in 2018

Even higher growth would be required in **annual offshore wind capacity additions** – around a ten-fold increase, to 45 GW per year by 2050 from 4.5 GW added in 2018

10. At a regional level. Which will be the **investment trends in wind energy**?

Onshore wind at a regional level

Asia – mainly China (at more than 2 000 GW) and India (at more than 300 GW) – would continue to lead global onshore wind power installations, with the region accounting for more than half (2 656 GW) of the total global capacity by 2050.

After Asia, significant onshore wind power deployments would occur in **North America** (mainly the US, at more than 850 GW), where the installed capacity would grow more than ten-fold from 2018 levels, reaching around 1 150 GW by 2050.

Africa would be a key market for rapid onshore wind deployment in the next three decades installing onshore wind capacity of more than 500 GW by 2050.

Offshore wind at a regional level

Asia would eventually dominate global offshore wind power installations with a total capacity exceeding 100 GW by 2030 and 600 GW by 2050.

China would dominate offshore wind installations, outpacing Europe in less than two decades from now

Europe would continue to dominate offshore wind installations for a decade or so, with total offshore wind capacity growing four-fold to 78 GW by 2030 and more than eleven-fold to 215 GW by 2050, compared to 19 GW in 2018.

After Asia and Europe, **North America** would be another emerging offshore wind market. In the US, offshore wind installed capacity would grow more strongly, from less than 1 GW today to almost 23 GW by 2030 and 164 GW by 2050.

11. Which should the aggregate **investment trends in wind energy**?

Investments in **Onshore wind** power should increase by more than two-fold from now until 2030 (USD 146 billion/year) and more than three-fold over the remaining period to 2050 (USD 211 billion/year) compared to 2018 investments (USD 67 billion/year).

For **offshore wind**, global average annual investments would need to increase three-fold from now until 2030 (USD 61 billion/year) and more than five-fold over the remaining period to 2050 (USD 100 billion/year) compared to 2018 investments (USD 19 billion/year).

12. Which will be the evolution of **total wind installation cost**?

The **total installation cost** of **onshore wind projects** would continue to decline in the next three decades with the average cost falling in the range of USD 800 to 1 350 per kilowatt (kW) by 2030 and USD 650 to 1 000/ kW by 2050, compared to the global-weighted average of USD 1 497/kW in 2018.

For **offshore wind projects**, the average total installation cost would further drop in coming decades to between USD 1 700 and 3 200/kW by 2030 and between USD 1 400 and 2 800/kW by 2050 (figure, next slide).

13. Which will be the evolution of **levelised cost of electricity for wind energy**?

The **levelised cost of electricity (LCOE)** for **onshore wind** will continue to fall from an average of USD 0.06 per kilowatt-hour (kWh) in 2018 to between USD 0.03 to 0.05/kWh by 2030 and between USD 0.02 to 0.03/kWh by 2050.

The LCOE of **offshore wind** would drop from an average of USD 0.13/kWh in 2018 to an average between USD 0.05 to 0.09/kWh by 2030 and USD 0.03 to 0.07/kWh by 2050.

14. Which will be the evolution of **wind capacity factors**?

Ongoing **innovations** and **technology enhancements** towards larger capacity turbines as well as increased hub heights and rotor diameters help improve yields for the same location.

- For **onshore wind plants**, global weighted average capacity factors would increase from 34% in 2018 to a range of 30% to 55% in 2030 and 32% to 58% in 2050
- For **offshore wind farms**, even higher progress would be achieved, with capacity factors in the range of 36% to 58% in 2030 and 43% to 60% in 2050, compared to an average of 43% in 2018

15. Can you define the **levelized cost of energy**?

The levelized cost of energy (LCOE), or levelized cost of electricity, is a measure of the average net present cost of electricity generation for a generating plant over its lifetime

The LCOE is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered

16. Can you define the **capacity factor of energy**?

The **net capacity factor** is the unitless **ratio** of an **actual electrical energy output over a given period of time** to the **maximum possible electrical energy output over that period**

The capacity factor is defined for any electricity producing installation, such as a fuel consuming power plant or one using renewable energy, such as wind or the sun

The average capacity factor can also be defined for any class of such installations, and can be used to compare different types of electricity production.

17. Can you define the **the Betz' coefficient**?

The capacity factor of a wind turbine measures actual production relative to possible production, it is unrelated to **Betz's coefficient** of $16/27 \simeq 59.3\%$, which limits production vs. energy available in the wind.

Betz's law indicates the maximum **power that can be extracted from the wind**, independent of the design of a wind turbine in open flow

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