Ch5. Sustainable Energy: Wind

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Spring 2022 - NHH

Chapter outline

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

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**?

History

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**

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

History

The **oil shortages of the 1970s** changed the energy environment for the United States and the world

The U.S. federal government supported research and development of large wind turbines. In the early 1980s, thousands of wind turbines were installed in **California**, largely because of federal and state policies that encouraged the use of renewable energy sources

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

Technology

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**

Technology

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

Technology

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:

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

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)

Technology

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:

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

Technology

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).

Technology

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).

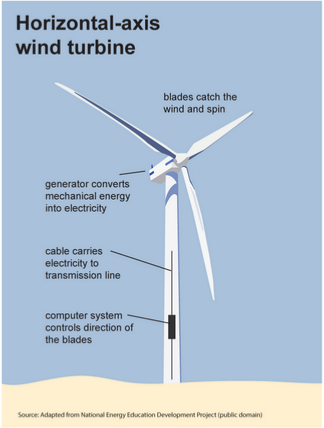
Technology

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. Figure next slide.

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. **Very few vertical-axis wind turbines are in use today because they do not perform as well as horizontal-axis turbines**. Figure next slide.

Technology

Figure: Types of wind turbines



Technology

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.

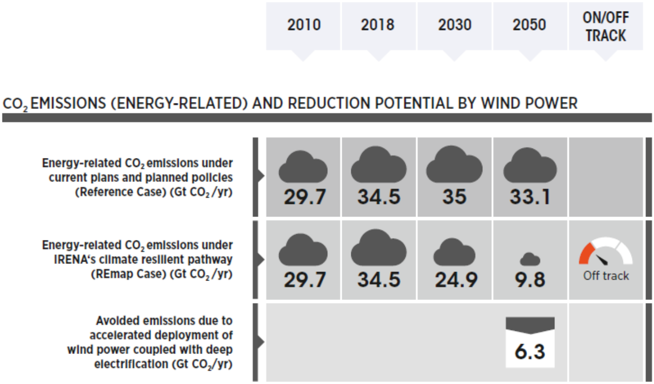
It provides **free access to data on wind power density and wind speed at multiple heights** using the latest historical weather data and modeling, at an output resolution of 250 meters.

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).

Wind energy. Key trends. CO2 emissions

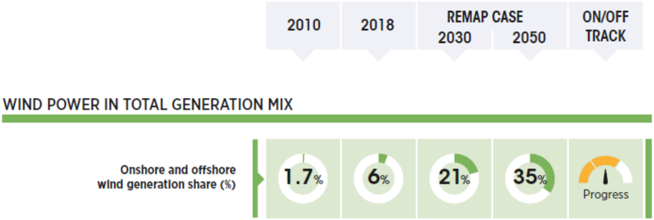
1. Wind power when coupled with deep electrification would contribute to more than one-quarter of the total emissions reductions needed **(nearly 6.3 gigatonnes of carbon dioxide (Gt CO2) annually) in 2050**



Wind energy. Key trends. Installed capacity

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

Figure: Wind power in total generation mix

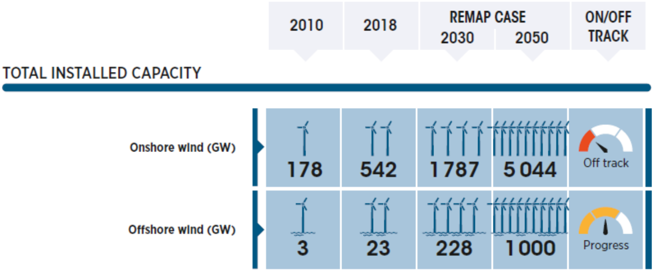


Wind energy. Key trends. Installed capacity

2.a. 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)

2.b. 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

Figure: Wind total installed capacity

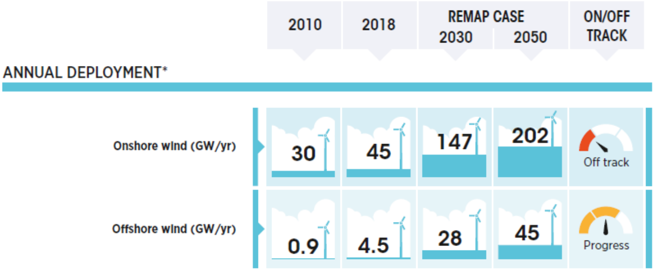


Wind energy. Key trends. Installed capacity

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: Wind annual deployment



Wind energy. Key trends. Regional investments

4.a. Onshore wind at a regional level

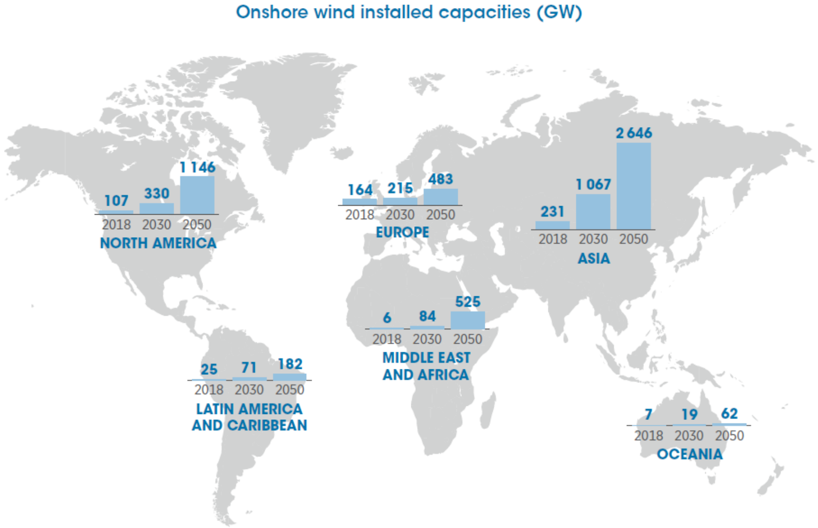
Asia – mainly China (at more than 2 000 GW) and India (at more than 300 GW) – would continue to lead global onshore wind power installations, with the region accounting for more than half (2 656 GW) of the total global capacity by 2050 (figure, next slide).

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, next slide).

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, next slide).

Wind energy. Key trends. Regional investments

Figure: Onshore world wind installed capacities (GW)



Wind energy. Key trends. Regional investments

4.b. 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 (figure, next slide)

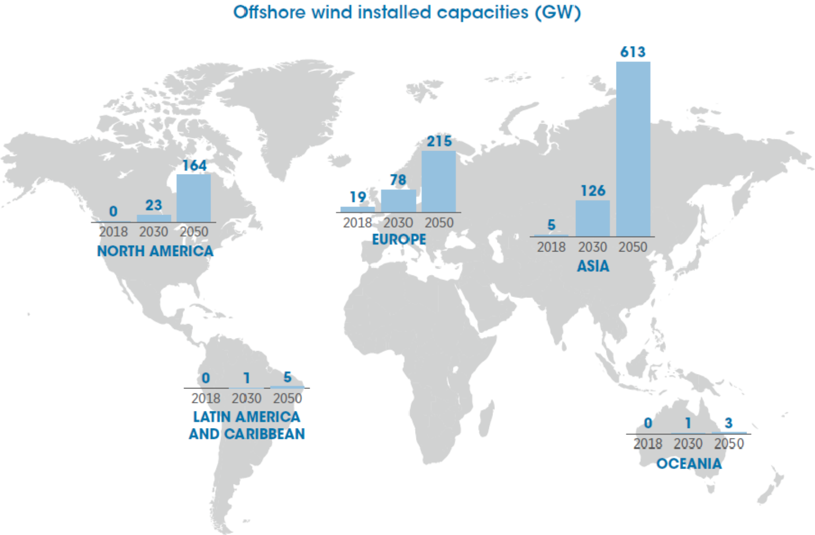
China would dominate offshore wind installations, outpacing Europe in less than two decades from now

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, next slide).

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, next slide).

Wind energy. Key trends. Regional investments

Figure: Offshore world wind installed capacities (GW)



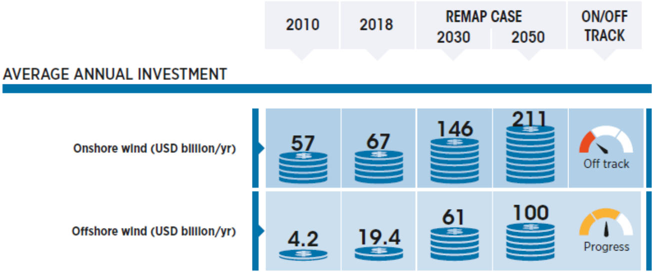
Wind energy. Key trends. Investments

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).

Wind energy. Key trends. Investments

Figure: Wind average annual investment



Wind energy. Key trends. Installation costs

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

6.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

6.b. 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)

Wind energy. Key trends. Installation costs

Figure: Wind total installation cost

TOTAL INSTALLATION COST	2010	2018	REMAP CASE 2030	REMAP CASE 2050	ON/OFF TRACK
Onshore wind (USD/kW)	1 913 (average)	1 497 (average)	800 – 1 350 (average range)	650 – 1 000 (average range)	On track
Offshore wind (USD/kW)	4 572 (average)	4 353 (average)	1 700 – 3 200 (average range)	1 400 – 2 800 (average range)	Progress

Wind energy. Key trends. Levelised cost

7.a. 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

7.b. 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

Wind energy. Key trends. Levelised cost

Figure: Wind levelised cost of electricity (LCOE)

LEVELISED COST OF ELECTRICITY (LCOE)	2010	2018	REMAP CASE 2030	REMAP CASE 2050	ON/OFF TRACK
Onshore wind (USD/kWh)	0.08 (average)	0.06 (average)	0.03–0.05 (average range)	0.02–0.03 (average range)	On track
Offshore wind (USD/kWh)	0.16 (average)	0.13 (average)	0.05–0.09 (average range)	0.03–0.07 (average range)	Progress

Wind energy. Key trends. Innovation

8. 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

Wind energy. Key trends. Innovation

Figure: Wind capacity factors

CAPACITY FACTORS	2010	2018	REMAP CASE 2030	REMAP CASE 2050	ON/OFF TRACK
Onshore wind (%)	27 (average)	34 (average)	30-55 (average range)	32-58 (average range)	Progress
Offshore wind (%)	38 (average)	43 (average)	36-58 (average range)	43-60 (average range)	On track

Wind energy. Key trends. Innovation

9.a. Onshore wind

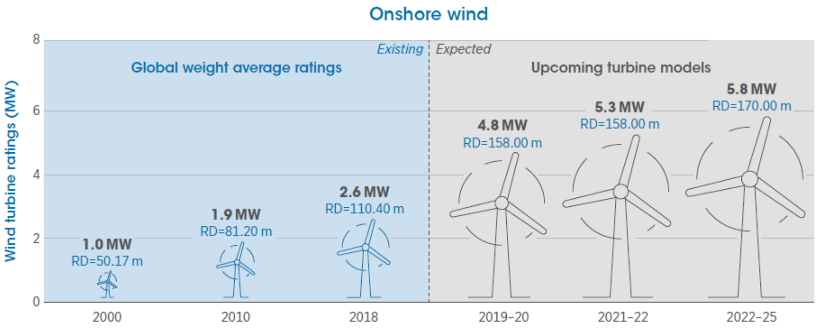
The key parameters that denote the improvements in wind turbine technologies are the **rotor diameter** and the hub height to access more power from wind turbines, even in areas with lower wind speeds
Larger rotors aid in decreasing specific power, which eventually boosts capacity factors and opens up 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, next slide)

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

Wind energy. Key trends. Innovation

Figure: Onshore wind turbines improvements



Wind energy. Key trends. Innovation

9.b. Offshore wind

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, next slide)

Wind energy. Key trends. Innovation

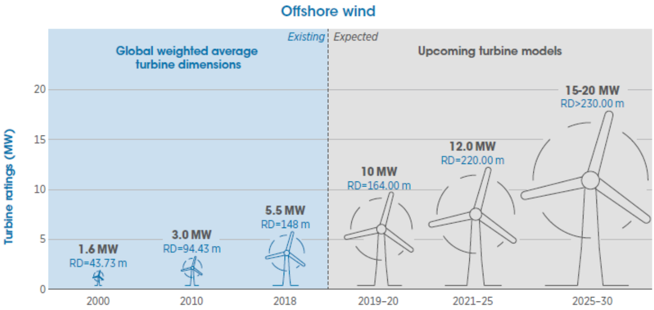


Figure: Offshore wind turbines improvements

Wind energy. Key trends. Innovation

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

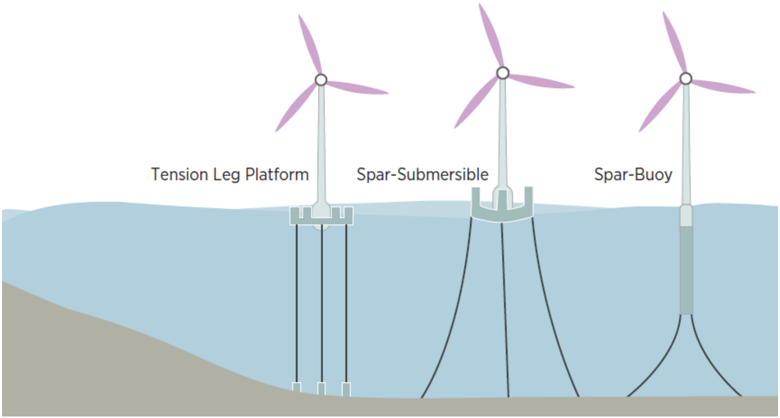
These turbines, rooted in the seabed by monopile or jacket foundations, are currently restricted to waters less than 60 metres deep

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.

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

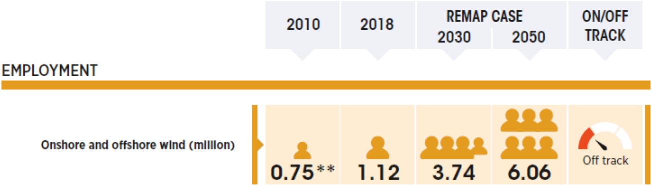
Wind energy. Key trends. Innovation

Three main designs are under development and have been tested: **spar-buoys**, **spar-submersibles** and **tension-leg platforms**



Wind energy. Key trends. Employment

10. 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



Wind energy. Key trends. Levelised cost

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

Wind energy. Key trends. Levelised cost

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

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.

Wind energy. Key trends. Capacity factor

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.

Wind energy. Key trends. Capacity factor

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**:

$$\frac{875.000 MW \cdot h}{(365\text{days })(24\text{hours/day})(209.3\text{MW})} = 0.477 = 47.7\% \qquad (1)$$

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

Wind energy. Key trends

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

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.

Questions to summarize the chapter

Group 1:

1. Can you explain briefly how the wind turbines **transform wind into electricity**?
2. Can you formulate **mathematically** the concept of wind energy?
3. Can you formulate **mathematically** the concept of power from wind energy?
4. Can you formulate **mathematically** the concept of energy?
5. Can you formulate **mathematically** the concept of power in electricity?

Group 2:

6. In which amount **carbon emissions** will decrease due to wind energy?
7. Which should be the **share of wind production in 2050** to satisfy the Paris Agreement?
8. Which should be the **wind production capacity** in 2050 to satisfy the Paris Agreement?
9. Which should be the **wind capacity additions** in 2050 to satisfy the Paris Agreement?

Questions to summarize the chapter

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

Group 3:

12. Which will be the evolution of **total wind installation cost**?
13. Which will be the evolution of **levelised cost of electricity for wind energy**?
14. Which will be the evolution of **wind capacity factors**?
15. Can you define the **levelized cost of energy**?
16. Can you define the **capacity factor of energy**?
17. Can you define the **the Betz' coefficient**?