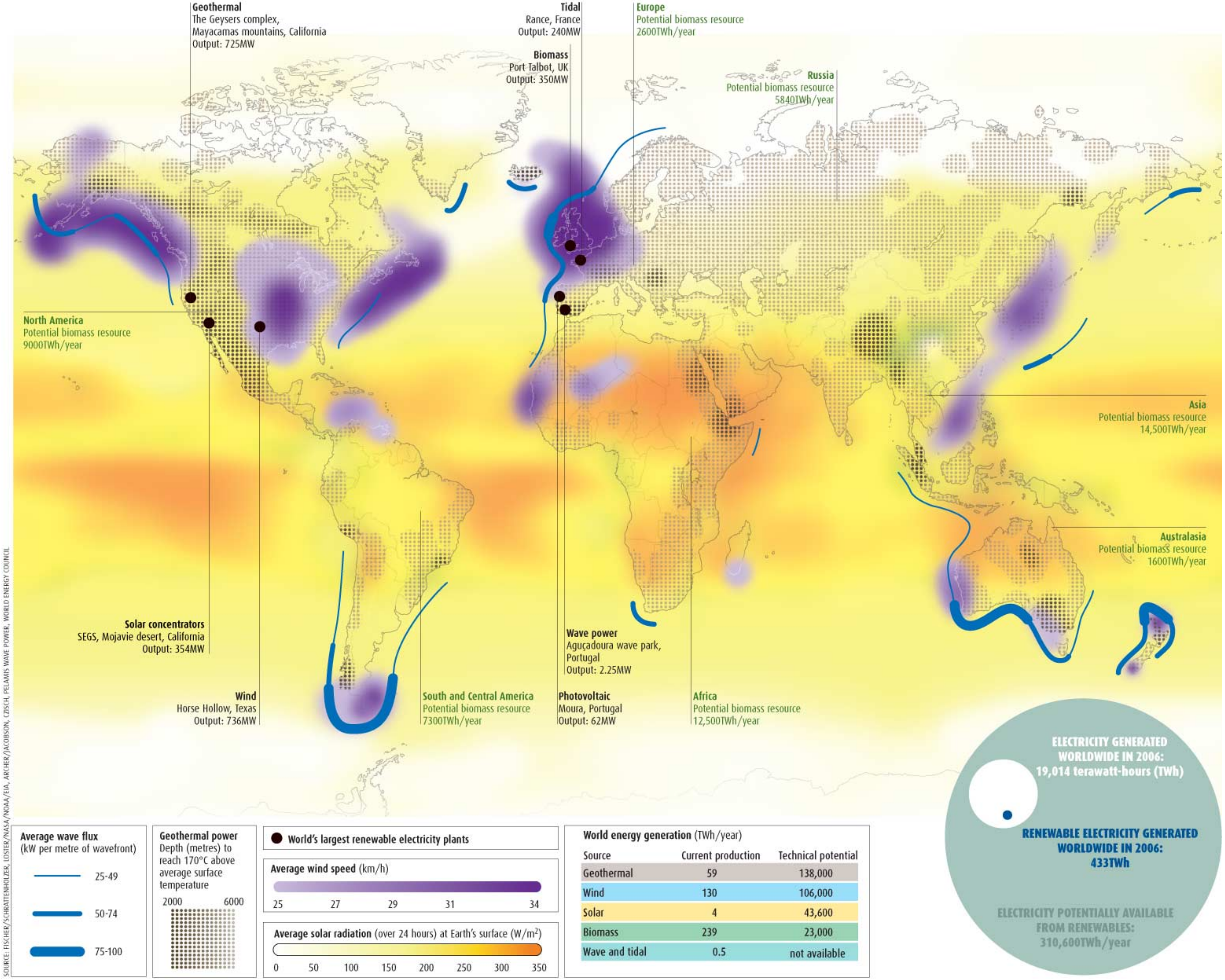
EMS717U/EMS717P

Renewable Energy Sources

Wind Power

Content

- **Wind characteristics:** wind speed, direction and frequency
- **Conversion of wind energy to power:** Betz limit
- **Wind turbine:** HAWT, VAWT, performance
- **Prediction of WT power output over a year:** local wind characteristics, WT performance, power output over a year
- **Environmental, economic and social impacts**
- **Offshore wind global outlook**

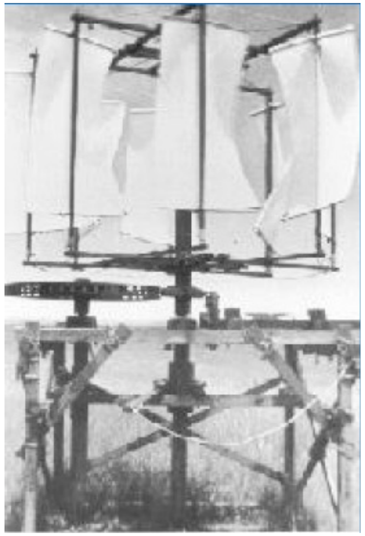


World energy generation (TWh/year)

Source	Current production	Technical potential
Geothermal	59	138,000
Wind	130	106,000
Solar	4	43,600
Biomass	239	23,000
Wave and tidal	0.5	not available

History of wind power

- **Wind Energy is one of first non-animal energy forms exploited by man during early civilizations.**
- **First recorded use – 10th century Persia using vertical axis windmills to pump water and grind grain.**
- **Today - Wind power is now one of fastest growing RE technologies World-wide at ~40% capacity/yr.**
- **Modern systems for electricity generation are called wind turbines to distinguish from earlier *windmill* types.**



Example vertical axis windmill Persia c.900

Example modern horizontal axis wind turbine

History of wind power

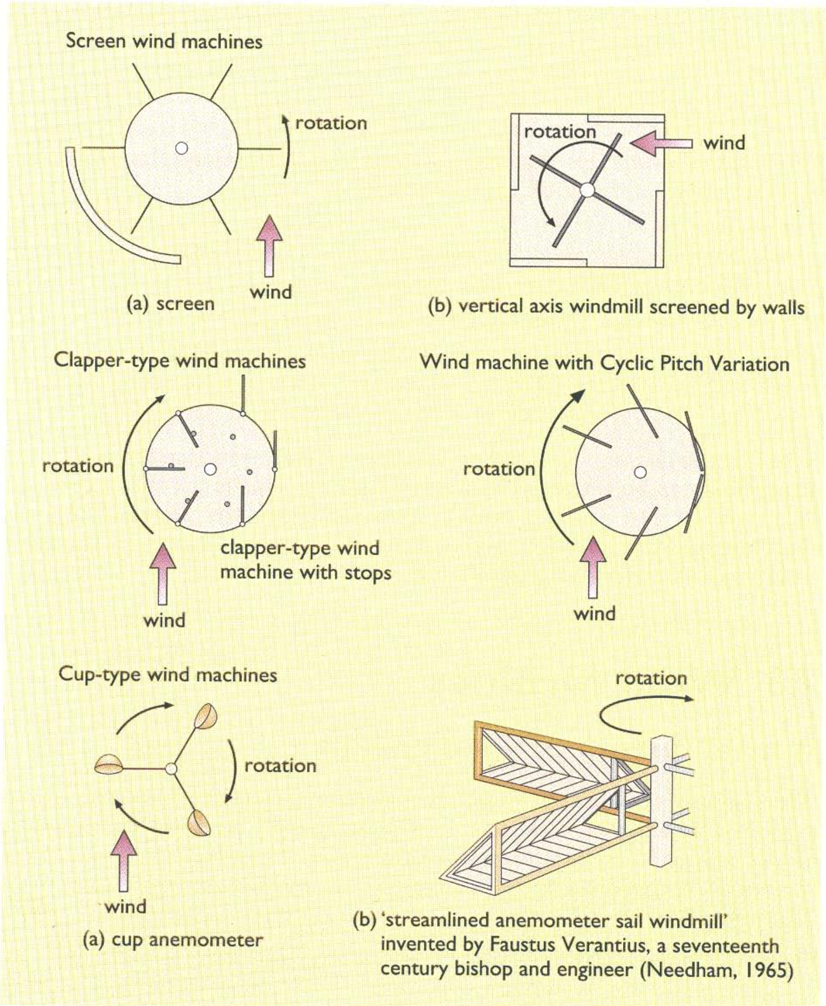


Figure 7.8 Some examples of traditional vertical axis windmills

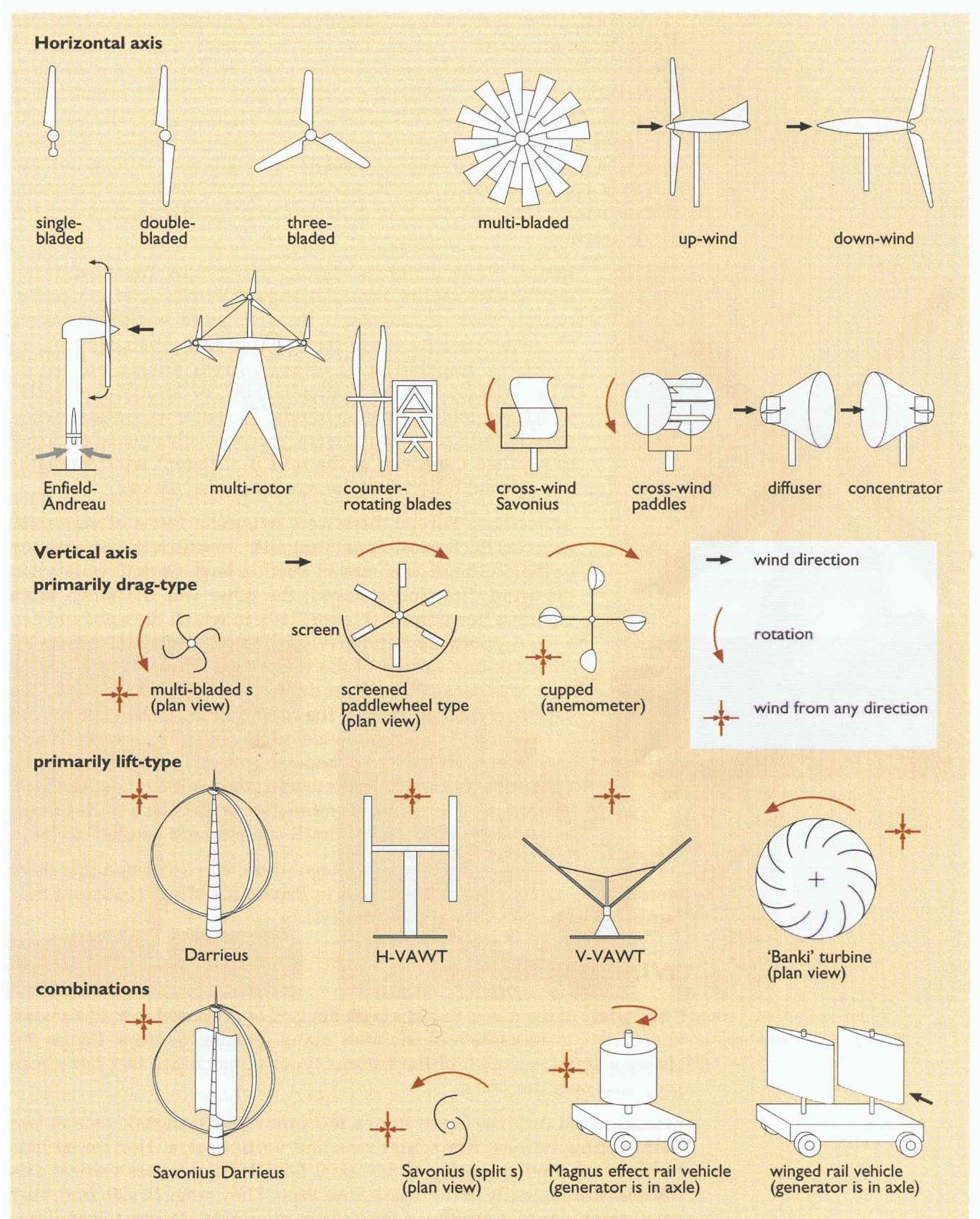
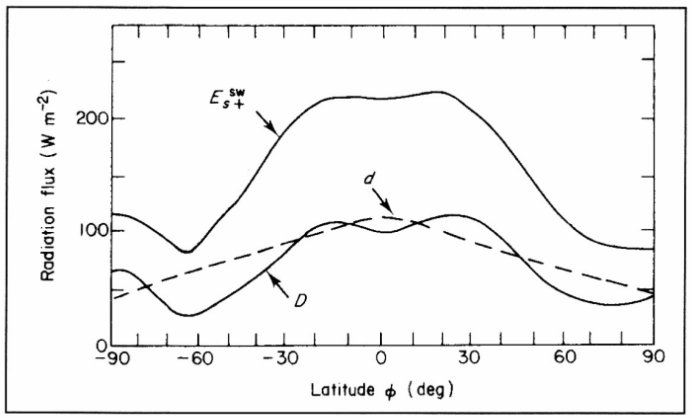


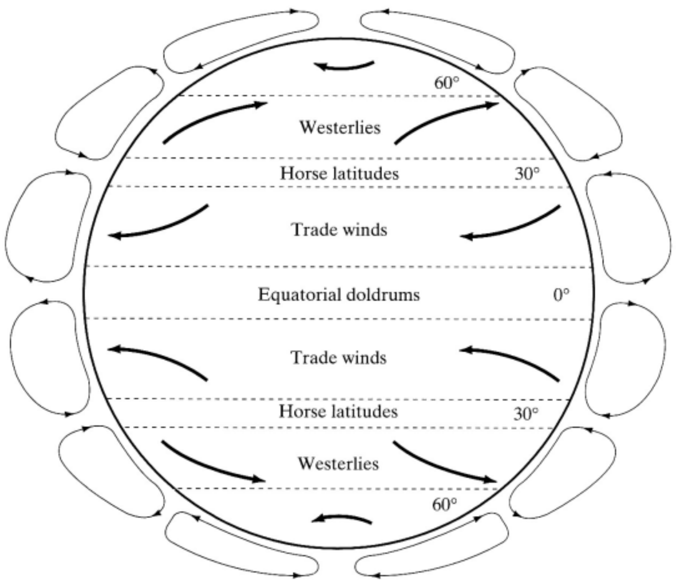
Figure 7.9 Some examples of the machines that have been proposed for wind energy conversion (source: adapted from Eldridge, 1975. For further information on these machines see Eldridge, 1975 and Golding, 1955)

Nature and origin of wind sources

Winds arise due to varying amount of solar radiation with latitude



Average incoming radiation fluxes on a horizontal plane at Earth's surface



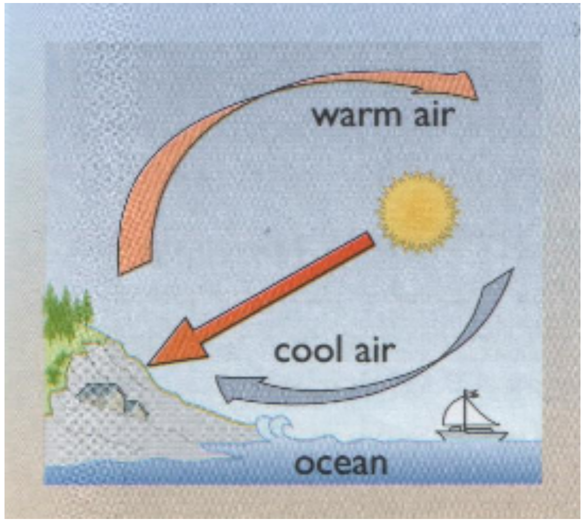
Source: *Renewable Energy* Sorensen

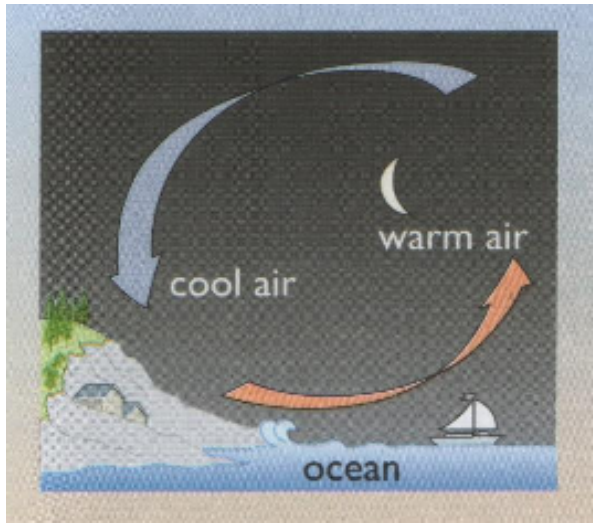
- **Winds blow between belts of high and low pressure.**
- **Heated air reaches top of troposphere then descends at 30° latitude.**
- **This then returns to the equator.**
- **This forms a Hadley cell.**
- **Around 24 W/m^2 of absorbed solar radiations goes into forming wind and air currents.**

Nature and origin of wind sources

Another mechanism for wind generation in coastal areas is due to differing heat capacities of land and water.

Land has a lower heat capacity – heats up quicker by day but cools more rapidly at night.





Source: *Renewable Energy* Boyle

Coastal air currents during night and day

Wind characteristics

- **Height: distribution**
- **Speed: frequency**
- **Direction: the wind rose**

$$v\,(z) = v(ref) * \left(\frac{z}{z_{ref}}\right)^{\alpha}$$

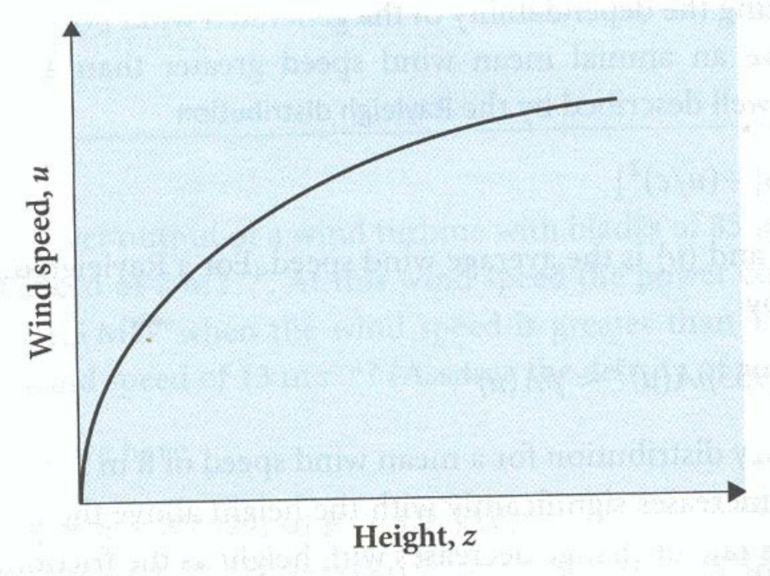


Fig. 5.13 Typical variation of wind speed with height.

The wind speed is normal measured at a particular location using the anemometer installed at a height of 10 m from the ground. The wind speed at height above 10 m is determined empirically using the above equation. v(z) is the wind speed at height z, $v(z_{ref})$ is the wind speed measured by anemometer at a given height z_{ref}. Alph is related to the surface roughness.

Wind characteristics

- **Height: distribution**
- **Speed: frequency**
- **Direction: the wind rose**

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right)$$

Weibull probability density function:

c – scale factor, having a value between 1 and 3. It is a measure of wind speed characteristics of time and is proportional to the mean wind speed.

k – shape factor. The higher the value, the less variable wind.

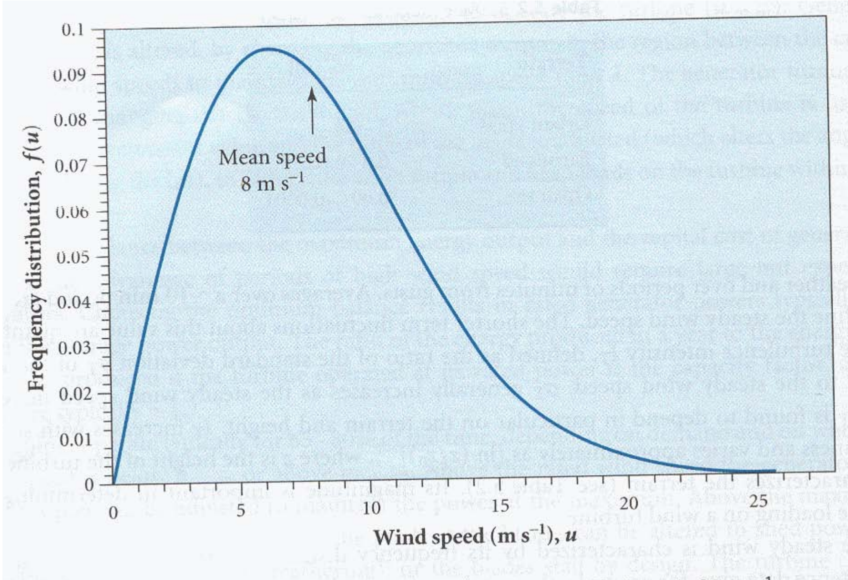


Fig. 5.12 The Rayleigh frequency distribution for a mean wind speed of 8 m s^{-1}.

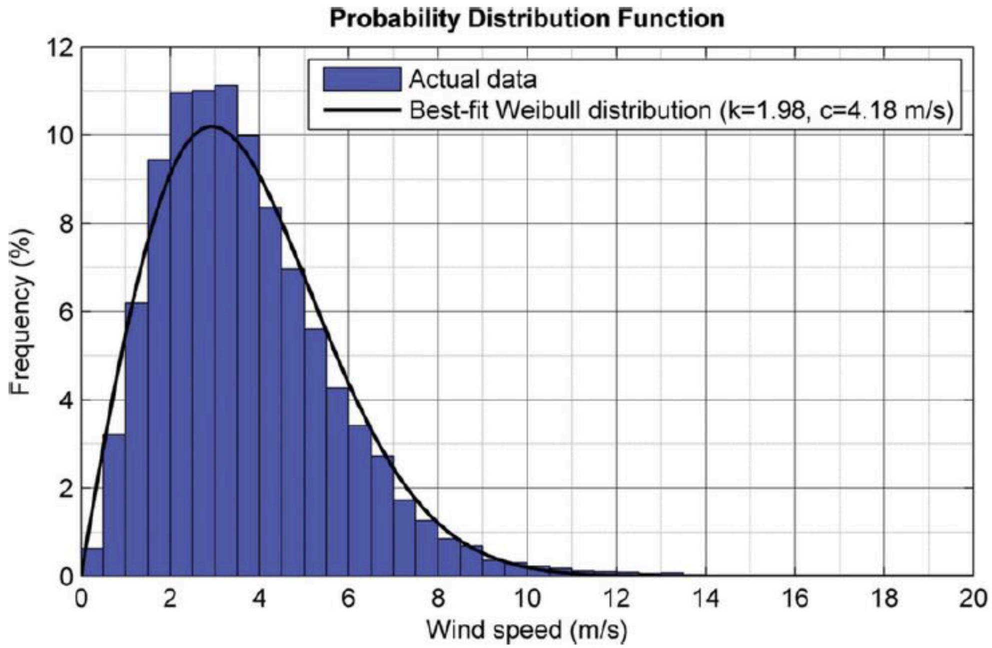


Figure 1-9: Weibull distribution function of wind speed (Ricci, Vitali and Montelpare, 2015)

Wind characteristics

- **Height: distribution**
- **Speed: frequency**
- **Direction: the wind rose**

Table 2 Typical Relationship of Hourly Wind Speed U_{met} to Annual Average Wind Speed U_{annual}

Percentage of Hourly Values That Exceed U_{met}	Wind Speed Ratio U_{met}/U_{annual}
90%	0.2 ± 0.1
75%	0.5 ± 0.1
50%	0.8 ± 0.1
25%	1.2 ± 0.15
10%	1.6 ± 0.2
5%	1.9 ± 0.3
1%	2.5 ± 0.4

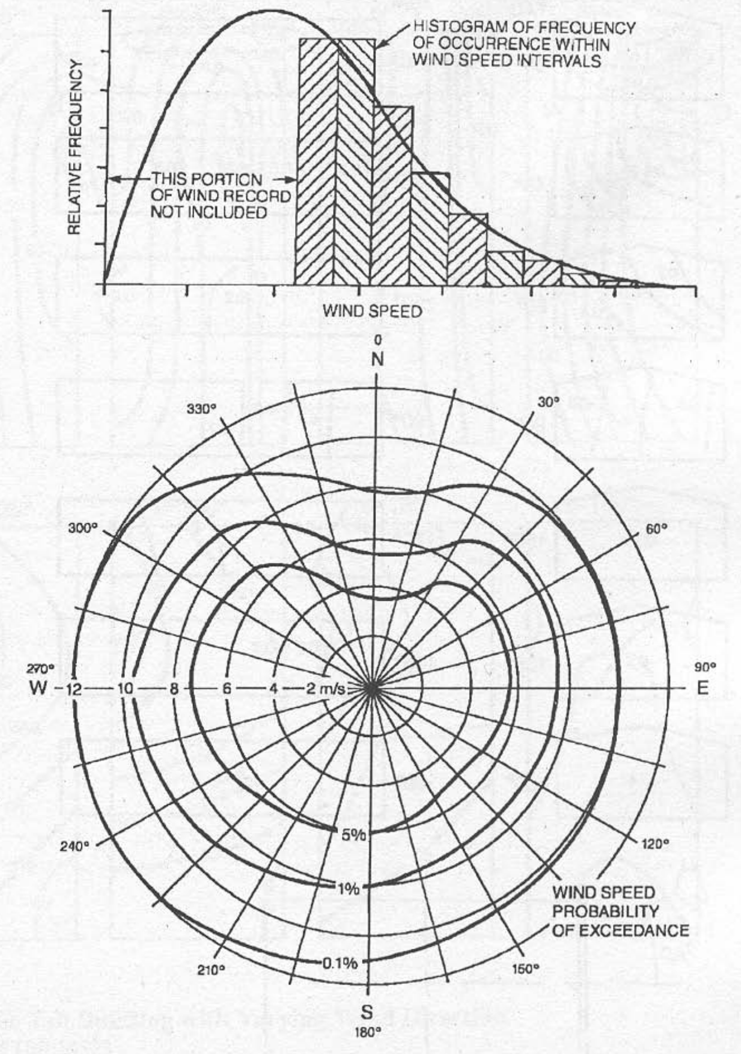


Fig. 10 Frequency Distribution of Wind Speed and Direction

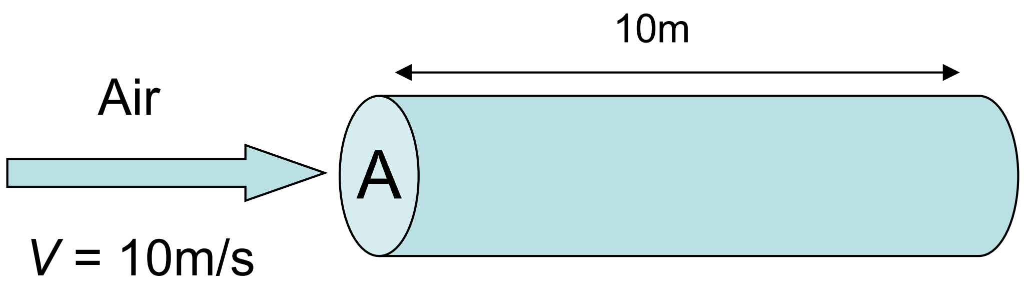
Energy from wind sources

Wind power is due to the kinetic energy (KE) carried by a mass of moving air, given by

$$KE = \frac{1}{2} m V^2$$

where *m* is the mass of air in kg and *V* is the velocity in m/s

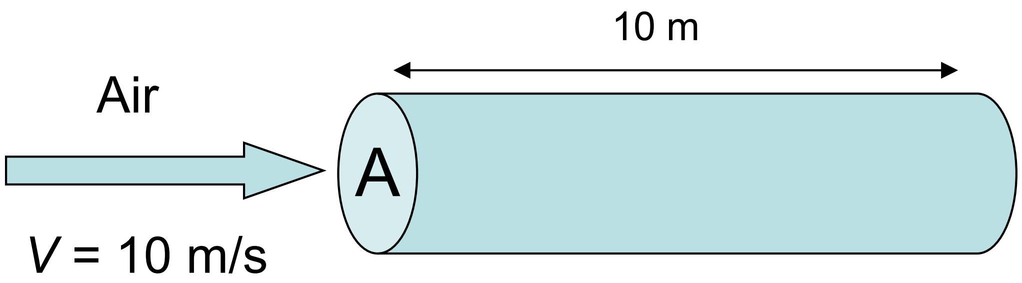
The energy of wind with speed *V* passing through a hoop of area *A*



This gives a cylinder of air with length 10 m flowing through the hoop each second

Therefore, the volume of air passing through the hoop each second is equal to (A x 10) m^3 or AV m^3/s

Energy from wind sources



This gives a cylinder of air with length 10 m flowing through the hoop each second

The mass of air passing through the hoop is given by

$$\text{Mass flow rate} = \rho A V$$

Hence, we have the available KE per second as

$$KE = \tfrac{1}{2}\rho A V \times V^2 = \tfrac{1}{2}\rho A V^3$$

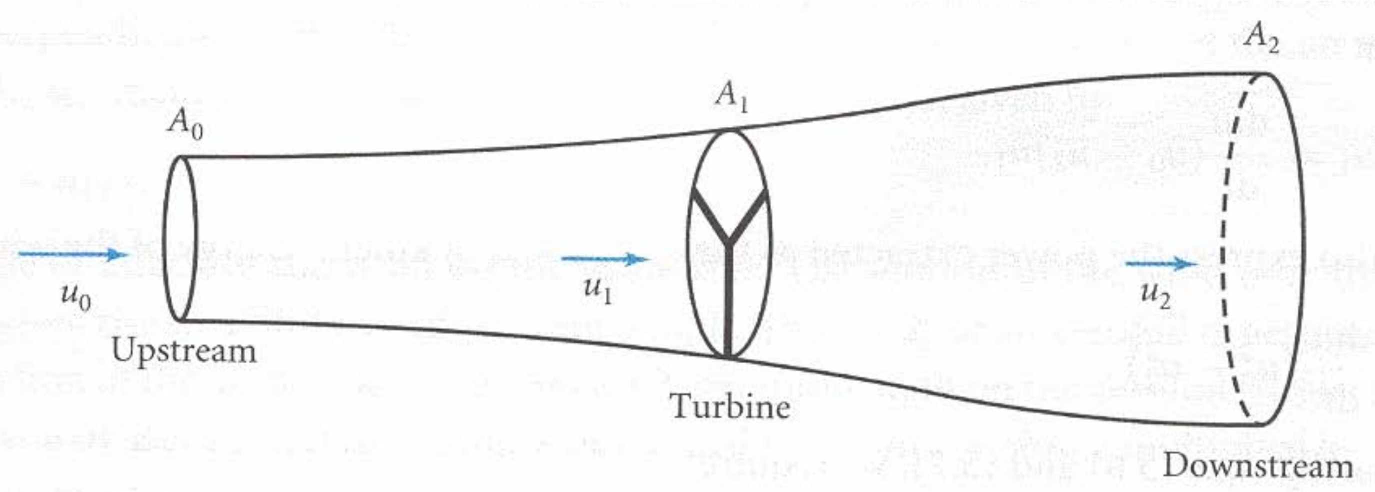
The energy available per second is equal to the power (*P*), therefore

$$P = \tfrac{1}{2}\rho A V^3 \,(\mathrm{W})$$

Harnessing wind energy

How much power is produced?

Wind flow through a turbine



$$P = C_P \left(\frac{\rho V^3 A}{2} \right) \qquad P_{max} = \left(\frac{16}{27} \right) \frac{\rho V^3 A}{2}$$

Therefore, the power from wind is proportional to

1. **Density of air - lower at higher elevation and higher in colder climates.**
2. **Area through which air is passing - larger capture area – more *P*.**
3. **The cube of wind speed - air velocity has large effect on power *P*.**

Harnessing wind energy

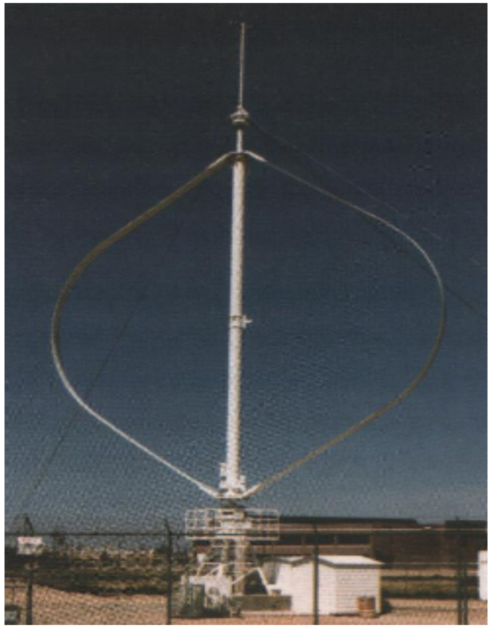
Types of wind turbine

Modern wind turbines for electricity generation principally come in two types: horizontal and vertical axis types

Example high solidity windmill used for water pumping, US mid-west c.1800

Source: *Renewable Energy* Boyle

Example of 3 bladed horizontal axis wind turbine (HAWT) 'axial flow' type



Source: *Renewable Energy* Boyle

Example of vertical axis wind turbine (VAWT) 'cross flow' type

Harnessing wind energy

Types of wind turbine

HAWTs predominantly have 2 to 3 blades (called low-solidity devices) or many blades (high solidity device)

Source: *Renewable Energy* Boyle

Example of 3 bladed horizontal axis wind turbine (HAWT) 'axial flow' type

With 2 – 3 bladed turbines the swept area is largely void – hence low-solidity.

Low solidity HAWTs are by far most common for electricity generation and they have benefited from improved aerodynamics knowledge due to developments in aircraft wing/propeller design.

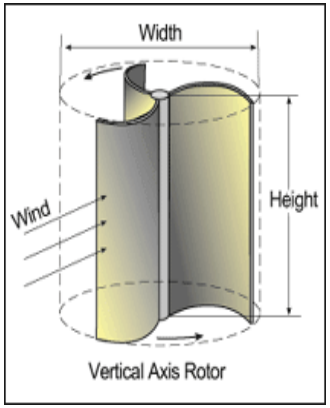
Range in size from very small turbines producing 10-100 W up to very large turbines with up to 5 MW power output.

Harnessing wind energy

Types of wind turbine

Modern VAWTs

Savonius-Drag

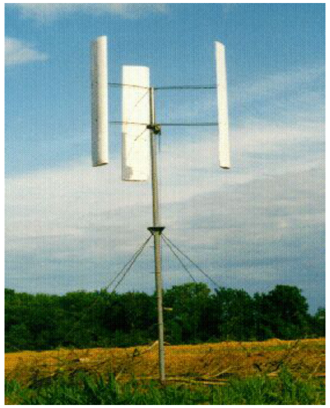


From: www.reuk.co.uk

Darrieus-Curved Blade

From: www.nachi.org/wind-turbines

Darrieus-Straight Blade



From: www.wind-energy-the-facts.org

Quietrevolution

From: www.quietrevolution.co.uk

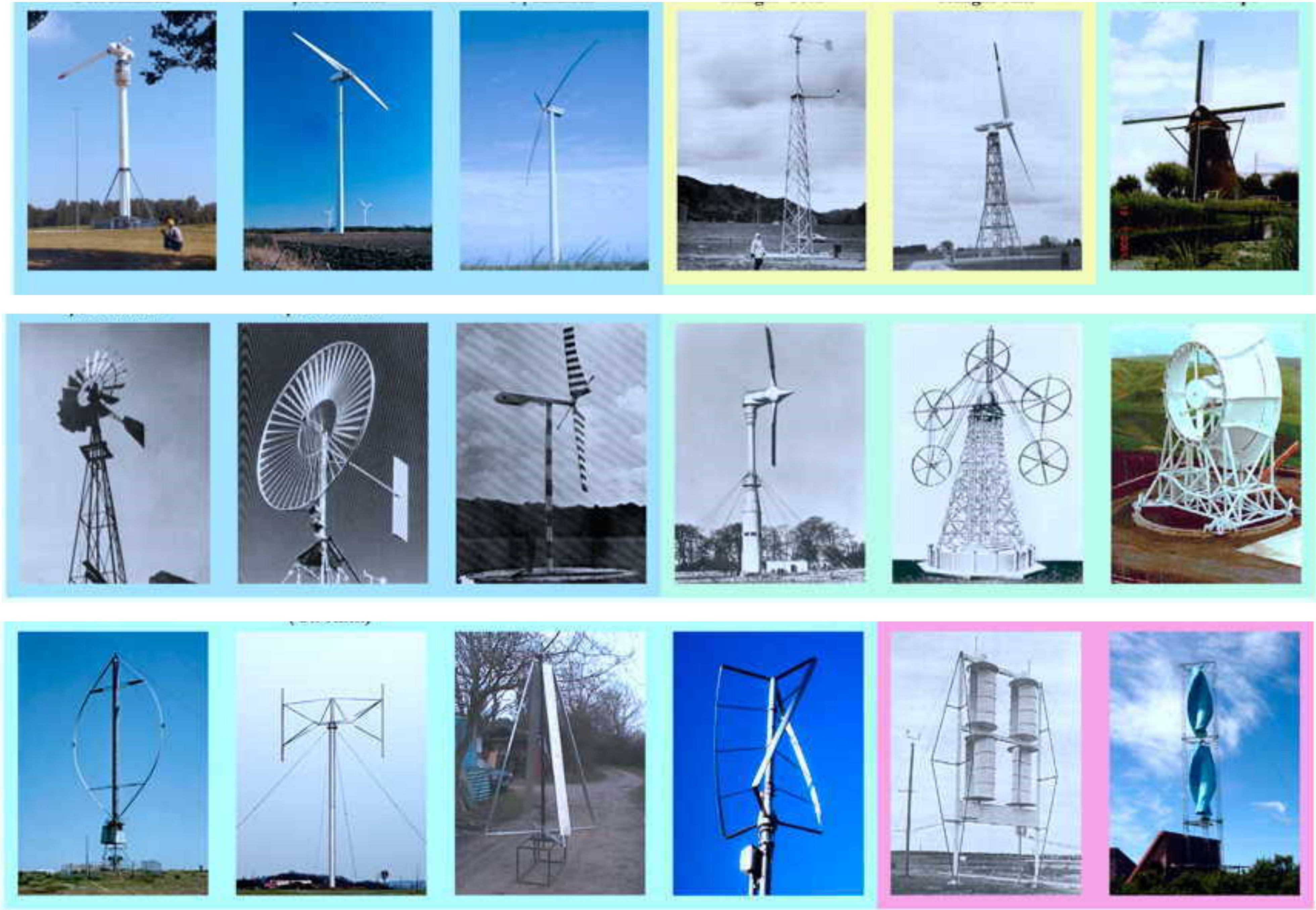
Aerotecture

From: www.aerotecture.com

Windspire

From: www.windspireenergy.com

Types of wind turbine



Onshore wind farm

Figure 1:

39.6 MW Central-Grid Windfarm in Spain.

Offshore wind farm

Figure 2:

2 MW Wind Turbines at 40 MW Offshore Windfarm in Denmark.

Photo Credit:

Photo © BONUS Energy A/S

Off-grid wind turbine

Figure 4:

10 kW Off-Grid Wind Turbine in Mexico.

Photo Credit:

Charles Newcomber/NREL Pix

Isolated-grid wind turbine

Figure 5:
50 kW Isolated-Grid Wind Turbine in the Arctic.

Structure of a typical wind turbine

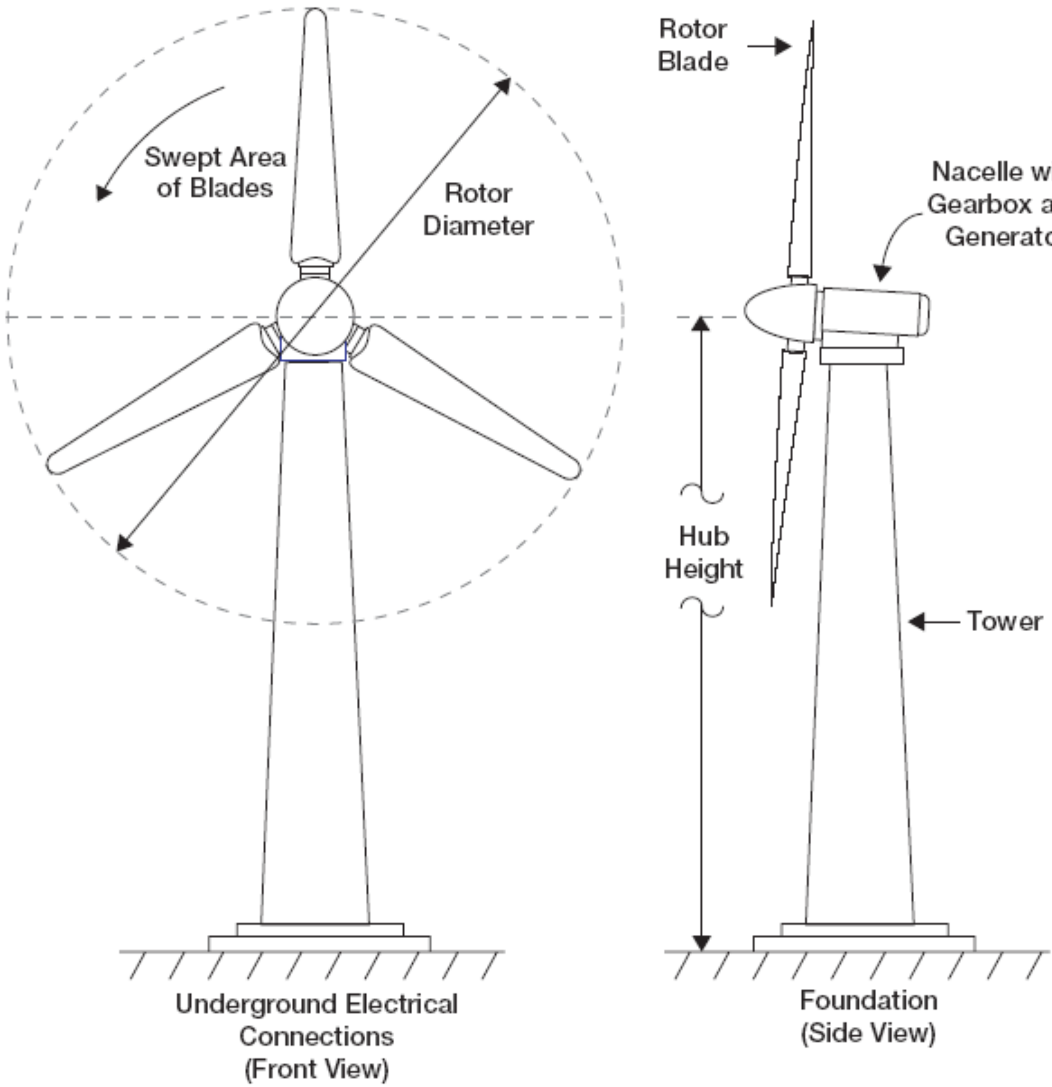


Figure 3:

Wind Energy System Schematic.

Cost breakdown

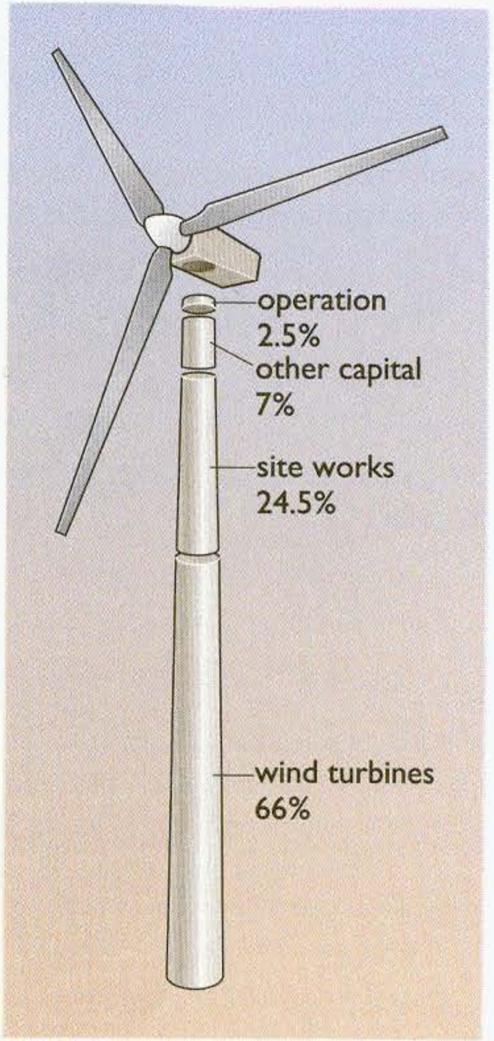
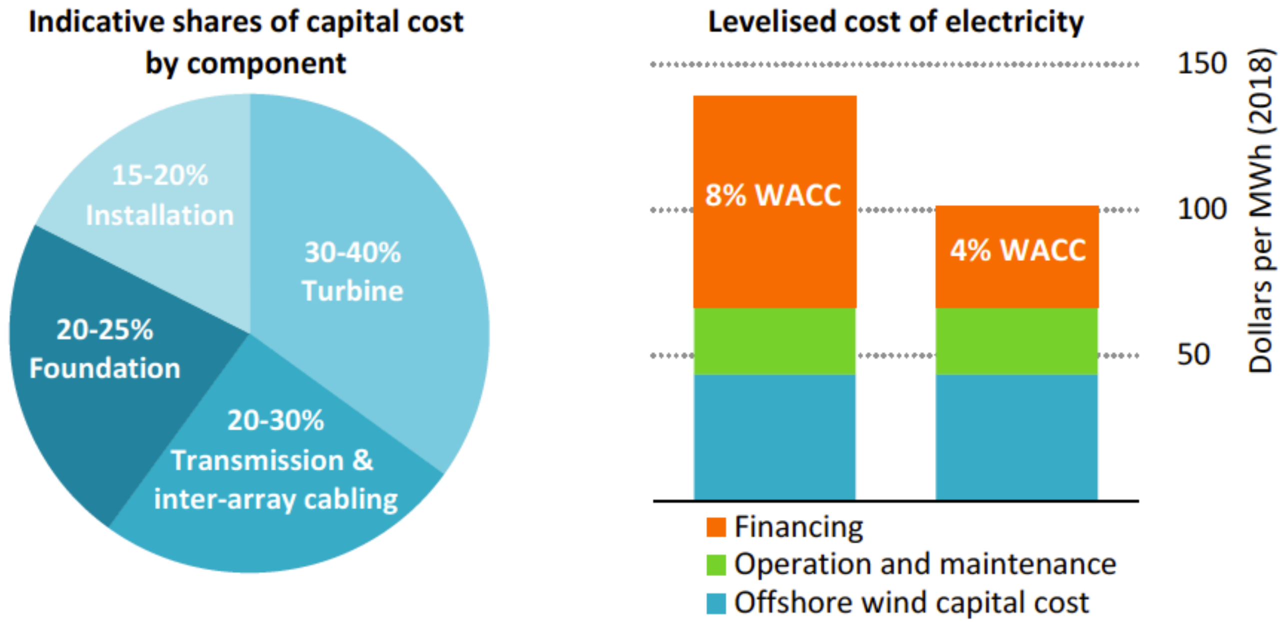


Figure 7.36 Breakdown of costs per unit of energy (kWh) from wind plant (source: adapted from EWEA, 1991)

Figure 7 ▹ Offshore wind indicative shares of capital costs by component and levelised cost of electricity for projects completed in 2018



Offshore wind generation costs are heavily influenced by the cost of capital and were about $100/MWh for projects completed in 2018 based on low financing costs

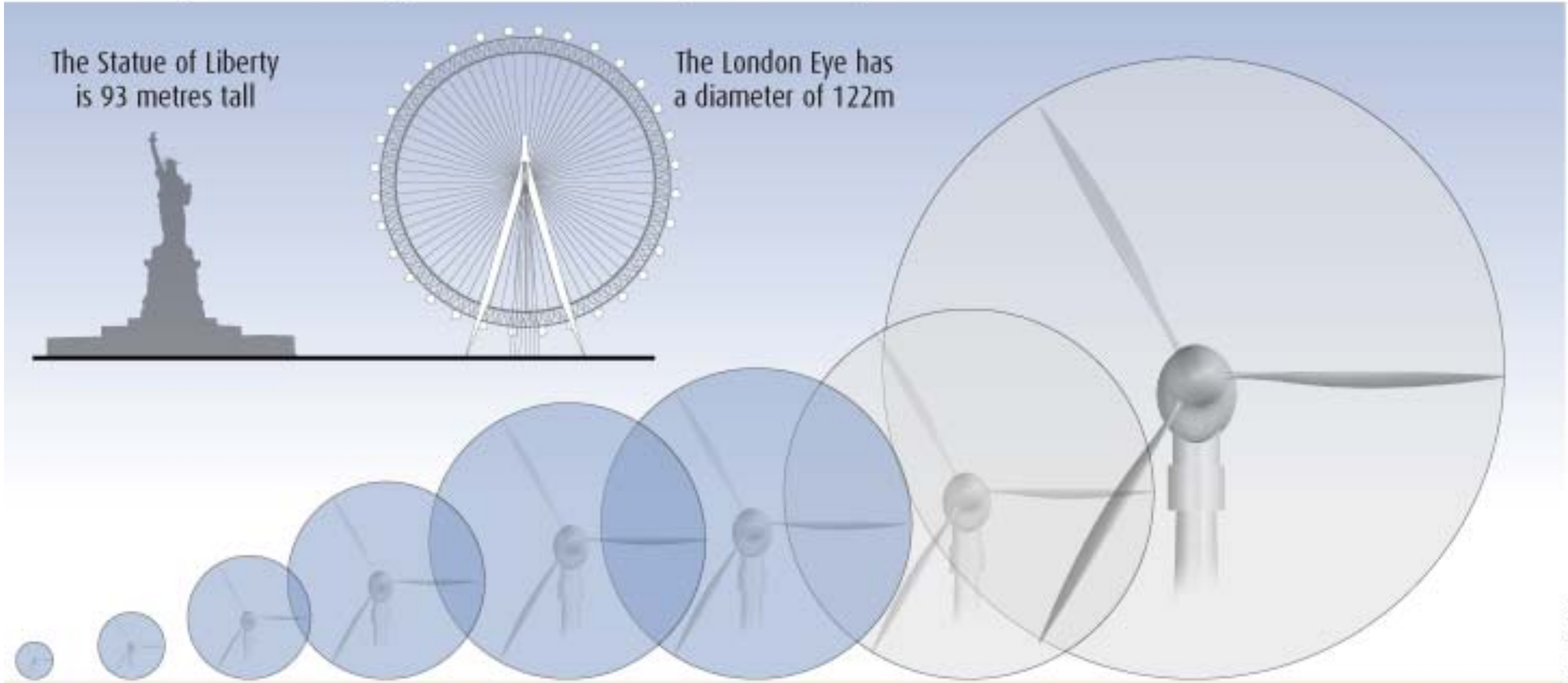
Notes: WACC = weighted average cost of capital; Transmission includes offshore substations.

Source: IEA analysis based on IRENA (2019), IJGlobal (2019) and BNEF (2019).

Harnessing wind power

GIANT STEPS

Turbines have grown 10 times bigger and 100 times more powerful in 20 years

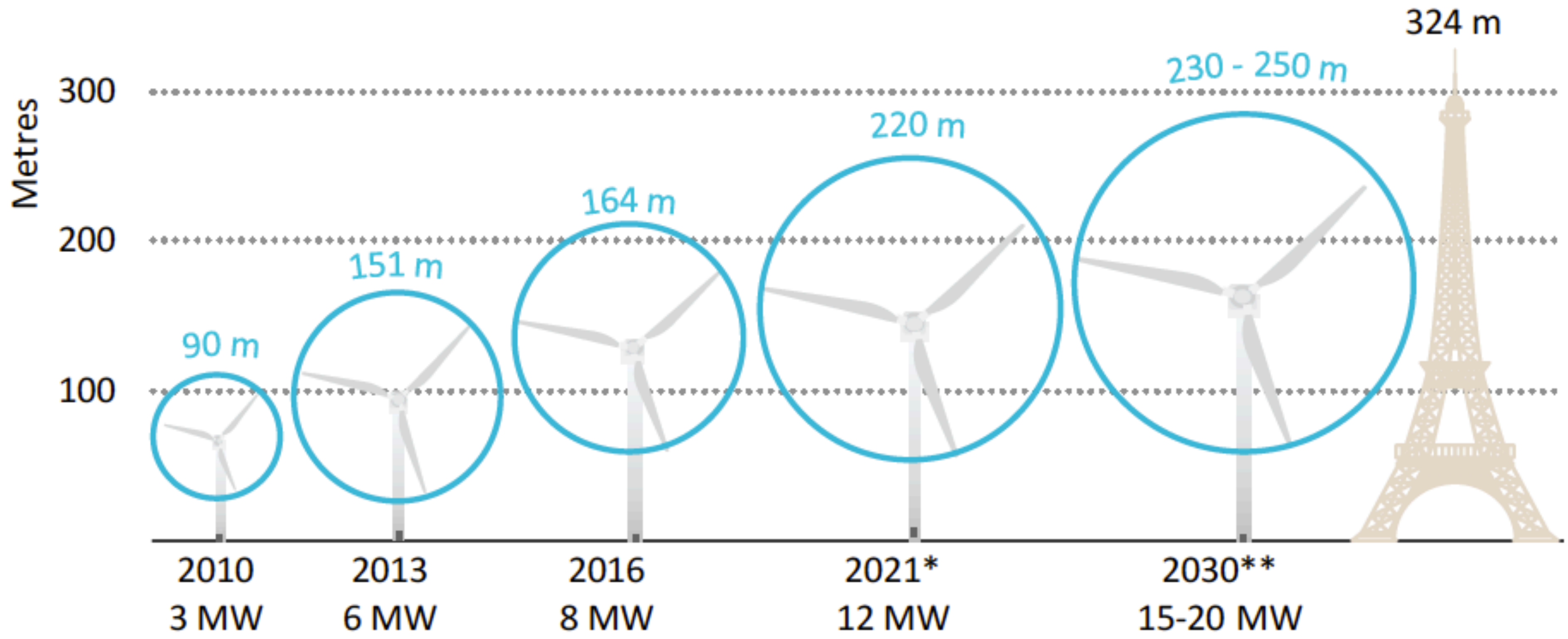


1980	1985	1995	1997	2000	2005	2010	2020	**Date**
15m	25m	50m	80m	112m	126m	150m	252m	**Diameter**
50kW	225kW	1MW	2.5MW	4.5MW	5MW	10MW	20MW	**Output**

SOURCE: GARRAD HASSAN, UPWIND

Harnessing wind power – IEA Offshore Wind Outlook 2019

Figure 3 ▷ Evolution of the largest commercially available wind turbines



Technology advances enabled offshore wind turbines to become much bigger in just a few years and are supporting ongoing increases in scale

* Announced expected year of commercial deployments. ** Further technology improvements through to 2030 could see bigger turbines sizes of 15-20 MW.

Notes: Illustration is drawn to scale. Figures in blue indicate the diameter of the swept area.

Harnessing wind power

How much power is produced?

Power output varies with wind speed.

Every turbine has a characteristic wind speed-power curve

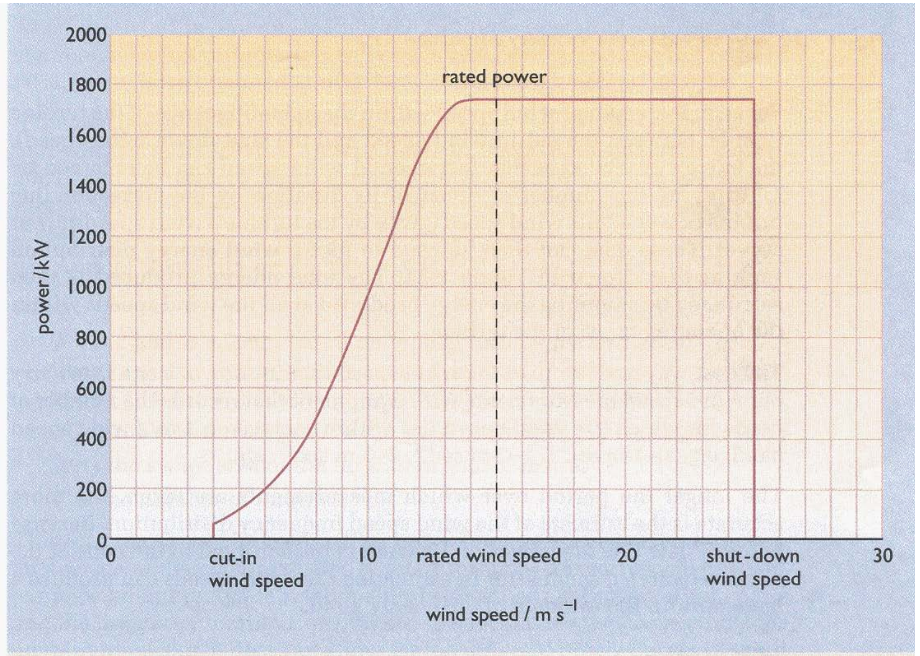


Figure 7.29 Typical wind turbine wind speed-power curve

Typical wind turbine wind speed-power curve

Source: *Renewable energy* Boyle

The power extracted is related to the wind energy by the power coefficient C_p

$$P = C_P \left(\frac{\rho V^3 A}{2} \right)$$

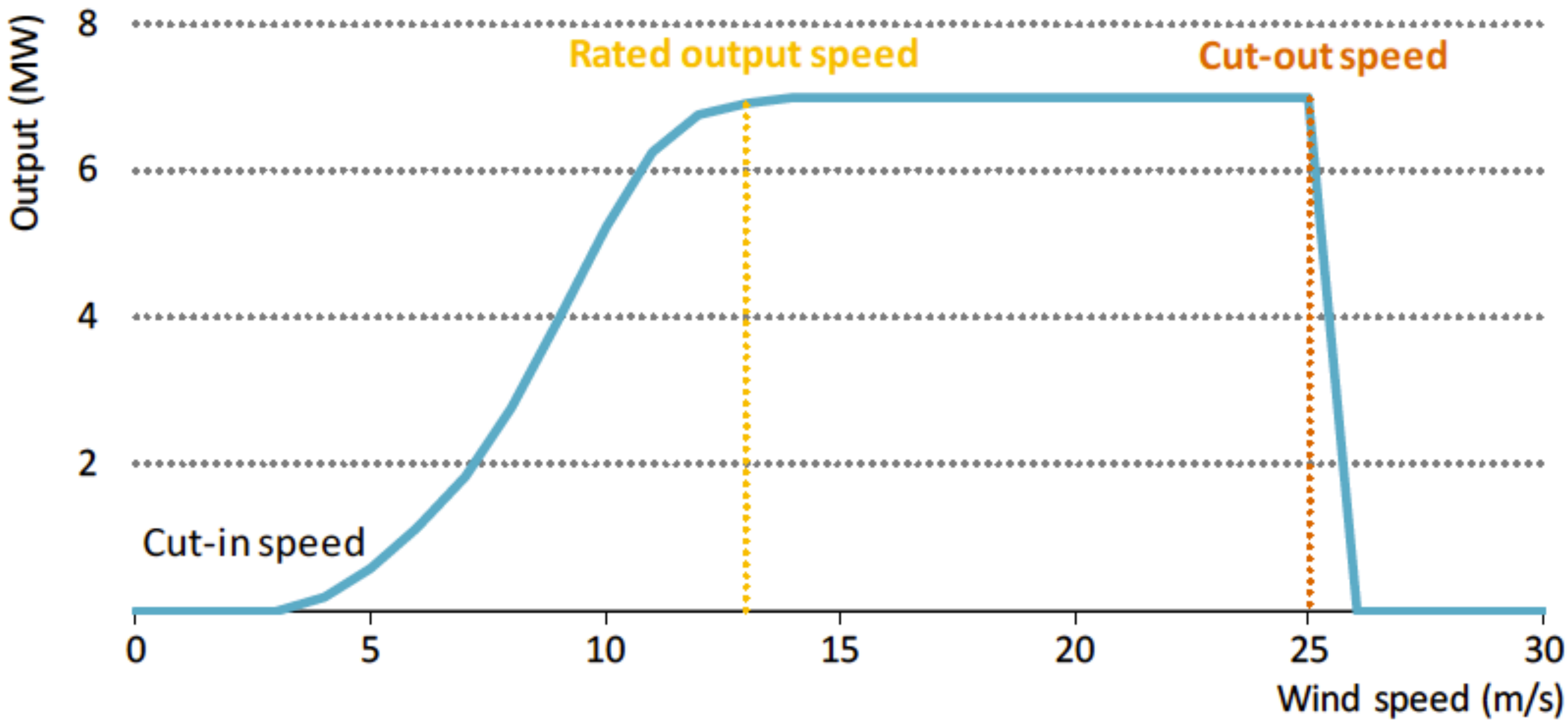
According to Betz' law the limit for the power coefficient is 16/27, hence

$$P_{max} = \left(\frac{16}{27} \right) \frac{\rho V^3 A}{2}$$

This gives a maximum mechanical extraction of ~59% from incident wind energy

IEA – Offshore Wind Outlook 2019

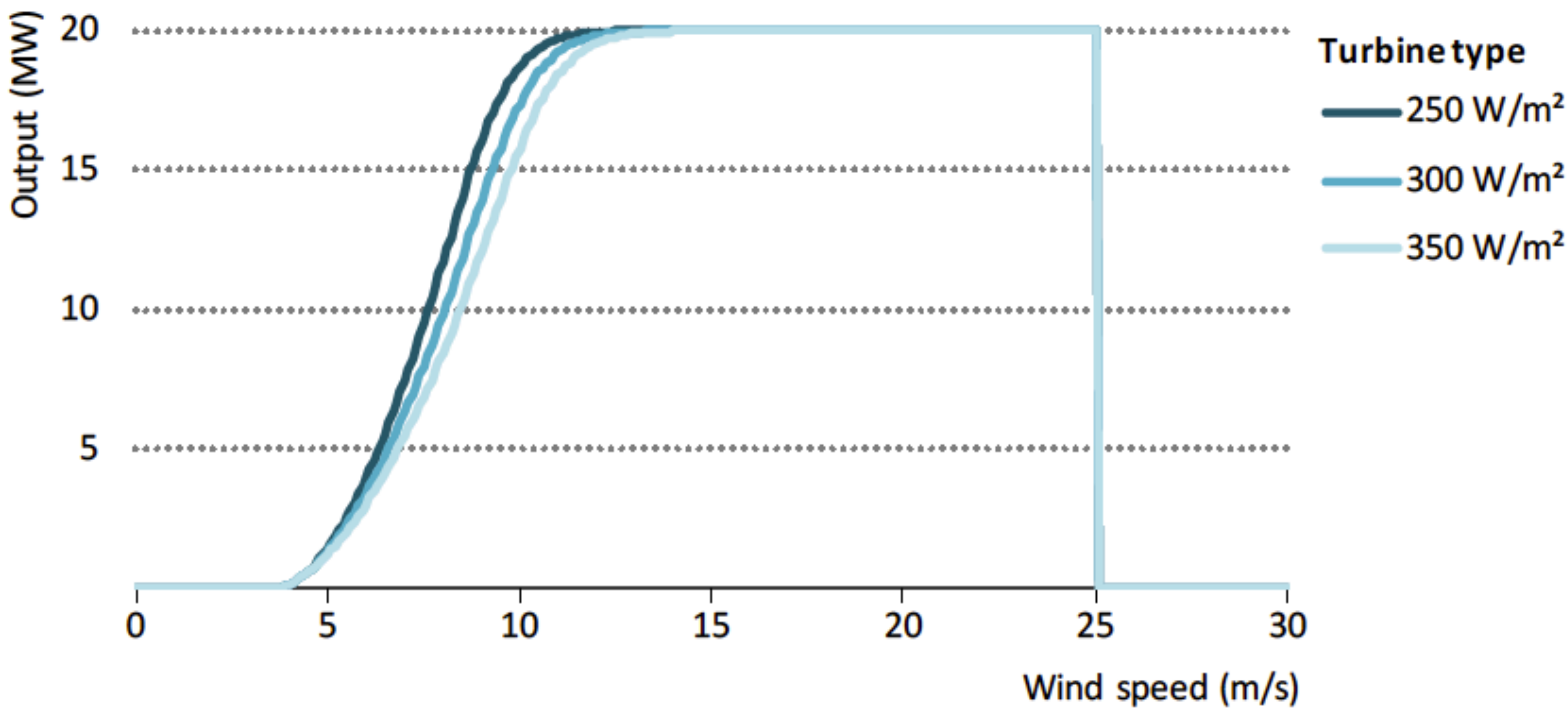
Figure B.1 ▷ Illustrative power curve for a 7 MW wind turbine



Electrical output of a wind turbine depends on the wind speed and varies across different wind turbine models

Note: MW = megawatt.

Figure B.2 ▷ Illustrative power curves for 20 MW wind turbines



Power curves for three turbine types by specific power were synthesised for this study, which correspond to low-medium, medium and high wind speeds.

Source: Saint-Drenan et al. (2019).

Harnessing wind power

How much power is produced?

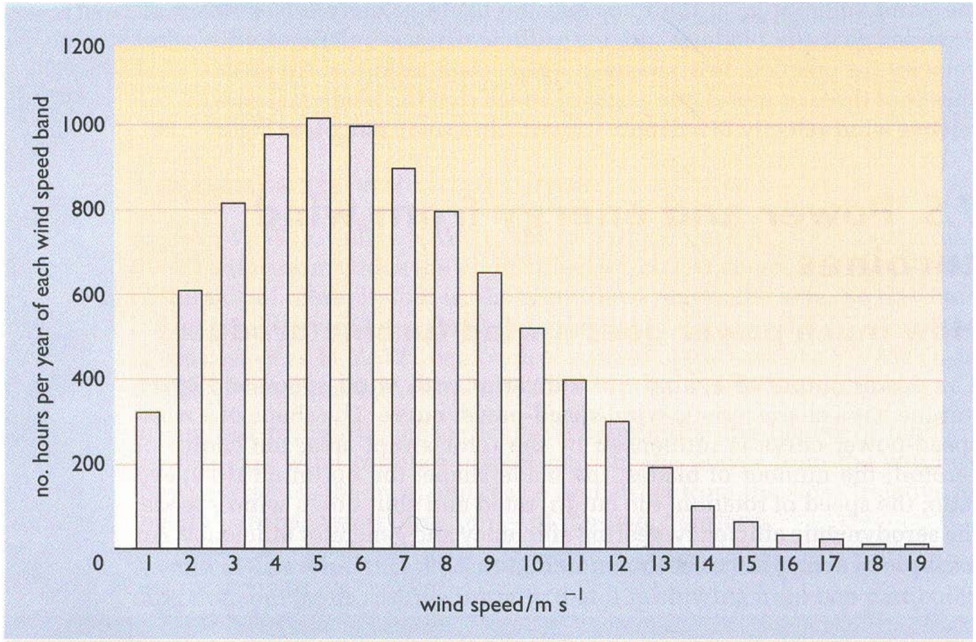


Figure 7.30 A typical wind speed frequency distribution

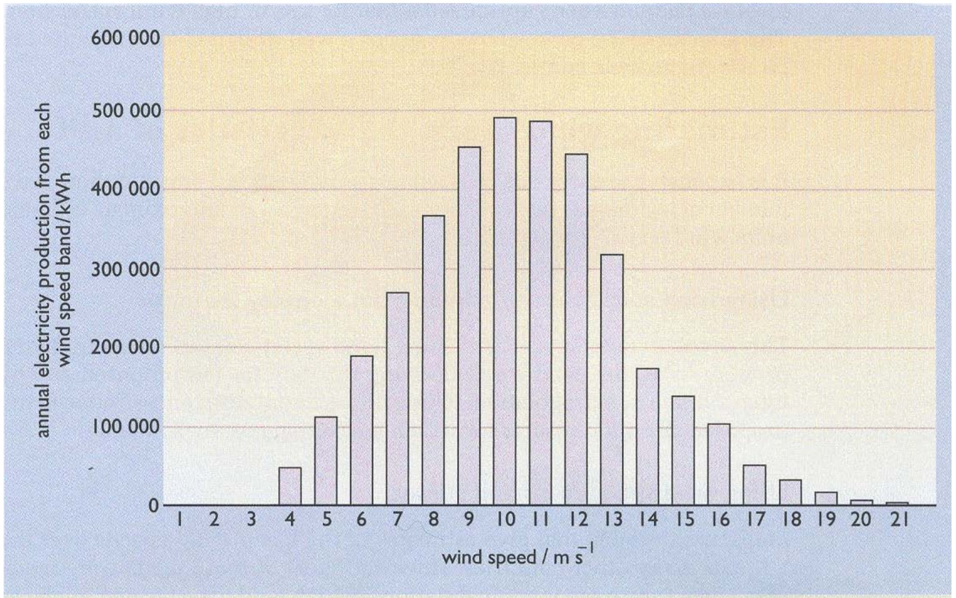


Figure 7.31 Wind energy distribution for the same site as in Figure 7.30, showing energy produced at this site by a wind turbine with the wind speed-power curve shown in Figure 7.29

Environmental impacts of wind power

Emissions from wind power?

Wind farms largely considered as emission free RE sources - however, a small amount of carbon dioxide emissions are associated with construction ~10 tonne per GWh.

Environmental impacts of wind power

Other environmental impacts

Noise: There has been much concern over the noise produced by wind farms due to large moving structures involved.

Typical noise level comparison:

Busy general office: ~ 60 dB

Wind farm at 350 m distance:~35-45 dB

Of course, not many people tend to live offshore!!

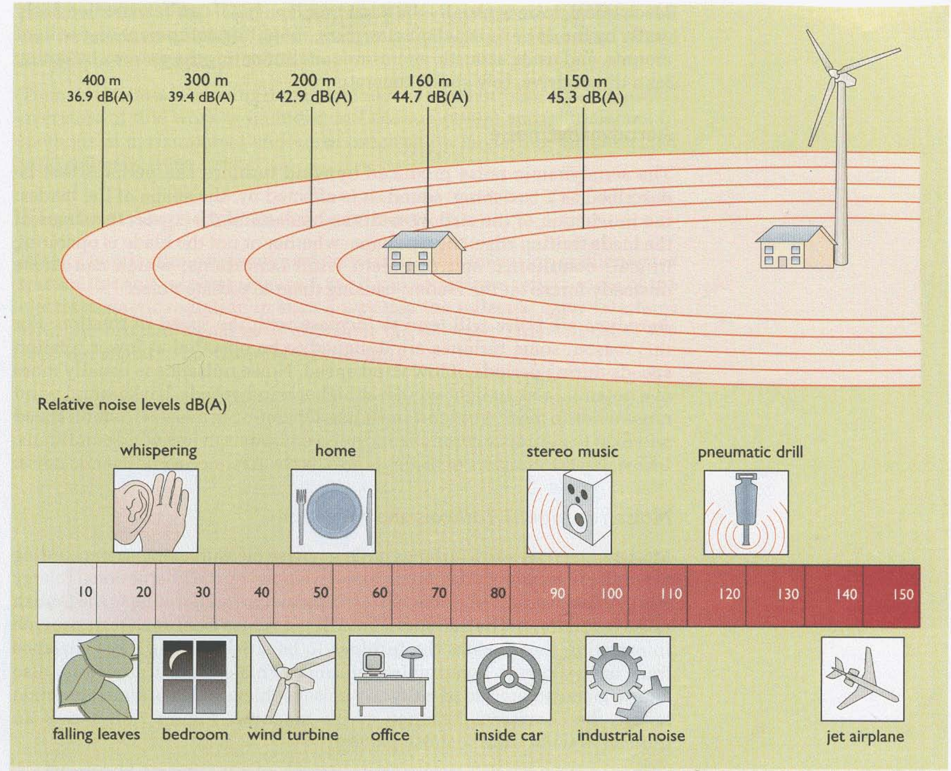


Figure 7.33 Noise pattern from a typical wind turbine (source: EWEA, 1991)

Table 7.1 Noise of different activities compared with wind turbines

Source/activity	Noise level in dB(A)*
Threshold of pain	140
Jet aircraft at 250 m	105
Pneumatic drill at 7 m	95
Truck at 48 km h^{-1} (30 mph) at 100 m	65
Busy general office	60
Car at 64 km h^{-1} (40 mph)	55
Wind farm at 350 m	35–45
Quiet bedroom	20
Rural night-time background	20–40
Threshold of hearing	0

* dB(A): decibels (acoustically weighted)
(Source: Department of the Environment, 1993)

Environmental impacts of wind power

Other environmental impacts

Blot on the landscape: Another concern has been the visual intrusion of wind farms which when onshore tend to occupy elevated ridge positions to maximise wind potential.

Beauty is in the eye of the beholder!

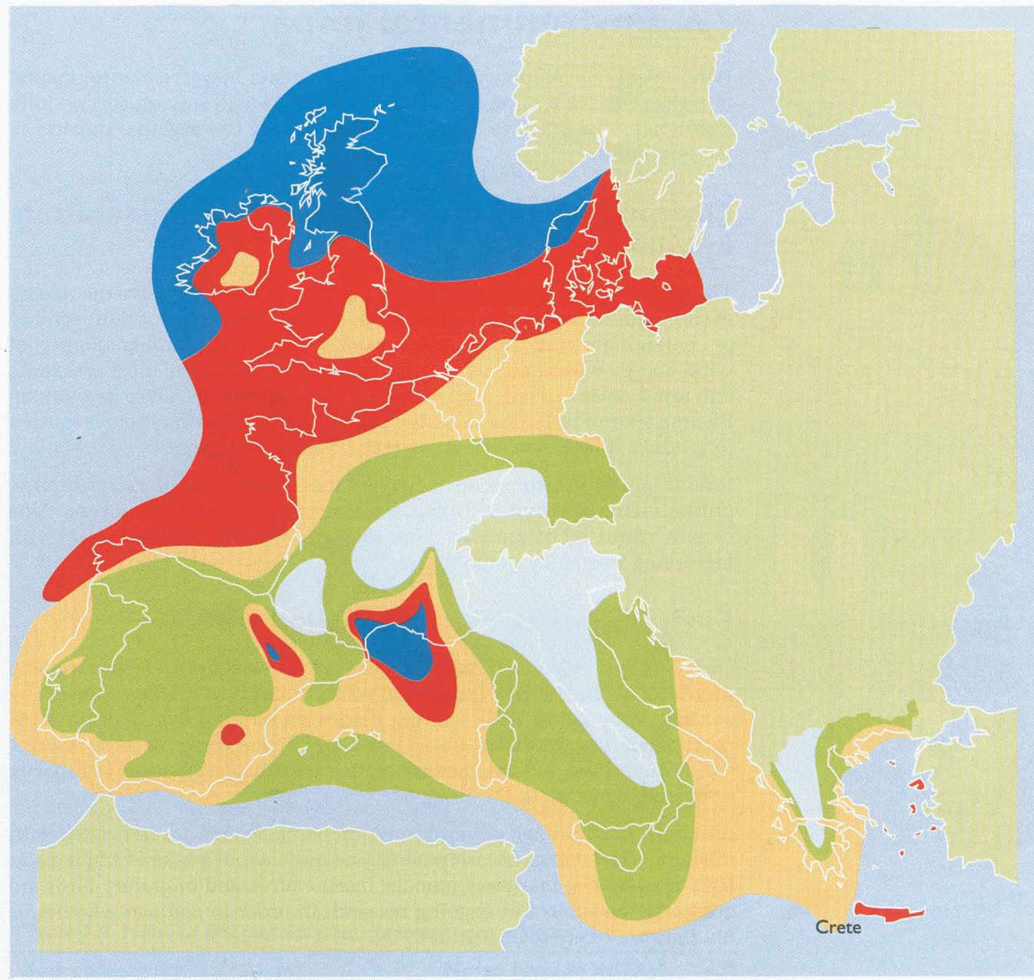
However, most new project are offshore and barely visible by land.

Harnessing wind power

European wind speed map

UK has largest potential onshore and offshore wind energy sources in EU;

UK wind power potential – 300% of electricity demand

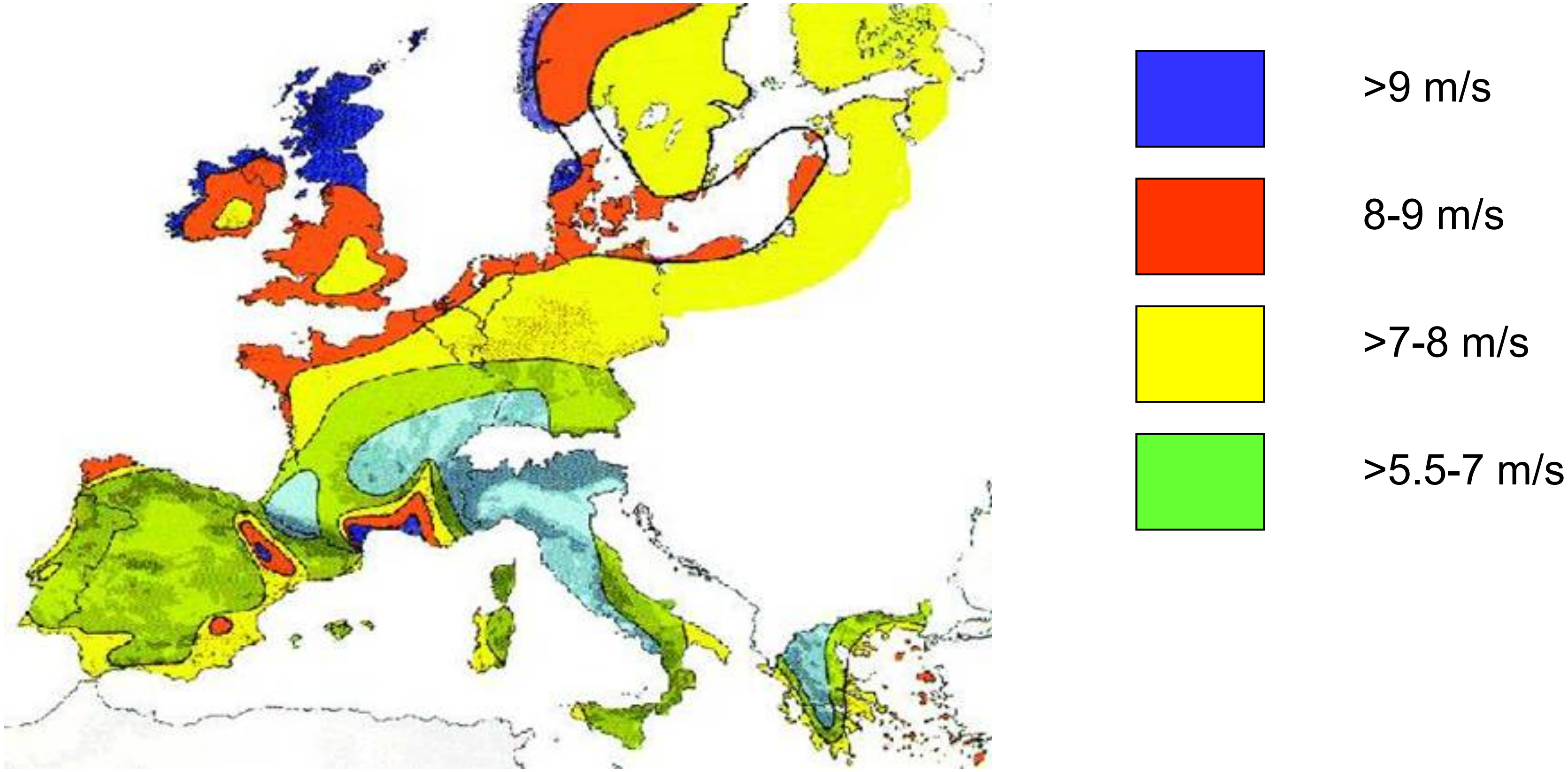


Wind resources at 50 m above ground level for five different topographic conditions

	Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
	$m\ s^{-1}$	$W\ m^{-2}$	$m\ s^{-1}$	$W\ m^{-2}$	$m\ s^{-1}$	$W\ m^{-2}$	$m\ s^{-1}$	$W\ m^{-2}$	$m\ s^{-1}$	$W\ m^{-2}$
(blue)	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
(red)	5.0–6.0	150–250	6.5–7.5	300–500	7.0–8.5	400–700	8.0–9.0	600–800	10.0–11.5	1200–1800
(orange)	4.5–5.0	100–150	5.5–6.5	200–300	6.0–7.0	250–400	7.0–8.0	400–600	8.5–10.0	700–1200
(green)	3.5–4.5	50–100	4.5–5.5	100–200	5.0–6.0	150–250	5.5–7.0	200–400	7.0–8.5	400–700
(pale blue)	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400

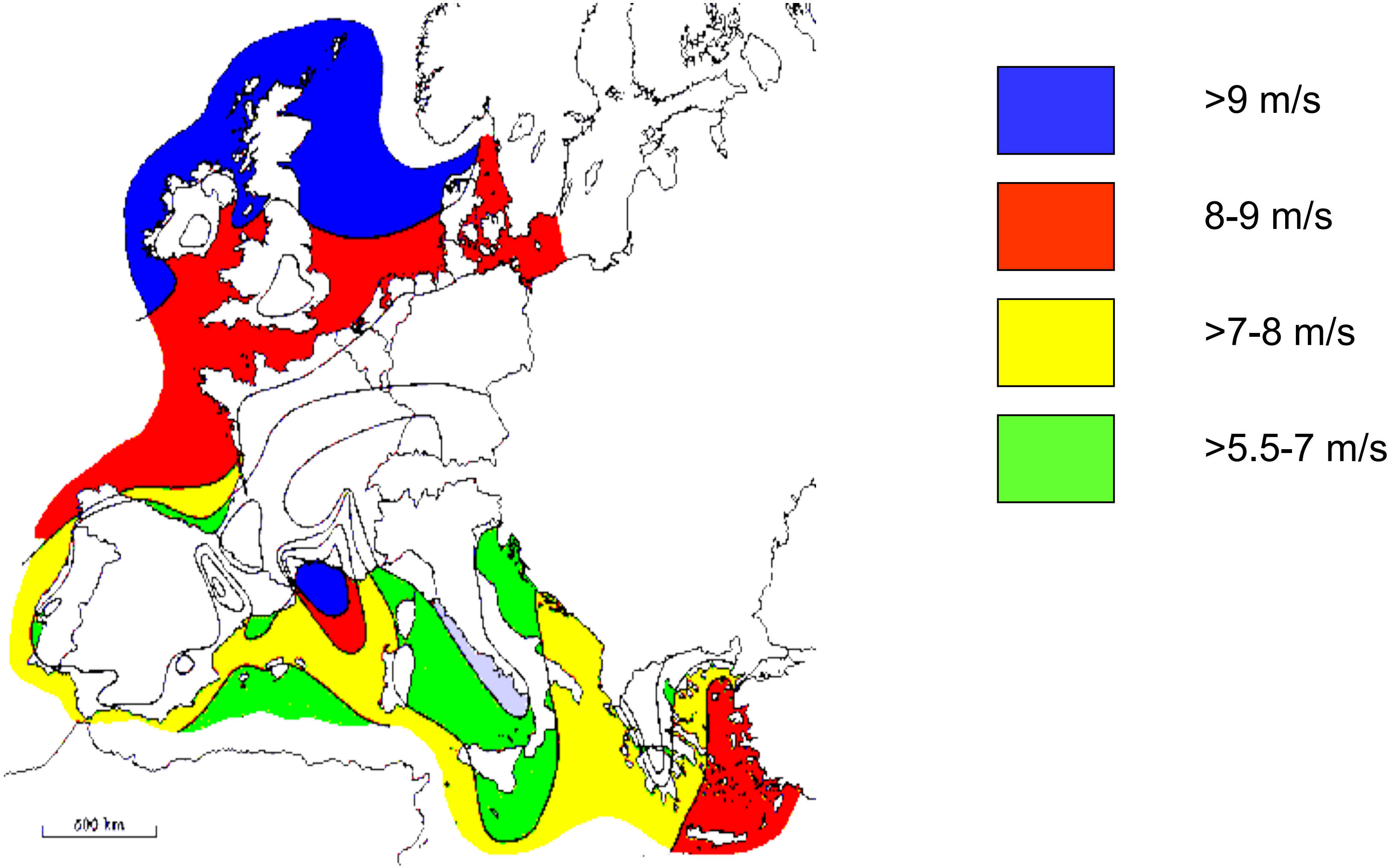
Figure 7.32 Annual mean wind speeds and wind energy resources over Europe (EU Countries) (source: Troen and Petersen, 1989)

40% of European wind source

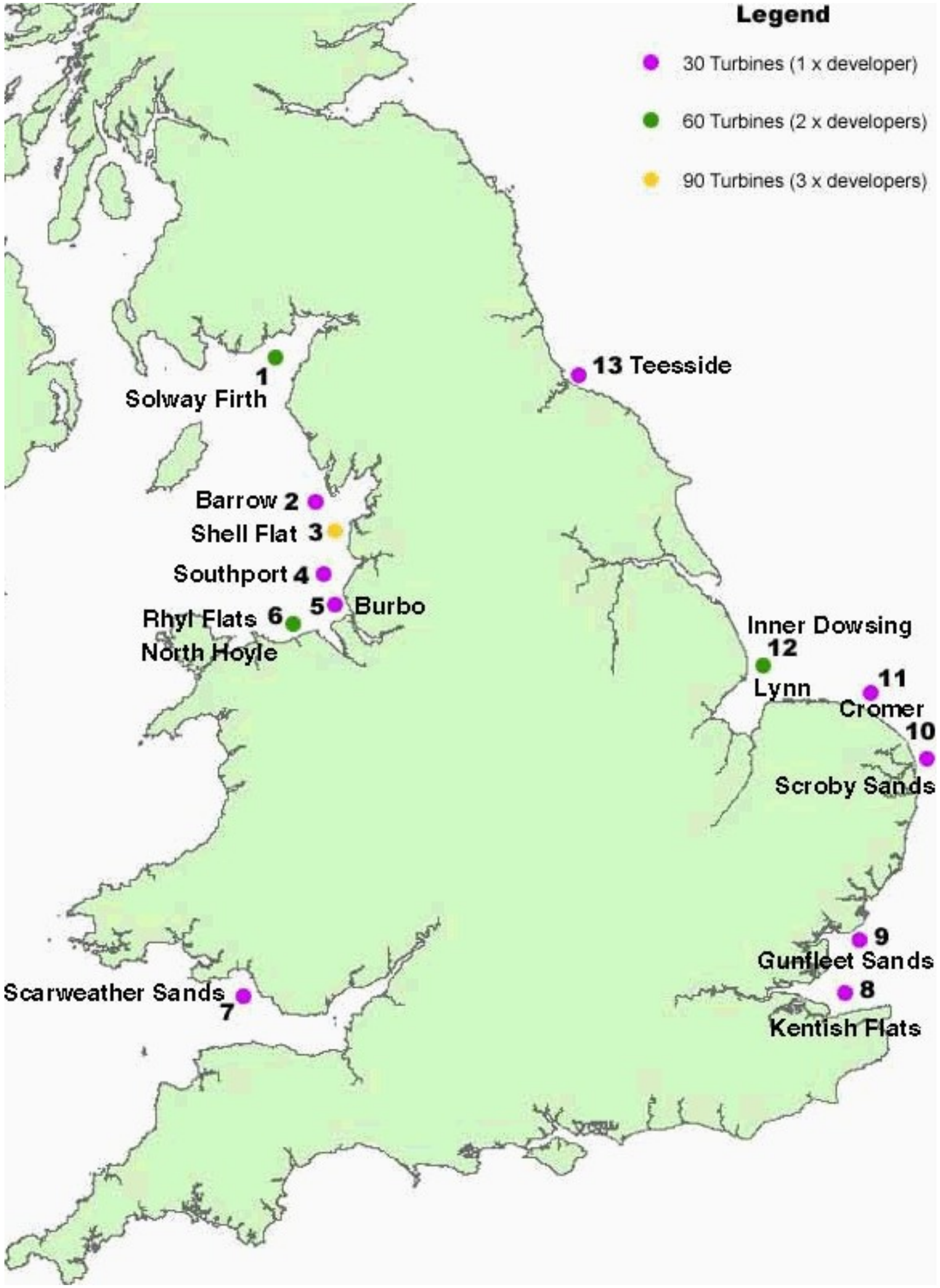


..and even more offshore

UK – Wind-Rich country – Extensive Offshore Wind Power



‘Round One’ - 2001



~500 turbines

1.5 GW

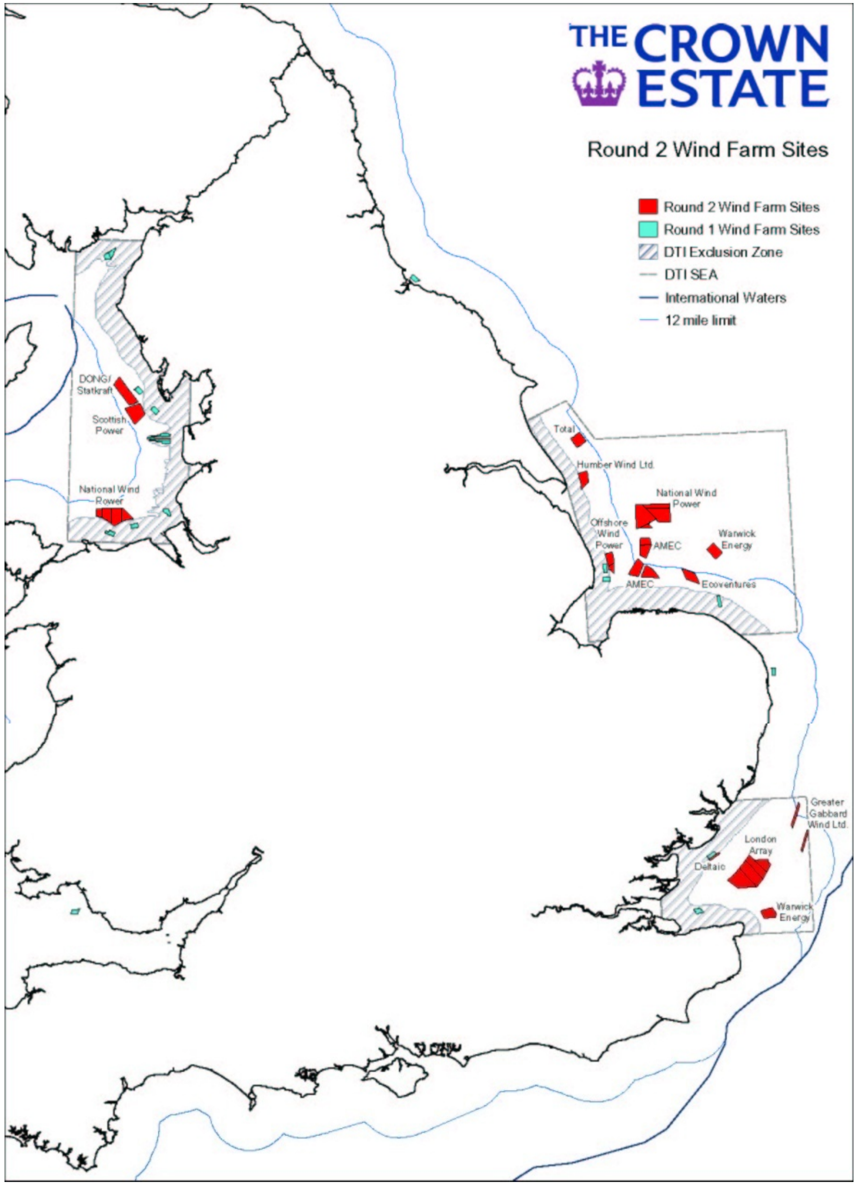
ca.

1% of total UK electricity supply

Outcome

- 15 projects awarded options to lease seabed
- Total of 5.4-7.2 GW
- Developments much larger than ‘Round One’
  - Largest project 1,200 MW
- Further offshore (8-13 km limits)
  - Some outside territorial waters
- Construction
  - Be phased through a number of seasons

Round 2 projects



Moving forward with Round 2

- **Round 2 build depends on satisfactory outcome of 05/06 review**
  - **Providing suitable framework for bankable projects**

- **Round 2 costs likely to be about 85% of Round 1**
  - **Could be as low as 75%**

- **Wind energy already makes a significant contribution to the UK, with an output of 15.5 TWh in 2011 — equivalent to the annual electricity demand of 4.7 million homes.**

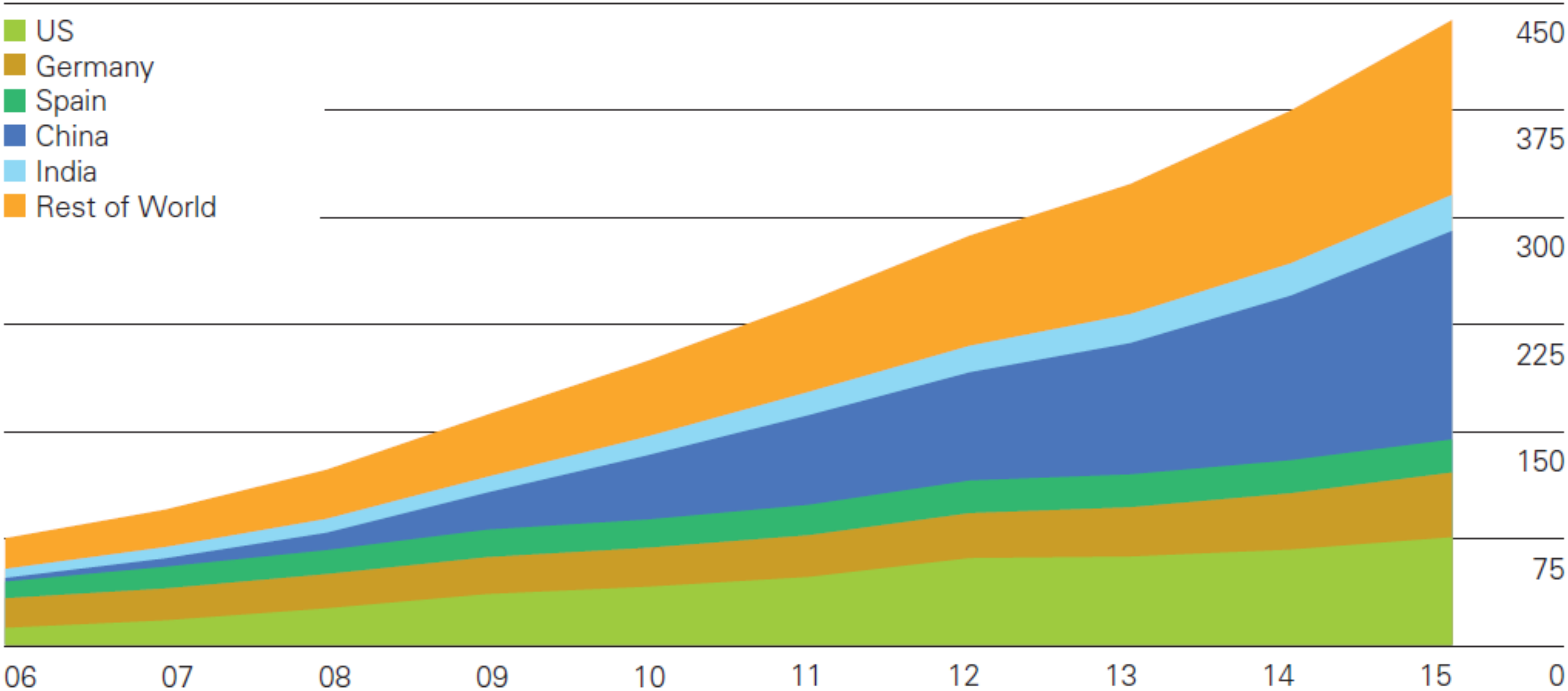
Round 3 - 2010

- "Round 3" projects in the nine zones could generate up to 32 GW of power, a quarter of the UK's electricity needs.
- Expansion into new areas requires extended survey
- Costs in 2020 could be 40% less than current levels
  - Similar to onshore costs now

IEA – Offshore Wind Outlook 2019

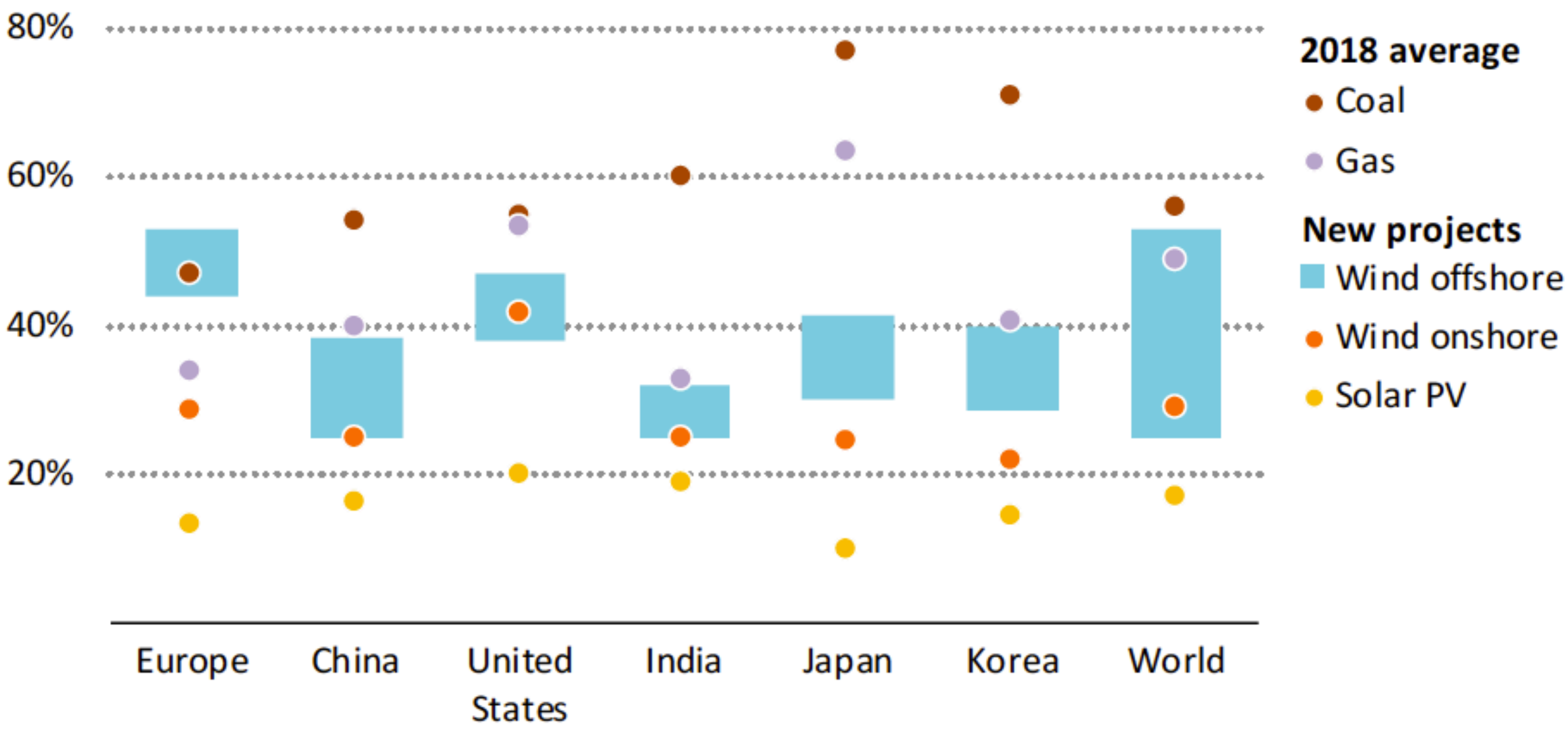
Wind capacity

Gigawatts, cumulative installed capacity



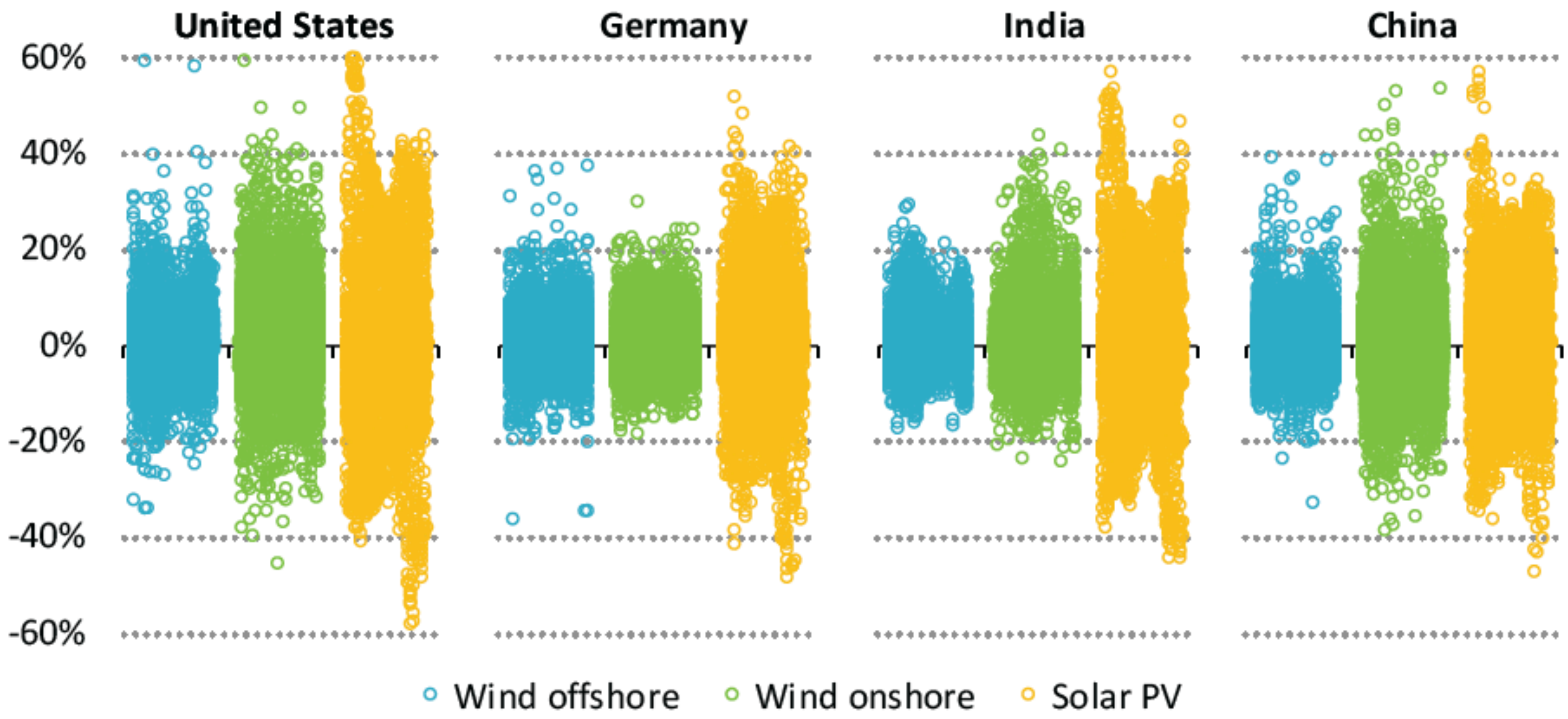
Source: includes data from Navigant Consulting and the Global Wind Energy Council.

Figure 4 ▷ Indicative annual capacity factors by technology and region



Offshore wind offers similar capacity factors to efficient gas-fired power plants in several regions, with levels well above those for other variable renewables

Figure 6 ▷ Range of simulated hour-to-hour variations in output for new projects by technology

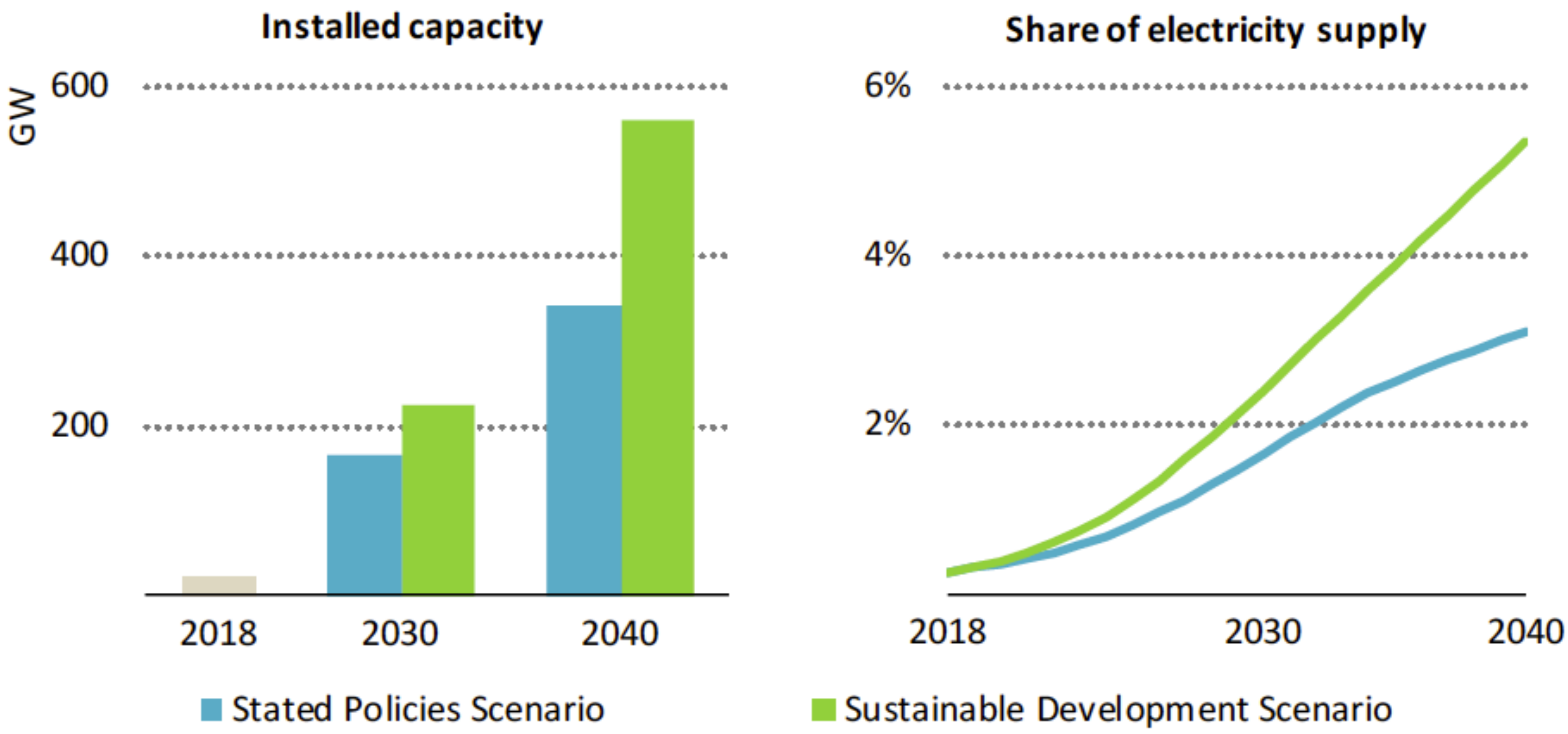


Offshore wind has similar hourly variability as onshore wind, but far less than solar PV

Note: Based on weather data for 2018.

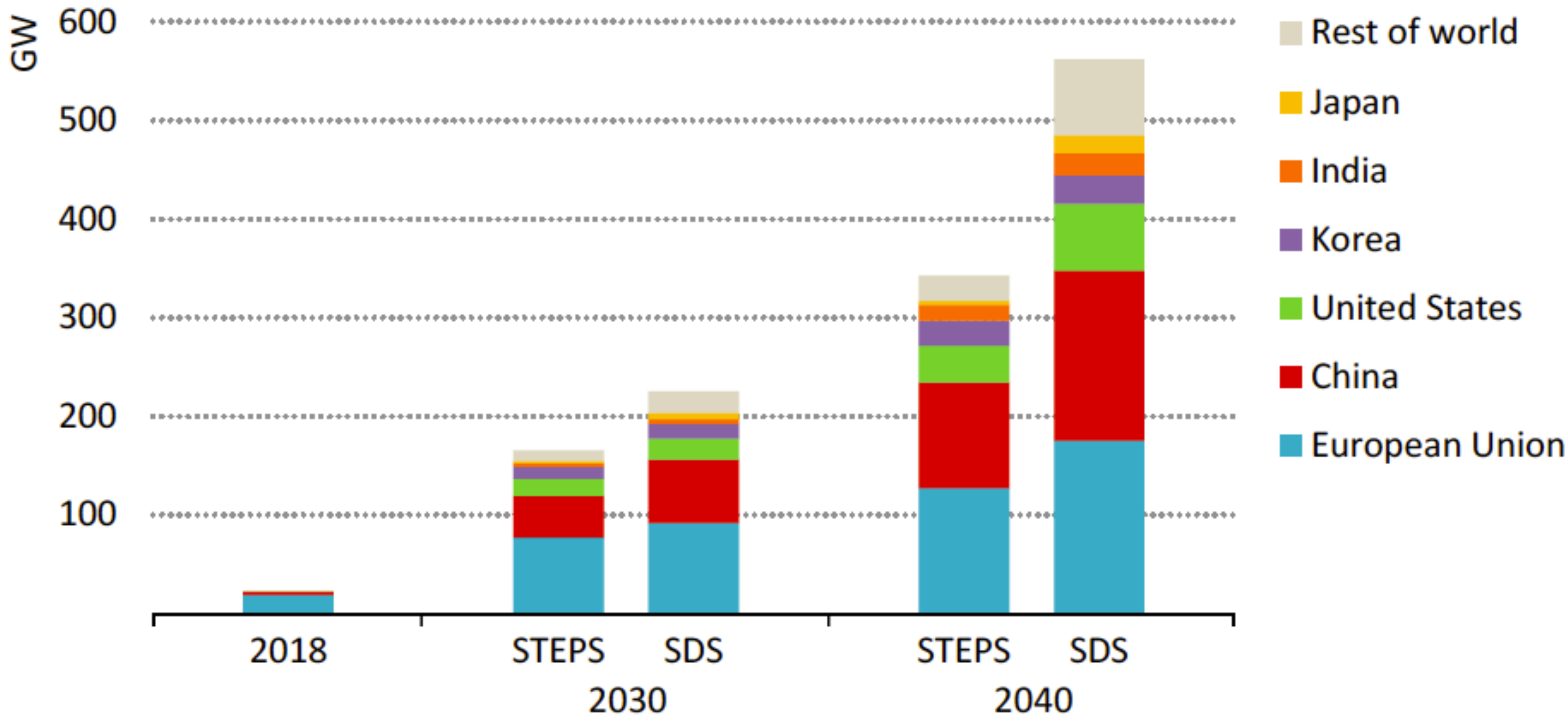
Source: IEA analysis based on Renewables.ninja.

Figure 9 ▷ Projected global offshore wind capacity and share of electricity supply by scenario



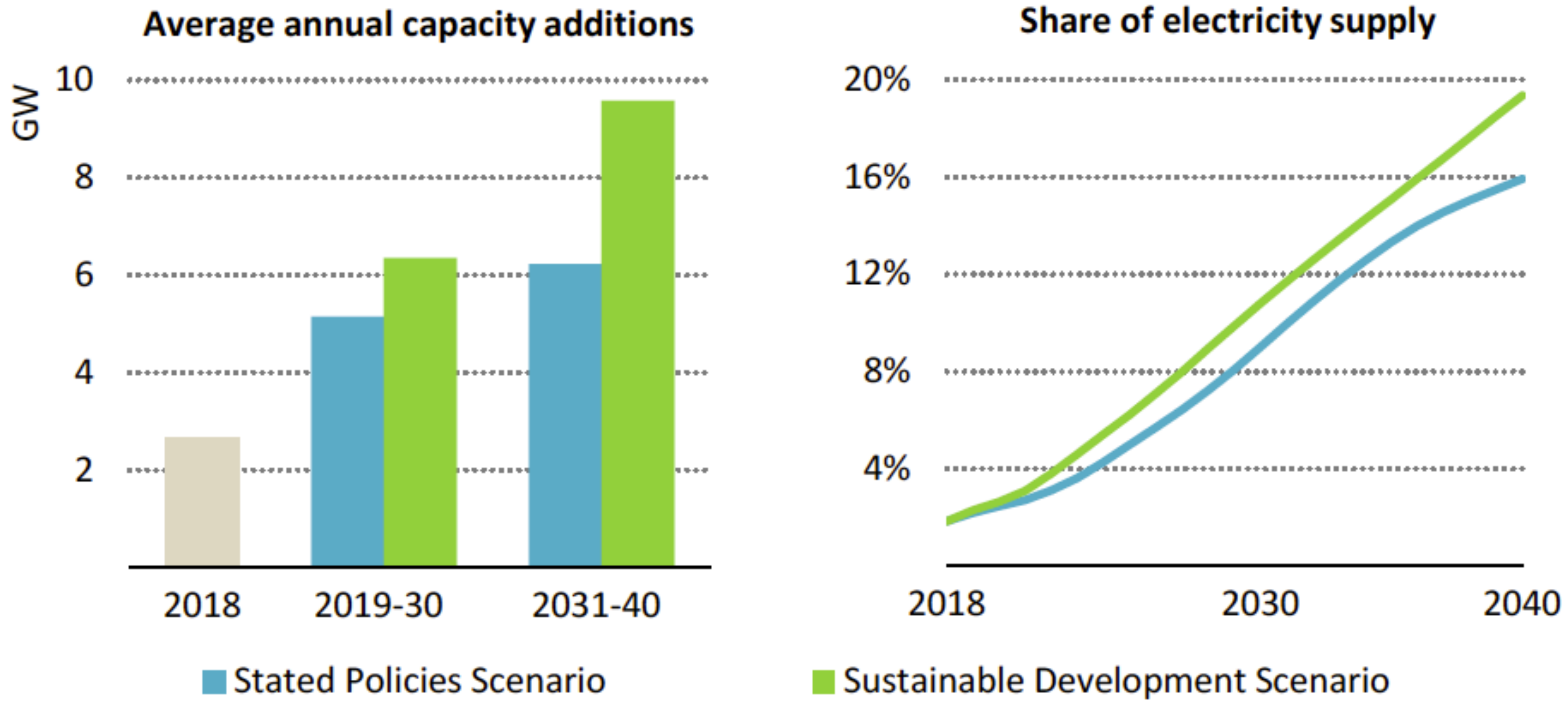
Global offshore wind installed capacity increases by fifteen-fold in the Stated Policies Scenario, raising its share of electricity supply to 3% in 2040

Figure 11 ▷ Installed capacity of offshore wind by region and scenario



European Union and China account for 70% of the global offshore wind market to 2040, but a number of countries enter the market and increase their capacity

Figure 12 ▷ Outlook for offshore wind in the European Union, 2018-2040

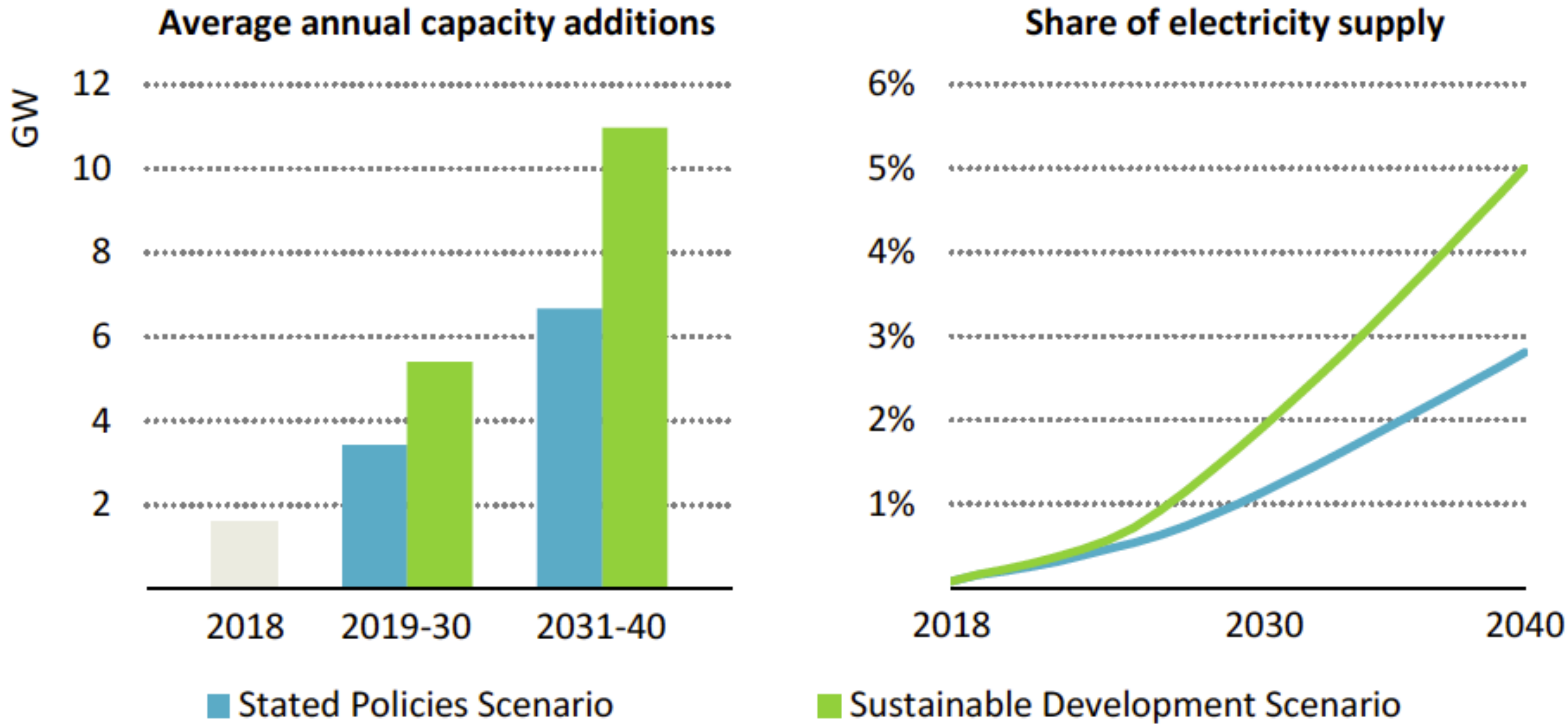


In the European Union, offshore wind is set to play a central role and has the potential to become the largest source of electricity supply, matching onshore wind

Table 4 ▻ Policy targets for offshore wind in the European Union

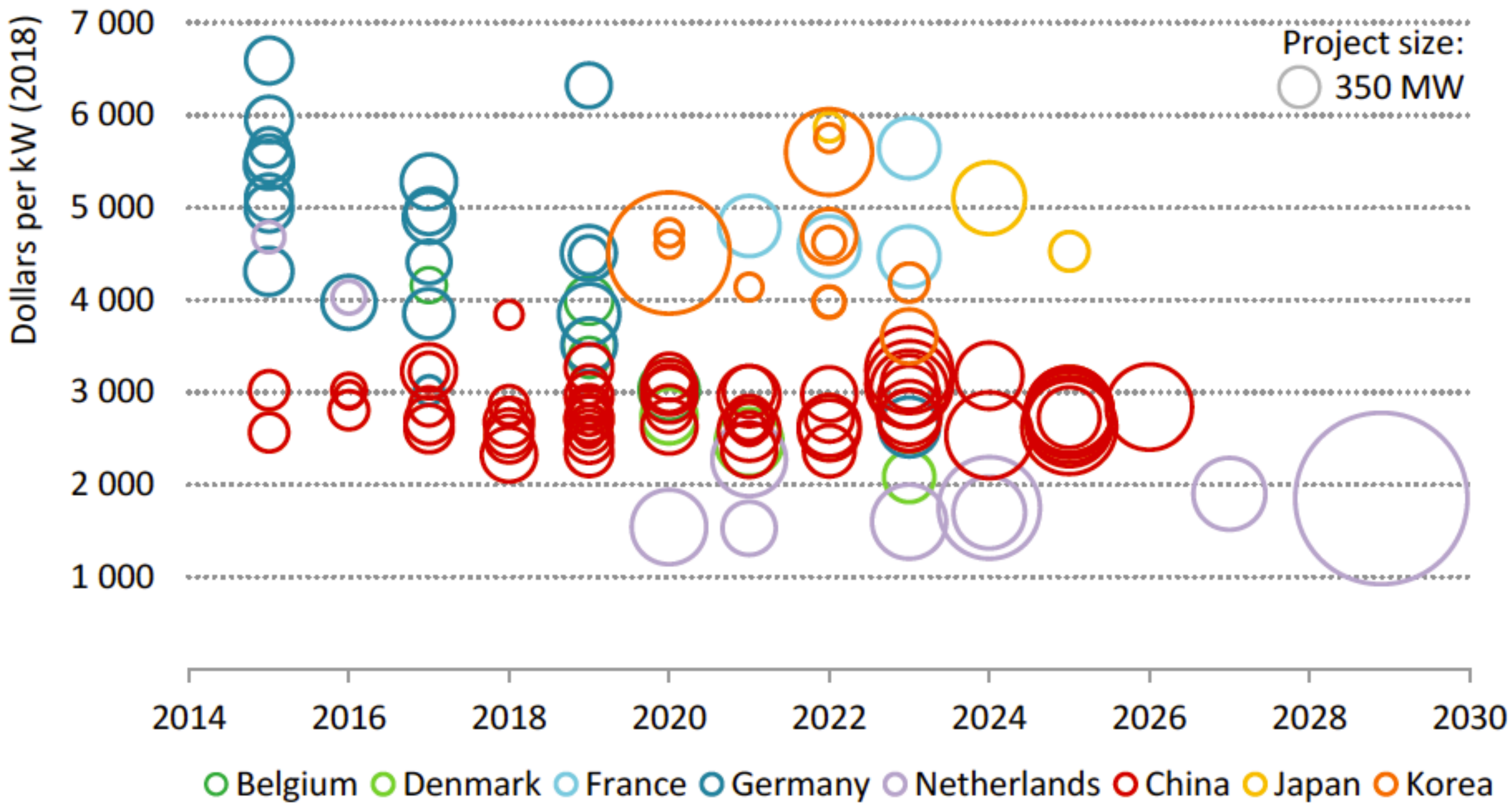
Country	Policy	Capacity target	Year set
United Kingdom	UK Offshore Sector Deal	Up to 30 GW by 2030	2019
Germany	The Renewable Energies Act	15-20 GW by 2030	2017
Netherlands	The Offshore Wind Energy Roadmap	11.5 GW by 2030	2017
Denmark	Energy Agreement	5.3 GW by 2030	2019
Poland	Draft National Energy and Climate Plan	Up to 5 GW by 2030	2018
France	Multi-Annual Energy Plan	4.7-5.2 GW by 2028	2019
Belgium	Draft National Energy and Climate Plan	4 GW by 2030	2019
Ireland	Climate Action Plan 2019	3.5 GW by 2030	2019
Italy	Draft National Energy and Climate Plan	0.9 GW by 2030	2018

Figure 13 ▷ Outlook for offshore wind in China, 2018-2040



China builds as much offshore wind capacity as the European Union over the next two decades, with its growth complementing other low-carbon sources

Figure 15 ▹ Capital costs of offshore wind projects excluding transmission, historical and projects in development

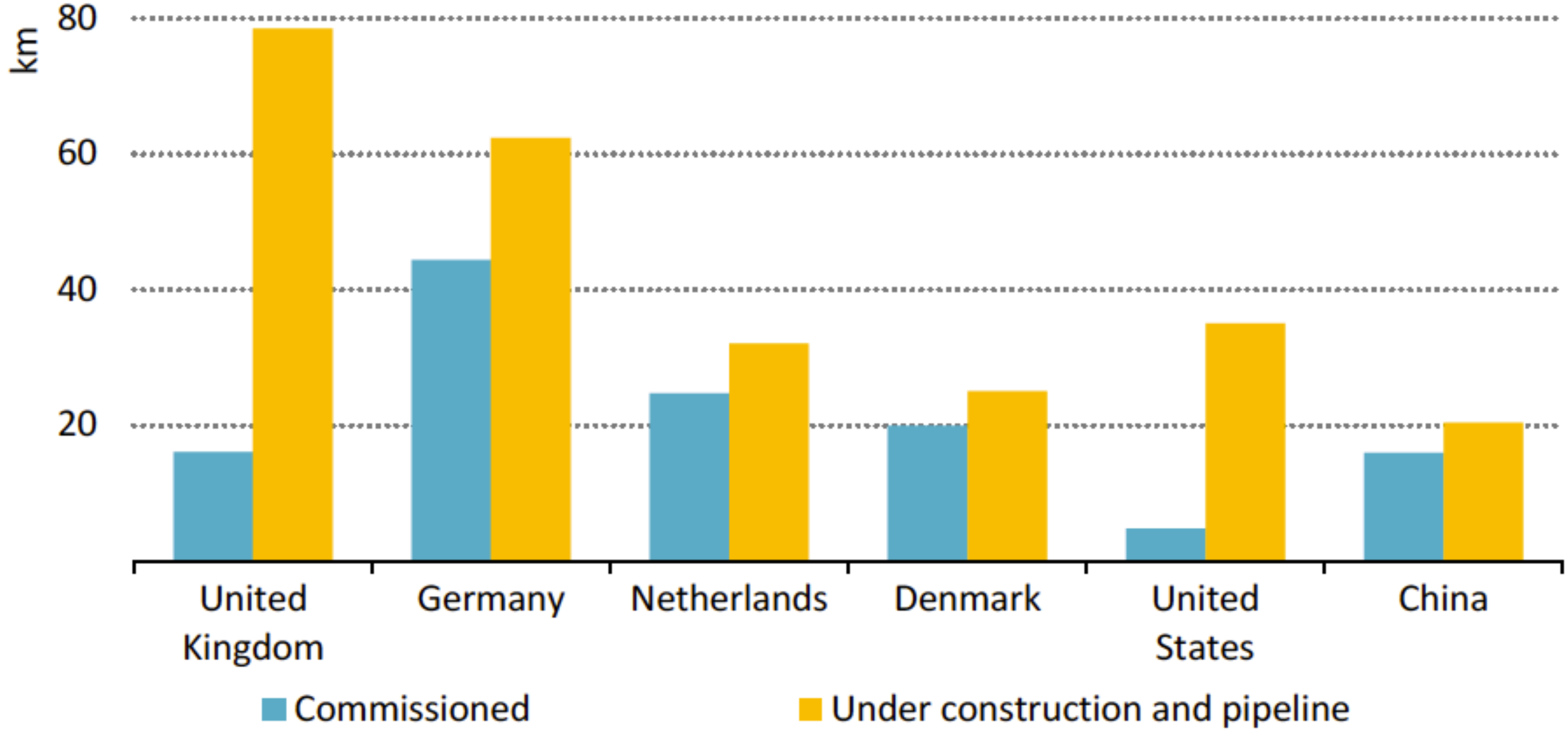


Continued industry learning propels offshore wind down the cost curve, and cost reductions can be enhanced through policy frameworks that support a healthy project pipeline

Note: Capital costs refer to the year of commissioning.

Sources: IEA analysis based on IJGlobal (2019), BNEF (2019) and company reports.

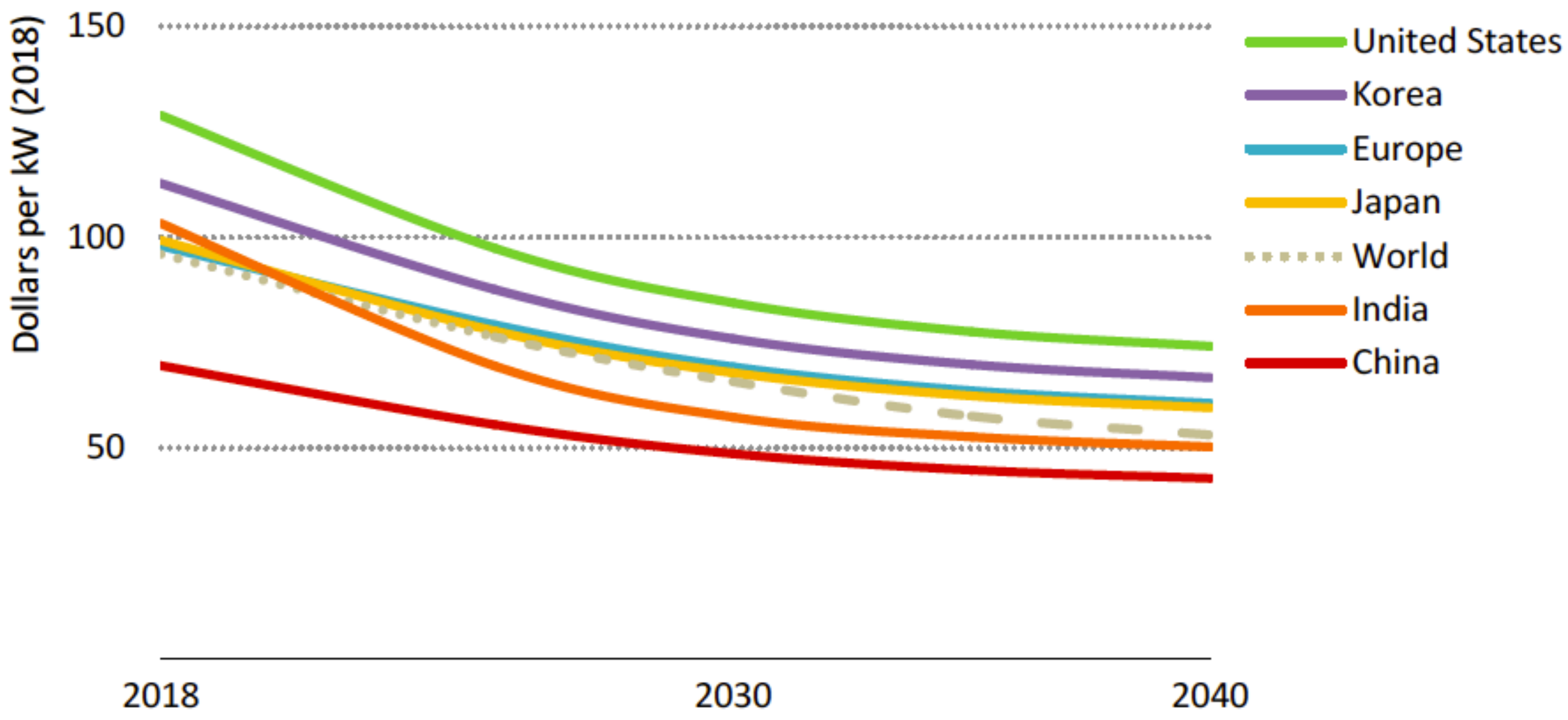
Figure 16 ▷ Offshore wind: average distance from shore by country



Offshore wind farms have been moving into deeper waters, amid a trend of increasing project sizes, that have impacted offshore transmission design as well as foundations

Sources: IEA analysis based on The Wind Power (2019) and BNEF (2019).

Figure 18 ▷ Regional average annual O&M costs for new projects



Economies of scale and industry synergies, along with digitalisation and technology development will bring current costs for O&M down by 40% in 2040

Figure 27 ▷ Regional technical potentials for offshore wind

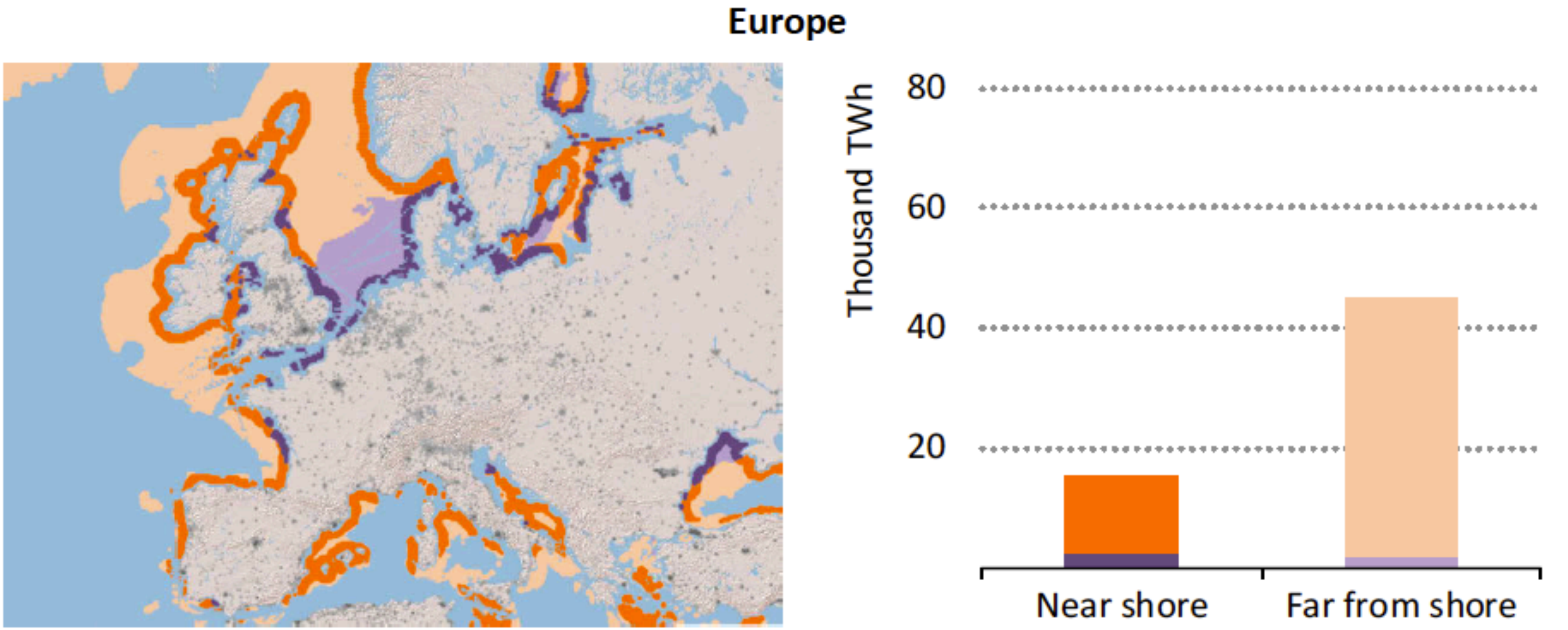
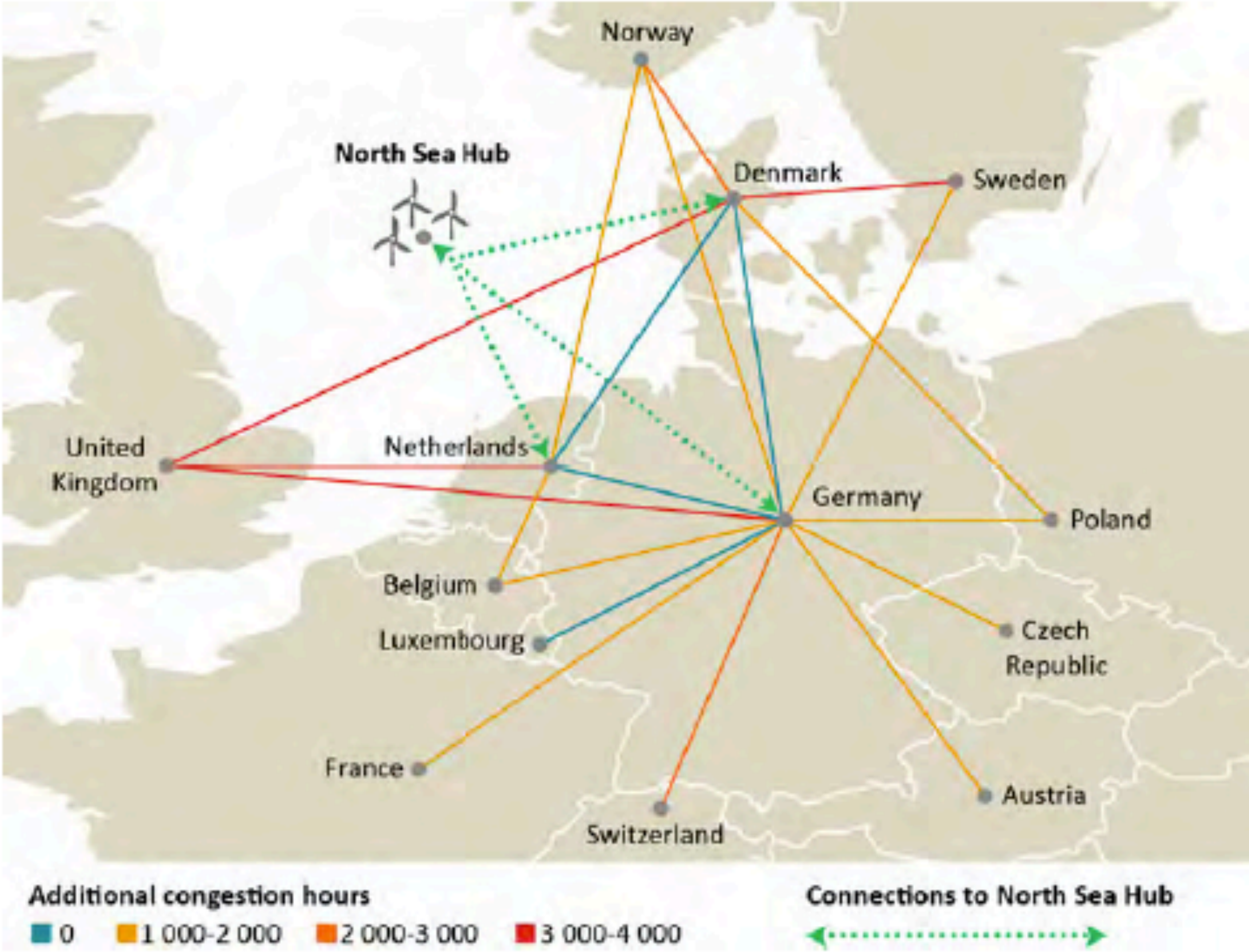


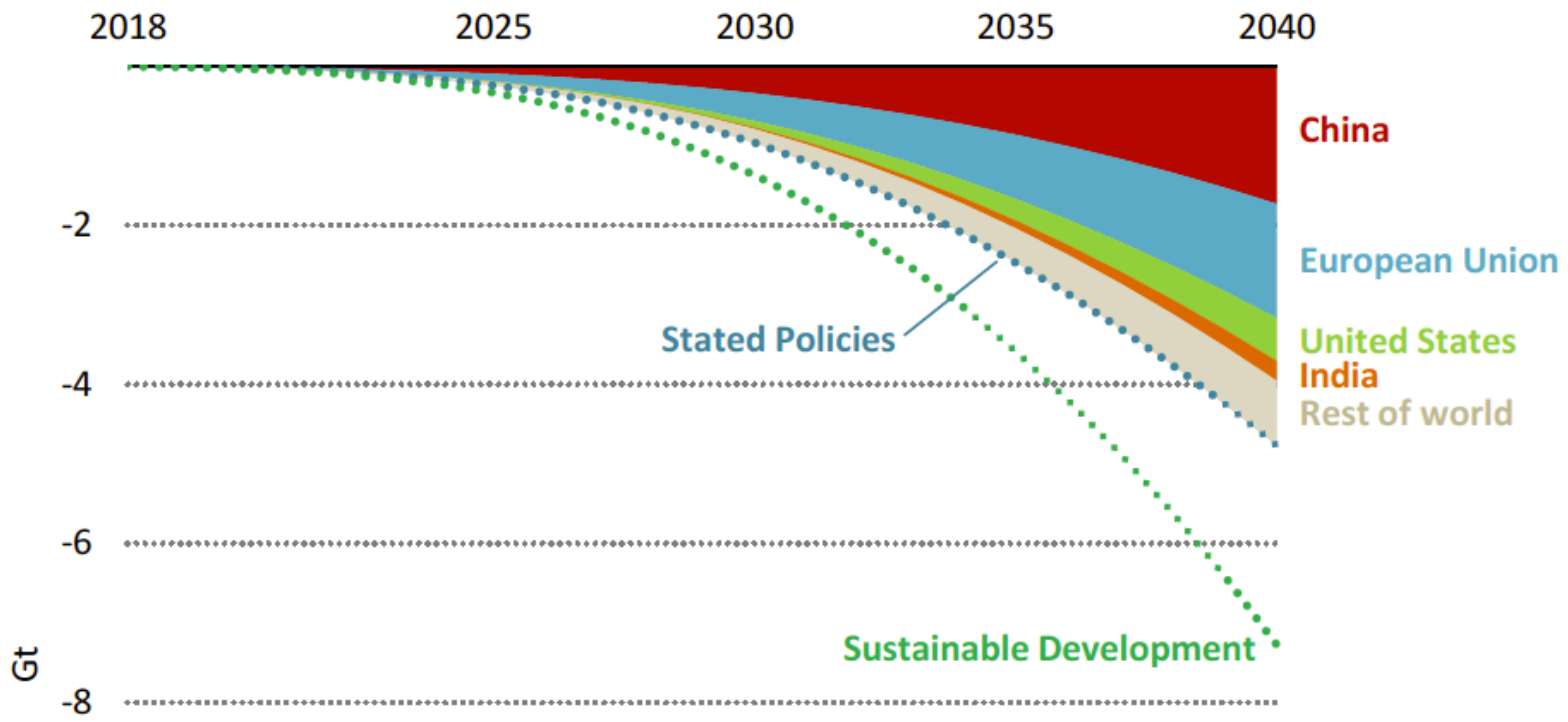
Figure 30 ▷ Rise in the number of hours of cross-border grid congestion with the addition of a 12 GW hub in the North Sea



Expanding offshore wind capacity would increase congestion on the grid without additional network investment

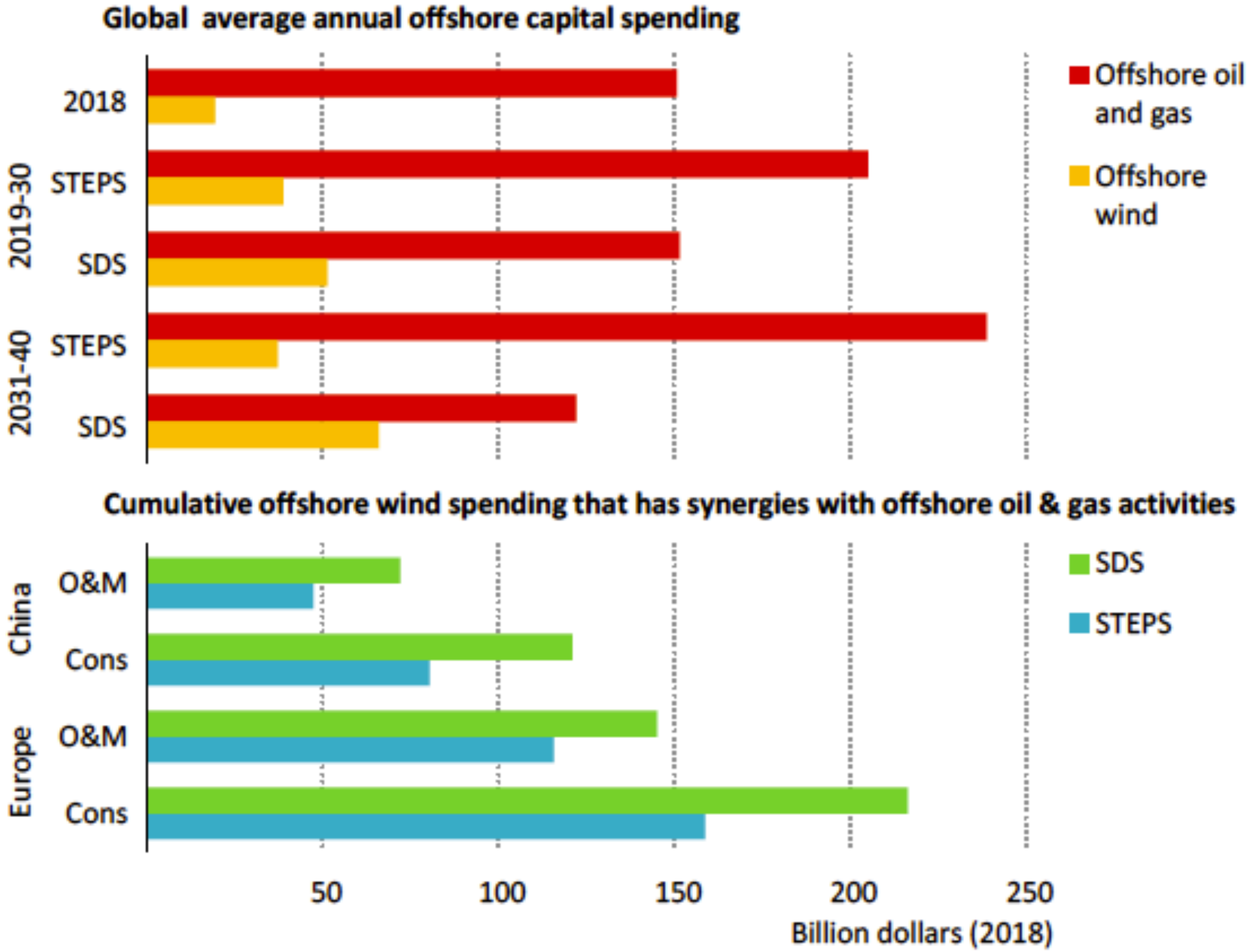
Note: Other interconnections with zero additional congestion hours were not included in the figure.

Figure 32 ▷ **Avoided CO_2 emissions due to the deployment of offshore wind in the Stated Policies and Sustainable Development scenarios**



Offshore wind complements the growth of other clean energy sources, avoiding more than 7 Gt of CO_2 emissions to 2040 in the Sustainable Development Scenario

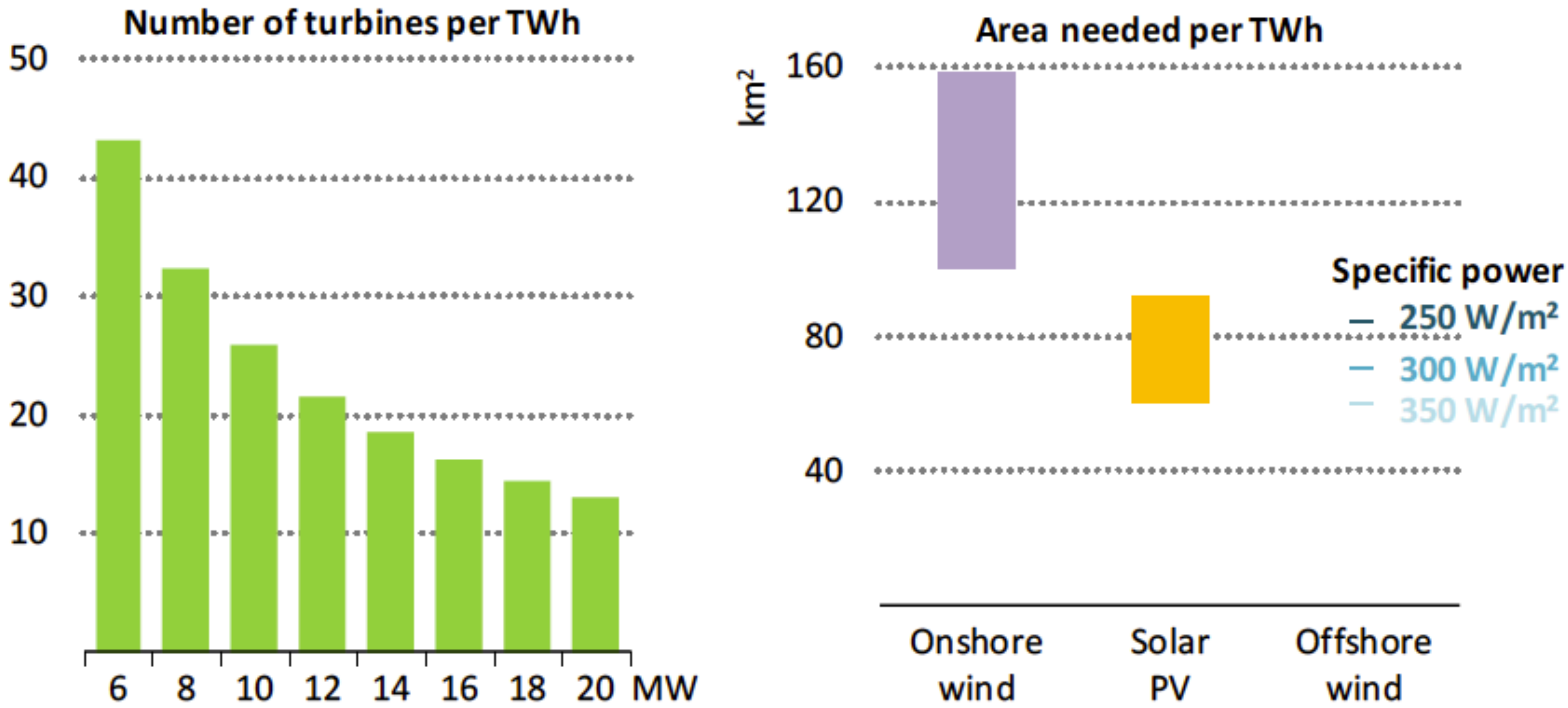
Figure 33 ▹ Global offshore wind capital spending and potential synergies with offshore oil and gas activities



A growing pipeline of offshore wind projects opens new opportunities for traditional oil and gas companies, and these increase in the Sustainable Development Scenario

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Con = construction and includes activities considered as potential synergies, e.g. foundations, installation and logistics. O&M includes potential synergies in operation and maintenance of offshore wind installations.

Figure B.3 ▷ Number of turbines and space requirements



The number of turbines required per unit of electricity generated decreases with bigger turbines, and space requirements are often less than for onshore wind or solar PV

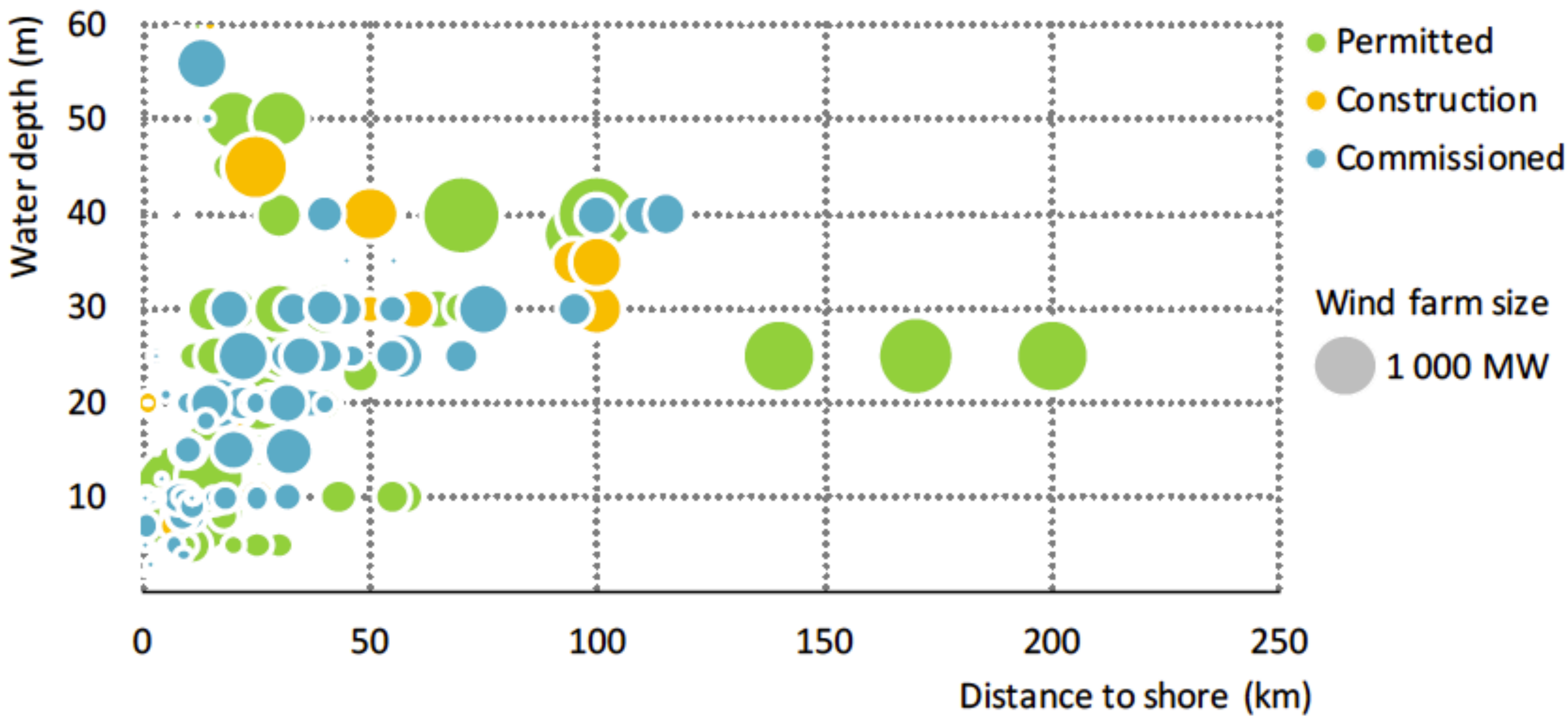
Notes: TWh = terawatt-hour. Based on an 8 x 8 rotor diameter equivalent spacing configuration and 50% capacity factor for offshore wind.

Sources: IEA analysis; van Zalk et al. (2018).

Table B.1 ▹ Wind farm configuration of selected projects

Country	Projects	Capacity	Wind farm configuration (rotor diameter equivalent)
Germany	Sandbank	72 x 4 MW	8 x 9
	Wikinger	70 x 5 MW	6.7 x 4.5
	Arkona	60 x 6 MW	6.4 x 4.7
Denmark	Horns Rev 1	80 x 2 MW	8.7 x 7.0
	Horns Rev 2	91 x 2.3 MW	9.3 x 7.1
	Anholt	111 x 3.6 MW	9.9 x 9.2
United Kingdom	Gunfleet Sands	48 x 3.6 MW	9.3 x 5.8
	Greater Gabbard	140 x 3.6 MW	10.3 x 9.8
	Galloper	56 x 6.3 MW	8.6 x 6.9

Figure B.4 ▷ Water depth and distance to shore for offshore wind projects



Projects are moving further away from shore and also into deeper waters

Source: The Wind Power (2019).