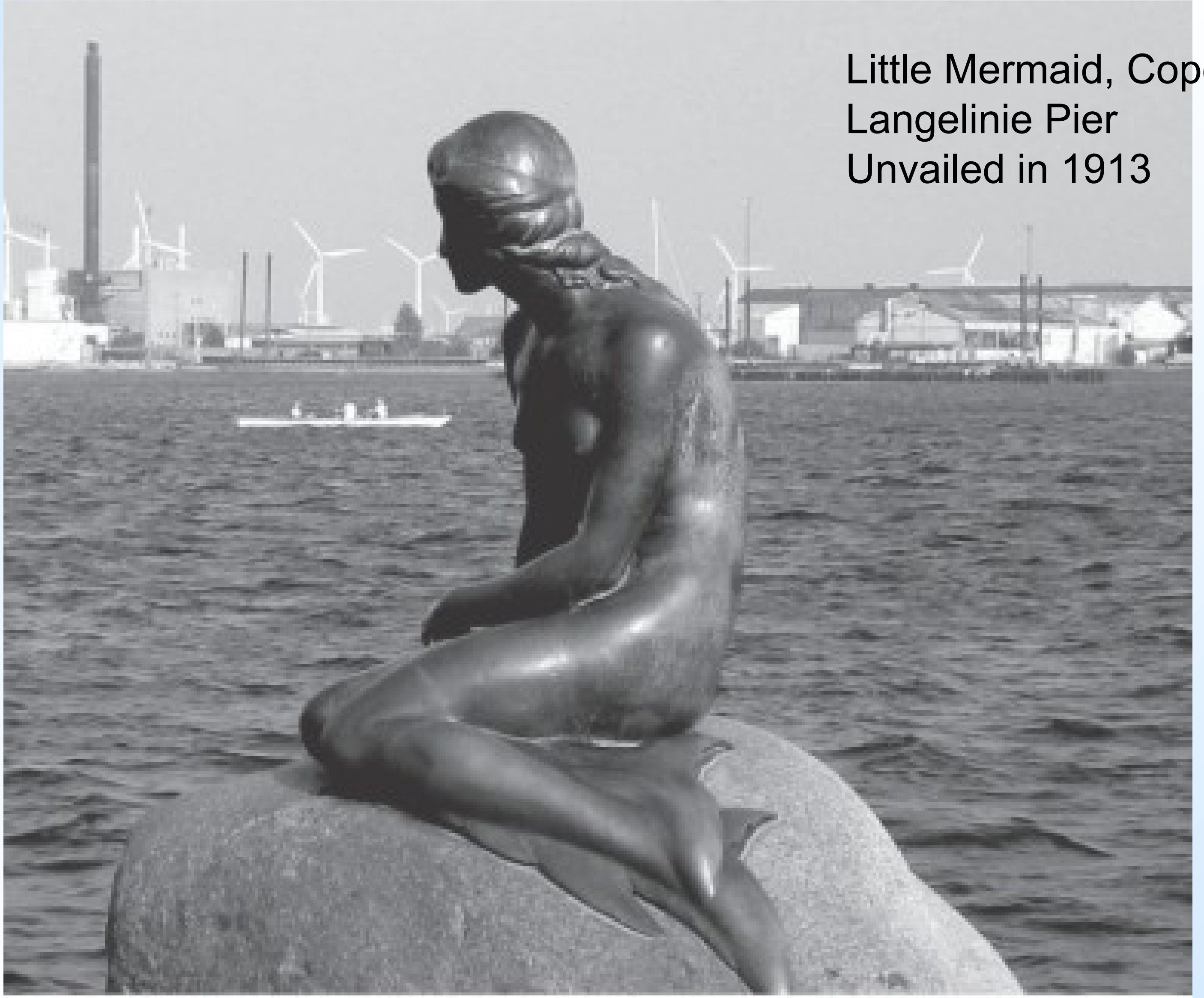
Wind Energy

The Netherlands



Little Mermaid, Copenhagen
Langelinie Pier
Unvailed in 1913

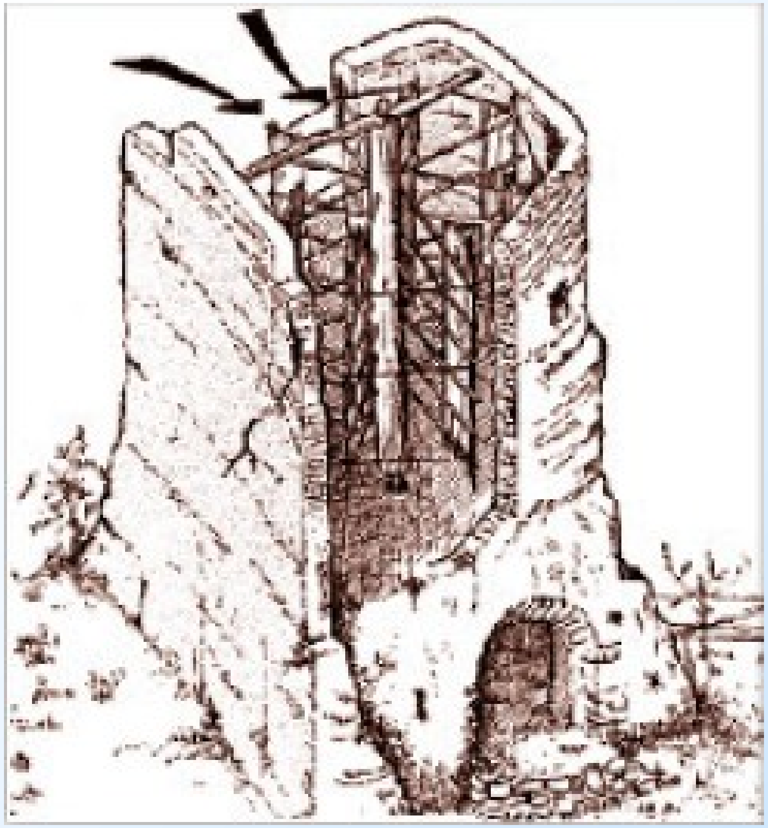

Bozcaada Wind Farm
10 MW
Commissioned in 2000

Brief History – Early Systems

Harvesting wind power isn't exactly a new idea (Sailing ships, wind mills, wind pumps)

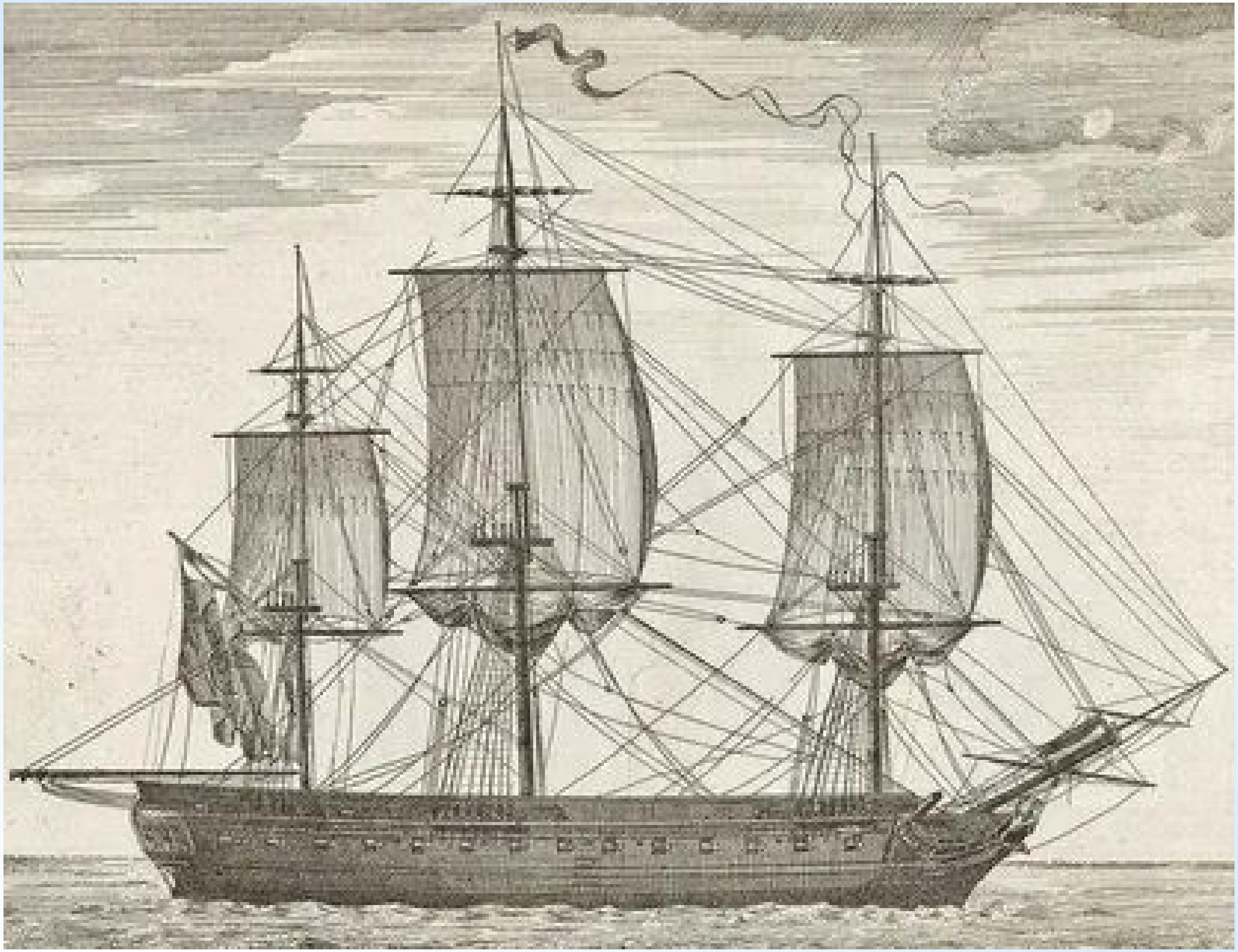
First Wind Energy Systems:

- Ancient civilizations in the near east / Persia
- Vertical-axis wind mill: sails connected to a vertical shaft connected to a grinding stone for milling



Wind in the Middle Ages:

- Post mill introduced in Northern Europe
- Horizontal-axis wind mill: sails connected to a horizontal axis on a tower encasing gears and axles for translating horizontal into rotational motion



Otoman Frigate, 1798

Catamaran Racing

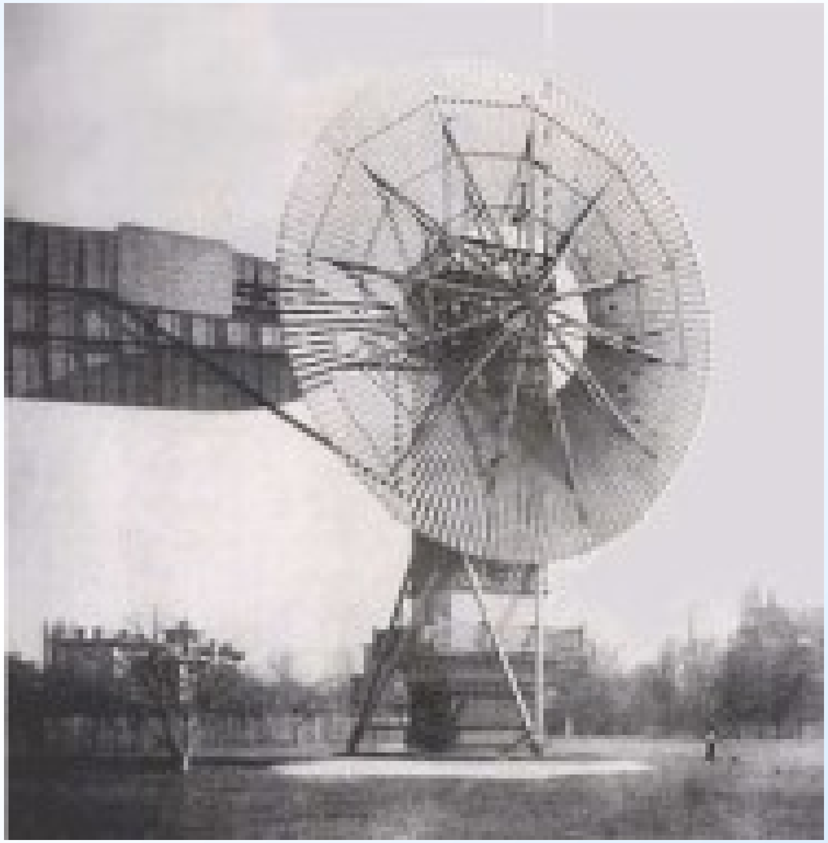
Wind in the 19th century US:

- Wind-rose horizontal-axis water-pumping wind mills found throughout rural America

Brief History – Rise of Wind Powered Electricity

1888: Charles Brush builds first large-size wind electricity generation turbine

17 m diameter wind rose configuration, 12 kW generator



1890's: Lewis Electricity Company of New York sells generators to retro-fit onto existing wind mills

1920's – 1950s: Propeller-type 2 & 3 blade horizontal-axis wind electricity conversion systems (WECS)

1940's – 1960s: Rural electrification in the US and Europe leads to decline in WECS use

Brief History – Modern Era

Key attributes of this period:

- Scale increase
- Commercialization
- Competitiveness
- Grid integrations

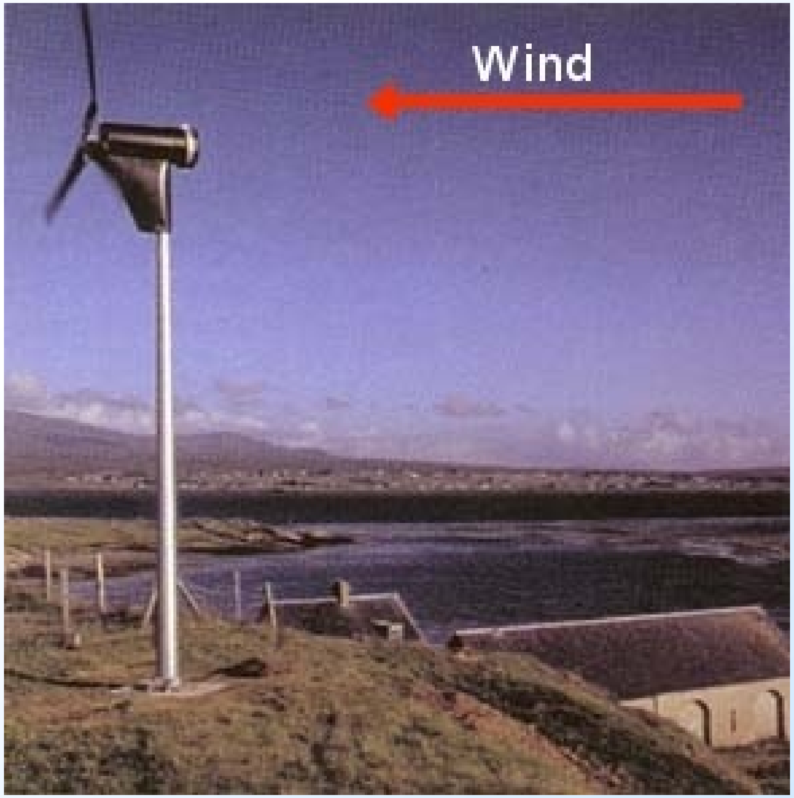
Catalyst for progress:

- Economics
- Energy independence
- Environmental benefits

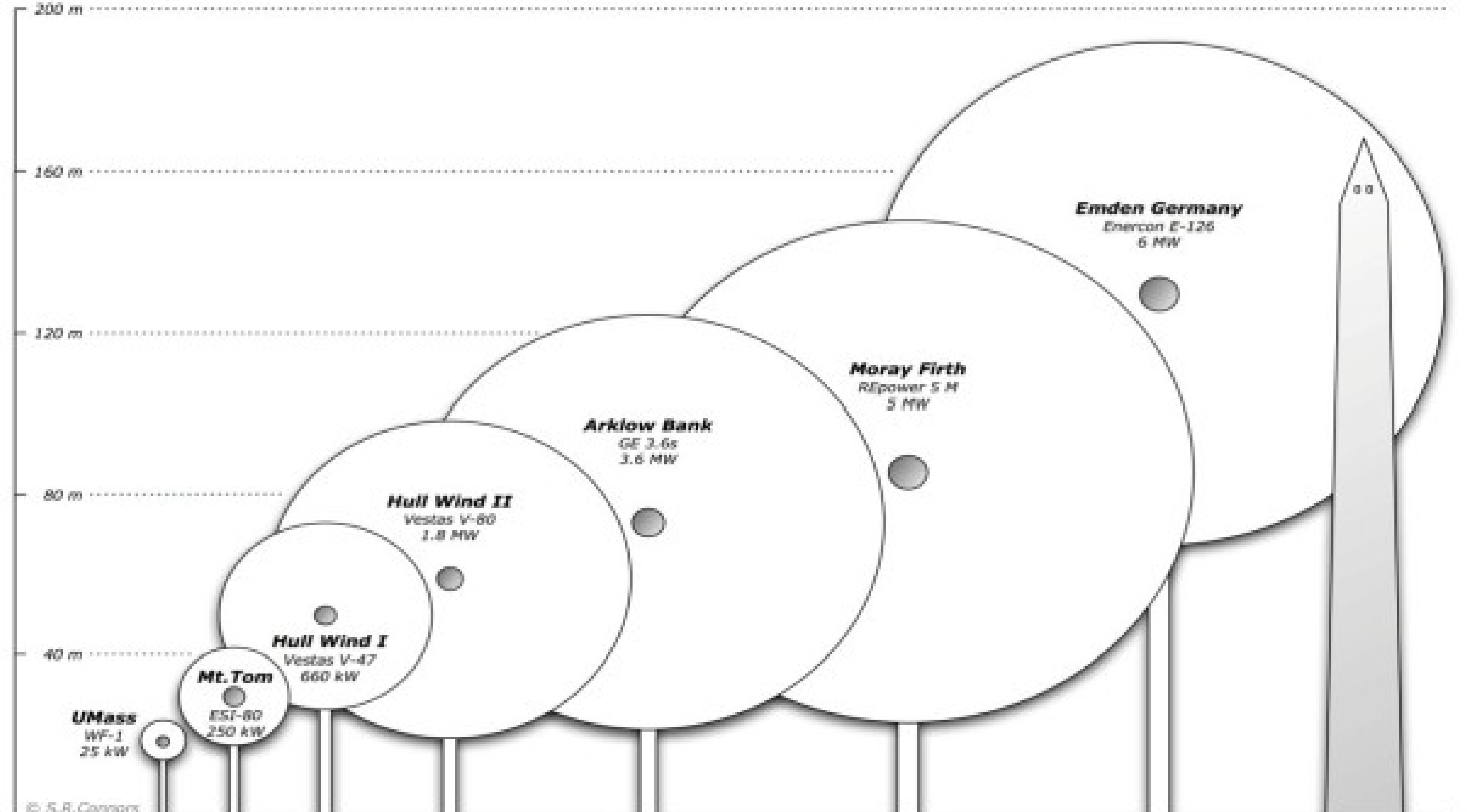
Turbine Standardization:

- 3-blade Upwind
- Horizontal axis
- On a monopole tower

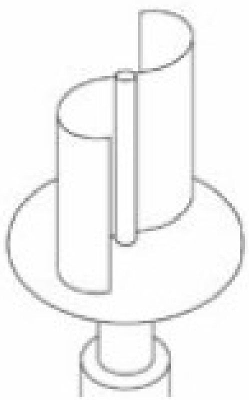
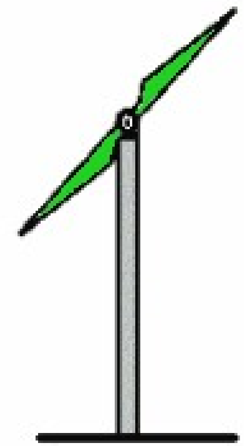
Upwind



Downwind



Capacity:	25 kW	250 kW	660 kW	1800 kW	3600 kW	5000 kW	6000 kW	
Rotor Dia:	10 m	24.4 m	47 m	80 m	104 m	126 m	126 m	
Tower Hgt.	18 m	30 m	50 m	60 m	74 m	87 m	131 m	170 m

Savonius VAWT	Helical VAWT	Darrieus VAWT	3-blades HAWT	2 blades HAWT
				

See: «Wind Energy: An Overview», by Hemanth Kumar J., 2021

Wind Energy: An Overview. Renewable energy is the key to create a… | by Hemanth Kumar J | Medium

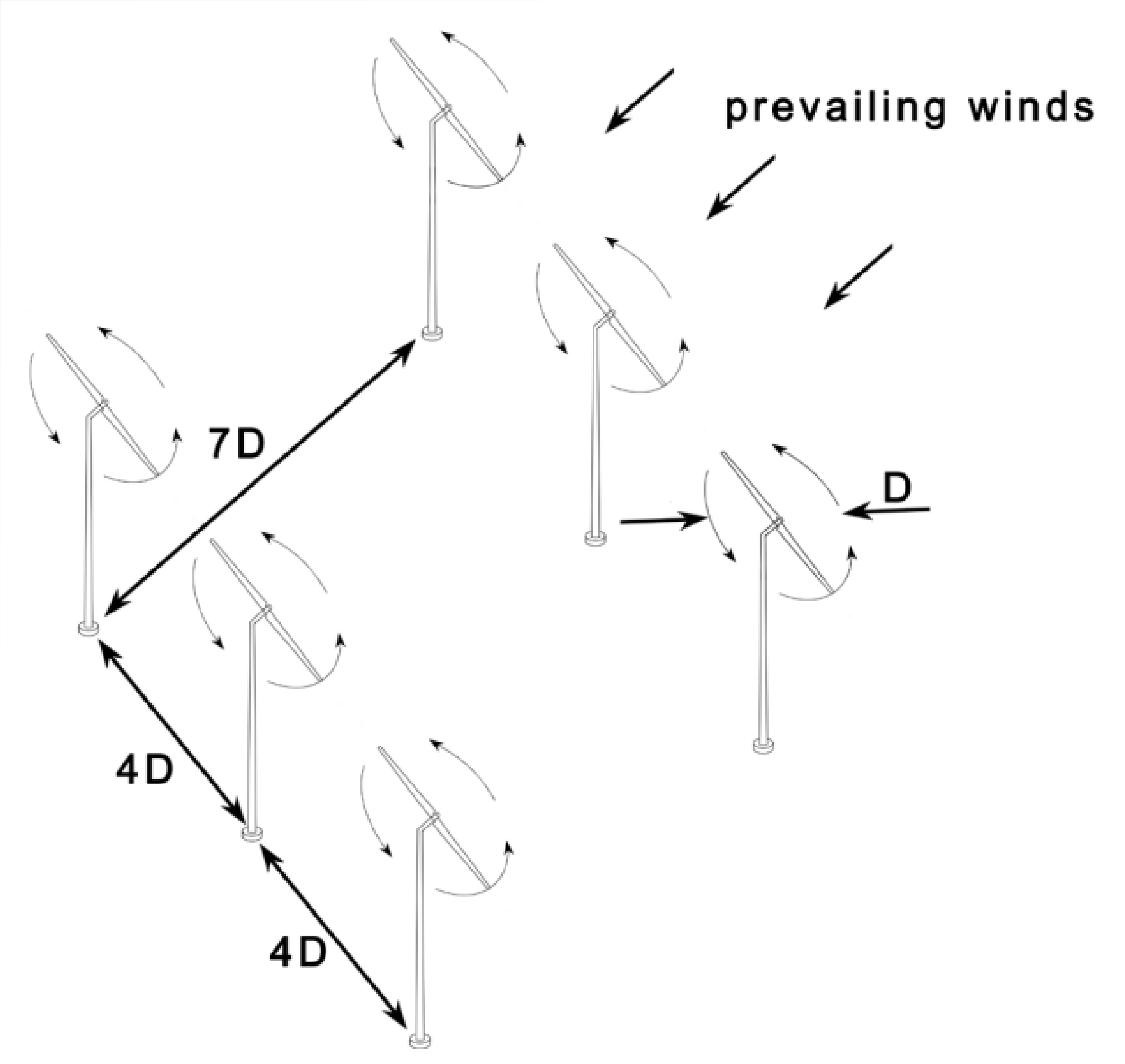
A small Quietrevolution QR5 Gorlov type vertical axis wind turbine on the roof of Bristol Beacon in Bristol, England. Measuring 3 m in diameter and 5 m high, it has a nameplate rating of 6.5 kW.

Remember the movie «Water World», by Kevin Kostner

Wind Farm

Optional Design

Parameters



Wind Notables

Cost competitive in areas with good wind resource

Most economically feasible and fastest growing ‘new’ renewable energy

5 countries account for roughly 75% of total world usage –

USA, Germany, China, Spain and India

Share of wind as a % of total power in wind power leaders is on

average 10-20 % and continuing to increase

Almost all electrical power on Earth is produced with a turbine of some type.
Turbine – converting rectilinear flow motion to shaft rotation through rotating airfoils.

Type of Generation	Combustion Type	Turbine Type: Gas	Turbine Type: Steam	Turbine Type: Water	Turbine Type: Aero	Primay Power	Electrical Conversion
[3] Traditional Boiler	External		●			Shaft	Generator
[3] Fluidized Bed	External		●			Shaft	Generator
Combustion						–	–
Integrated Gasification	Both	●	●			Shaft	Generator
Combined-Cycle						–	–
Combustion Turbine	Internal	●				Shaft	Generator
Combined Cycle	Both	●	●			Shaft	Generator
[3] Nuclear			●			Shaft	Generator
Diesel Genset	Internal					Shaft	Generator
Micro-Turbines	Internal	●				Shaft	Generator
Fuel Cells						Direct	Inverter
Hydropower				●		Shaft	Generator
[3] Biomass & WTE	External		●			Shaft	Generator
Windpower					●	Shaft	Generator
Photovoltaics						Direct	Inverter
[3] Solar Thermal			●			Shaft	Generator
[3] Geothermal			●			Shaft	Generator
Wave Power		●				Shaft	Generator
Tidal Power				●		Shaft	Generator
[3] Ocean Thermal			●			Shaft	Generator

ONSHORE & OFFSHORE WIND RESOURCE MAP

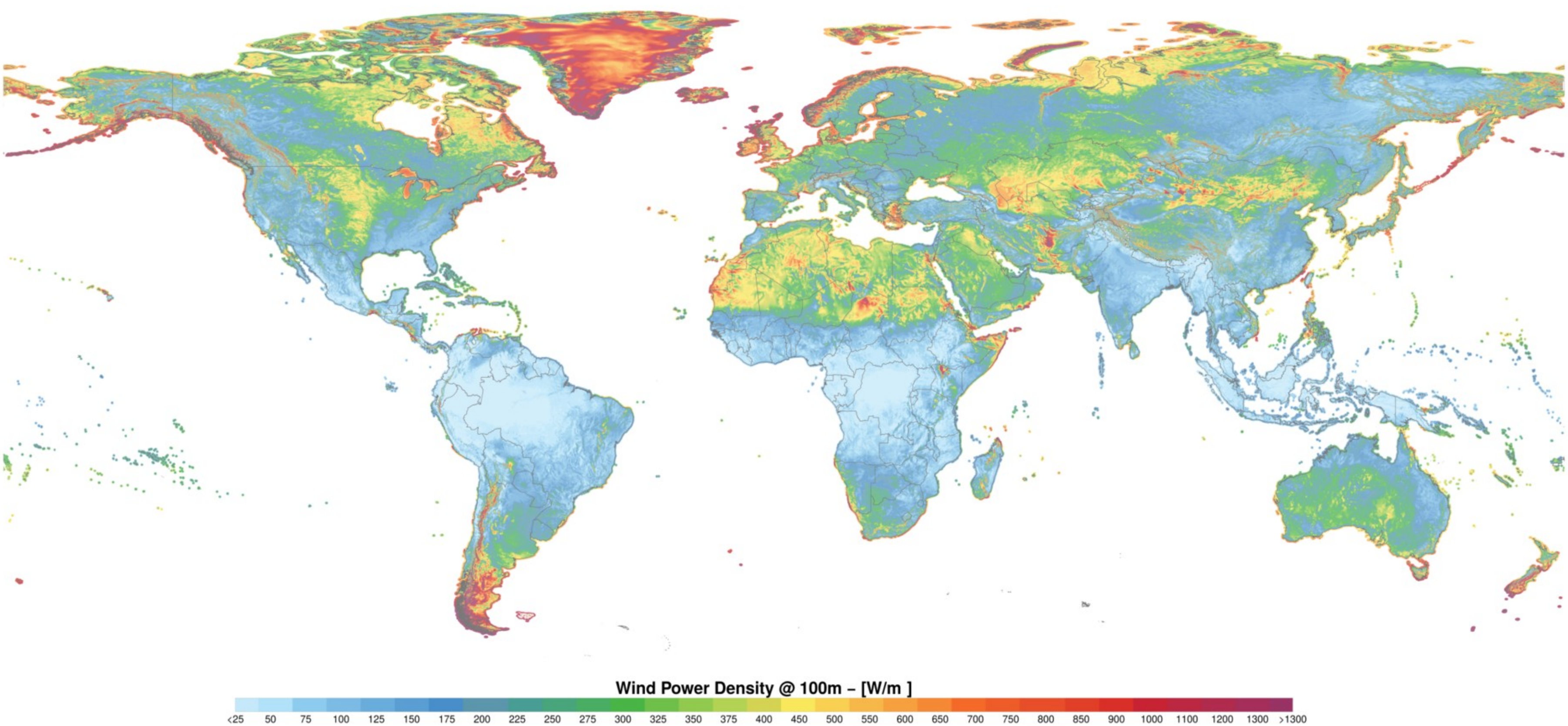
WORLD BANK GROUP

DTU Wind Energy
Department of Wind Energy

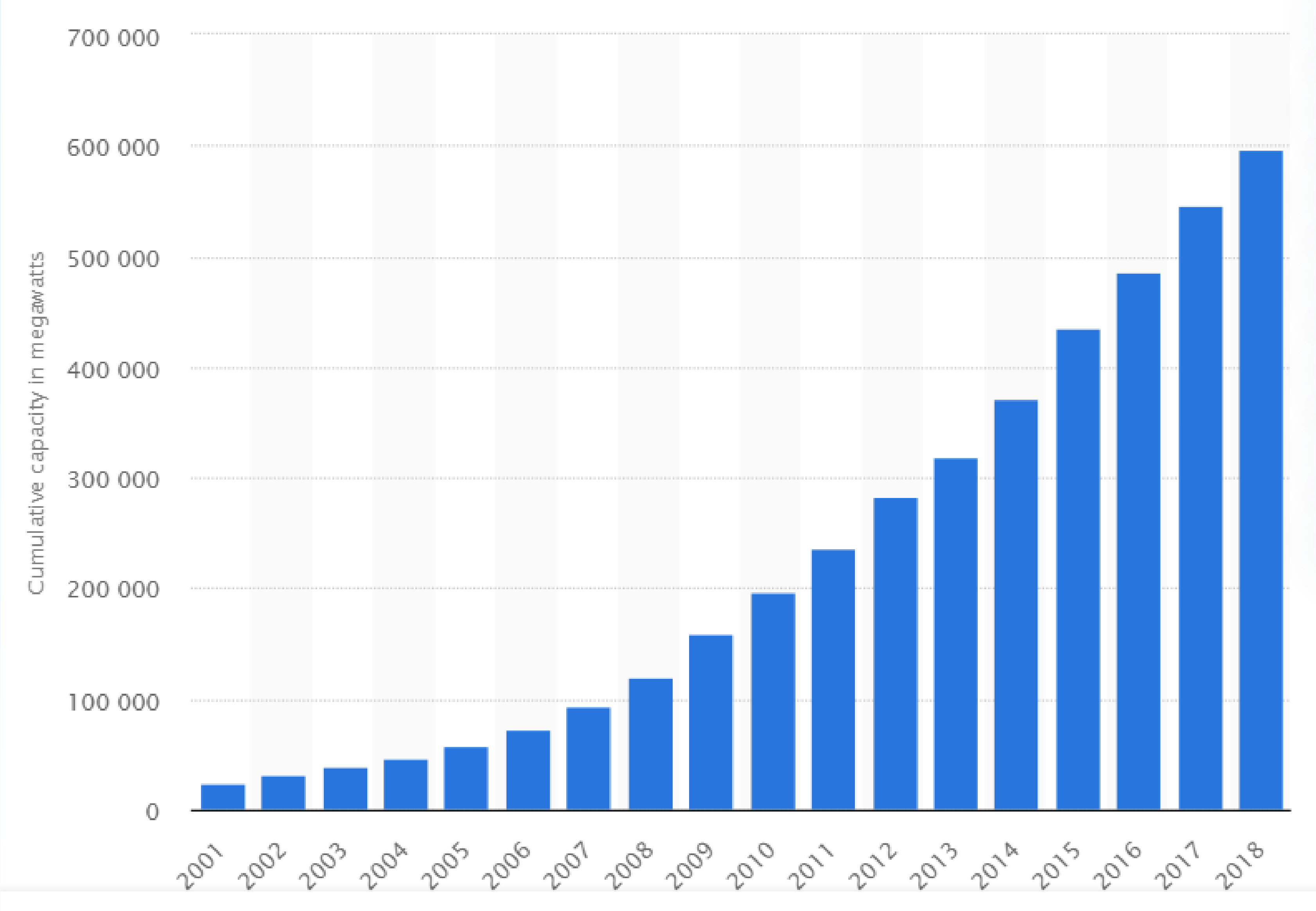
ESMAP

VORTEX

WIND POWER DENSITY POTENTIAL



This map is published by the World Bank Group, funded by ESMAP, and prepared by DTU and Vortex. For more information and terms of use, please visit http://globalwindatlas.info



700 000
600 000
500 000
400 000
300 000
200 000
100 000
0
Cumulative capacity in megawatts
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

Wind Energy Installed Capacity Top 10 Countries in 2018	
Country	**GW**
China	221
USA	96.4
Germany	59.3
India	35
Spain	23
UK	20.7
France	15.3
Brazil	14.5
Canada	12.8
Italy	10.1

Turkey 11 % Wind

17 % Solar

2 % Geothermal

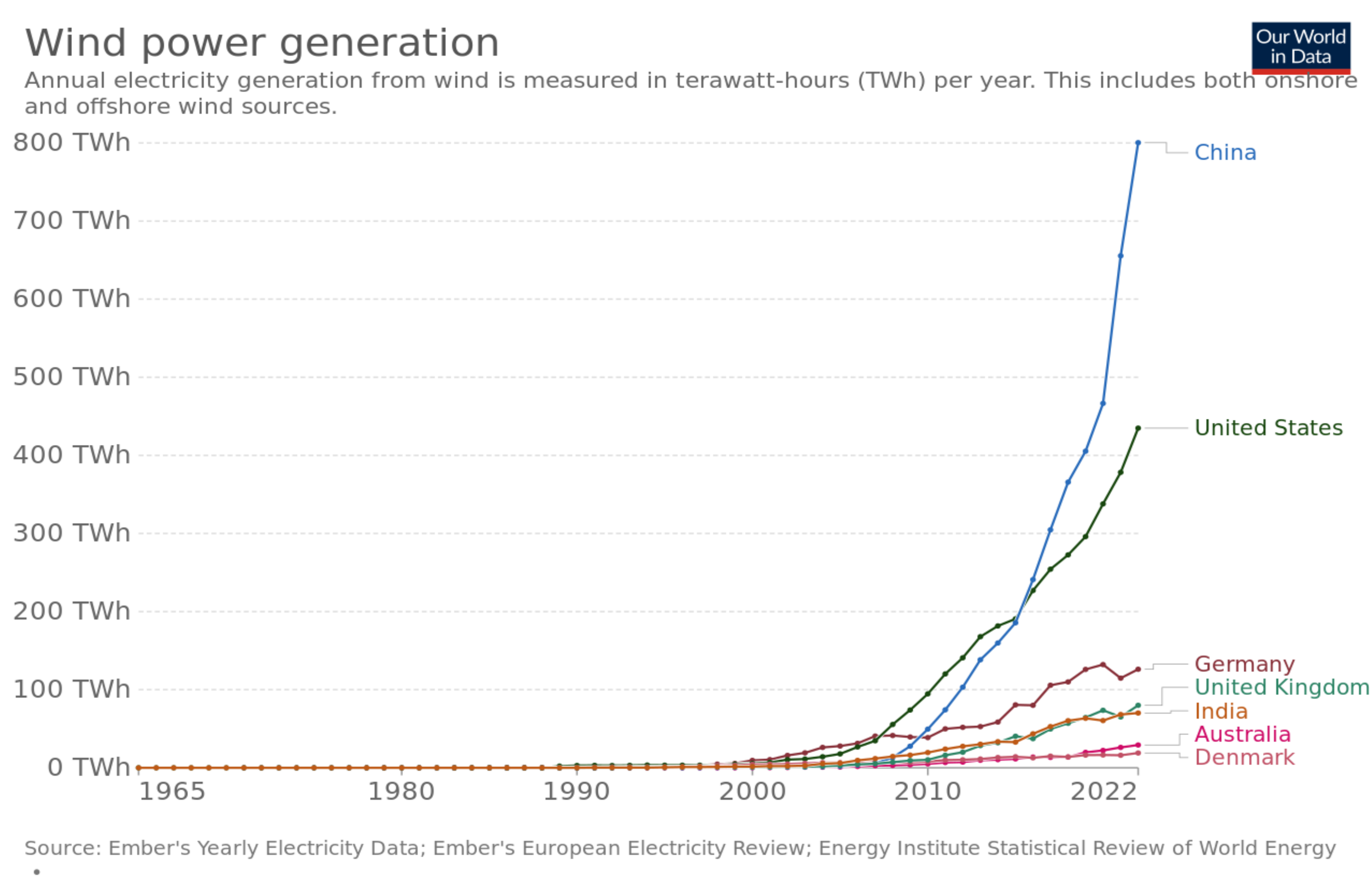
28 % Hydro

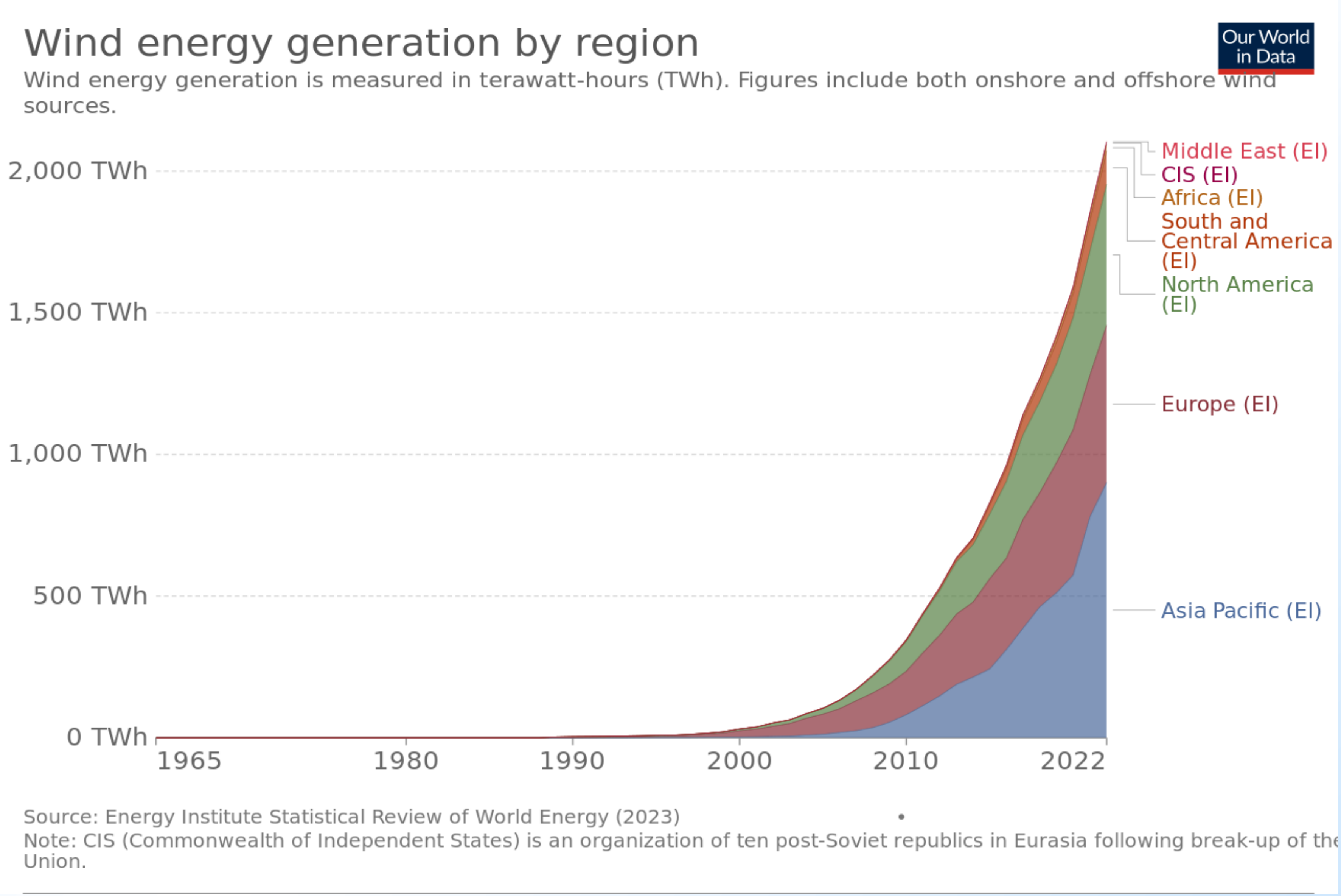
19 % Coal

21 % Natural Gas

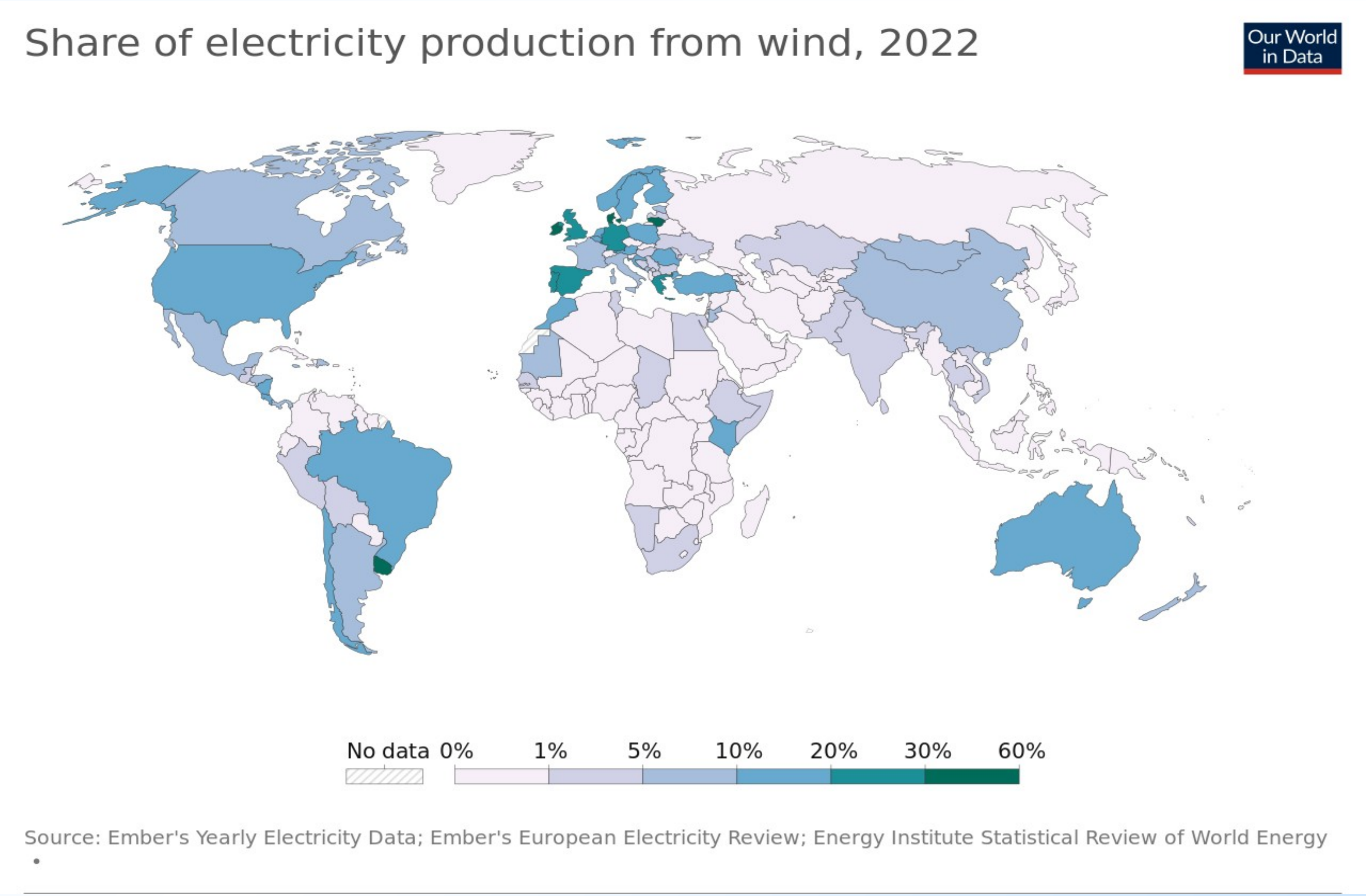
2 % Others

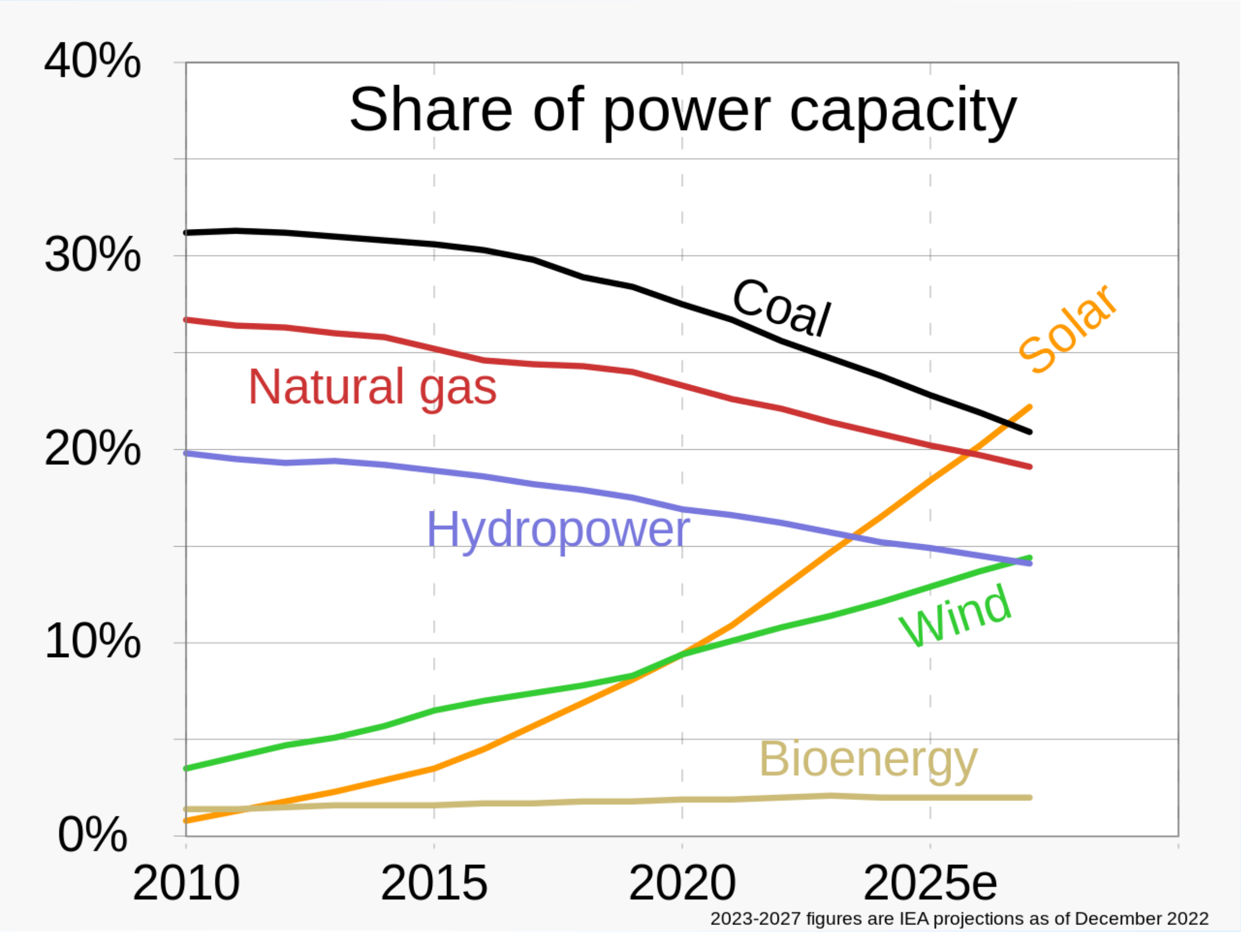
Total 2024 116 GW_e


Wind power generation
Annual electricity generation from wind is measured in terawatt-hours (TWh) per year. This includes both onshore and offshore wind sources.
Our World in Data
800 TWh
700 TWh
600 TWh
500 TWh
400 TWh
300 TWh
200 TWh
100 TWh
0 TWh
1965
1980
1990
2000
2010
2022
China
United States
Germany
United Kingdom
India
Australia
Denmark
Source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy



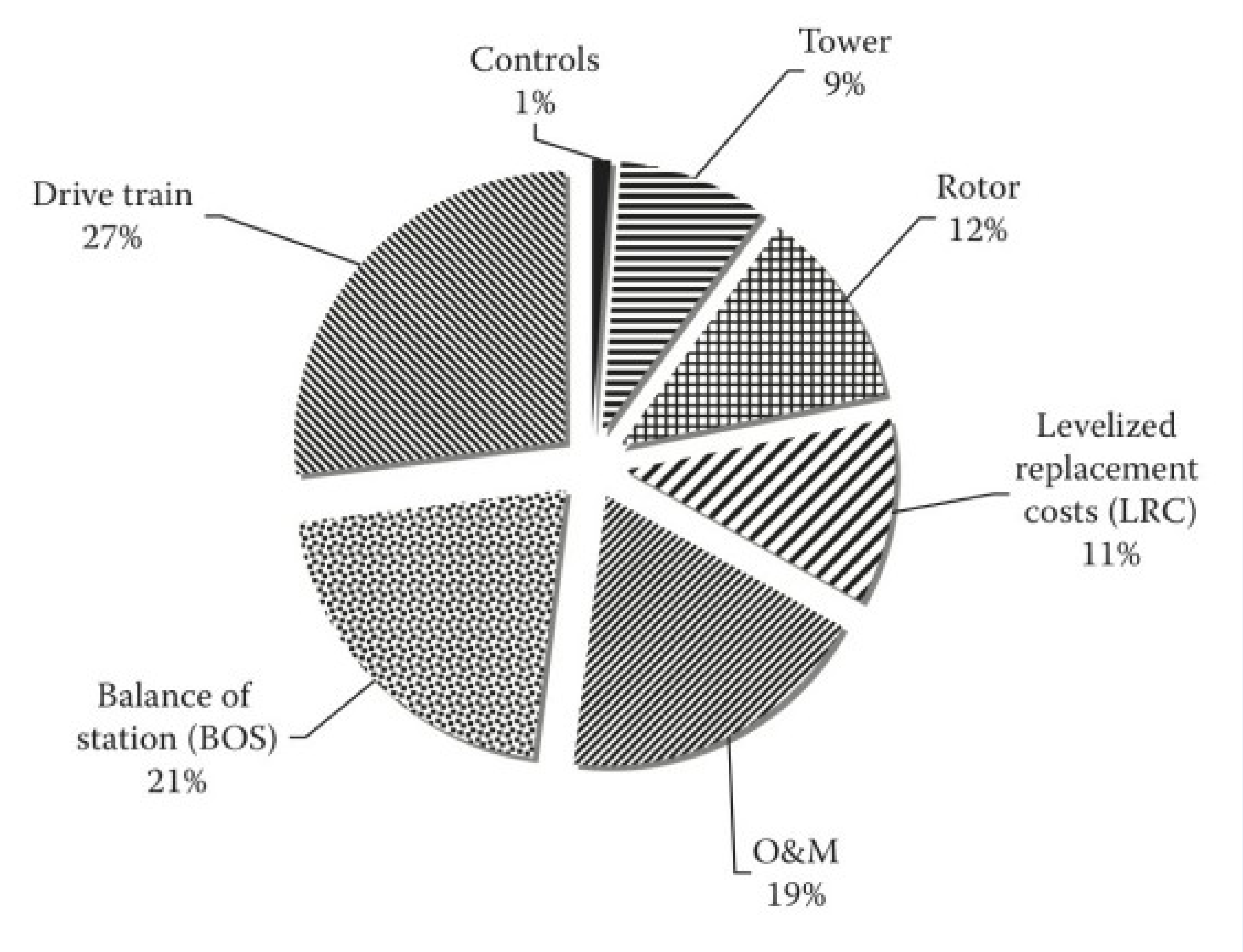
Wind energy generation by region
Wind energy generation is measured in terawatt-hours (TWh). Figures include both onshore and offshore wind sources.
Our World in Data
2,000 TWh
1,500 TWh
1,000 TWh
500 TWh
0 TWh
1965
1980
1990
2000
2010
2022
Middle East (EI)
CIS (EI)
Africa (EI)
South and Central America (EI)
North America (EI)
Europe (EI)
Asia Pacific (EI)
Source: Energy Institute Statistical Review of World Energy (2023)
Note: CIS (Commonwealth of Independent States) is an organization of ten post-Soviet republics in Eurasia following break-up of the Union.


Share of electricity production from wind, 2022
Our World in Data
No data
0%
1%
5%
10%
20%
30%
60%
Source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy

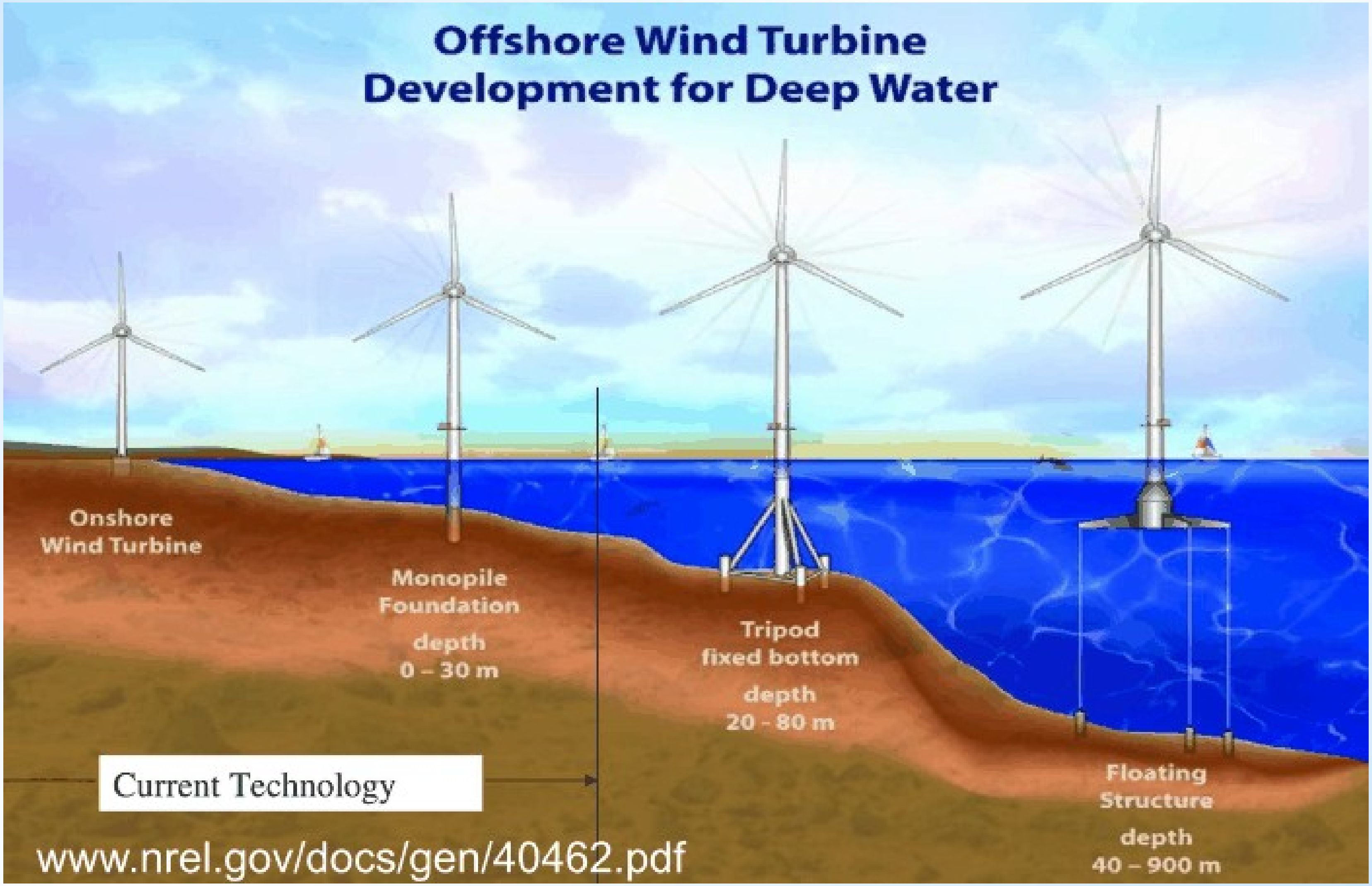


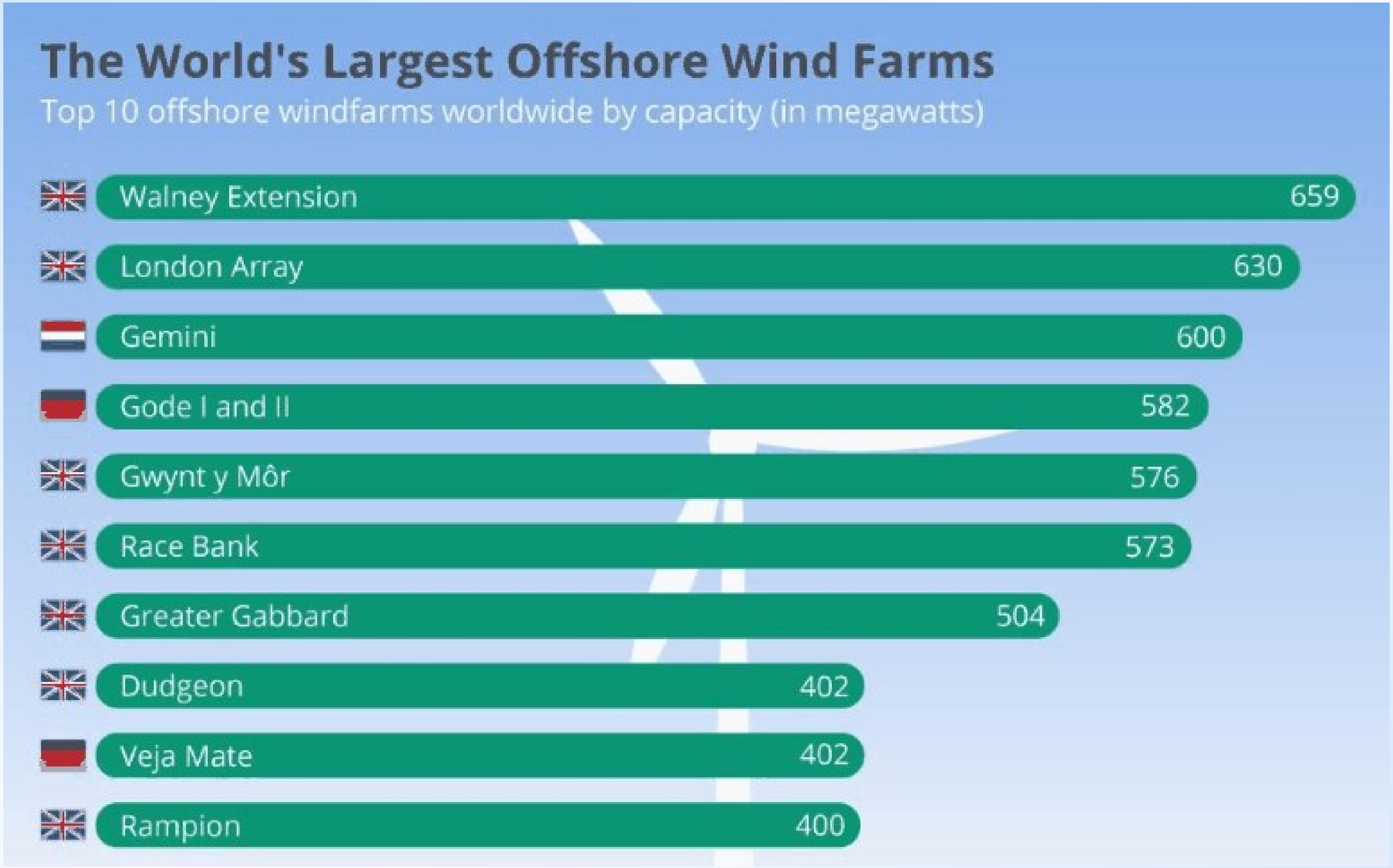
Line charts showing power capacity by technology - including projections in December 2022 by the International Energy Agency (IEA)

What goes into the cost of energy



Offshore Technology





See: https://en.wikipedia.org/wiki/List_of_offshore_wind_farms

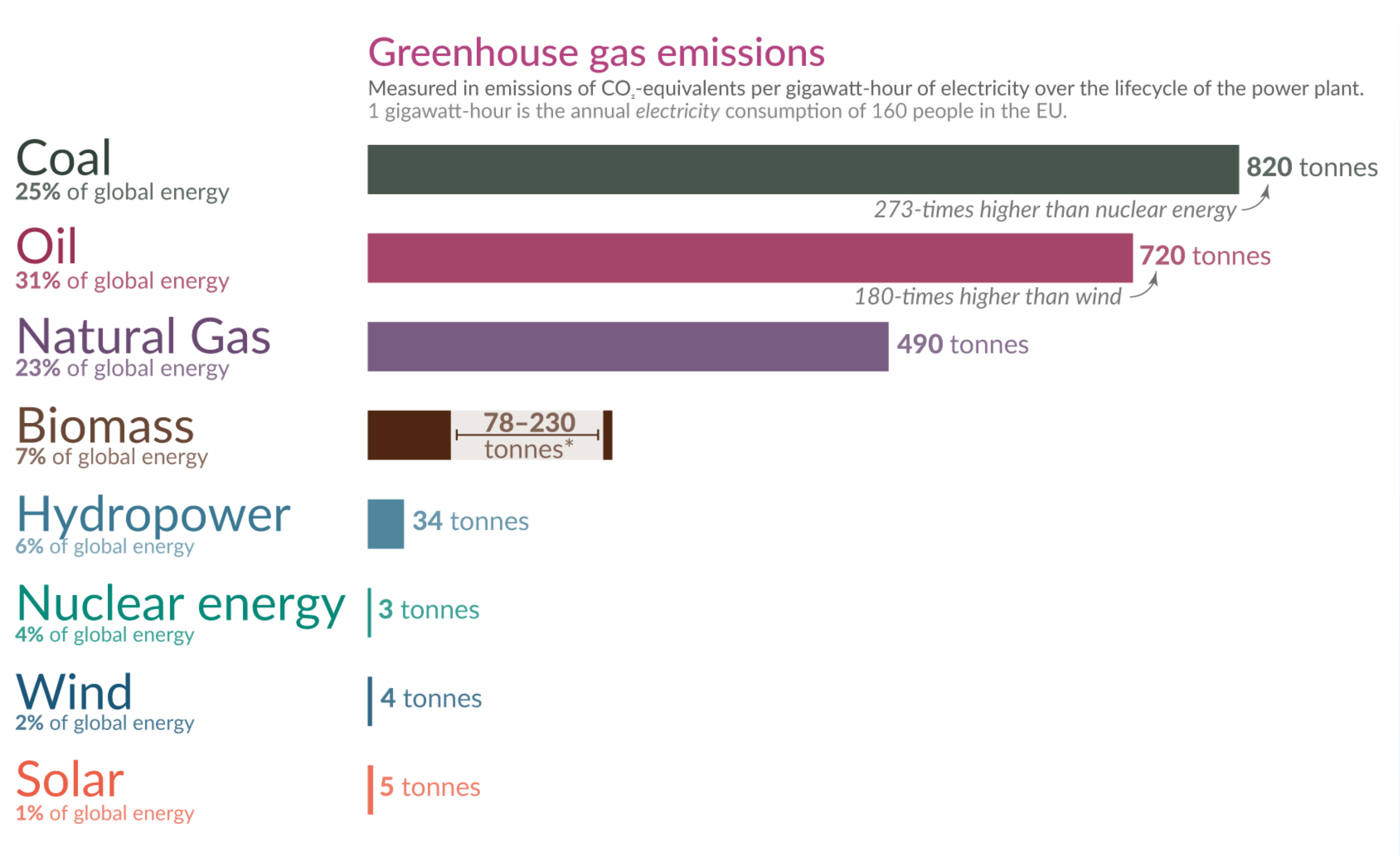
Hornsea 1 => 1218 MWe

Hornsea 1 Project:

Hornsea 1 Project:

- 120 km off the Yorkshire Coast
- Area of 407 km^2
- Water depths between 20 m and 40 m
- 174 Siemens Gamesa 7 MW turbines
- Hob height: 190 m, rotor diameter: 178 m
- 900 km of cables to shore
- Construction company: Orsted (Danish, 6500 employees)

A semi-submersible type floating offshore wind turbine foundation called the WindFloat operating at rated capacity (2MW) approximately 5 km offshore of Agucadoura, Portugal



Greenhouse gas emissions
Measured in emissions of CO2-equivalents per gigawatt-hour of electricity over the lifecycle of the power plant.
1 gigawatt-hour is the annual electricity consumption of 160 people in the EU.
Coal
25% of global energy
820 tonnes
273-times higher than nuclear energy
Oil
31% of global energy
720 tonnes
180-times higher than wind
Natural Gas
23% of global energy
490 tonnes
Biomass
7% of global energy
78–230 tonnes*
Hydropower
6% of global energy
34 tonnes
Nuclear energy
4% of global energy
3 tonnes
Wind
2% of global energy
4 tonnes
Solar
1% of global energy
5 tonnes

Wind Energy – Basic Principles

Kinetic energy in the moving air (wind) picked up and transferred as shaft work to an electric generator. Next figure shows a sketch of a modern wind turbine.

Theoretically, 59% of the kinetic energy in the wind can be converted to mechanical energy. In reality, the efficiency is close to 50%. The table below shows the theoretically possible generation per unit area at different wind speeds. The theoretical power output is proportional to the wind speed in third power.

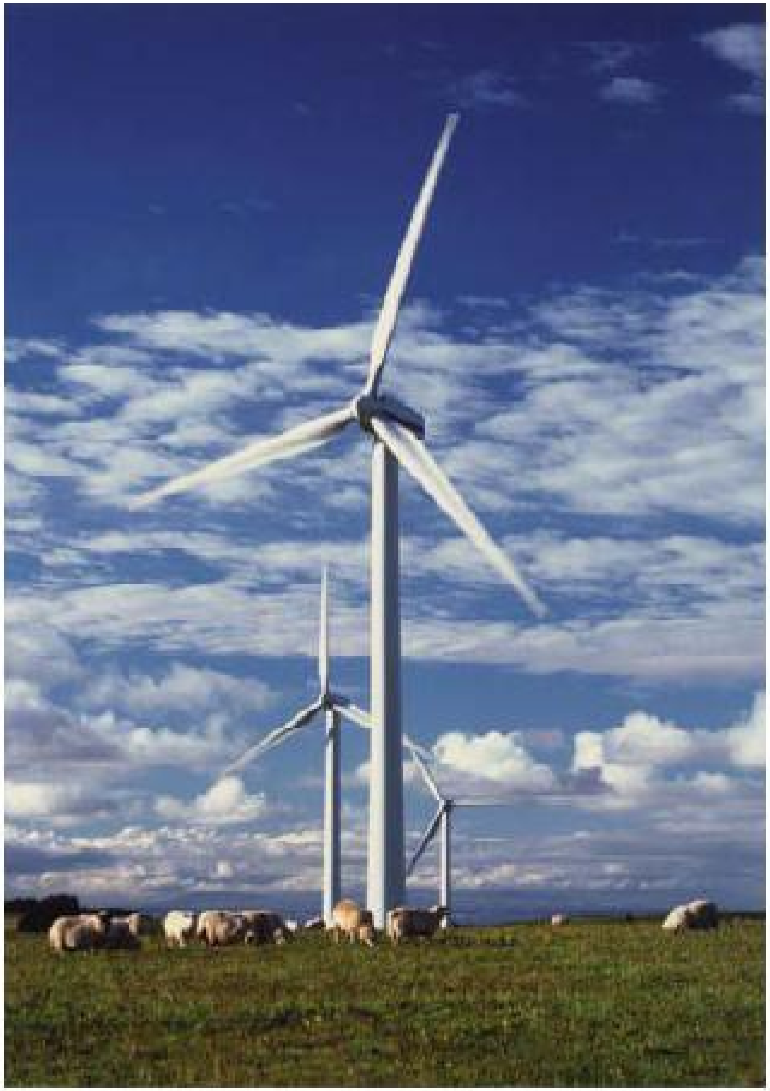
Complete wind generators in the capacity range from a few kW to about 5 MW are available on commercial conditions from several suppliers.

Wind speed (m/s)	Power/area (W/m^2)
0	0
5	80
10	610
15	2070
20	4900
25	9560
30	16 550

Sites with average wind speeds below 3 m/s are normally considered as unsuitable for wind power. It is equally important that the wind is steady blowing in one direction for a long time.

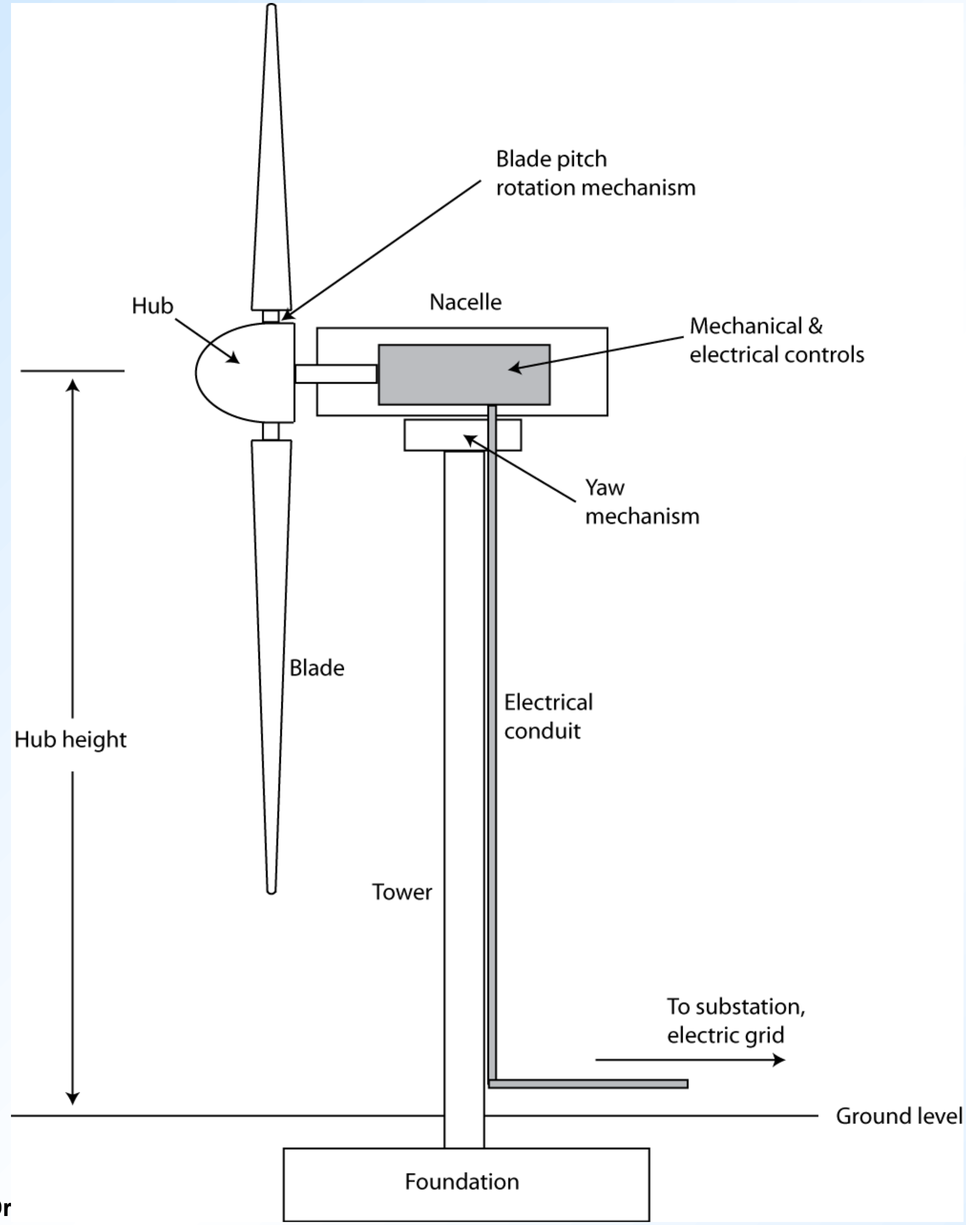
The purpose of the upper limit for the wind speed is to avoid damage to the whole structure. The tangential speed of the tip of the blades is one concern. The momentum imposed on the tower and the foundation is another.

Horizontal axis wind turbine

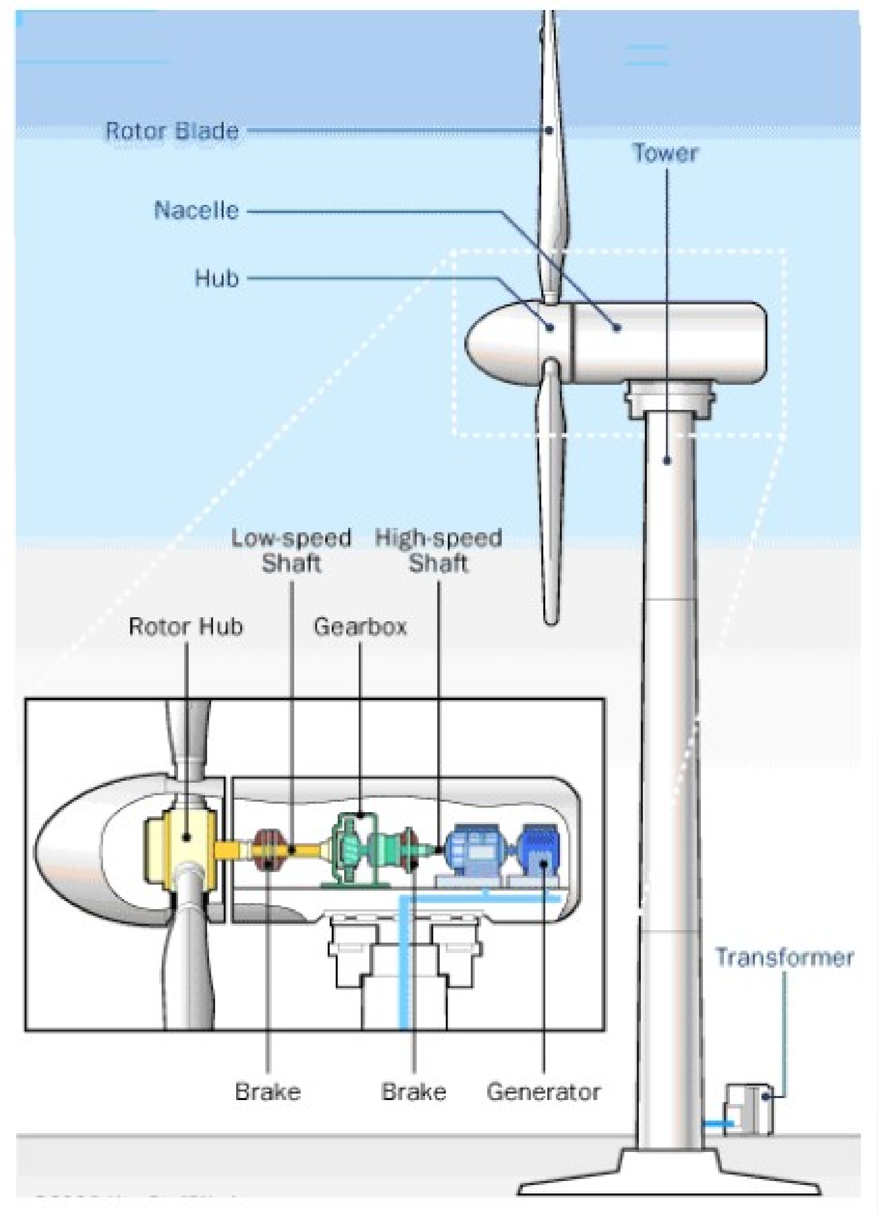


Vertical axis wind turbine

Reason	HAWT Advantage	VAWT Advantage
Less strain on the axle, reduces maintenance	Yes	
Easy maintenance because rotor housing is near ground		Yes
Wind direction does not matter		Yes
Has a higher efficiency because the blades don’t rotate into the wind (so don’t drag)	Yes	
Can be installed in locations where taller structures are prohibited or are undesirable		Yes
Higher installations increase the available wind energy	Yes	

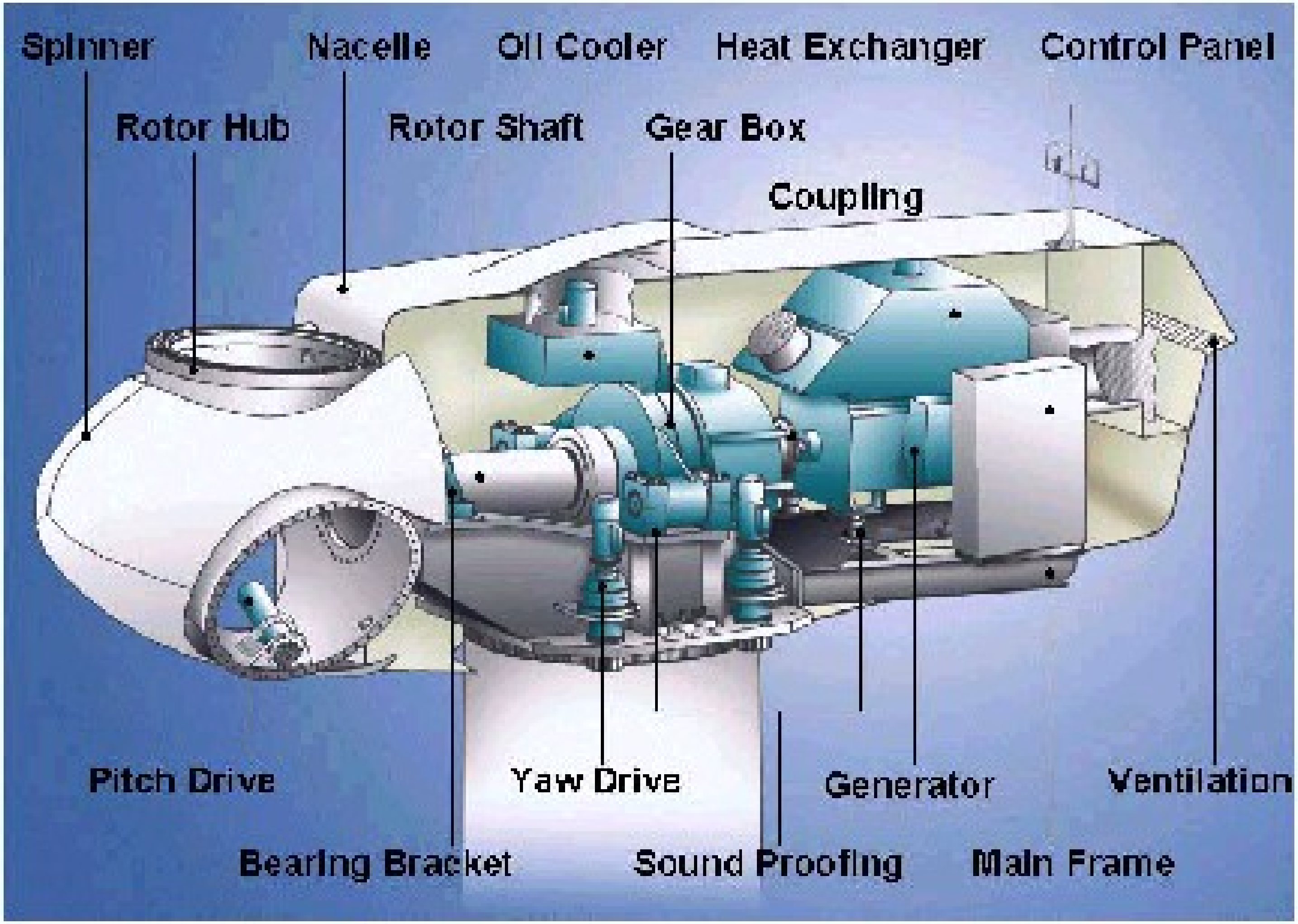


Typical design of an up-wind turbine with yaw mechanism



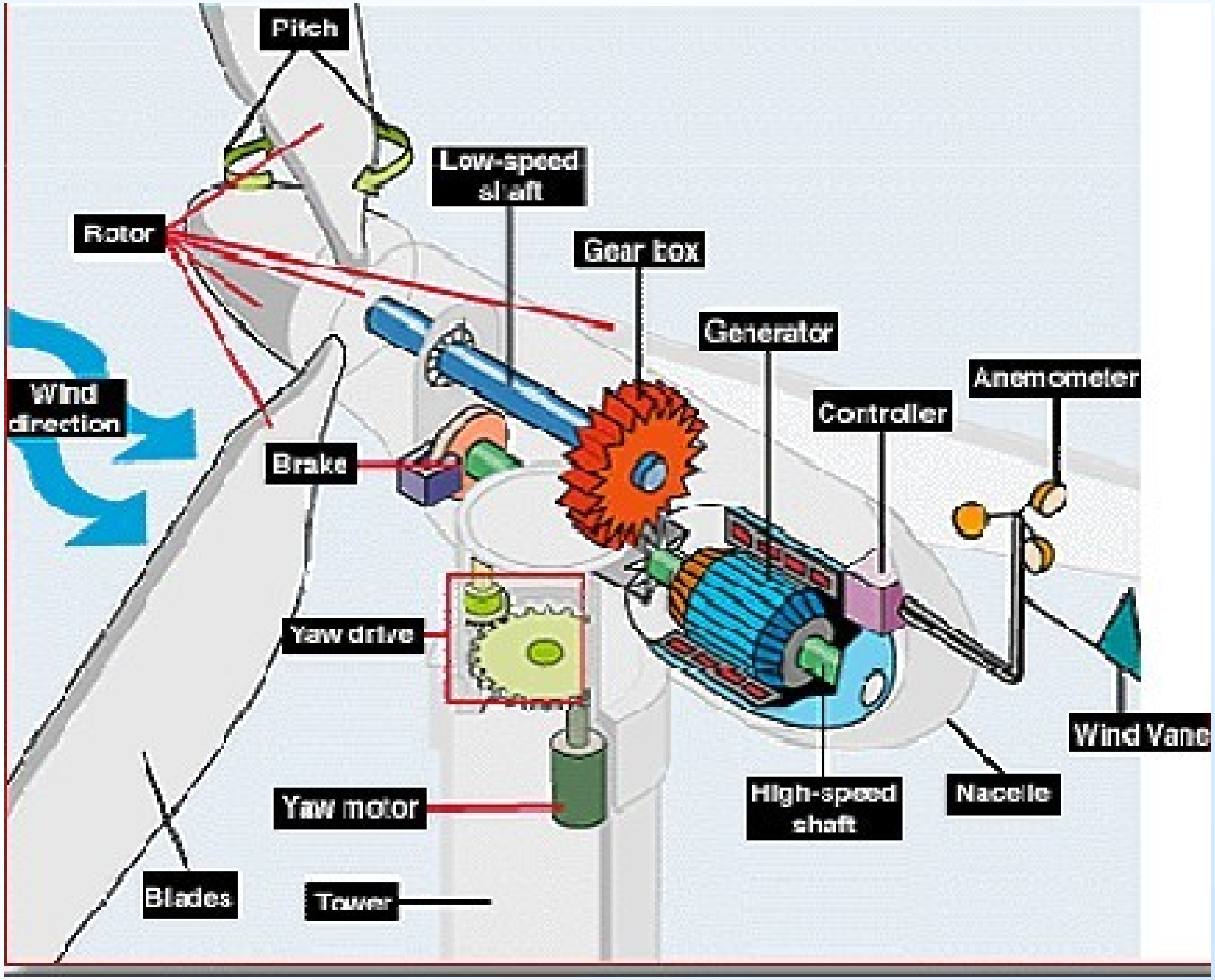
Rotor Blade
Nacelle
Hub
Tower
Low-speed Shaft
High-speed Shaft
Rotor Hub
Gearbox
Transformer
Brake
Brake
Generator

Components - Turbine Layout



Wind turbine subsystems

- Foundation
- Tower
- Nacelle
- Hub & Rotor
- Drivetrain
  - Gearbox
  - Generator
- Electronics & Controls
  - Yaw
  - Pitch
  - Braking
  - Power Electronics
  - Cooling
  - Diagnostics



Wind turbines convert kinetic energy in the wind to electrical energy. The efficiency of conversion depends on:

- Meteorological data
- Topography of the site
- Blade profiles
- Number of blades
- Tower height

Few critical parameters:

- The rotor diameter and the hub height is approximately the same.
- The rotational speed of the rotor is between 20 to 50 rpm. The rotational speed of the generator shaft is between 1000 and 3000 rpm. That necessitates the use of a gear box.
- Most blades are manufactured from glass fiber reinforced plastic with sufficient strength, high fatigue endurance limit, and low cost.

See E-Book on OdtuClass, »Wind Energy Explained»

Kinetic energy in the wind

$$E = \frac{1}{2} m_a V^2$$

where m_a is the air mass and V is the speed

Kinetic energy available to the turbine

$$E = \frac{1}{2} \rho_a \nu V^2$$

where ρ_a is the air density and ν is the moving air parcel

Power available in the wind stream

$$P = \frac{1}{2} \rho_a A_T V^3$$

where A_T is the cross-sectional area of the rotor

Maximum power that can be produced

$$P_{max} = \frac{1}{2} \rho_a A_T V^3 \left(\frac{16}{27}\right)$$

Betz limit

Albert Betz

German Physicist

1885 - 1968

Example 1

A wind turbine rotates with the speed 20 m/s and has a blade length of 30 m. Calculate the wind power.

Density of air is $\rho = 1.23\ kg/m^3$

$$\text{Wind Power} = \frac{1}{2}\rho A V^3 = \frac{1}{2}(1.23)(\pi\, 30^2)(20)^3 = 13.91\ \text{MW}$$

Note that this is in the power in the wind all of which is not available for conversion. The maximum power that can be given to the turbine blades has Betz limit.

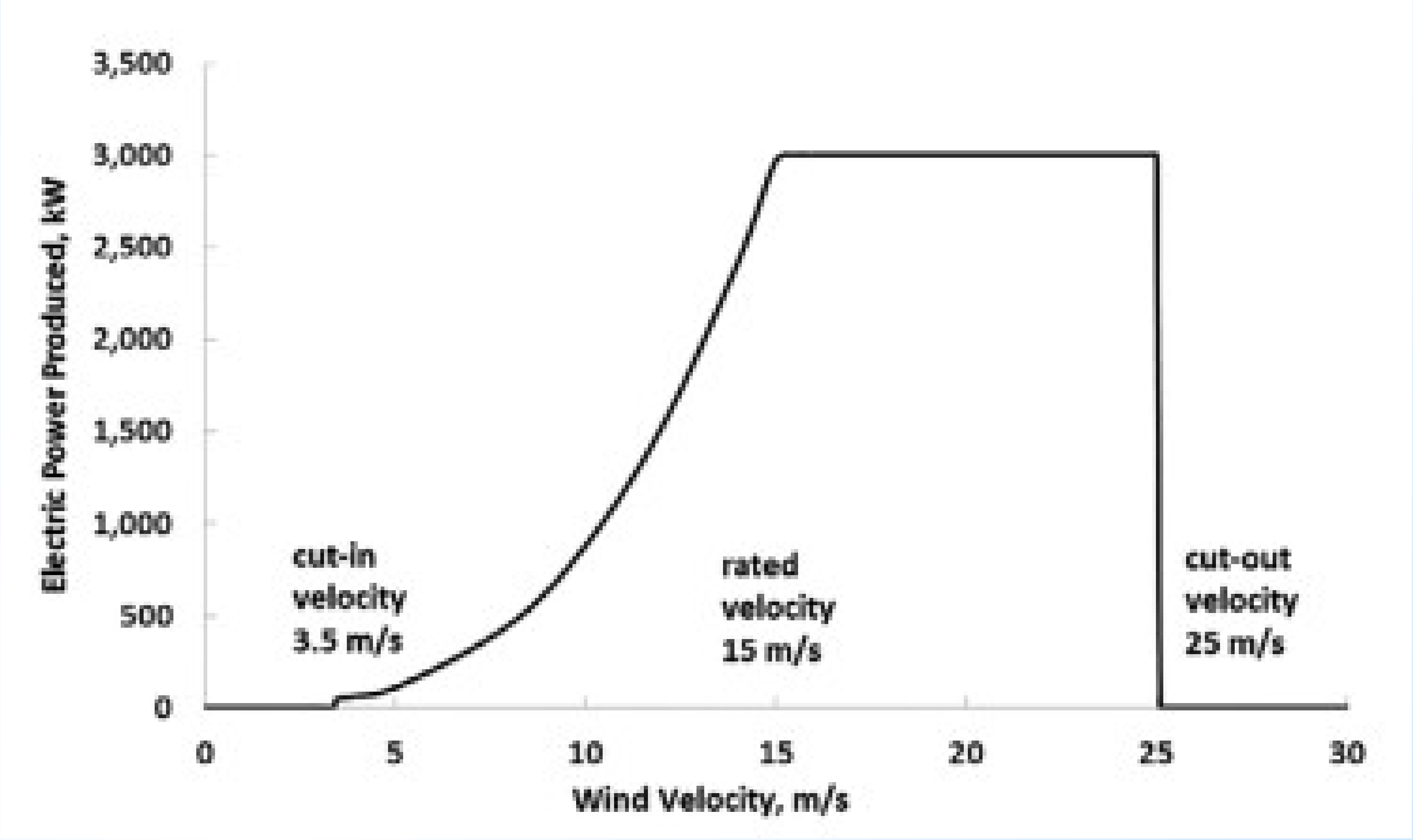
See the article, «Betz’s Equation», on «OdtuClass»

Power Curve of Wind Turbine

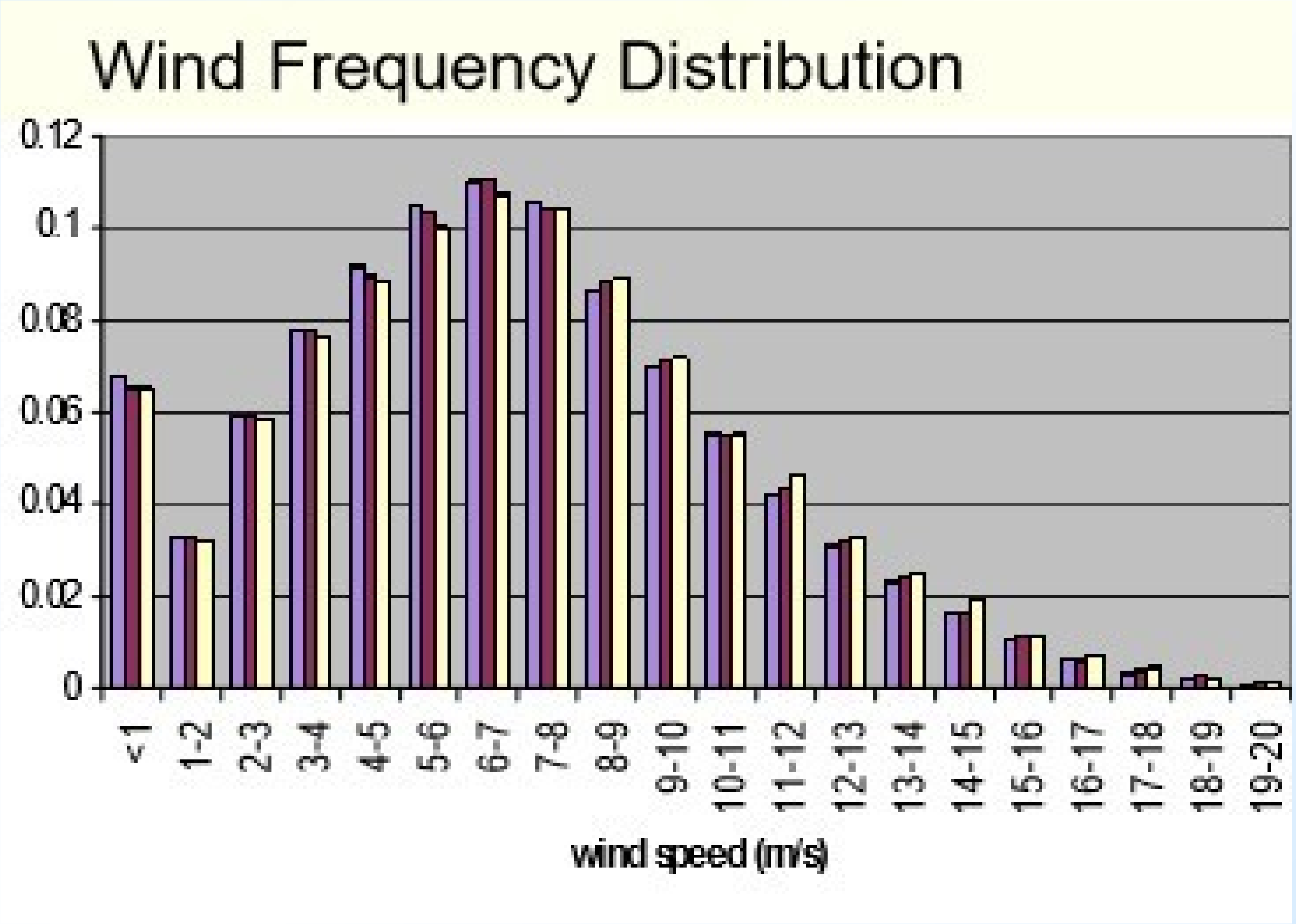
The fraction of the year the turbine generator is operating at rated (peak) power

$$\text{Capacity Factor} = \frac{\text{Average Output}}{\text{Peak Output}} \cong 30\ \%$$

CF is based on both the characteristics of the turbine and the site characteristics (typically 0.3 or above for a good site)



3,500
3,000
2,500
2,000
1,500
1,000
500
0
Electric Power Produced, kW
0
5
10
15
20
25
30
Wind Velocity, m/s
cut-in velocity 3.5 m/s
rated velocity 15 m/s
cut-out velocity 25 m/s

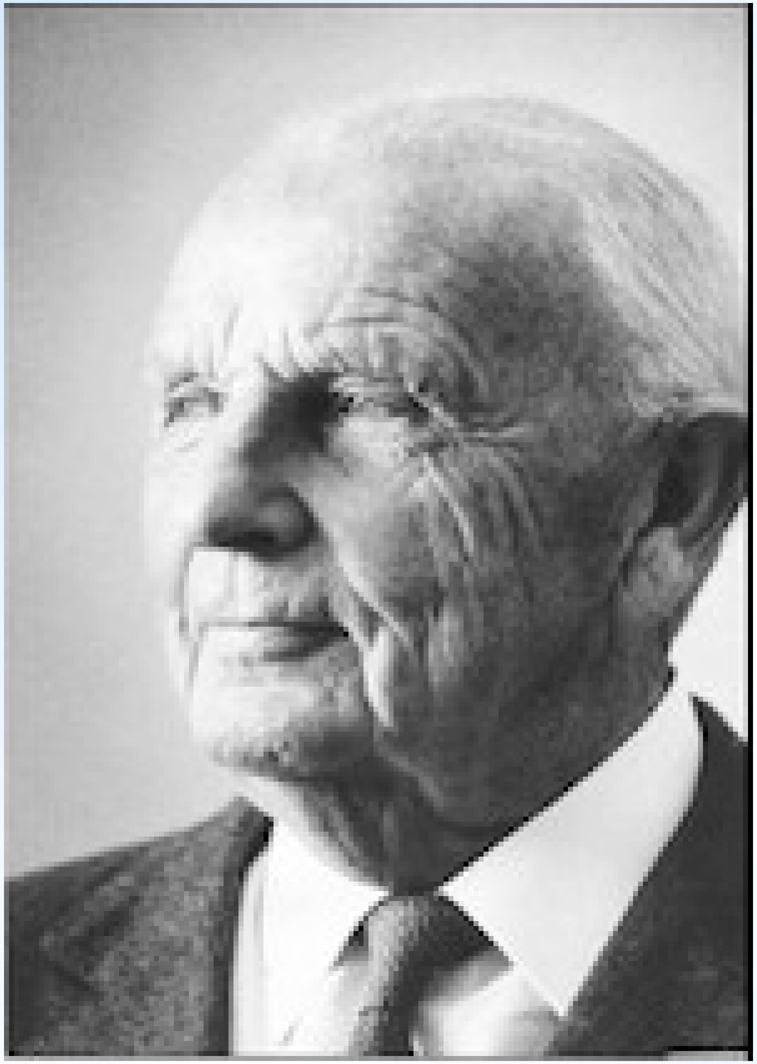

Wind Frequency Distribution
0.12
0.1
0.08
0.06
0.04
0.02
0
<1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
wind speed (m/s)

The wind variation for a typical site is usually described using the so-called Weibull distribution, named after the Swedish engineer Waloddi Weibul (1887–1979). The Weibull distribution represents a mathematical distribution which resembles the distribution of different wind speeds throughout the year. It is a statistical model that gives the probability of occurance.

The three-parameter Weibull distribution is: $$f(t) = \frac{\beta}{\eta}\left(\frac{t - \gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t - \gamma}{\eta}\right)^{\beta}}$$

f(t) is probability density function (called pdf – not portable document format). Integral of f(t) over time, t, from zero to infinity is 1, by definition.

This distribution for a data set (such as wind speed) can then be used to estimate important life characteristics of the product (wind) such as reliability or probability of failure at a specific time, the mean life and the failure rate.



Ernst Hjalmar Waloddi Weibull

Swedish Engineer

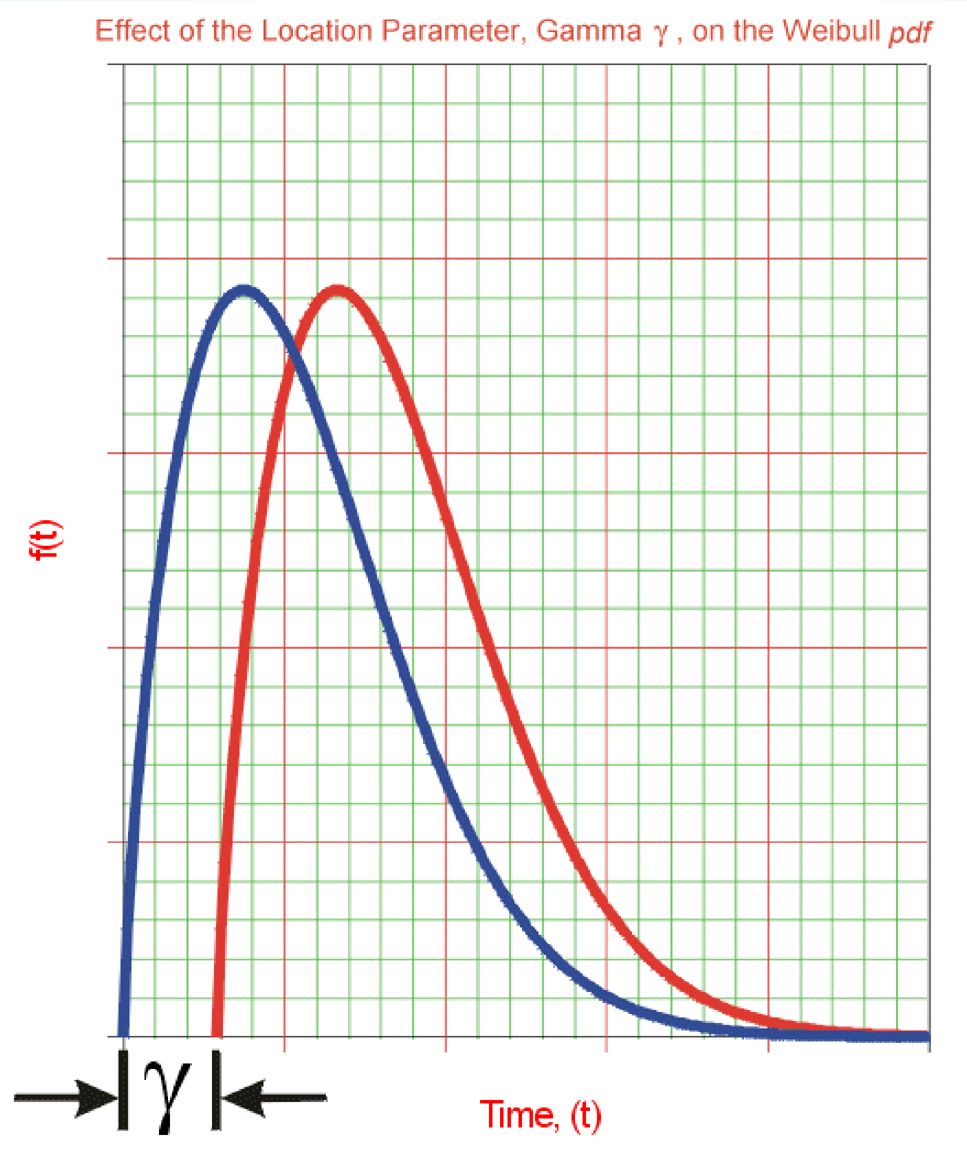
1887 - 1979

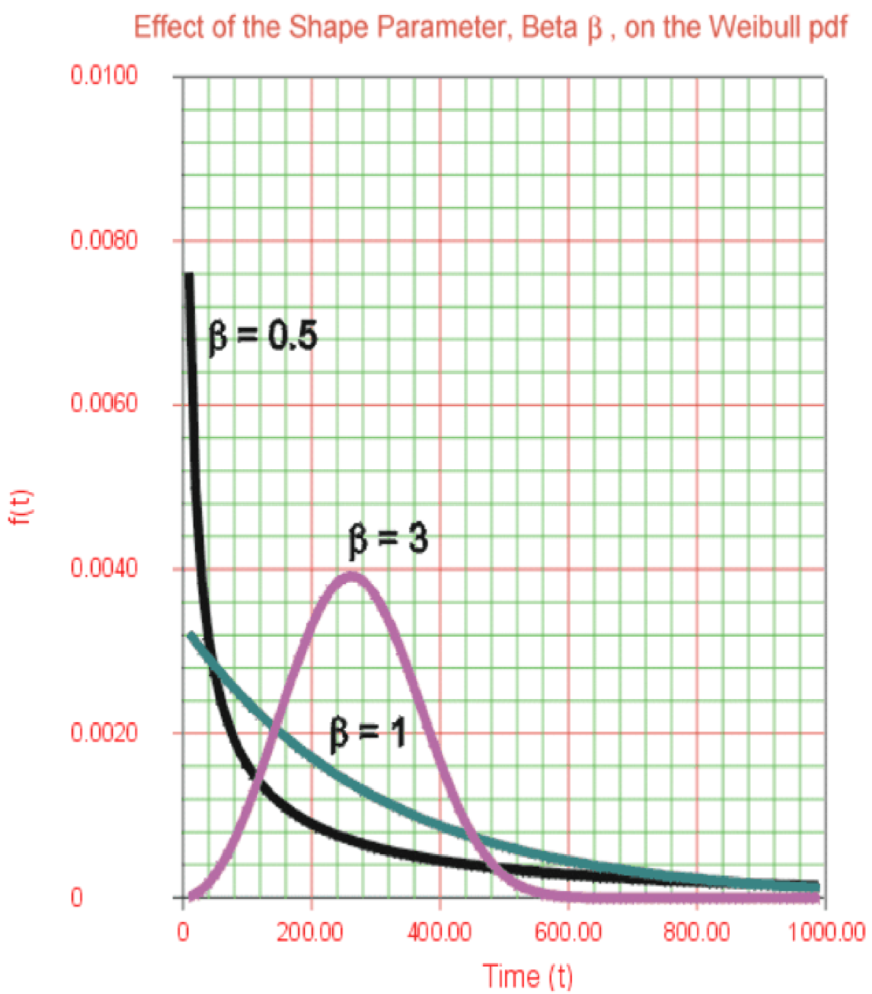
$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$

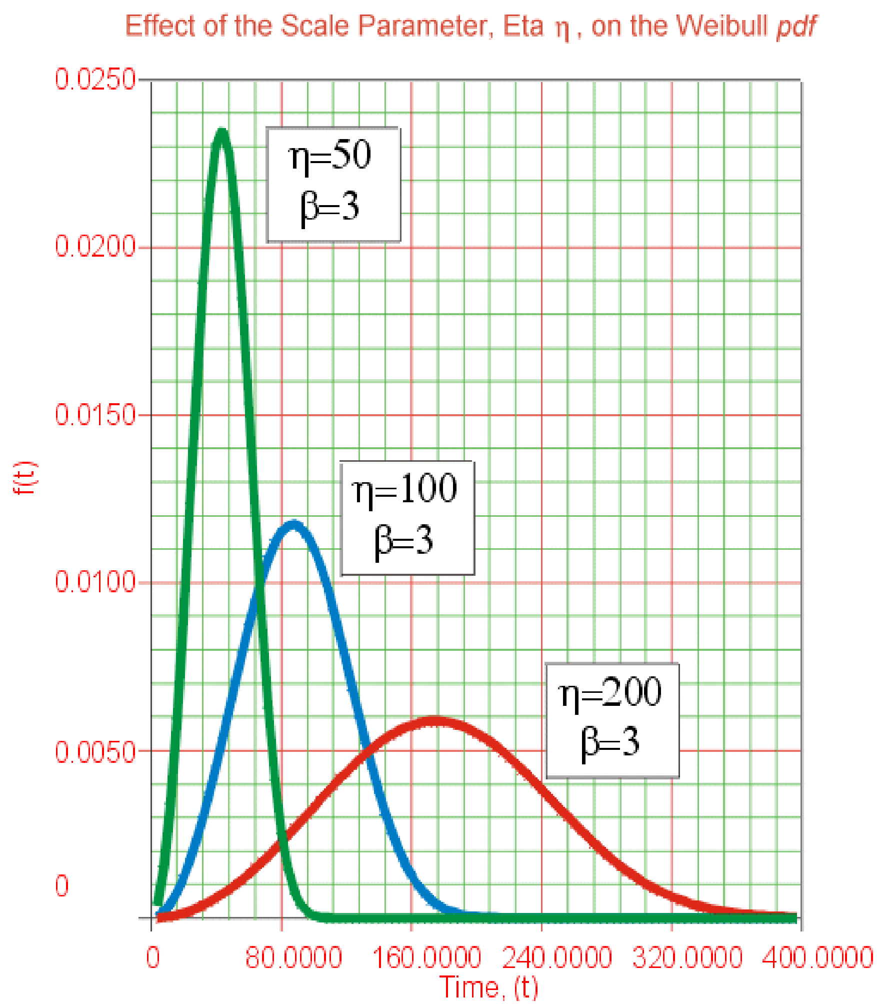
η: scale parameter - defines where the bulk of the distribution lies

β: shape parameter - defines the shape of the distribution

γ: location parameter - defines the location of the distribution in time




Effect of the Shape Parameter, Beta β , on the Weibull pdf
f(t)
0.0100
0.0080
0.0060
0.0040
0.0020
0
β = 0.5
β = 3
β = 1
0
200.00
400.00
600.00
800.00
1000.00
Time (t)


Effect of the Scale Parameter, Eta η , on the Weibull pdf
f(t)
0.0250
0.0200
0.0150
0.0100
0.0050
0
η=50
β=3
η=100
β=3
η=200
β=3
0
80.0000
160.0000
240.0000
320.0000
400.0000
Time, (t)

For wind speed data, γ = 0 and β = 2. Then, it is called Rayleigh distribution.

$$f(t) = \frac{\pi\ t}{2\ V^2}\ e^{-\left(\frac{\pi\ t^2}{4\ V^2}\right)}$$

where V is the annual average wind speed at hub height, h, above ground level

Wind turbine maufacturers often present performance figures for their machines using the Rayleigh distribution.

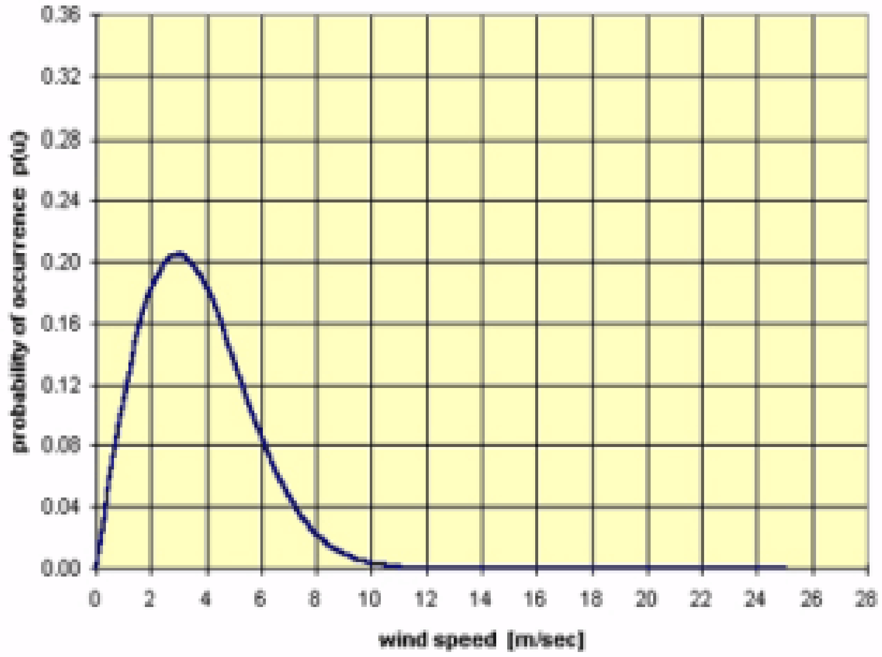


Figure 8.1: wind speed v = 3 m/s

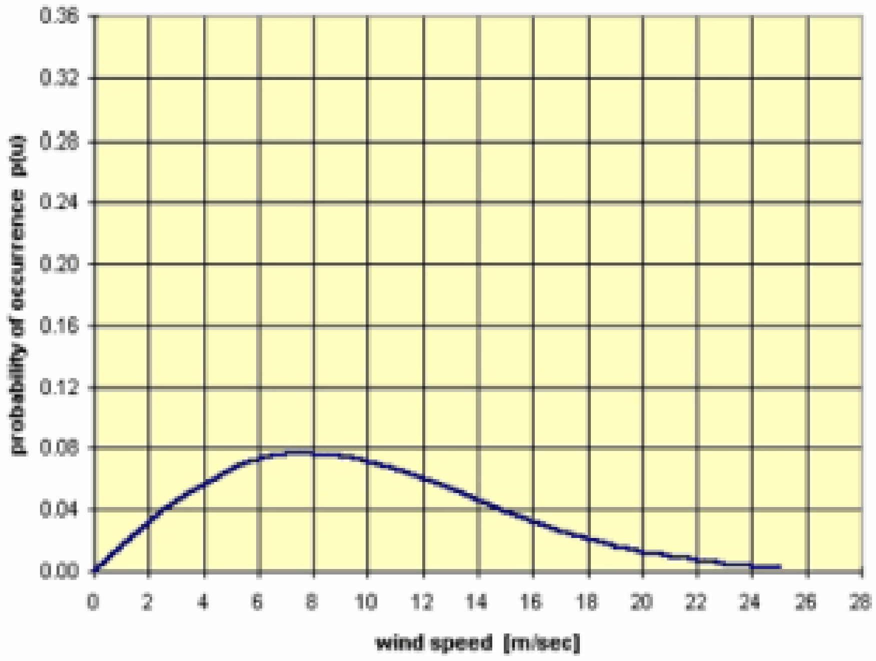


Figure 8.2: wind speed v = 8 m/s

Vestas V52 850 kW specifications

Rated capacity (kW)	850
Cut-in speed (m/sec)	4
Cut-out speed (m/sec)	25
Rated wind speed (m/sec)	16
Rotor diameter (m)	52
Swept area m^2	2124
Rotor speed (RPM)	14–31.4

Vestas Wind Systems A/S is a Danish manufacturer, seller, installer, and servicer of wind turbines that was founded in 1945. Many sites in Turkey uses Vestas wind turbine systems.

There are about 300 wind farms in Turkey, all onshore, totaling about 4,000 wind turbines. In 2022 total installed capacity passed 11 GW, and capacity factor is high at around 40 %.

The company with the most wind power (nine wind farms as of 2022) is Borusan EnBW Enerji, a joint venture between Borusan and Germany power utility Energie Baden-Wurttemberg. The maximum power of unlicensed installations is 5 MW. One billion euros was invested in 2021 and 1.4 GW built: average power rating was over 5 GW, which was higher than other European countries onshore. As of 2021 the largest wind farm in the country is Soma, followed by Karaburun.

Wind Power

Key Facts

1. Wind energy depends on the sun; it is a form of solar energy. Heating and cooling of air causes the wind to circulate.
2. Method: turbines convert wind energy into mechanical energy and then into electrical. It works like a fan in reverse.
3. Wind turbines now manufactured have power ratings from 250 W to 1.8 MW.

Wind Power

Advantages

1. Low price (~4 - 6 cents per kWh), renewable source, dependent on the sun. (*This compares with $0.04 per kWh for new conventional power plants so wind energy is close to competitive without subsidies)*
2. Does not pollute
3. A domestic source. Wind turbines on few percent of our land could generate all our electricity

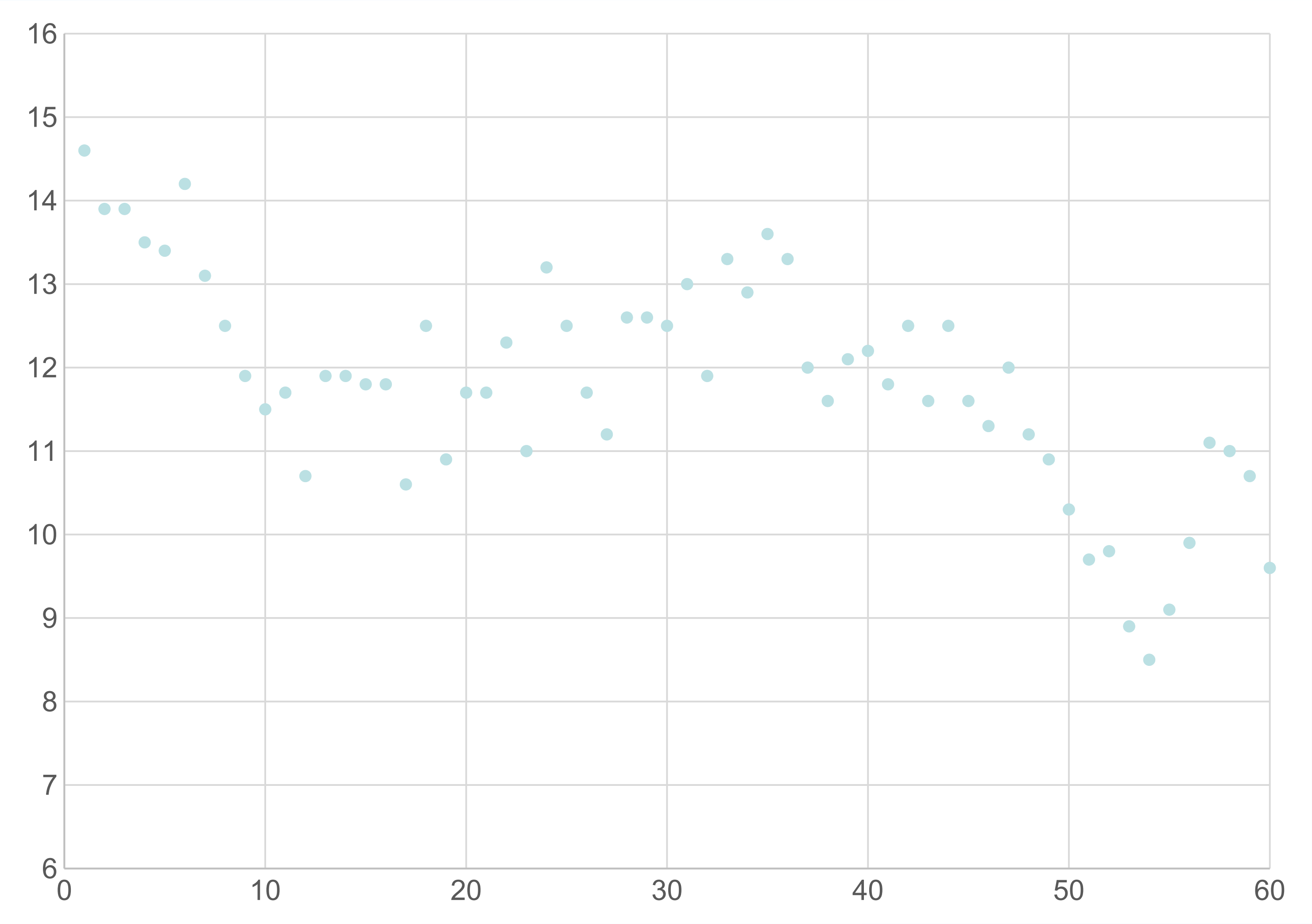
Disadvantages

1. Higher initial investment, not cost competitive in the short-term
2. Cannot be stored and timing of wind cannot be controlled
3. Noise, aesthetics, and bird danger

Example 2

During a typical day at a certain location, an anemometer near a wind turbine records the following data for a 1-hour period.

minute	mph	minute	mph	minute	mph	minute	mph
1	14.6	16	11.8	31	13	46	11.3
2	13.9	17	10.6	32	11.9	47	12
3	13.9	18	12.5	33	13.3	48	11.2
4	13.5	19	10.9	34	12.9	49	10.9
5	13.4	20	11.7	35	13.6	50	10.3
6	14.2	21	11.7	36	13.3	51	9.7
7	13.1	22	12.3	37	12	52	9.8
8	12.5	23	11	38	11.6	53	8.9
9	11.9	24	13.2	39	12.1	54	8.5
10	11.5	25	12.5	40	12.2	55	9.1
11	11.7	26	11.7	41	11.8	56	9.9
12	10.7	27	11.2	42	12.5	57	11.1
13	11.9	28	12.6	43	11.6	58	11
14	11.9	29	12.6	44	12.5	59	10.7
15	11.8	30	12.5	45	11.6	60	9.6


16
15
14
13
12
11
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40
50
60

The following data is available:

The air density is 1.18 kg/m^3

The wind turbine has a diameter of 3.2 m

The turbine parameters are that the turbine collects a fraction C_p = 0.335 of the wind, the generator efficiency is η_g = 0.80, and the bearing efficiency is η_b = 0.95.

The instantaneous electrical power that is generated by the wind is given by the expression,

$$P = \frac{1}{2} \rho A C_P \eta_g \eta_b V^3$$

where A is the swept area of the wind turbine.

a) Determine the instantaneous power for the wind turbine as a function of time.

b) Use the power data to estimate the cumulative electrical energy produced in kWh.

c) Assuming similar wind over the course of an entire day, estimate kWh for the day and then compare with the average energy consumption for a household in Turkey. Assume it is 10 kWh / day.

d) An electrolysis unit operates at 60% efficiency. If the theoretical amount of energy needed to convert 1 mole of liquid water into 1 mole of hydrogen and ½ mole of oxygen is 285 kJ, determine the mass of hydrogen produced in grams for one day. Use your answer in kWh from part c.

Solution

$$1 \text{ mph} = \frac{1 \text{ mile/h}}{3600 \text{ s/h}} (5280 \text{ ft/mile}) (0.3048 \text{ m/ft}) = 0.44704 \text{ m/s}$$

Swept area by the blades: $A = \dfrac{\pi d^2}{4} = \dfrac{\pi (3.2)^2}{4} = 8.04248 \text{ m}^2$

Convert the given data to m/s and find power in Watts for all the data points using the formula:

$$P(t) = \frac{1}{2} \rho A C_P \eta_g \eta_b V^3$$

Minute	mph	m/s	P(t), W
1	14.6	6.526784	335.890692
2	13.9	6.213856	289.857007
3	13.9	6.213856	289.857007
4	13.5	6.03504	265.546577
5	13.4	5.990336	259.689146
6	14.2	6.347968	309.032699
7	13.1	5.856224	242.634911
8	12.5	5.588	210.799434
9	11.9	5.319776	181.878049
10	11.5	5.14096	164.14699

11	11.7	5.230368	172.860987
12	10.7	4.783328	132.218046
13	11.9	5.319776	181.878049
14	11.9	5.319776	181.878049
15	11.8	5.275072	177.331311
16	11.8	5.275072	177.331311
17	10.6	4.738624	128.545536
18	12.5	5.588	210.799434
19	10.9	4.872736	139.771587
20	11.7	5.230368	172.860987

21	11.7	5.230368	172.860987
22	12.3	5.498592	200.842092
23	11	4.91744	143.653912
24	13.2	5.900928	248.23396
25	12.5	5.588	210.799434
26	11.7	5.230368	172.860987
27	11.2	5.006848	151.63291
28	12.6	5.632704	215.899202
29	12.6	5.632704	215.899202
30	12.5	5.588	210.799434

31	13	5.81152	237.120695
32	11.9	5.319776	181.878049
33	13.3	5.945632	253.918489
34	12.9	5.766816	231.690663
35	13.6	6.079744	271.491431
36	13.3	5.945632	253.918489
37	12	5.36448	186.501848
38	11.6	5.185664	168.466429
39	12.1	5.409184	191.203357
40	12.2	5.453888	195.983222

41	11.8	5.275072	177.331311
42	12.5	5.588	210.799434
43	11.6	5.185664	168.466429
44	12.5	5.588	210.799434
45	11.6	5.185664	168.466429
46	11.3	5.051552	155.730878
47	12	5.36448	186.501848
48	11.2	5.006848	151.63291
49	10.9	4.872736	139.771587
50	10.3	4.604512	117.937272

51	9.7	4.336288	98.5041675
52	9.8	4.380992	101.582204
53	8.9	3.978656	76.086818
54	8.5	3.79984	66.2820878
55	9.1	4.068064	81.3323984
56	9.9	4.425696	104.723702
57	11.1	4.962144	147.607471
58	11	4.91744	143.653912
59	10.7	4.783328	132.218046
60	9.6	4.291584	95.4889464

Total amount of electric energy produced by the panel: $E = \int P(t)\, dt$

Use trapezoidal rule to integrate the data:

$$E = \int P(t)\, dt \cong \left[\frac{1}{2}(P_1 + P_N) + \sum_{i=2}^{N-1} P_i \right] \Delta t$$

$$= 0.181 \text{ kWh}$$

Note that Δt = 1 minute = 1/60 hours.

Extrapolating over the course of a day, we have (0.181) (24) = 4.34 kWh/day

Fraction of daily use: 4.34 / 10 = 0.434 => 43.4 %

$$\text{Hydrogen production} = (4.34 \text{ kWh})\ (0.6)\ (3600 \text{ s/h}) \left(\frac{2 \text{ g/mol}}{285 \text{ kJ/mol}} \right)$$

$$= 65.84 \text{ g}$$

Example 3

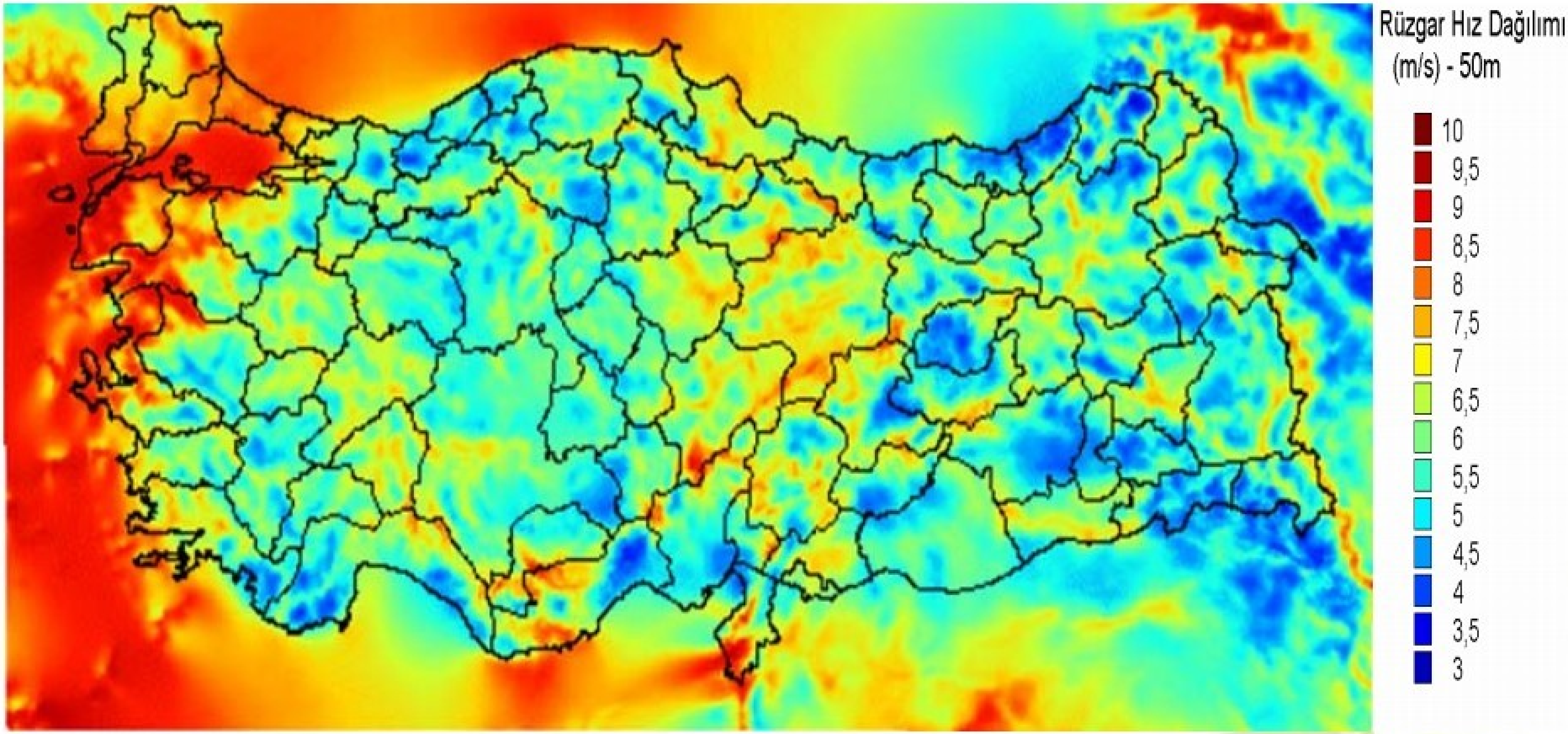
A wind farm is being considered for a ridge top site. Name 10 or more issues that might be considered in evaluating this site.

Considerations might include:

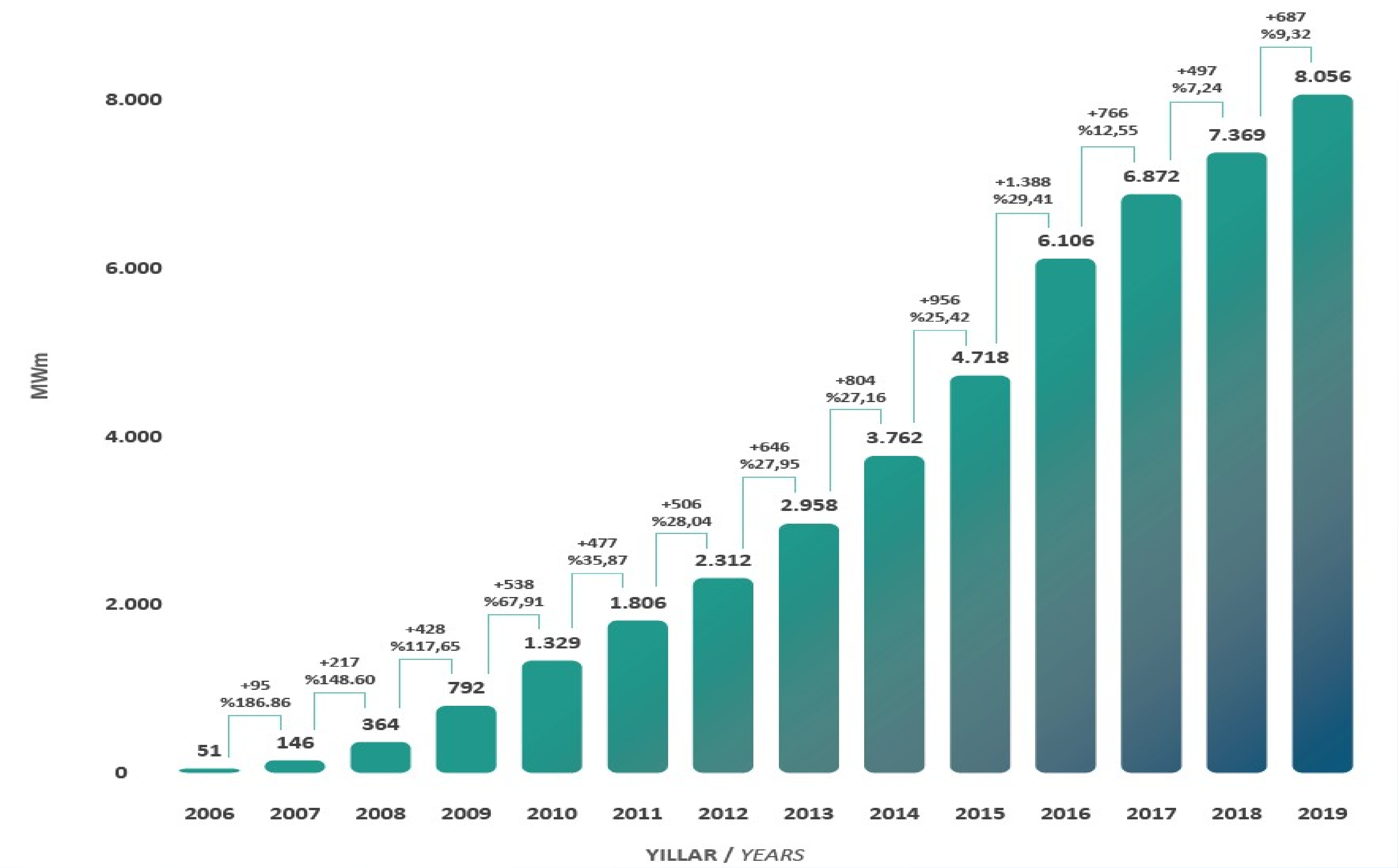
1) Mean wind speed
2) Variations of wind speed over the site
3) Turbulence intensity
4) Topographic effects on directional characteristics of the wind
5) Available area for turbines
6) The presence of nearby wind farms
7) Ease of access

8. Competing land use issues
9. Slope of the terrain
10. Endangered species
11. Environmentally sensitive areas (e.g. vernal pools)
12. Visibility
13. Proximity to houses
14. Grid strength
15. Need for a grid extension and cost of any grid extension
16. Legal issues
17. Visual pollution concerns
18. Extreme weather

19. The possibility of danger to hikers
20. Size of turbine that can be transported to the site
21. Cost of road building
22. Site preparation and turbine transport
23. Availability of cranes
24. Access for maintenance personnel
25. Interference wth microwave transmissions
26. Erosion and run-off from road and site work
27. The availability of accurate enough wind data for energy capture projections

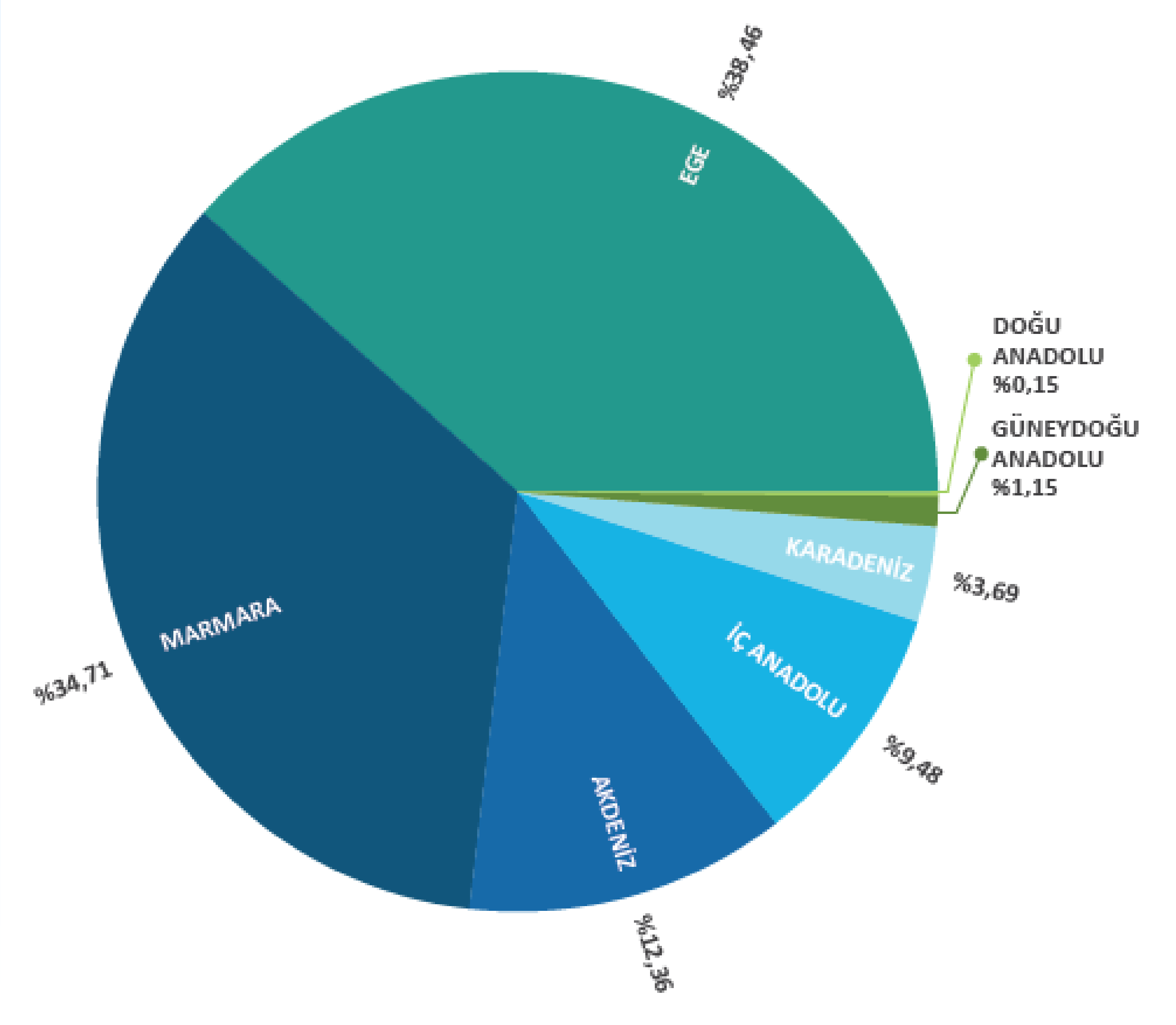


Source: General Directorate of Electrical Power Resources Survey and Development Administration



See OdtuClass for TÜBA's Report 2019 (in Turkish)

Existing Wind Power Plants



Wind Power Plants under Construction