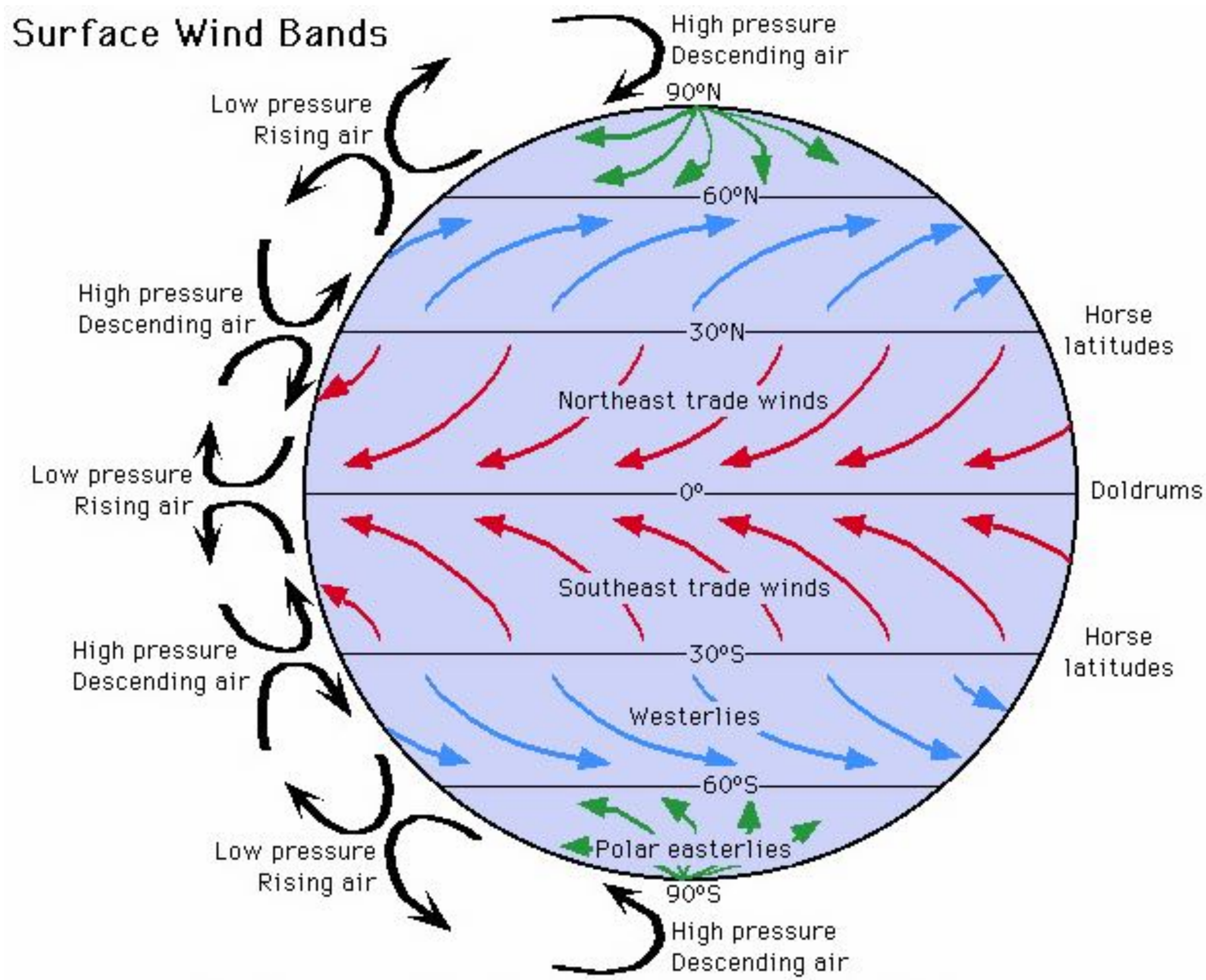
Thermodynamics of energy conversion

10) WIND POWER

10) Wind power

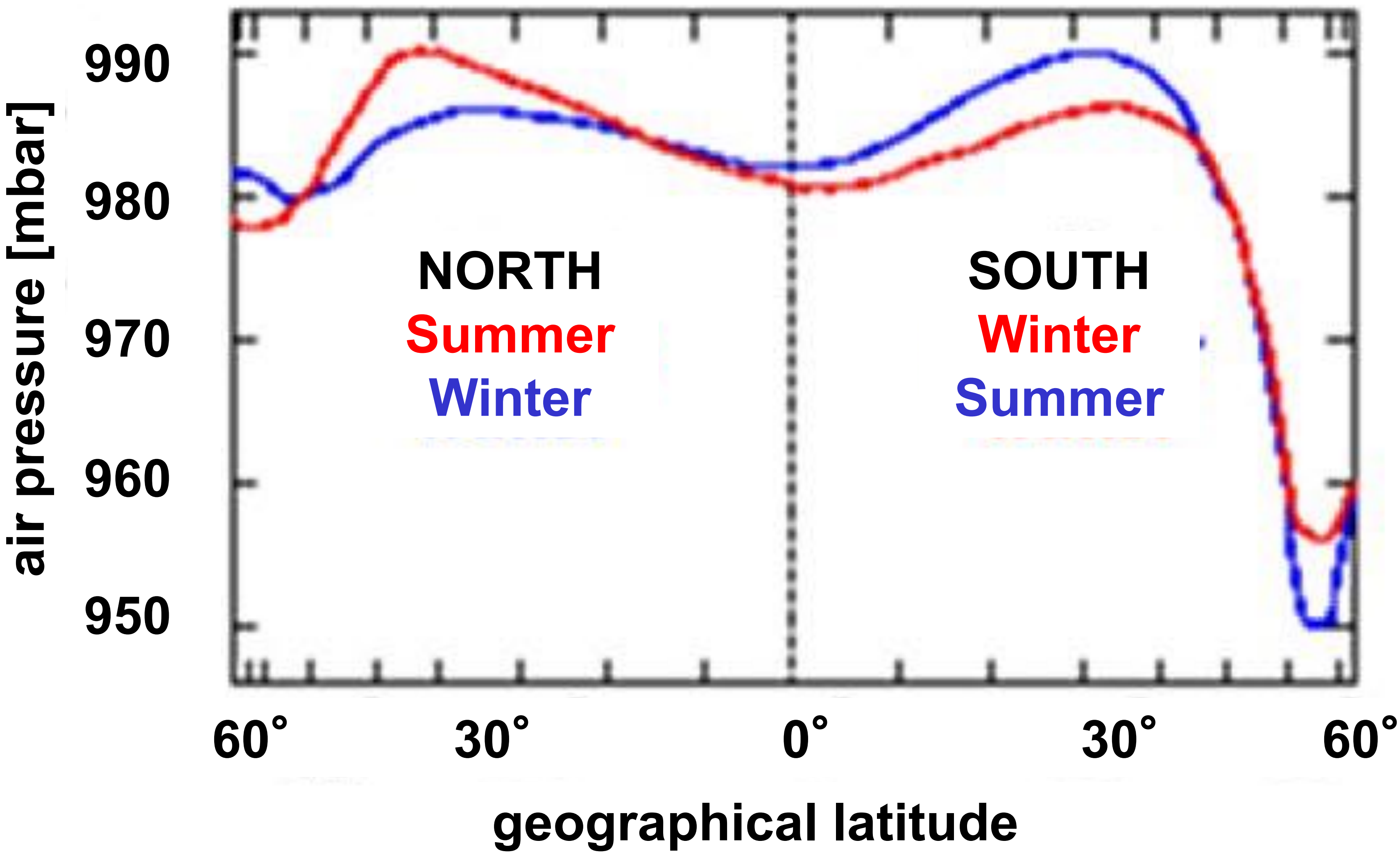
10) Wind power

10.1. GLOBAL WIND

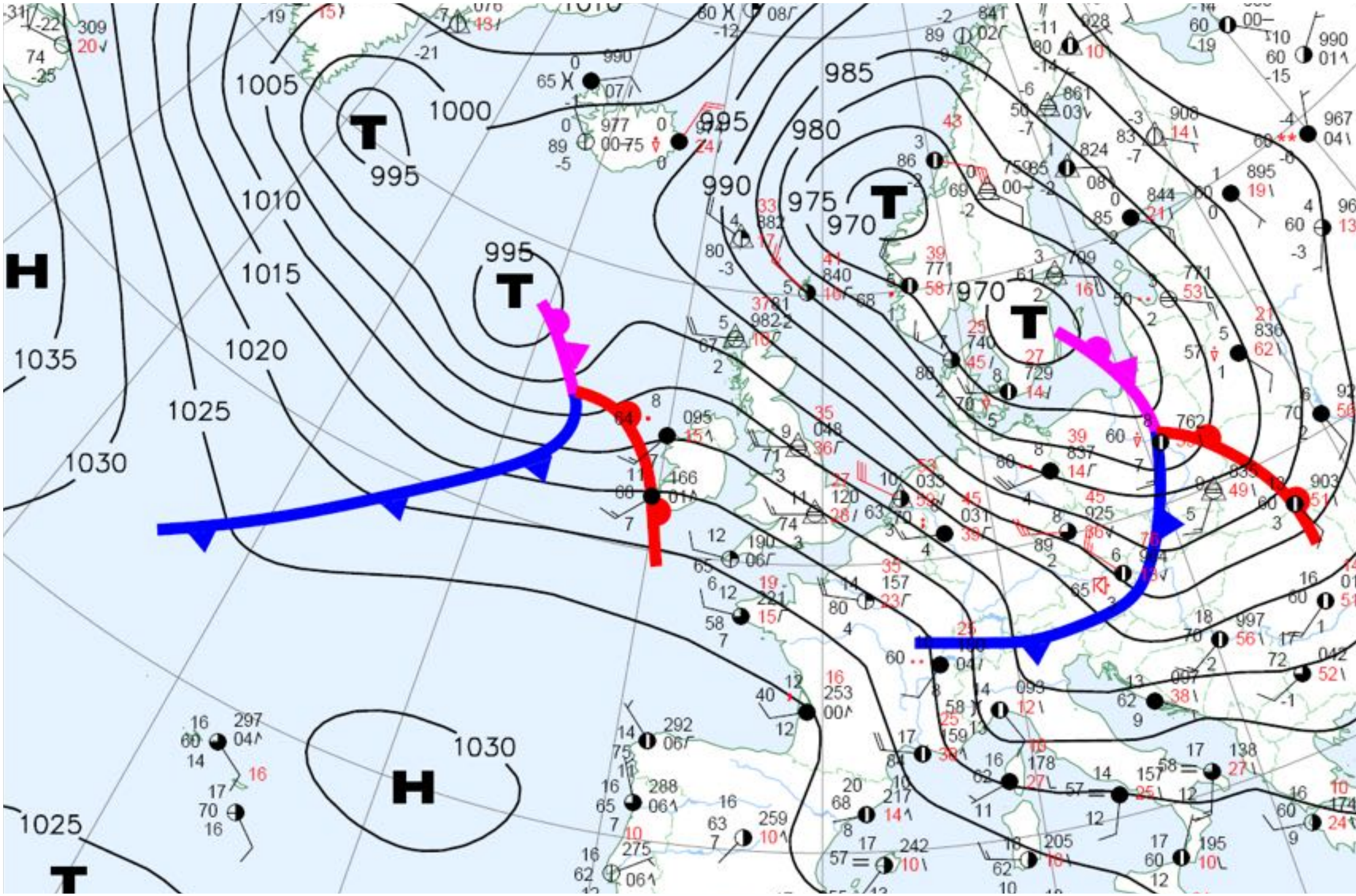


Adapted from Duxbury, Alyn C. and Alison B. Duxbury. *An Introduction to the World's Oceans, 4/e.*
Copyright © 1994 Wm. C. Brown Publishers, Dubuque, Iowa.

10.1.1. GLOBAL AIR PRESSURE

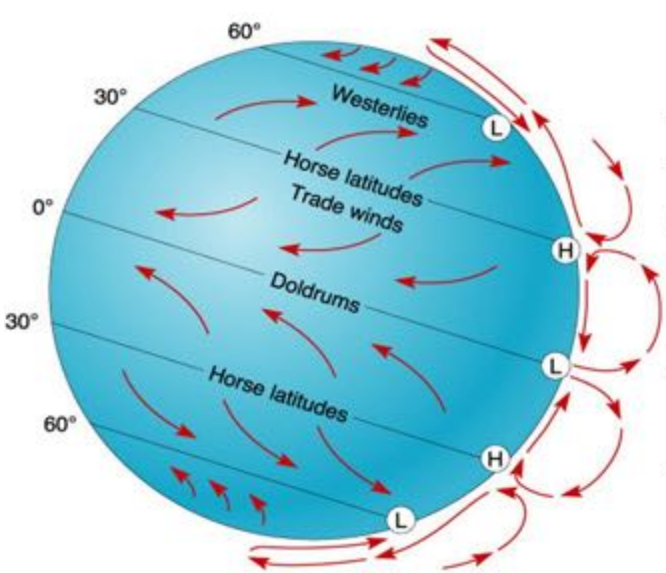


10.1.2. LOCAL AIR PRESSURE (Weather)

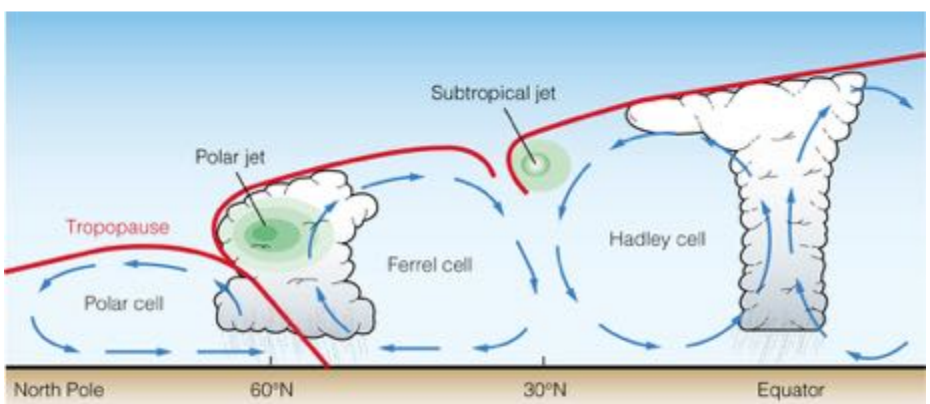


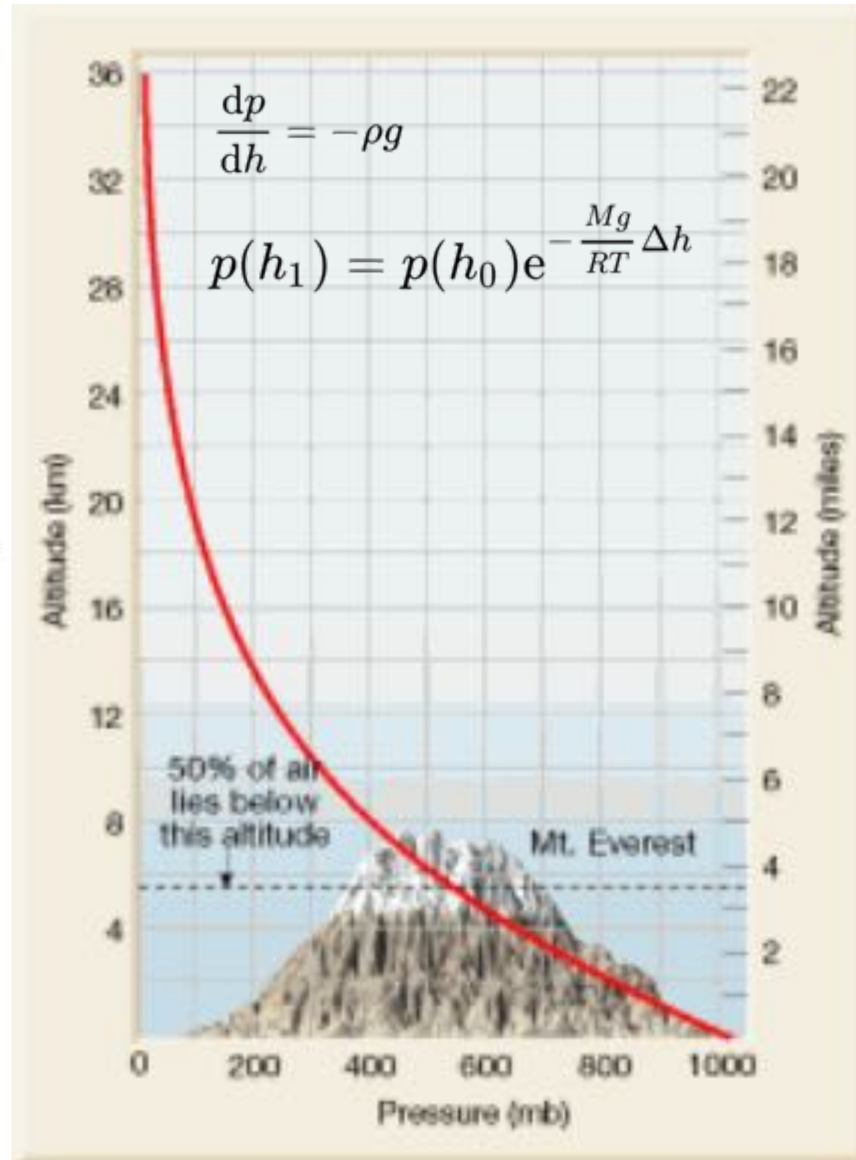
10.1.3. AIR PRESSURE

Convection and Atmospheric Pressure

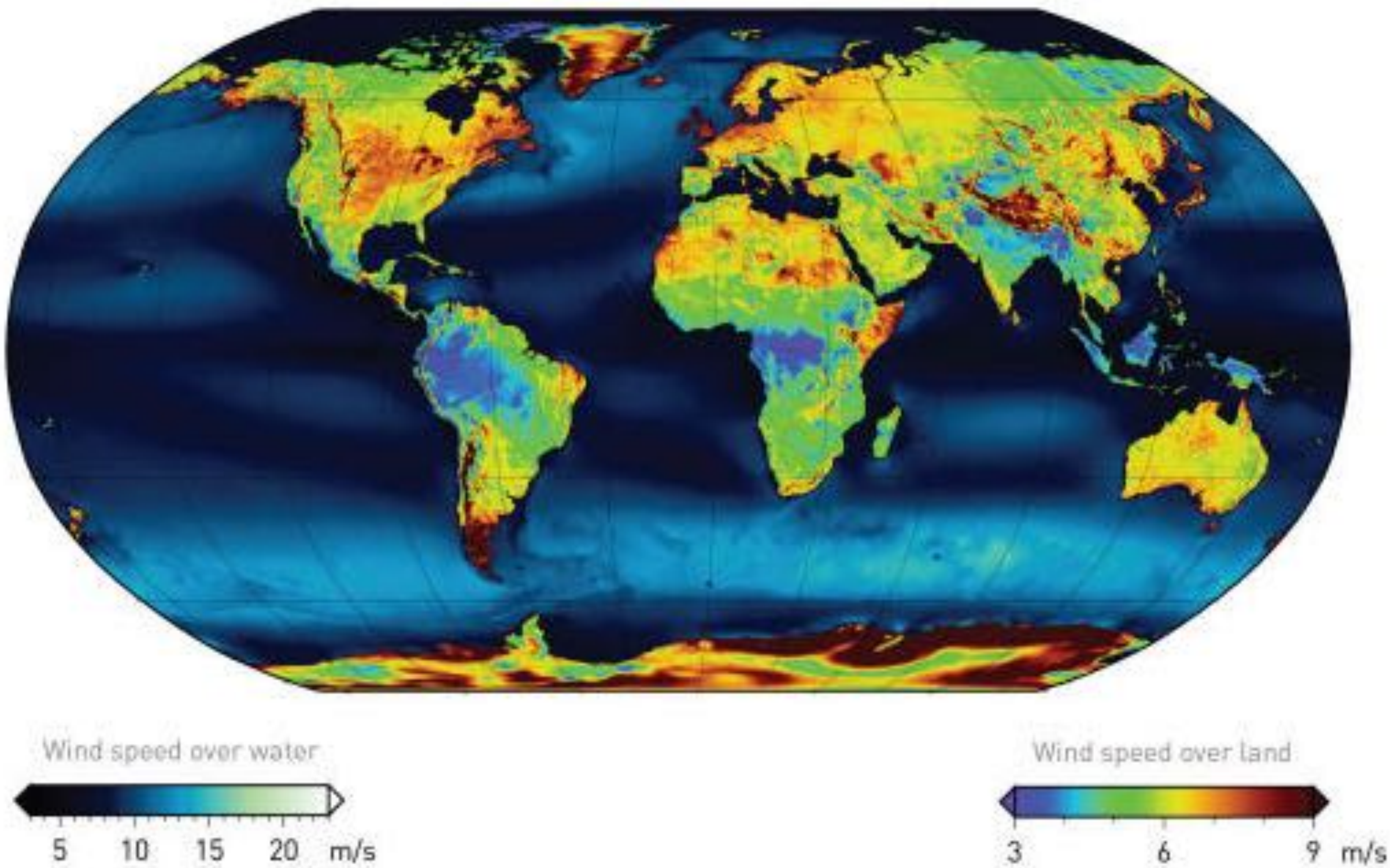


- Evaporation
- Latent heat
- Condensation
- Convection currents
- Air pressure differences
- Coriolis effect

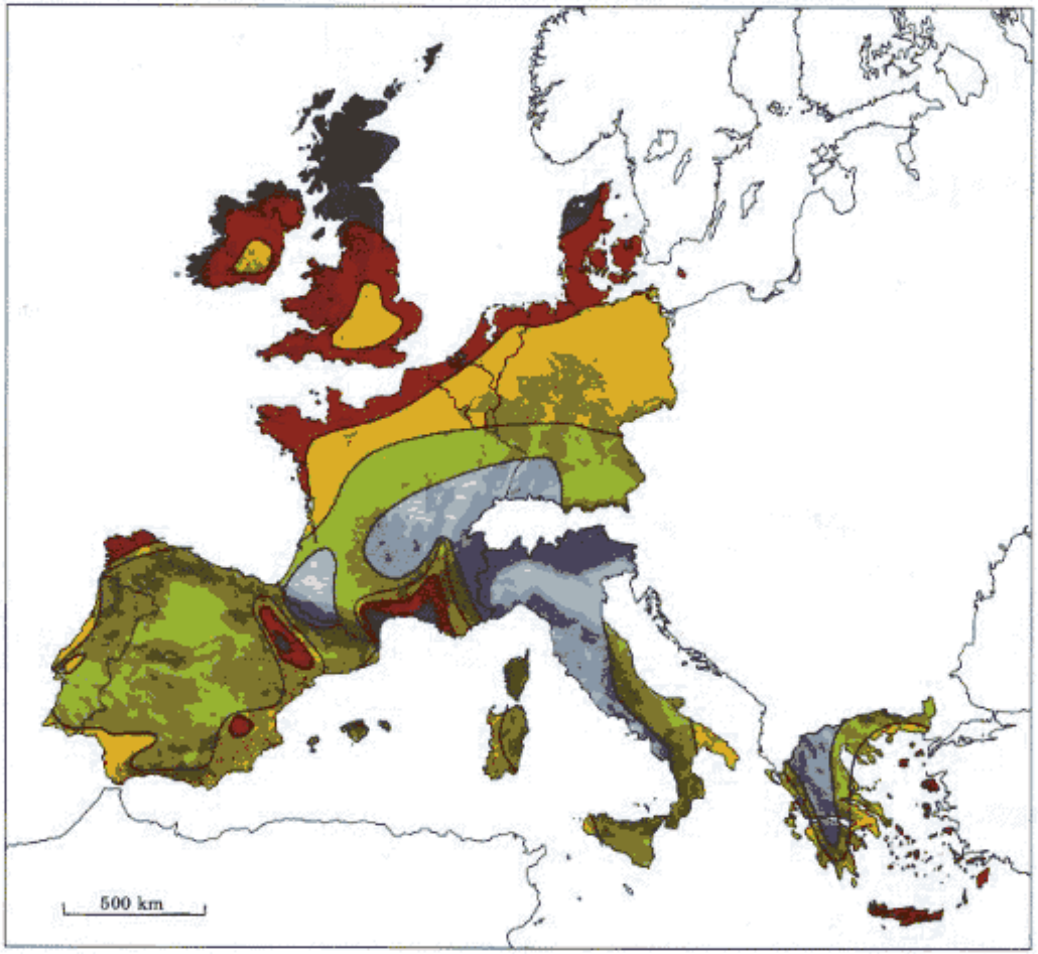




10.1.4. GLOBAL WIND SPEED CLOSE TO SURFACE



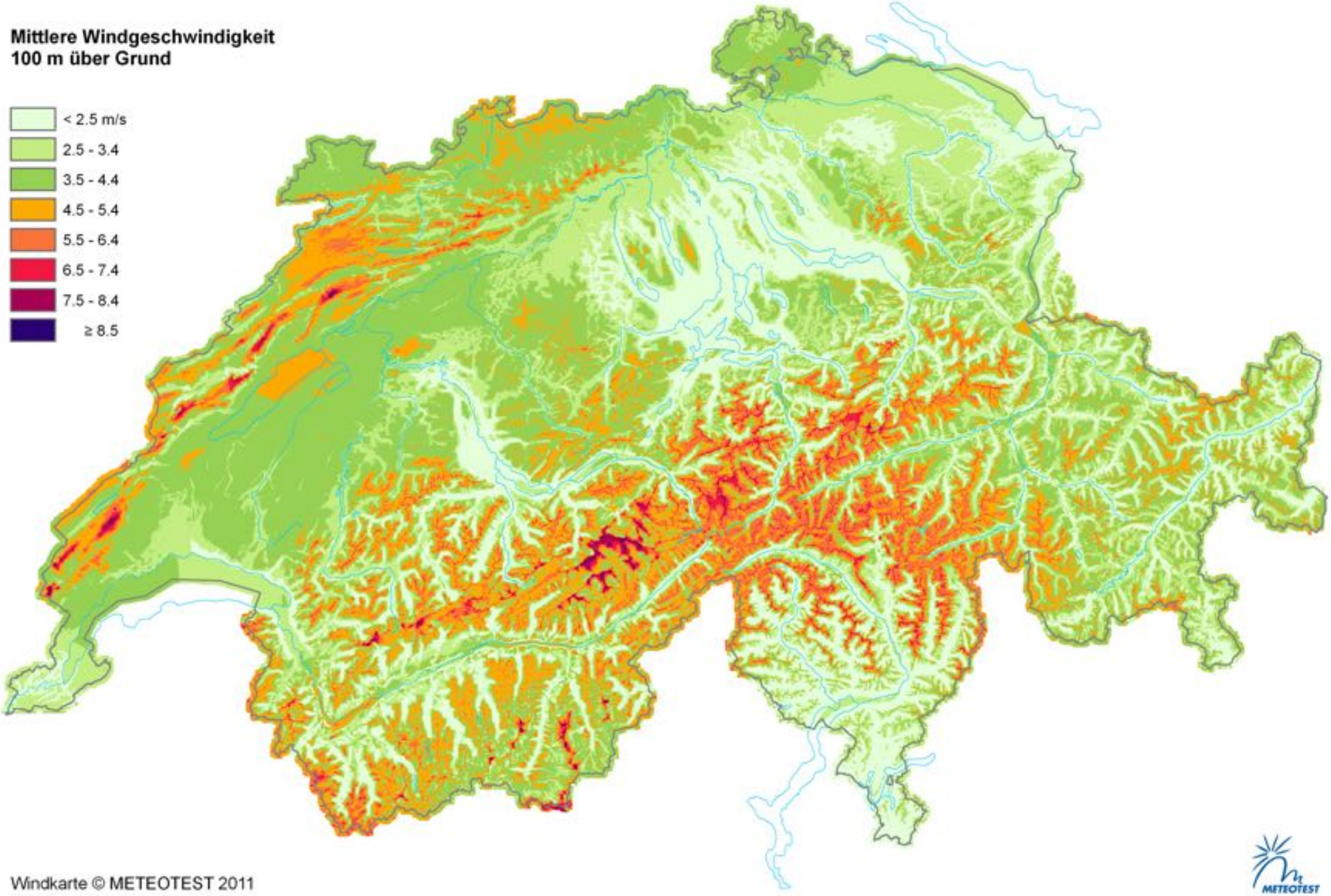
10.1.5. WIND SPEED CLOSE TO SURFACE IN EUROPE



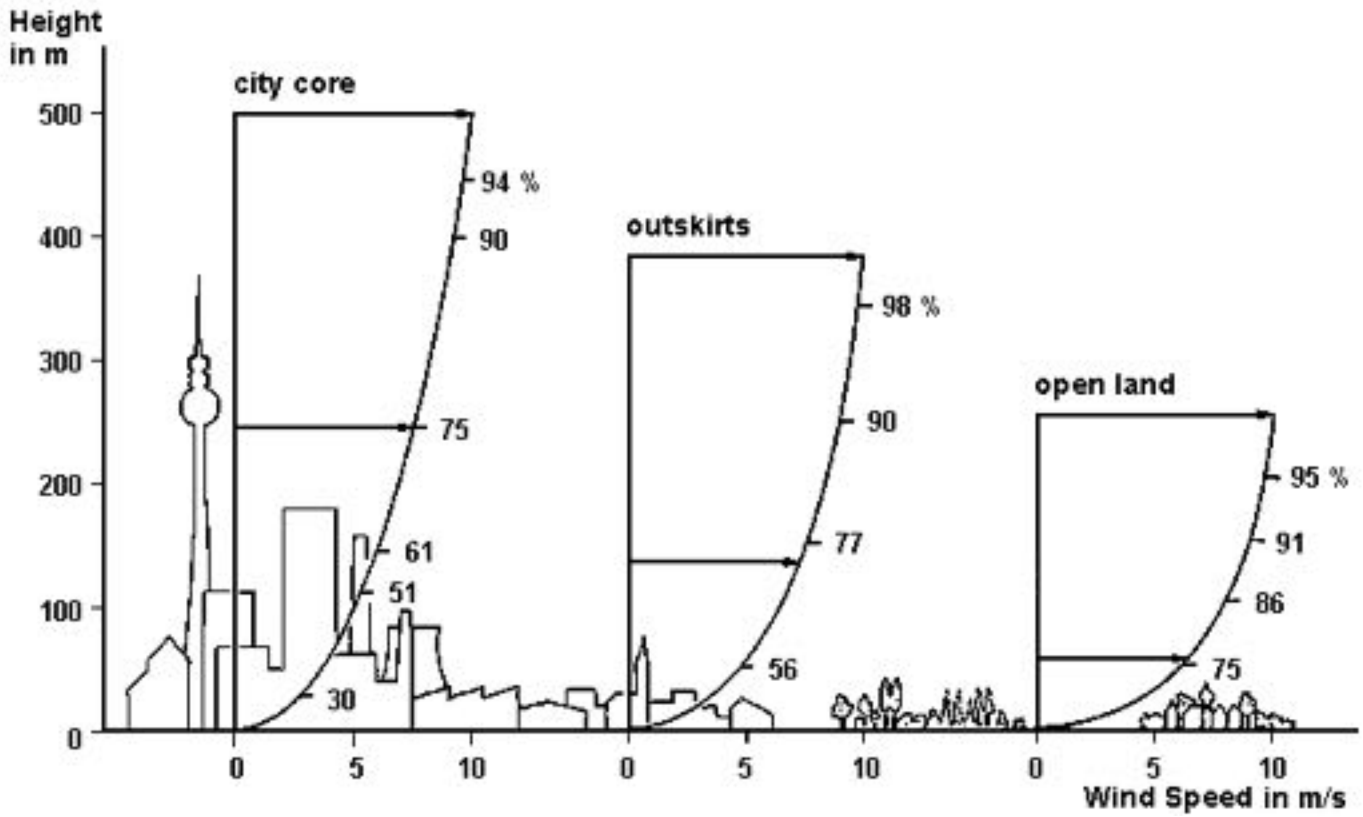
Wind resources[1] at 50 metres above ground level for five different topographic conditions

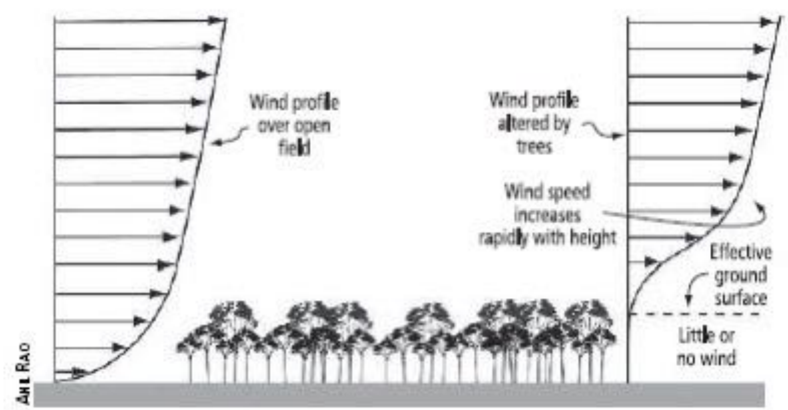
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	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
	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
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

10.1.6. WIND SPEED 100 m ABOVE THE GROUND IN SWITZERLAND

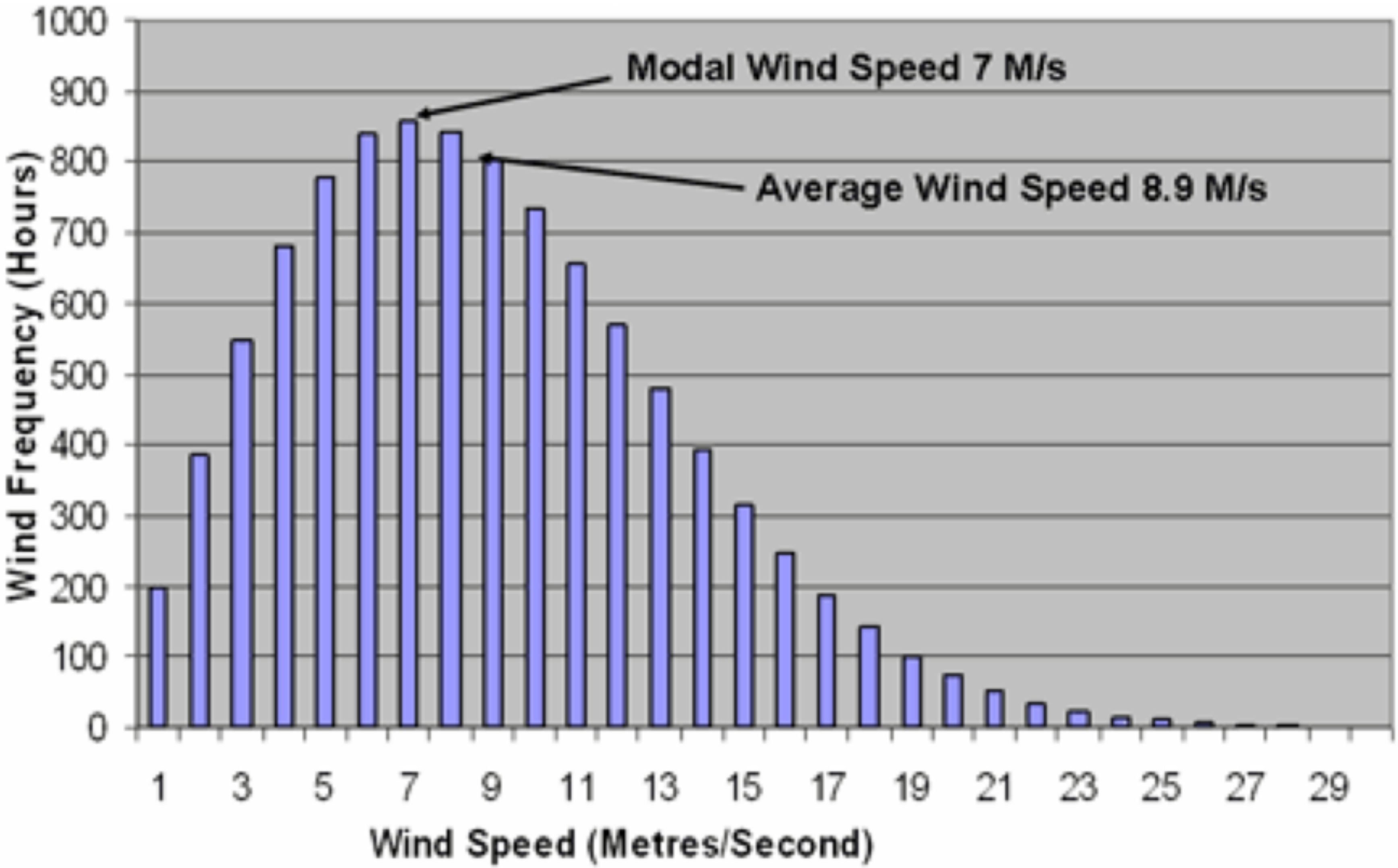


10.1.7. WIND SPEED CLOSE TO SURFACE WITH OBSTACLES





10.1.8. WIND SPEED DISTRIBUTION



10.2. POWER IN THE WIND

$$W = \frac{1}{2} \cdot m \cdot v^2$$

$$P = \frac{dW}{dt} = \frac{1}{2}\left(\frac{dm}{dt} \cdot v^2 + m \cdot 2v \cdot a\right)$$

$$\text{with } a = 0 \text{ and } \frac{dm}{dt} = A \cdot v \cdot \rho$$

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

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

$$W = P \cdot dt = \frac{1}{2} \cdot A \cdot \rho \cdot v^2 \cdot s$$

10.2.1. THEORY OF BETZ

$$P = \frac{1}{2} \cdot \dot{m} \cdot (v_1^2 - v_2^2)$$

change of kin. energy

$$P = F \cdot v = \dot{m} \cdot (v_1 - v_2) \cdot v$$

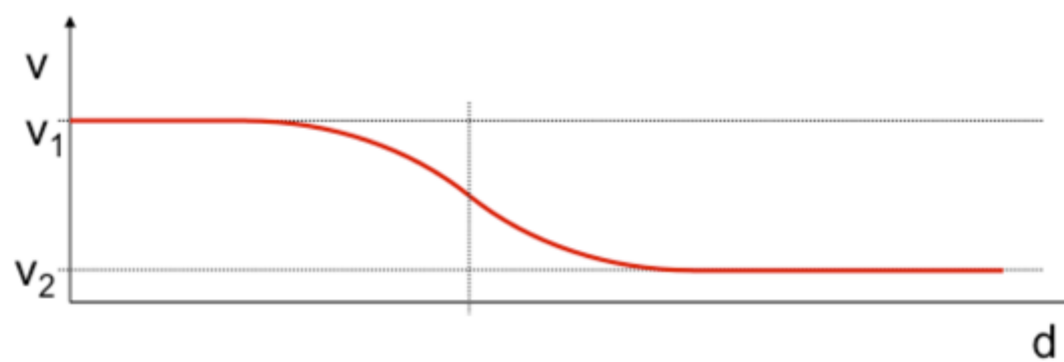
change of momentum

$$\frac{1}{2} \cdot (v_1^2 - v_2^2) = (v_1 - v_2) \cdot v$$

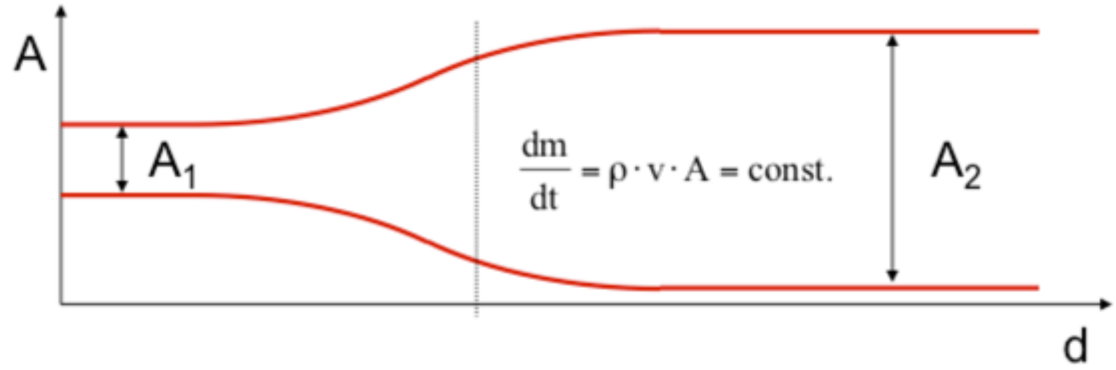
$$v = \frac{1}{2} \cdot (v_1 + v_2)$$

Albert BETZ

(* 25. Dezember 1885 in Schweinfurt; † 16. April 1968 in Göttingen) war ein deutscher Physiker und Flugzeugbauer



10.2.3. EQUATION OF CONTINUITY



$$P = F \cdot v = \dot{m} \cdot (v_1 - v_2) \cdot v = A \cdot \rho \cdot (v_1 - v_2) \cdot v^2$$

$$P = A \cdot \rho \cdot (v_1 - v_2) \cdot \left(\frac{v_1 + v_2}{2}\right)^2$$

$$P = \frac{1}{4} \cdot A \cdot \rho \cdot v_1^3 \cdot \left(1 - \frac{v_2}{v_1}\right) \cdot \left(1 + \frac{v_2}{v_1}\right)^2$$

$$\xi = \frac{v_2}{v_1}$$

$$P = \frac{1}{4} \cdot A \cdot \rho \cdot v_1^3 \cdot (1 - \xi) \cdot (1 + \xi)^2$$

10.2.4. MAXIMUM POWER

max(P):

$$\frac{dP}{d\xi} = 0 = \frac{dP}{d\xi}\left\{\frac{1}{4}\cdot A\cdot\rho\cdot v_1^3\cdot(1-\xi)\cdot(1+\xi)^2\right\}$$

$$\frac{dP}{d\xi} = \frac{1}{4}\cdot A\cdot\rho\cdot v_1^3 \cdot \{-(1+\xi)^2 + (1-\xi)\cdot 2(1+\xi)\} = 0$$

$$2\cdot(1-\xi)\cdot(1+\xi) = (1+\xi)^2$$

$$2\cdot(1-\xi^2) = (1+\xi)^2$$

$$\xi = \frac{1}{3}$$

10.2.5. POWER COEFFICIENT c_P

$$P_{max} = \frac{1}{4} \cdot A \cdot \rho \cdot v_1^3 \cdot \left(1 - \frac{1}{3}\right) \cdot \left(1 + \frac{1}{3}\right)^2 = \frac{1}{4} \cdot A \cdot \rho \cdot v_1^3 \cdot \frac{2}{3} \cdot \frac{16}{9}$$

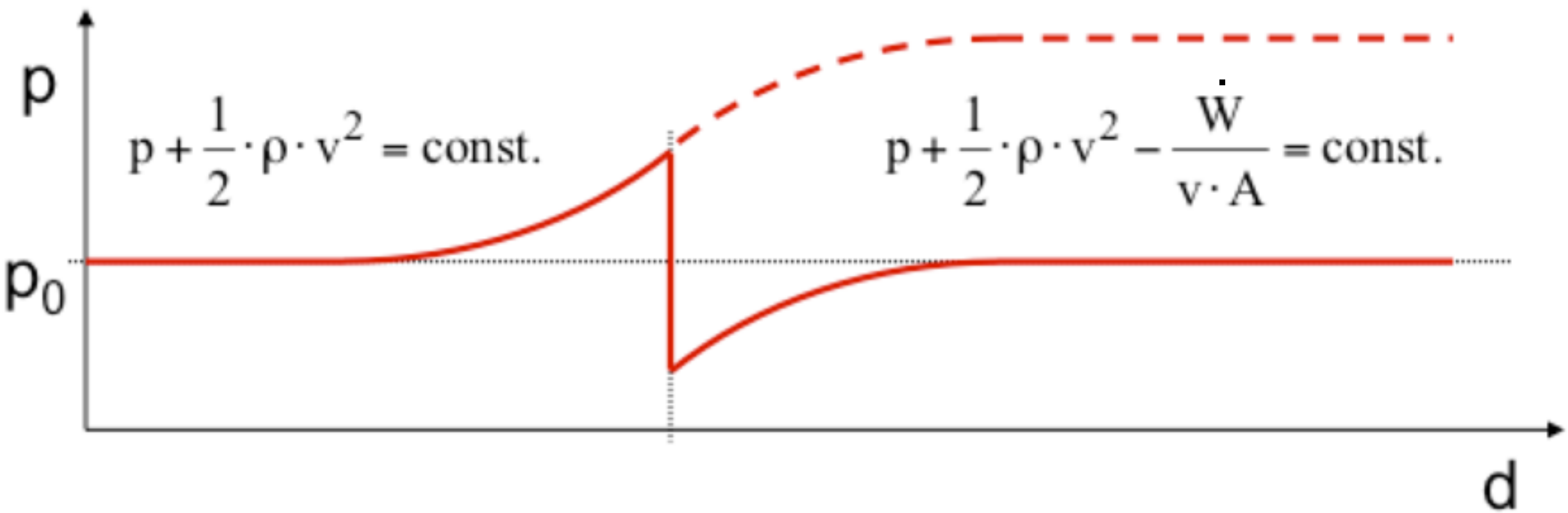
$$P_{max} = \frac{1}{2} \cdot A \cdot \rho \cdot v_1^3 \cdot \frac{16}{27}$$

$$P_{Betz} = P_0 \cdot \frac{16}{27} \quad with \quad P_0 = \frac{1}{2} \cdot A \cdot \rho \cdot v_1^3 \qquad c_p = \frac{16}{27} = 0.593$$

10.2.6. AIR PRESSURE

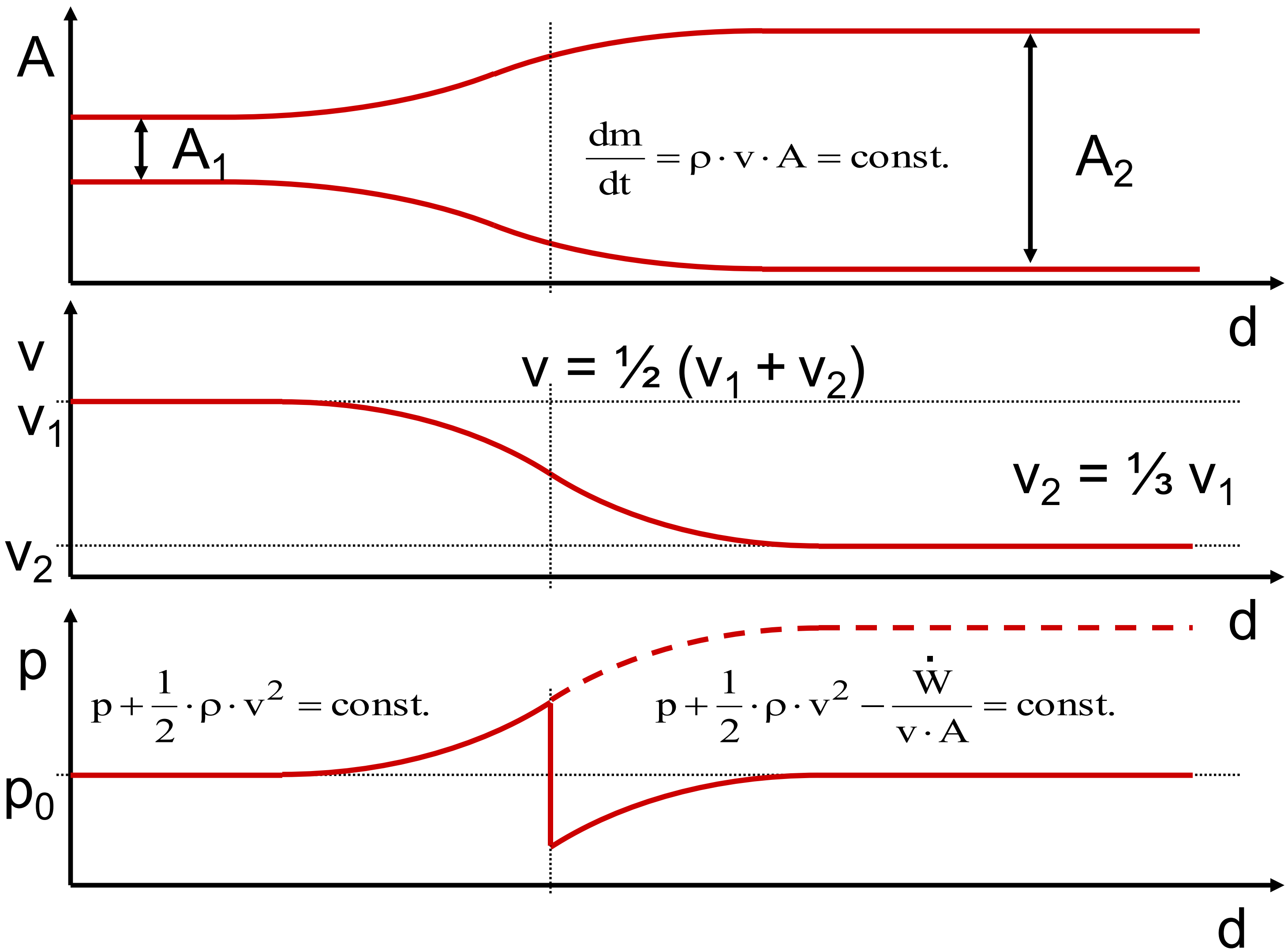
$$p + \frac{1}{2} \cdot \rho \cdot v^2 = const \qquad Bernoulli$$

Johann Bernoulli (* 27. Juli/ 6. August 1667 greg. in Basel; † 1. Januar 1748)

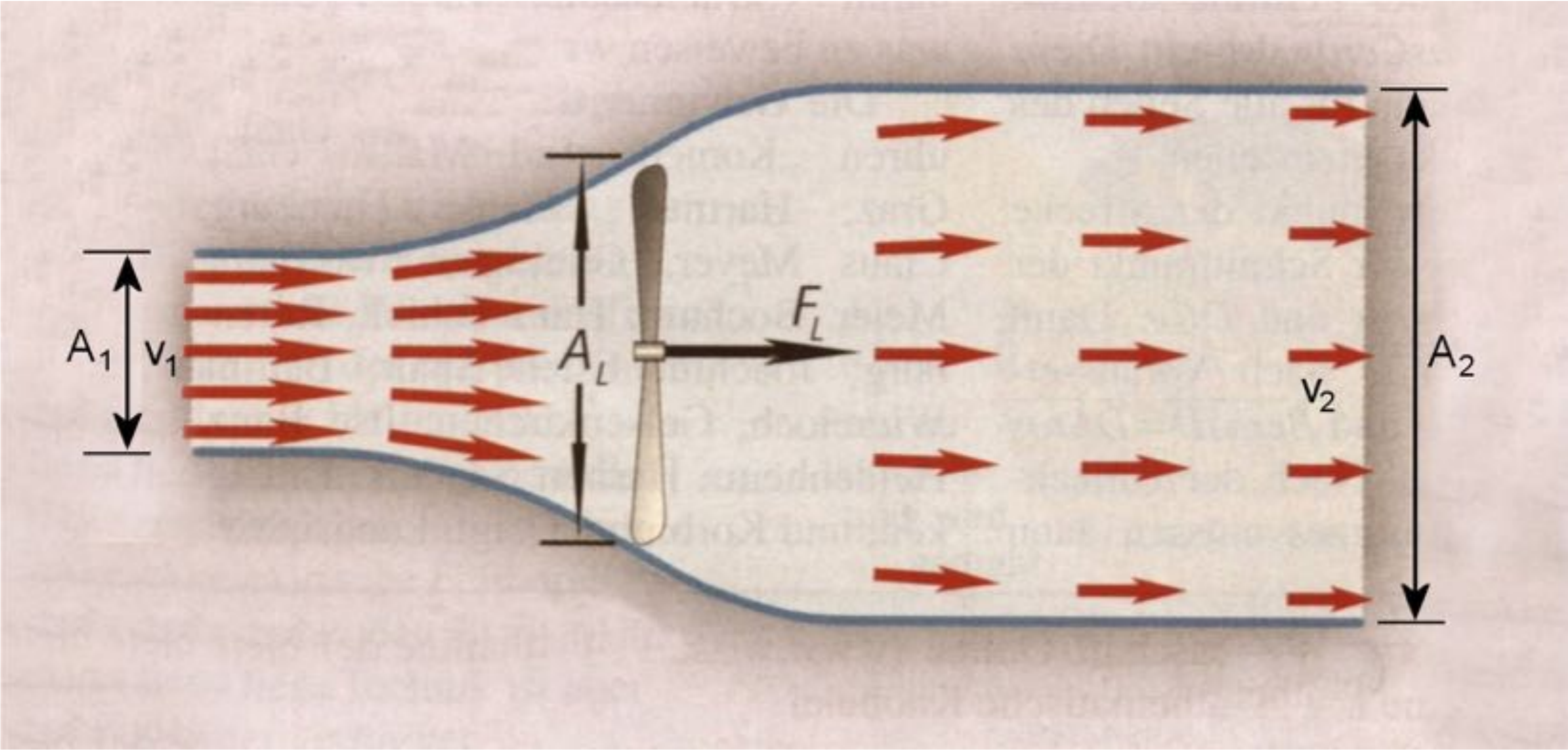


p\quad +\quad \frac { 1 }{ 2 } \cdot \rho \cdot { v }^{ 2 }\quad =\quad const\qquad \qquad Bernoulli\\

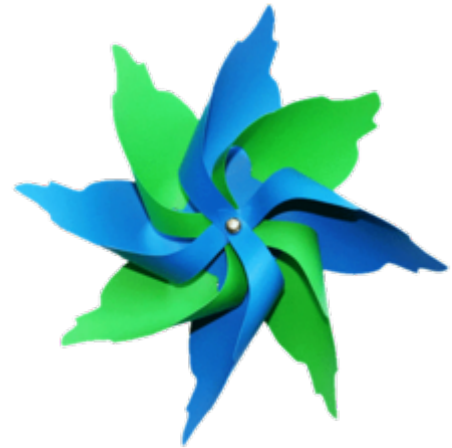
10.2.7. BETZ MODEL



10.2.8. WIND FLUX ON TURBINE



10.3. DRAG OF OBJECTS



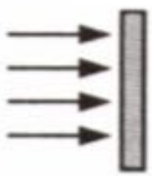
DRAG

$$P_W = F_W \cdot v$$

$$F_W = \frac{1}{2} \cdot c_W \cdot \rho \cdot A \cdot v^2$$

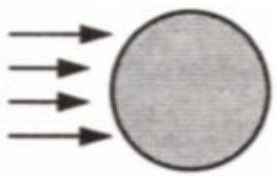
$$P_W = \frac{1}{2} \cdot c_W \cdot \rho \cdot A \cdot v^3$$

Plate



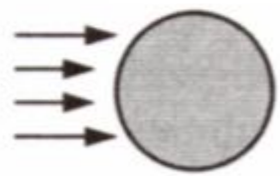
$c_W = 1{,}1 \ldots 1{,}3$

Cylinder



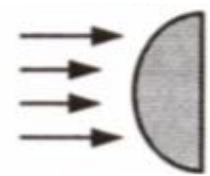
$c_W = 0{,}6 \ldots 1{,}0$

Sphere



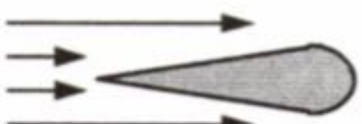
$c_W = 0{,}3 \ldots 0{,}4$

Semi sphere front



$c_W = 0{,}4$ closed
$c_W = 0{,}34$ back open

Cone with semi sphere

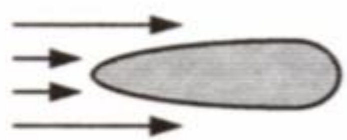


$c_W = 0{,}16 \ldots 0{,}2$

Semi sphere with cone

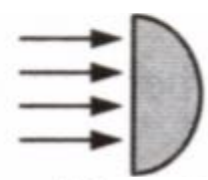
$c_W = 0{,}07 \ldots 0{,}09$

Streamlined body



$c_W = 0{,}055$

Semi sphere back



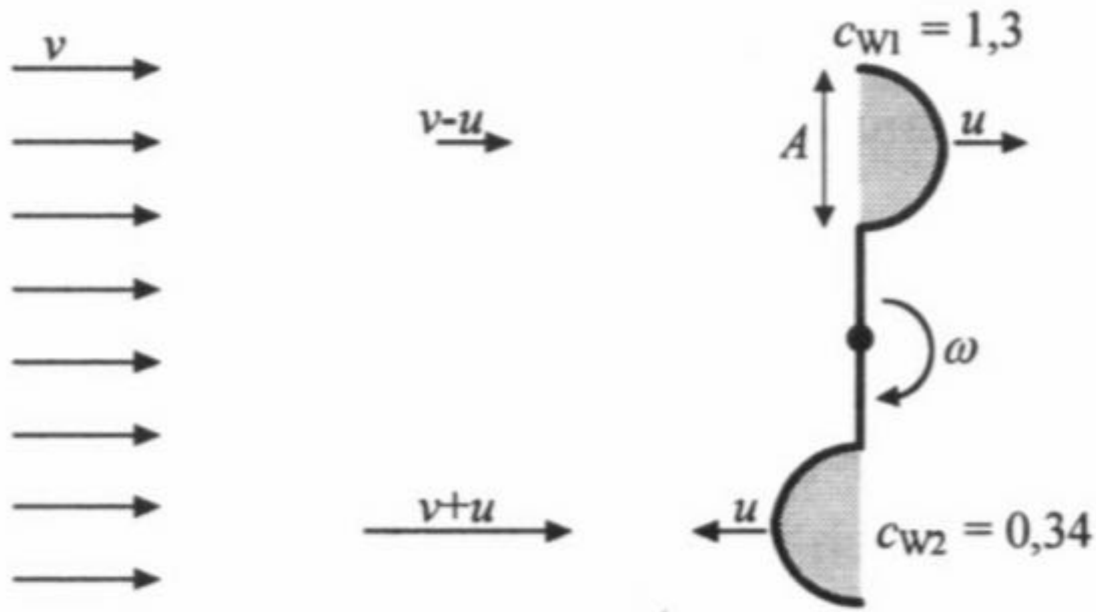
$c_W = 1{,}2$ closed
$c_W = 1{,}3$ front open

10.3.1. ANEMOMETER

$$F_W = \frac{1}{2} \cdot \rho \cdot A \cdot c_W \cdot v^2 \quad and \quad P_W = F_W \cdot u$$

$$F_W = \frac{1}{2} \cdot \rho \cdot A \cdot [c_{W1} \cdot (v-u)^2 - c_{W2} \cdot (v+u)^2]$$

$$P_W = \frac{1}{2} \cdot \rho \cdot A \cdot [c_{W1} \cdot (v-u)^2 - c_{W2} \cdot (v+u)^2] \cdot u$$



wind velocity

flow velocity

circumferenti al speed

10.3.2. DRAG OF ANEMOMETER

$$P_W = \frac{1}{2} \cdot \rho \cdot A \cdot \left[c_{W1} \cdot (v-u)^2 - c_{W2} \cdot (v+u)^2\right] \cdot u$$

$$c_{pw} = \frac{P_w}{P_0} = \frac{c_{W1} \cdot (v-u)^2 - c_{W2} \cdot (v+u)^2}{v^3} \cdot u$$

$$c_{pw} = \frac{P_w}{P_0} = \left\{c_{W1} \cdot \left(1-\frac{u}{v}\right)^2 - c_{W2} \cdot \left(1+\frac{u}{v}\right)^2\right\} \cdot \frac{u}{v}$$

$$opt.\ c_{pw}\ when\ c_{W2} = 0$$

$$c_{pw} = \left\{c_{W1} \cdot \left(1-\frac{u}{v}\right)^2\right\} \cdot \frac{u}{v}$$

$$max.\ c_{pw}\ when\ \frac{u}{v} = \frac{1}{3}$$

$$max.\ c_{pw} = \left\{c_{W1} \cdot \left(1-\frac{1}{3}\right)^2\right\} \cdot \frac{1}{3} = c_{W1} \cdot \frac{4}{27}$$

$$with\ c_{W1} = 1.3\ max.\ c_{pw} = 1.3 \cdot \frac{4}{27} = 0.193$$

10.4. HISTORY OF LIFT

Johann Bernoulli
(* 1667, † 1748)

$$p \cdot V + \frac{1}{2} m \cdot v^2 + m \cdot g \cdot h = const. \qquad /V$$

Energy conservation

$$p + \frac{1}{2} \rho \cdot v^2 + \rho \cdot g \cdot h = const.$$

1895 statement "**heavier-than-air flying machines are impossible**" (Australian Institute of Physics), followed by his 1896 statement, "I have not the smallest molecule of faith in aerial navigation other than ballooning...I would not care to be a member of the Aeronautical Society." Kelvin is also known for an address to an assemblage of physicists at the British Association for the advancement of Science in 1900 in which he stated, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." A similar statement is attributed to the American physicist Albert Michelson.

William Thomson, 1st Baron Kelvin
(* 1824 - † 1907)

The **Wright Brothers** - First Flight, **1903**. Orville's brother Wilbur piloting the record **flight lasting 59 seconds over a distance of 852 feet**. The brothers began their experimentation in flight in 1896 at their bicycle shop in Dayton, Ohio.

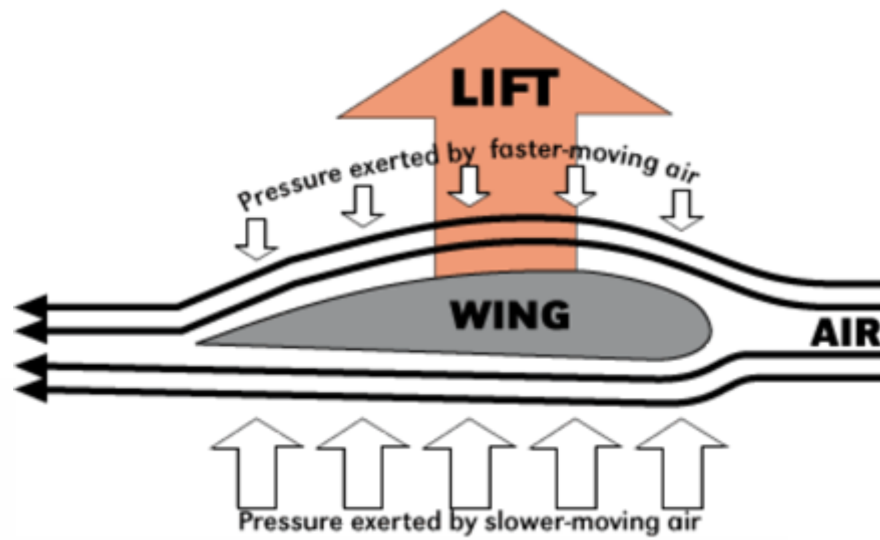
Ref.: https://www.newscientist.com/article/dn13556-10-impossibilities-conquered-by-science/

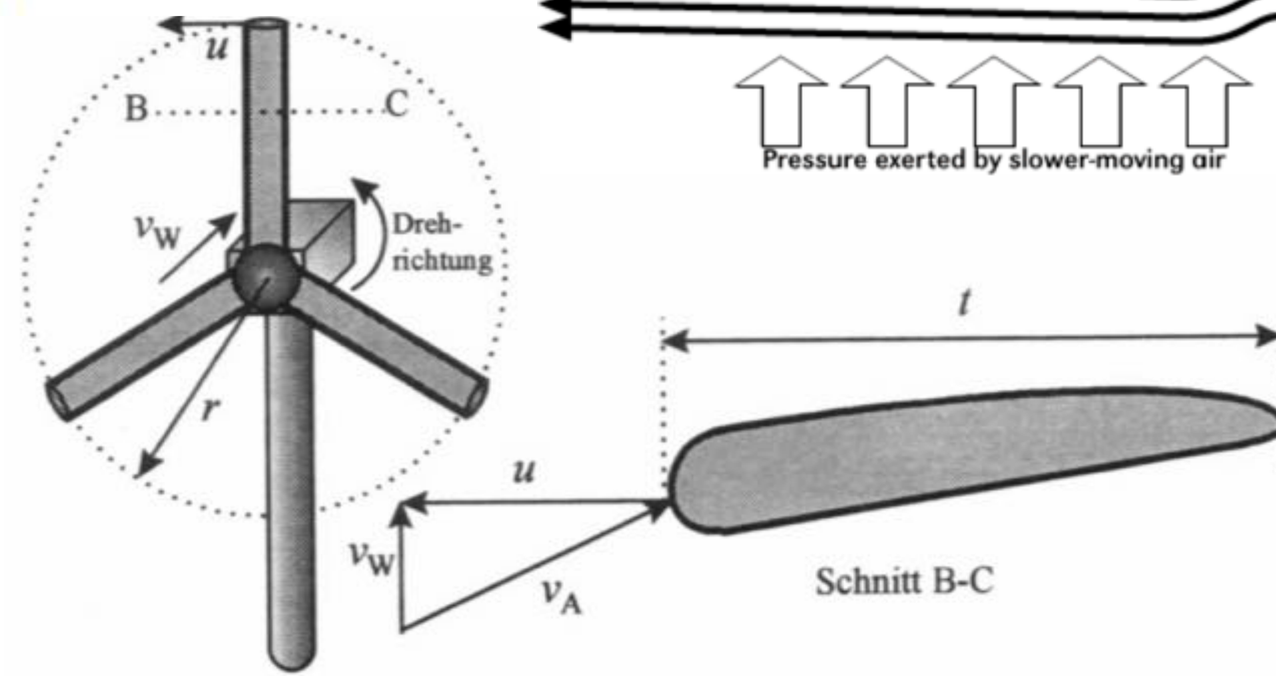
10.4.1. LIFT

$$p_1 + \frac{1}{2}\cdot\rho\cdot v_1^2 = p_2 + \frac{1}{2}\cdot\rho\cdot v_2^2$$ *Bernoulli*

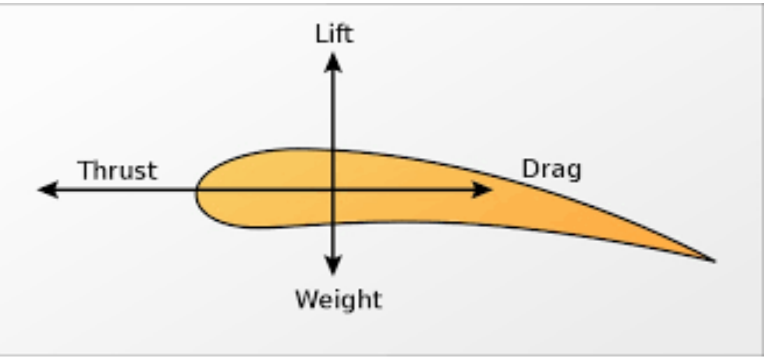
$$p_1 - p_2 = \frac{1}{2}\cdot\rho\cdot(v_2^2 - v_1^2)$$

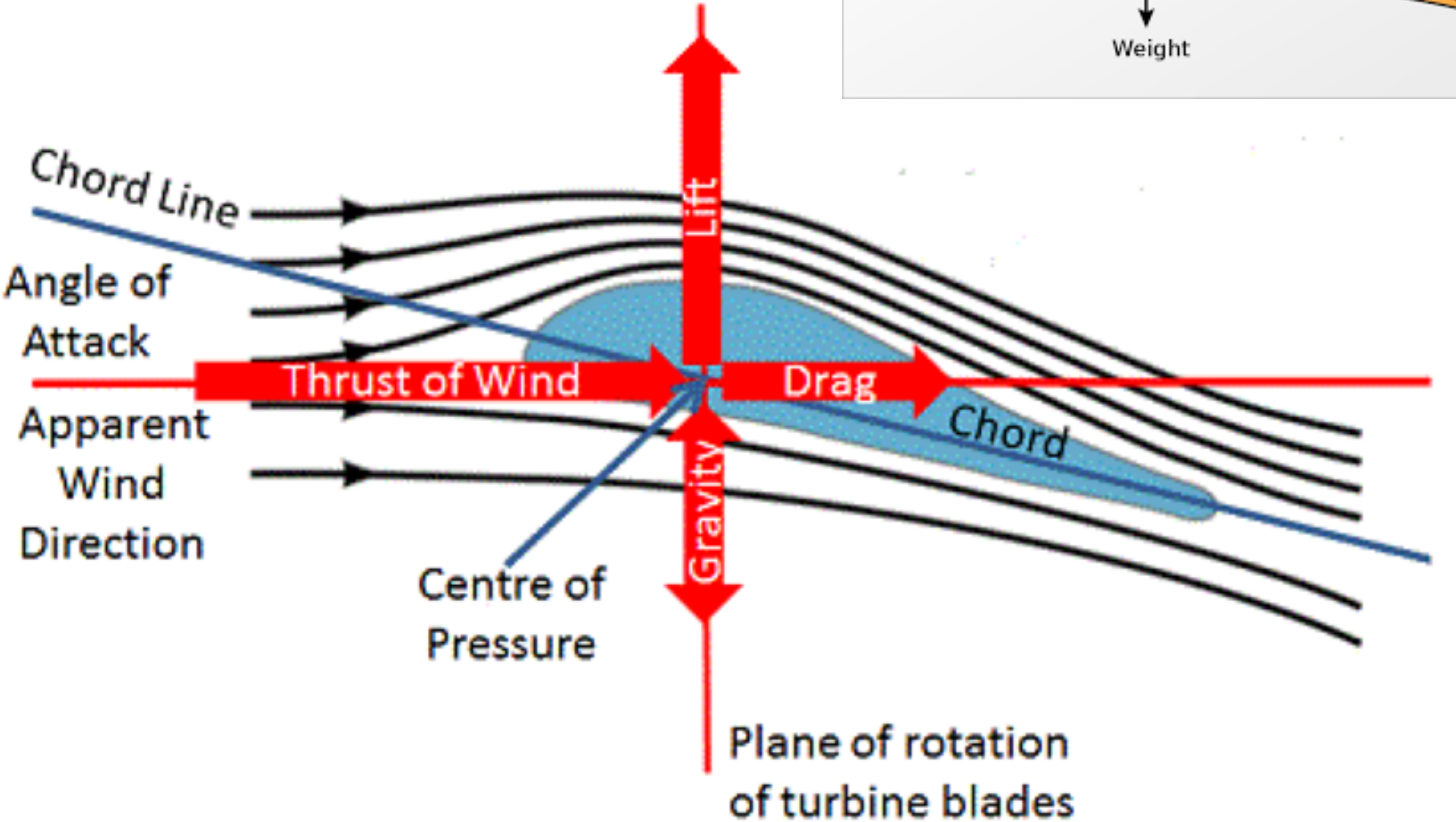
$$F = \Delta p \cdot A$$



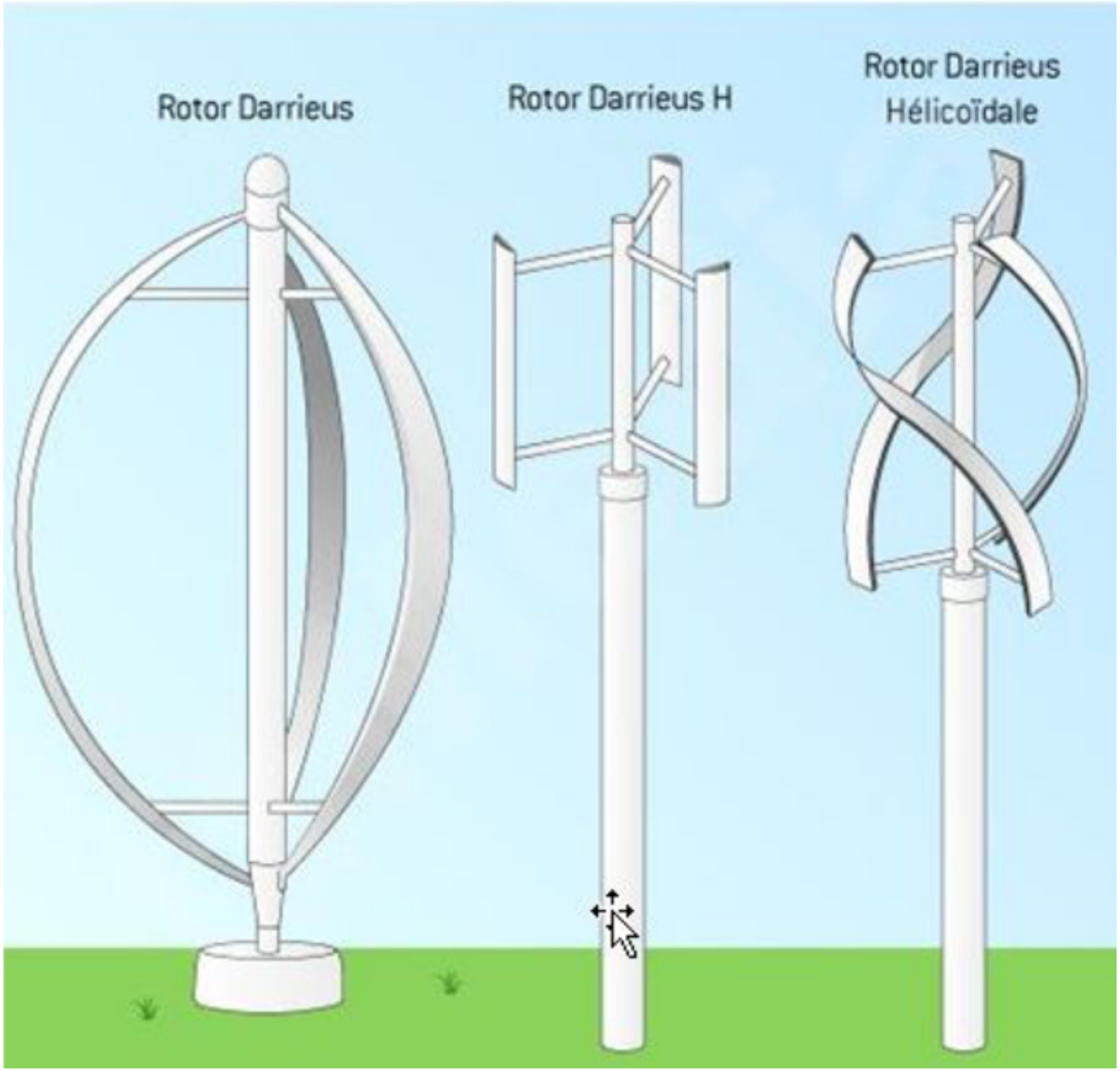


10.4.2. AEROFOIL LIFT & DRAG – WIND TURBINE BLADES

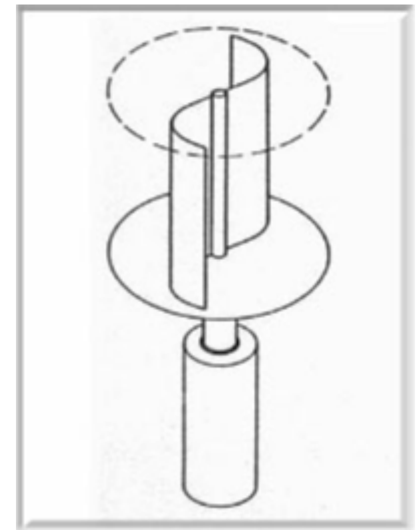




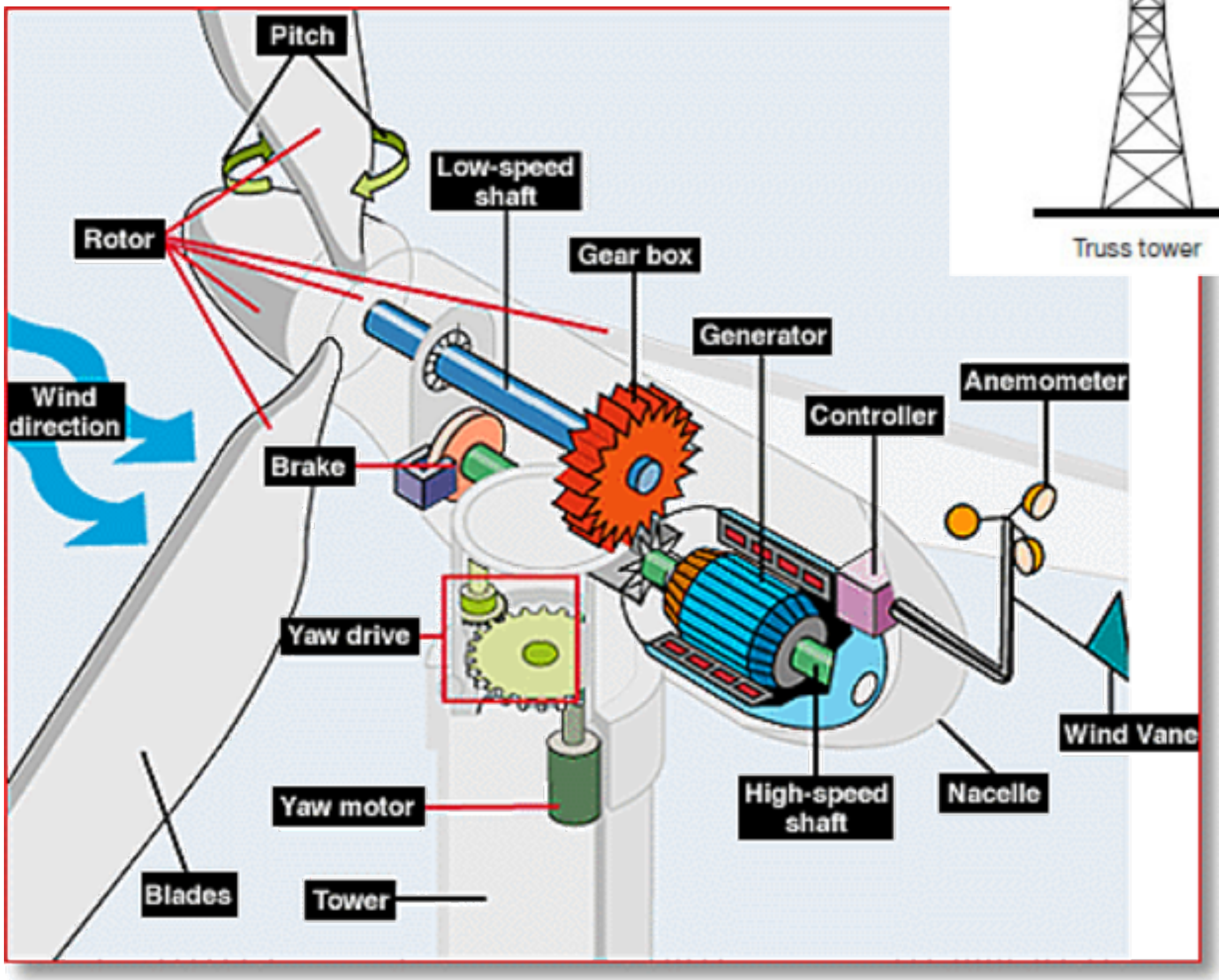
10.4.3. ROTOR TYPE (VERTICAL AXIS)

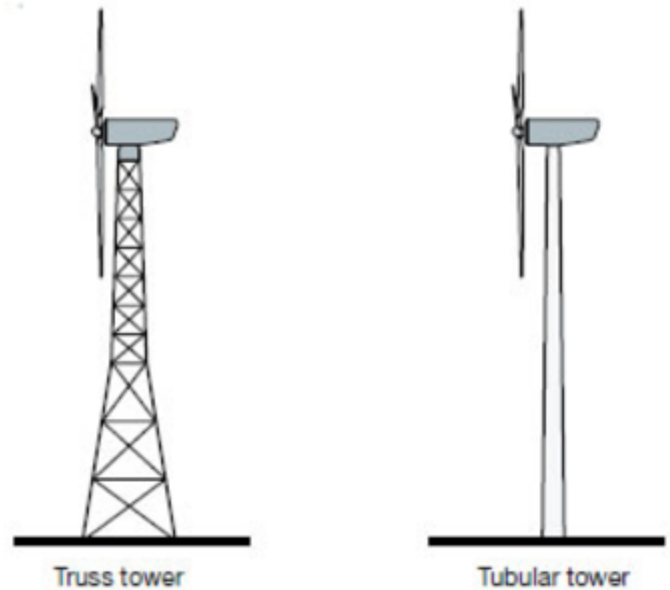


Savonius



10.4.4. ROTOR (HORIZONTAL AXIS)





10.4.5. TIP SPEED RATIO

Tip-speed ratio is the ratio of the speed of the rotating blade tip to the speed of the free stream wind.

There is an optimum angle of attack which creates the highest lift to drag ratio.

Because angle of attack is dependant on wind speed, there is an optimum tip-speed ratio

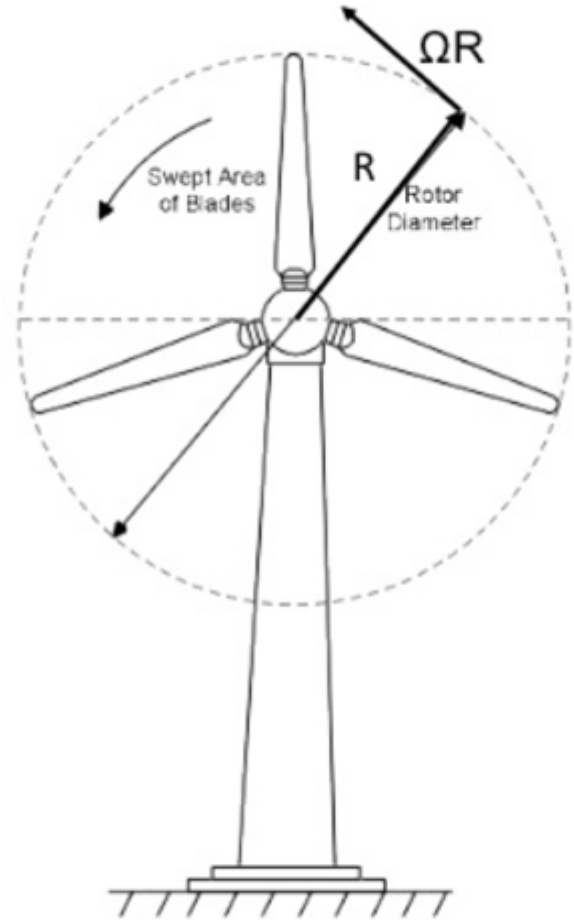
$$TSR = \frac{\Omega R}{V}$$

Where,

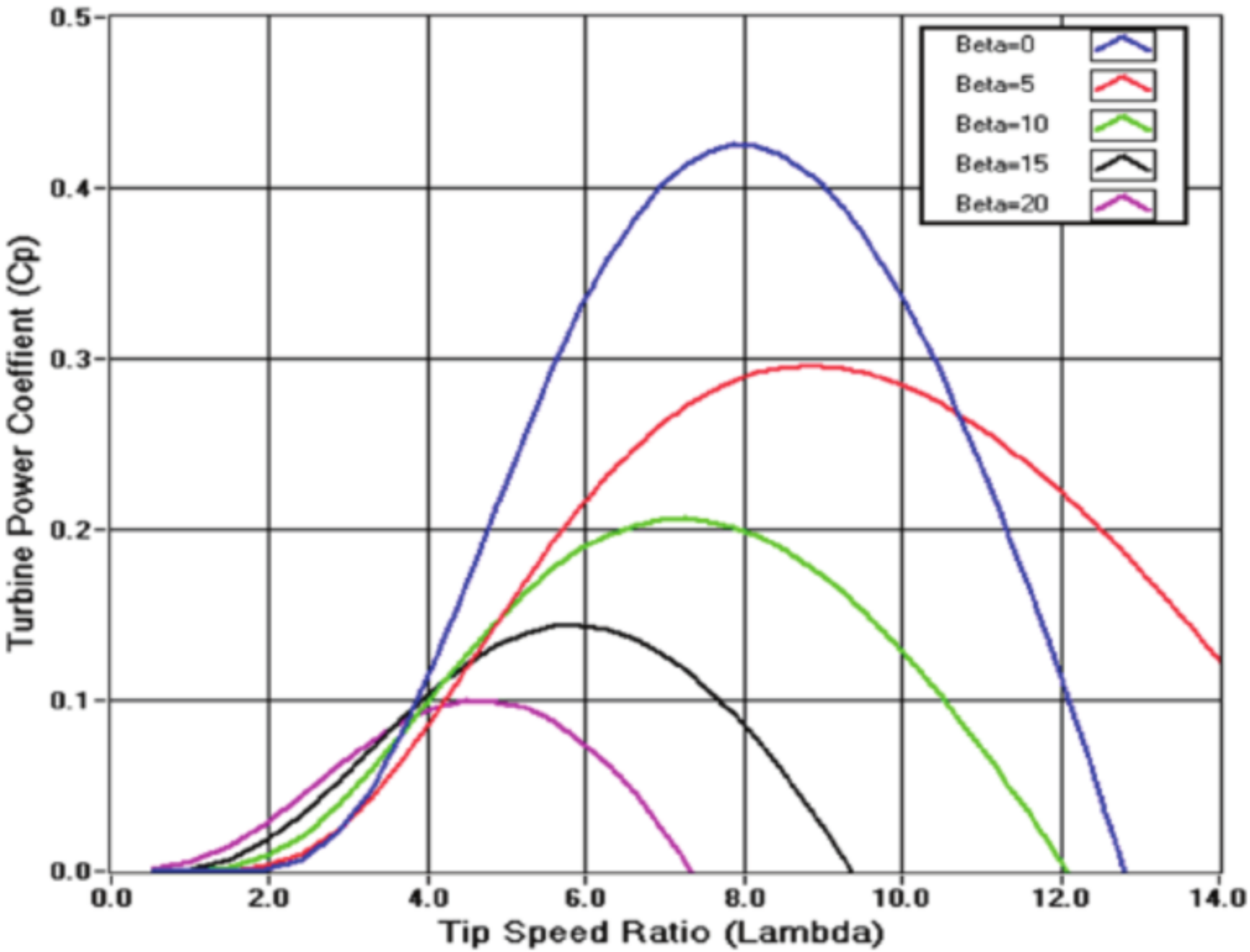
Ω = rotational speed in radians /sec

R = Rotor Radius

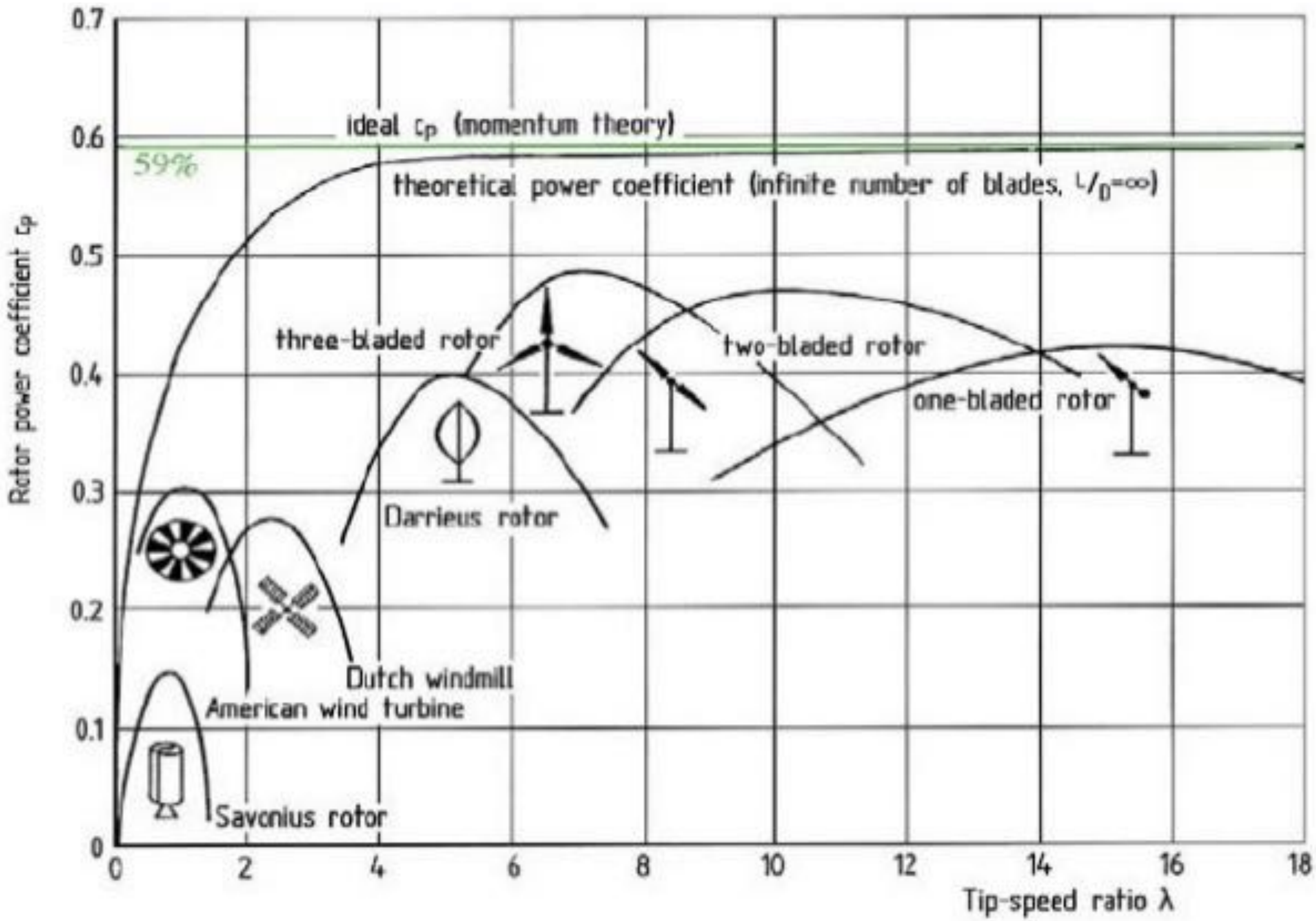
V = Wind "Free Stream" Velocity



10.4.6. POWER COEFFICIENT (c_P) VS TIP SPEED RATIO (TSR)

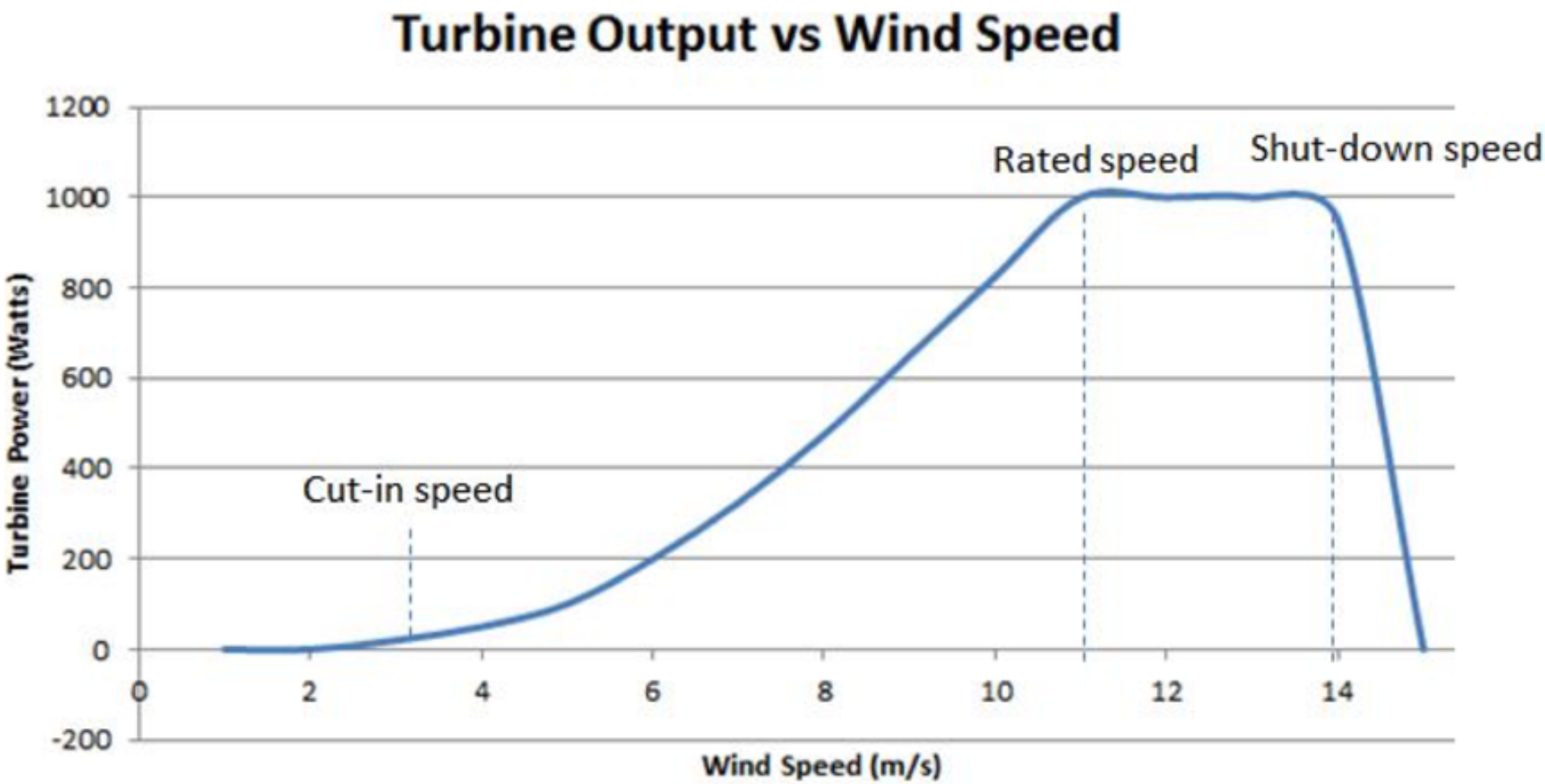


10.4.7. POWER COEFFICIENT (c_P) OF TURBINES



Coefficient of Performance (efficiency) of wind rotors of various designs
(Erich Hau, *Wind Turbines*, 2nd ed., 2006, Figure 5.10, page 101)

10.4.8. WIND POWER CONTROL

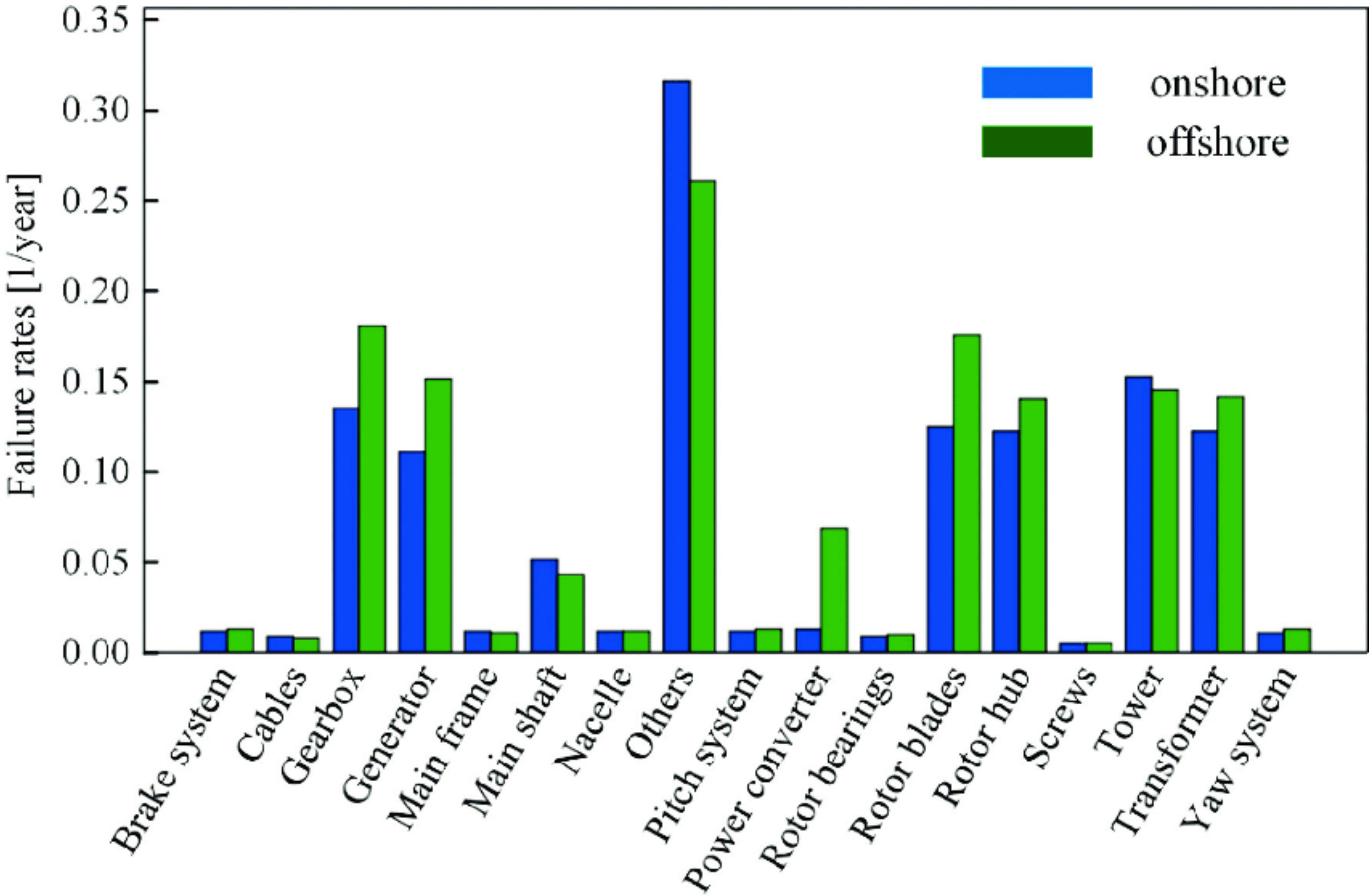


10.5. CONTROL & FAILURE

10.5.1. FAILURE (SPEED)

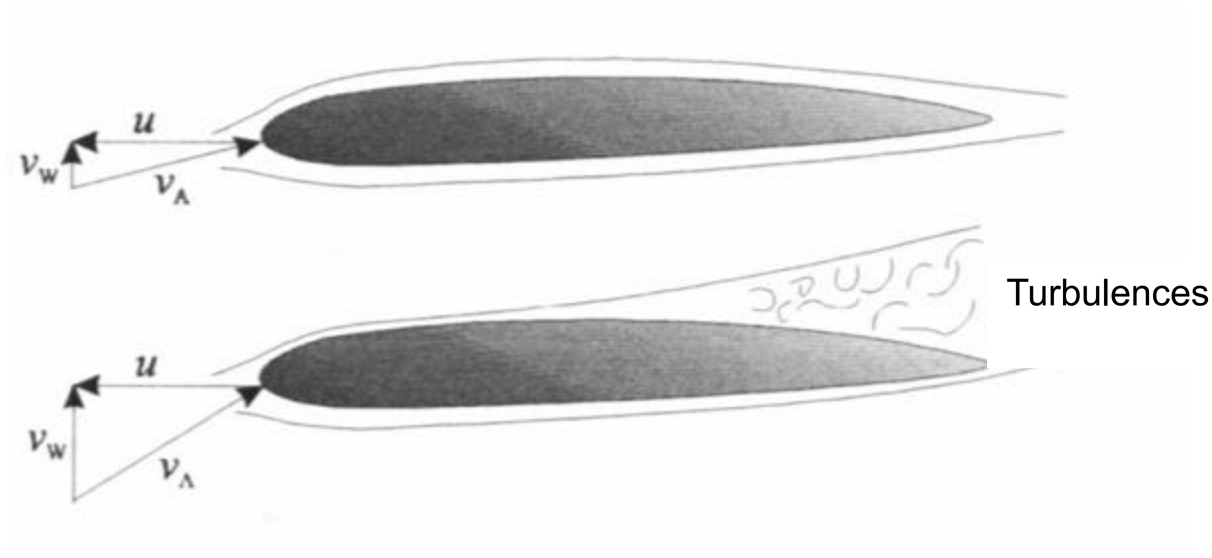
10.5.2. FAILURE (POWER)

10.5.3. FAILURE RATES OF COMPONENTS



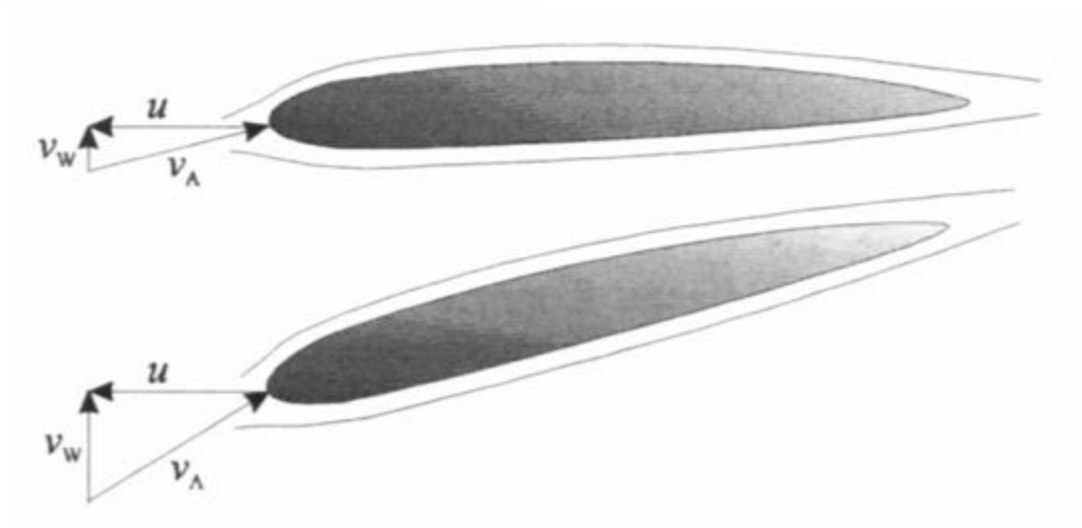
Ref.: Southern Ma, Caichao Zhu, Yao Li, “Reliability Analysis of Wind Turbines” (2018), DOI:10.5772/intechopen.74859 In book: Stability Control and Reliable Performance of Wind Turbines

10.5.4. POWER CONTROL

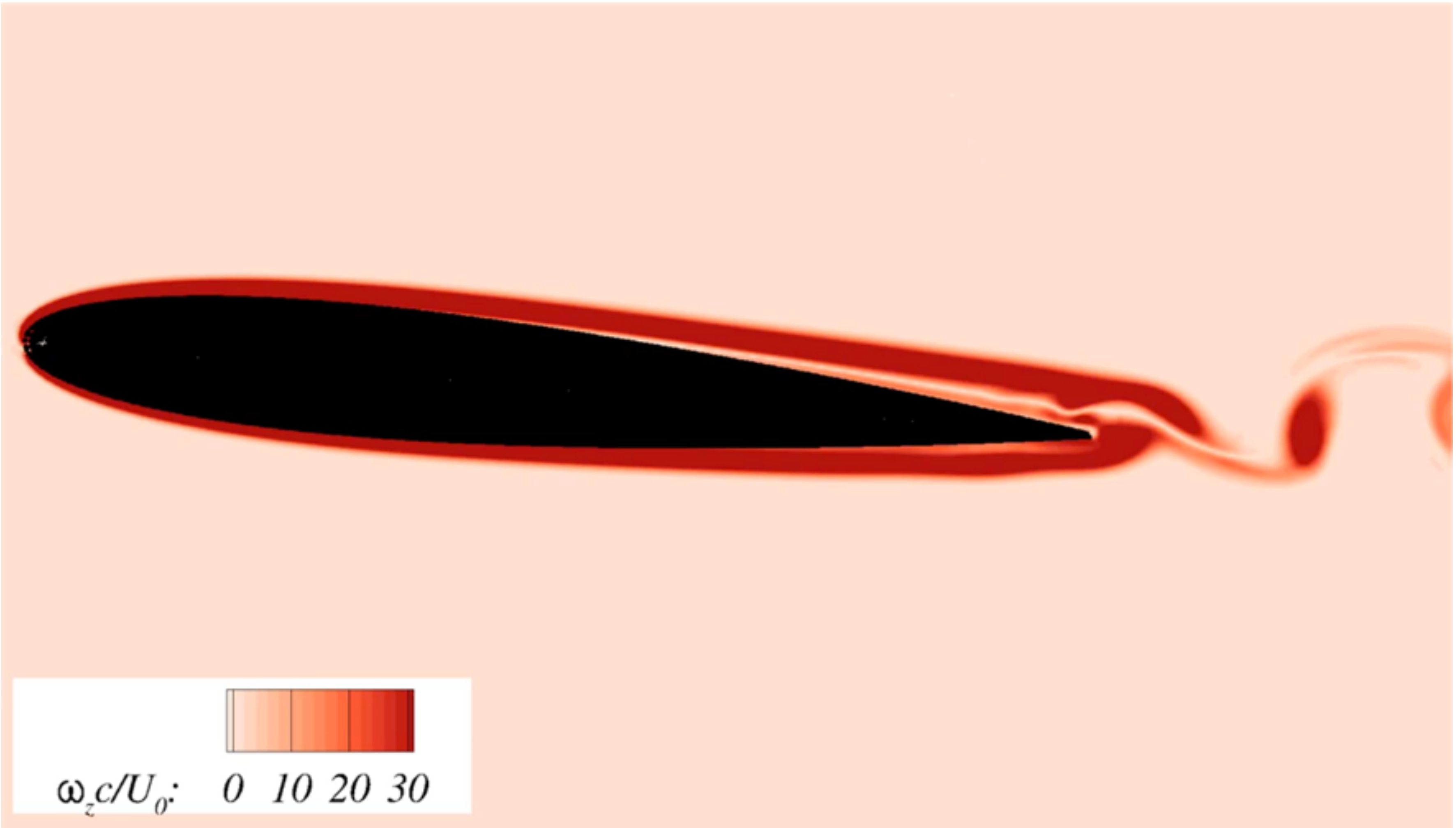


STALL-EFFECT

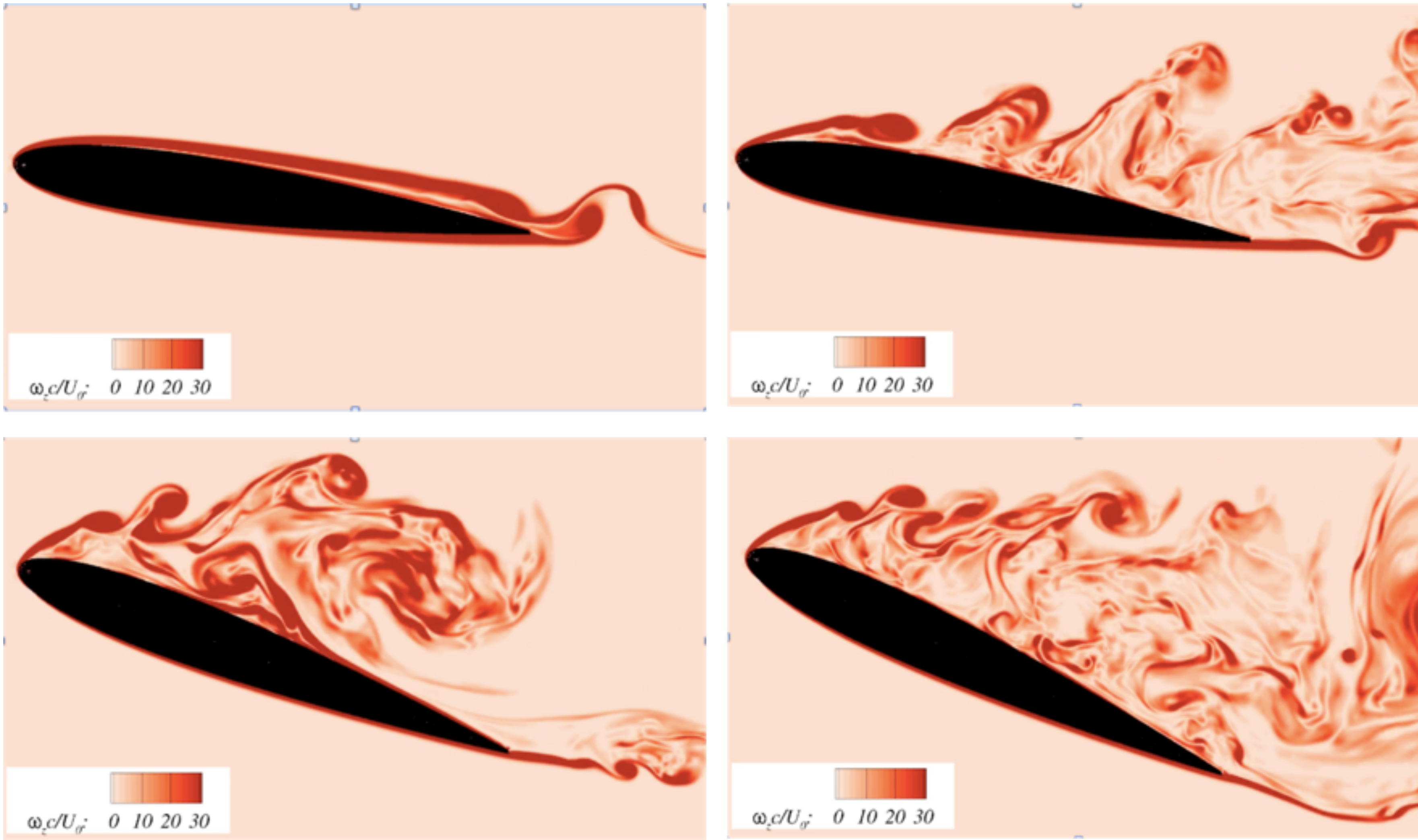
PITCH-CONTROL



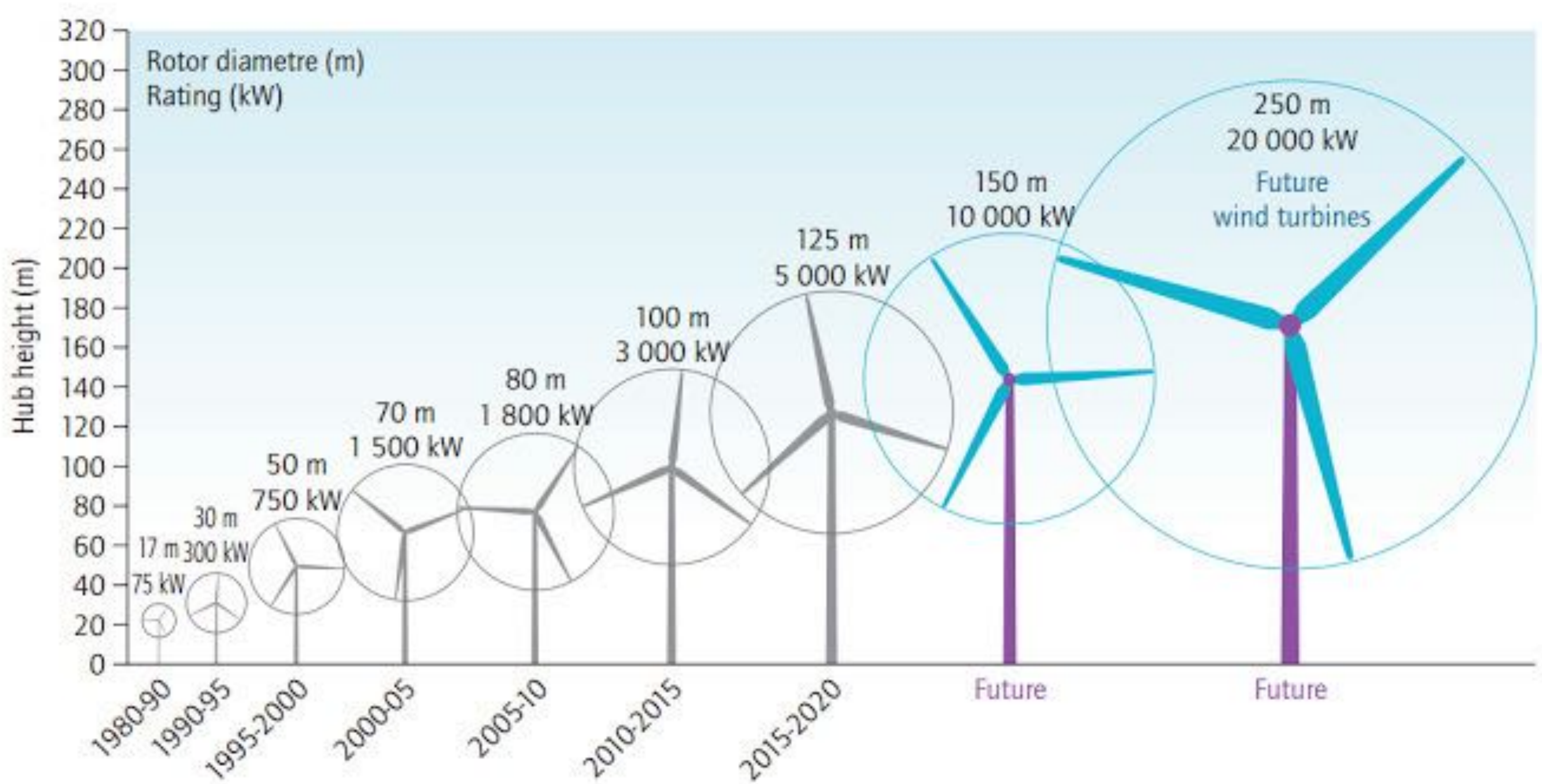
10.5.5. STALL-EFFECT FILM



10.5.6. STALL-EFFECT SEQUENCES



10.6. WIND POWER



Source: adapted from EWEA, 2009.

Ref.: Book: "Conceptual Framework of Antecedents to Trends on Permanent Magnet Synchronous Generators for Wind Energy Conversion System" (2017), Govindarajan, Uma; Ramachandaramurthy, Vigna K.; Oli, Sudar; Tamizharasan, T.; Kasinathan, Padmanathan

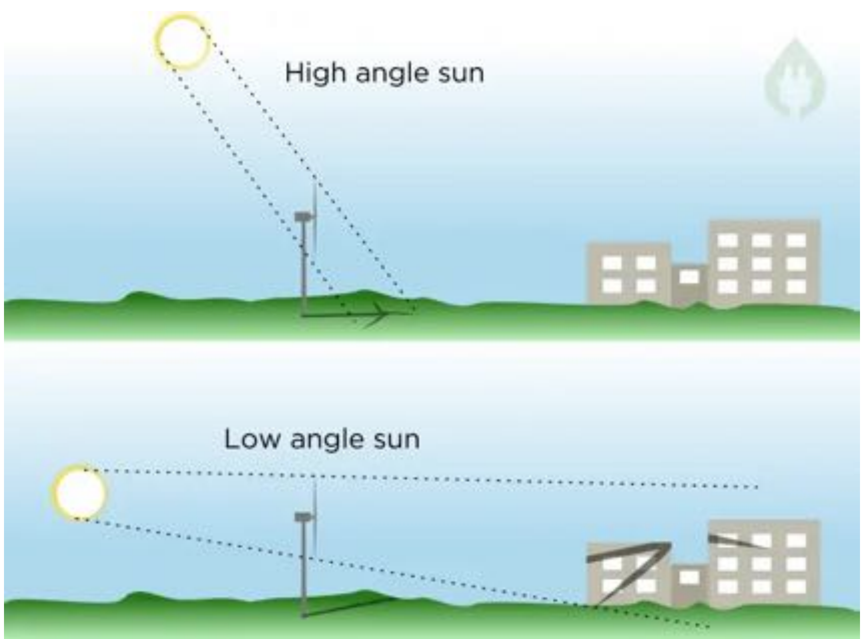
10.6.1. CONCRETE SUPPORT STRUCTURES

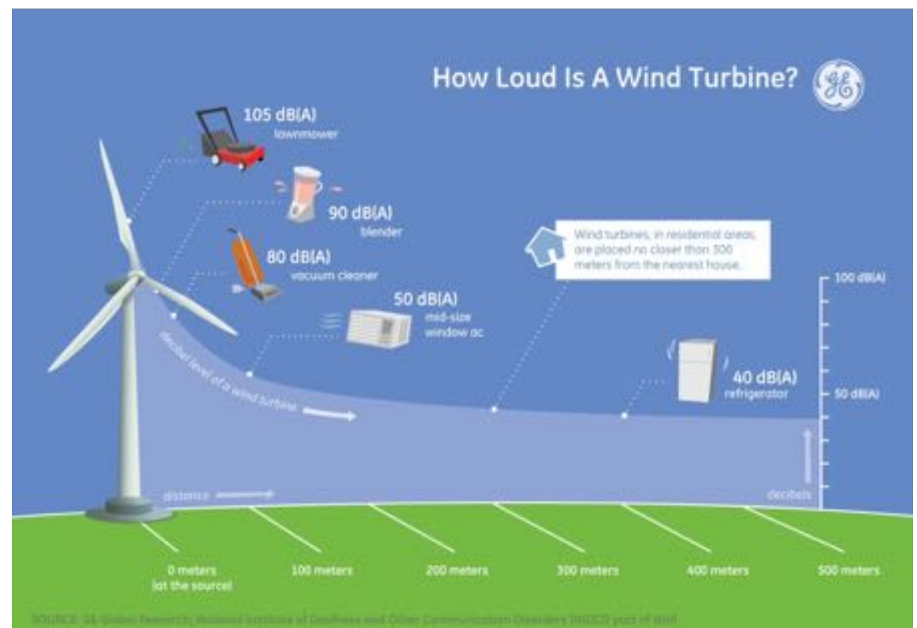
335 m^3 of concrete

Ref.: Alexandre Mathern, Christoph von der Haar and Steffen Marx, "Concrete Support Structures for Offshore Wind Turbines: Current Status, Challenges, and Future Trends", Energies 2021, 14(7), 1995; https://doi.org/10.3390/en14071995

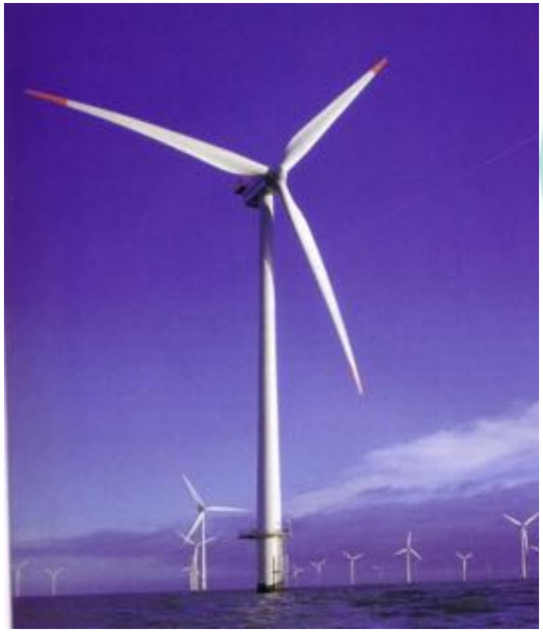
10.6.2. LIFECYCLE OF WINDTURBINE IS 20-25 YEARS

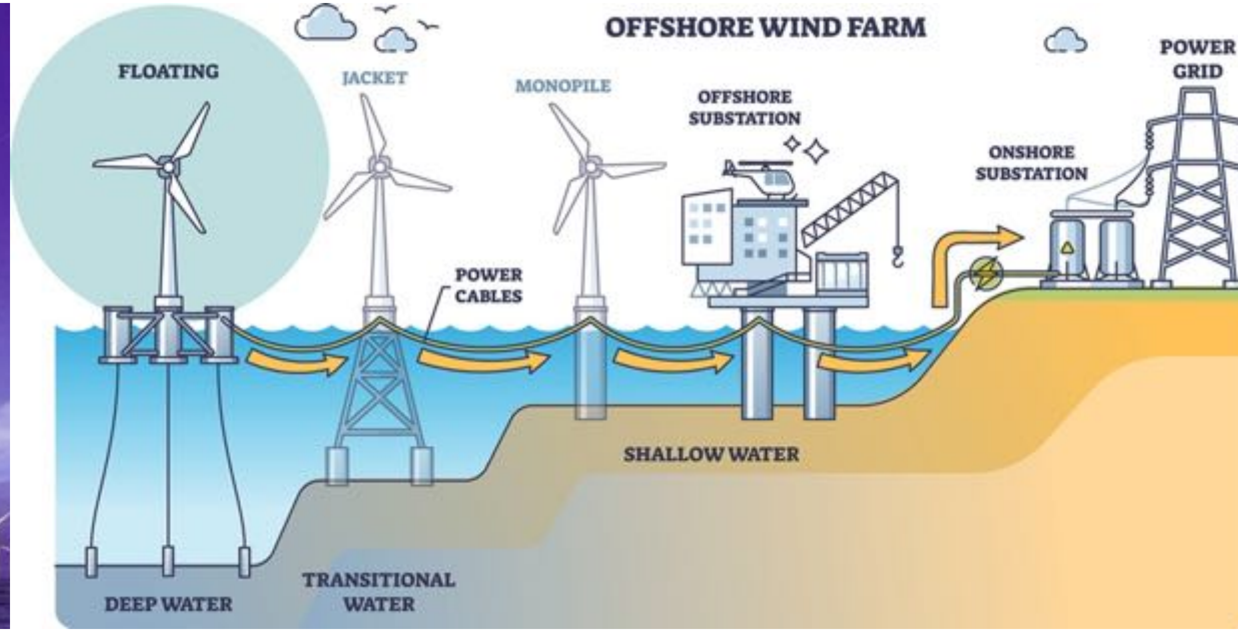
10.6.3. BIRD STRIKE, ICE THROW, SHADOW FLICKER AND NOIS

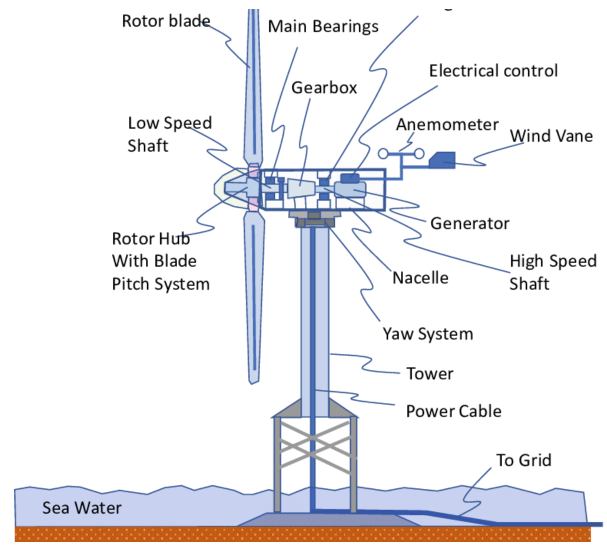




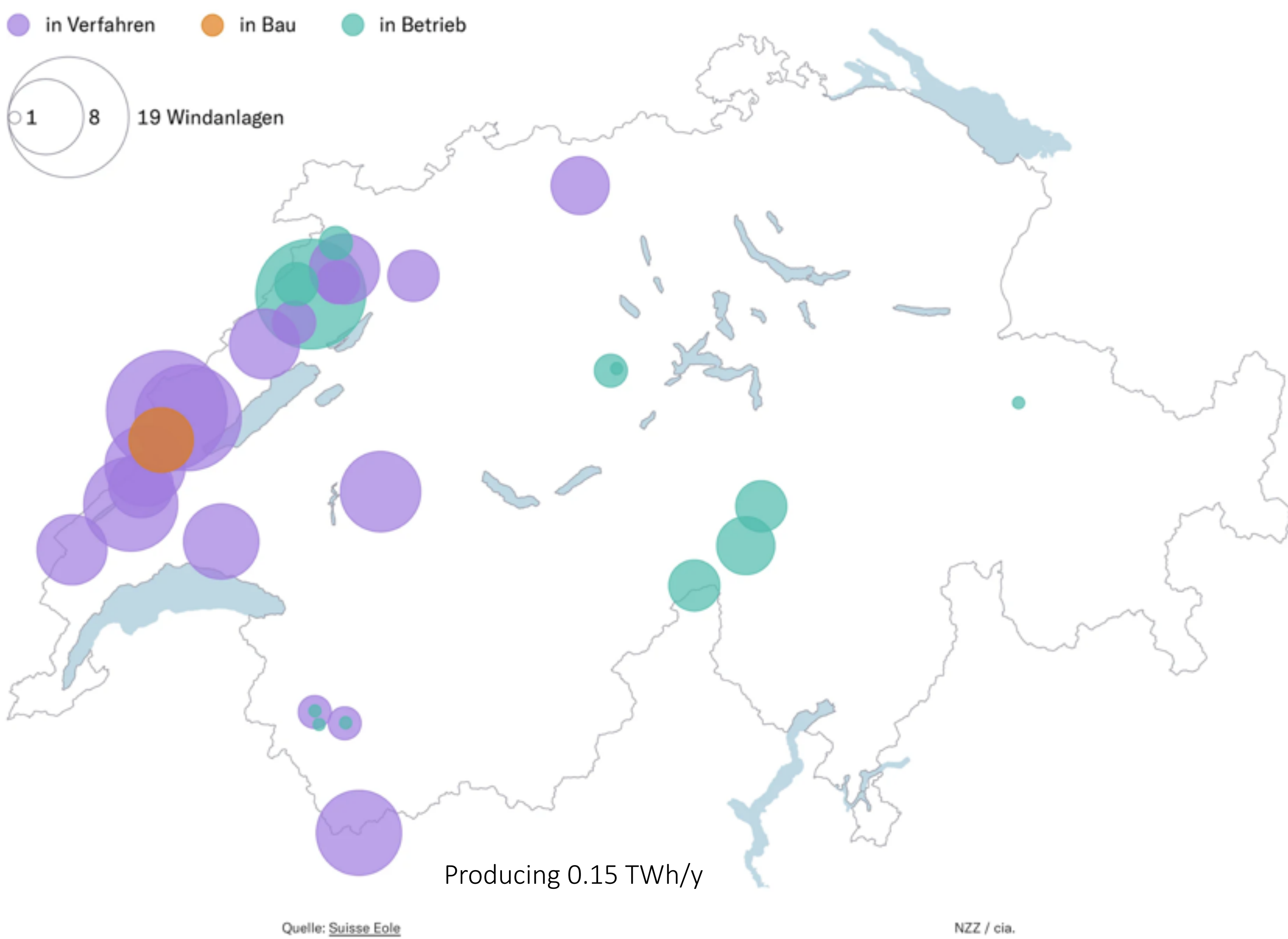
10.6.4. OFFSHORE







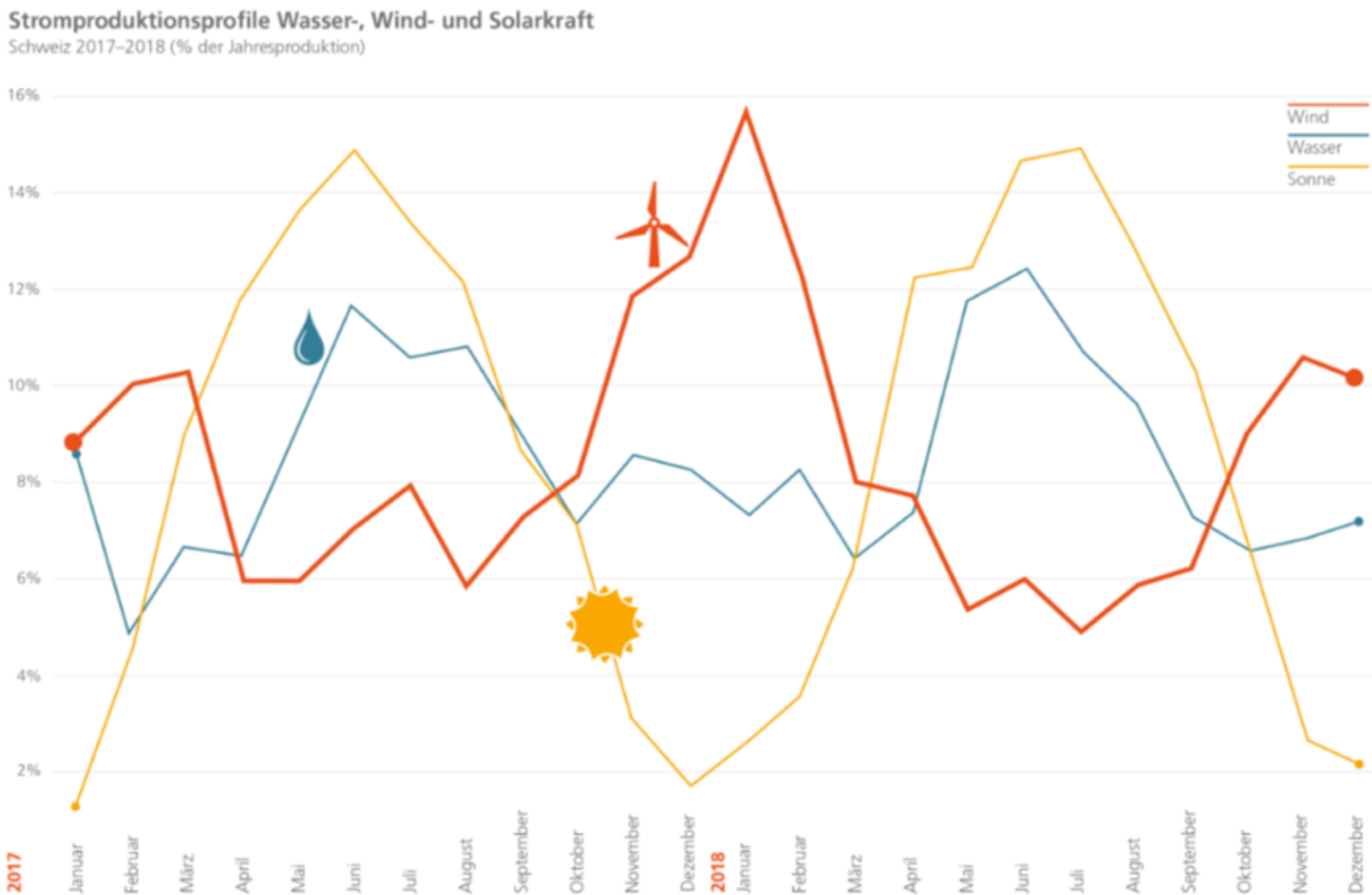
10.7. WIND TURBINES IN SWITZERLAND



Producing 0.15 TWh/y

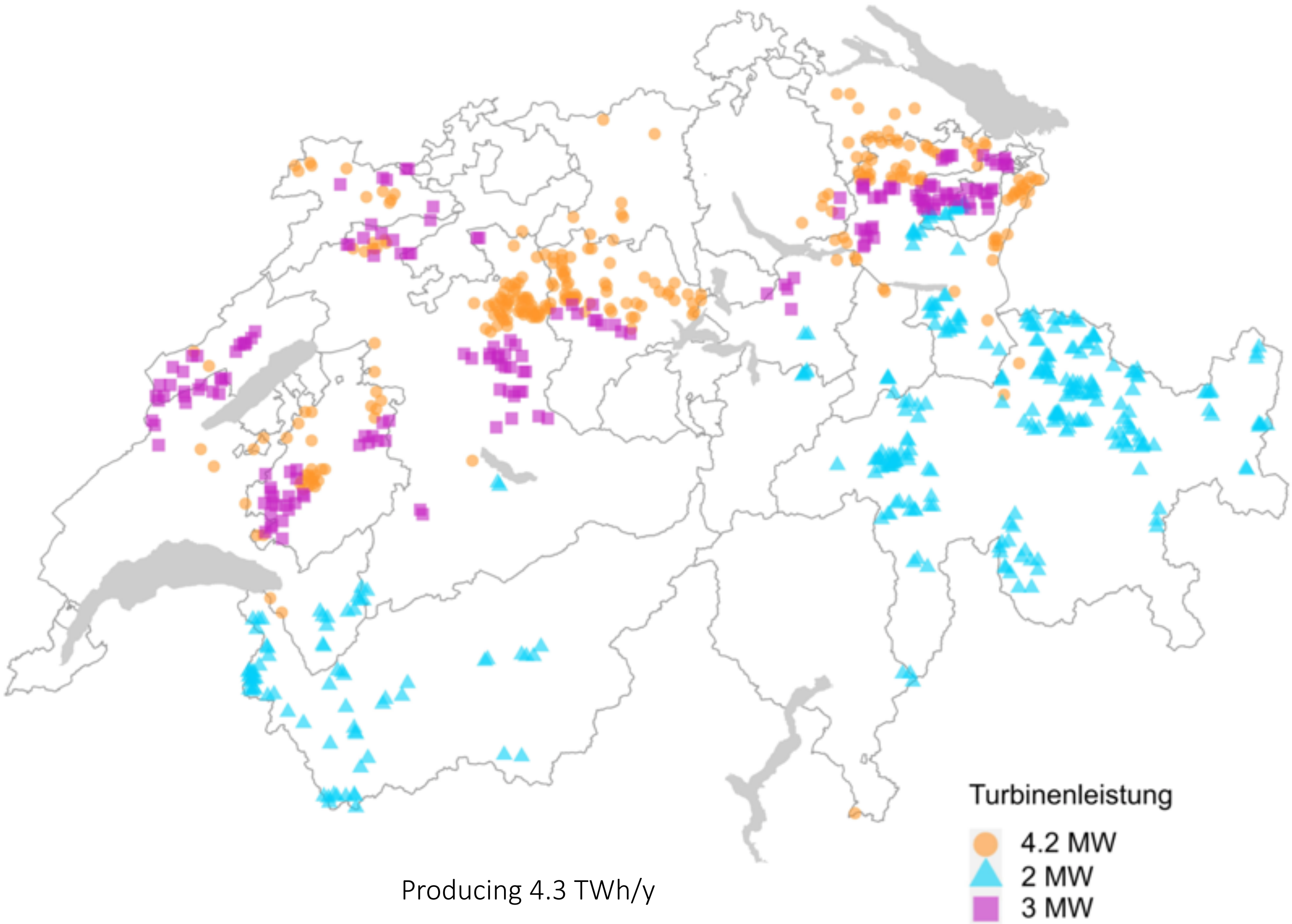
Ref.:https://www.nzz.ch/wirtschaft/warum-in-der-schweiz-nur-ein-dutzend-windparks-stehen-ld.1714458

10.7.1. ELECTRICITY PRODUCTION PROFILE



Ref.: https://www.bfe.admin.ch/bfe/de/home/versorgung/erneuerbare-energien/windenergie.html

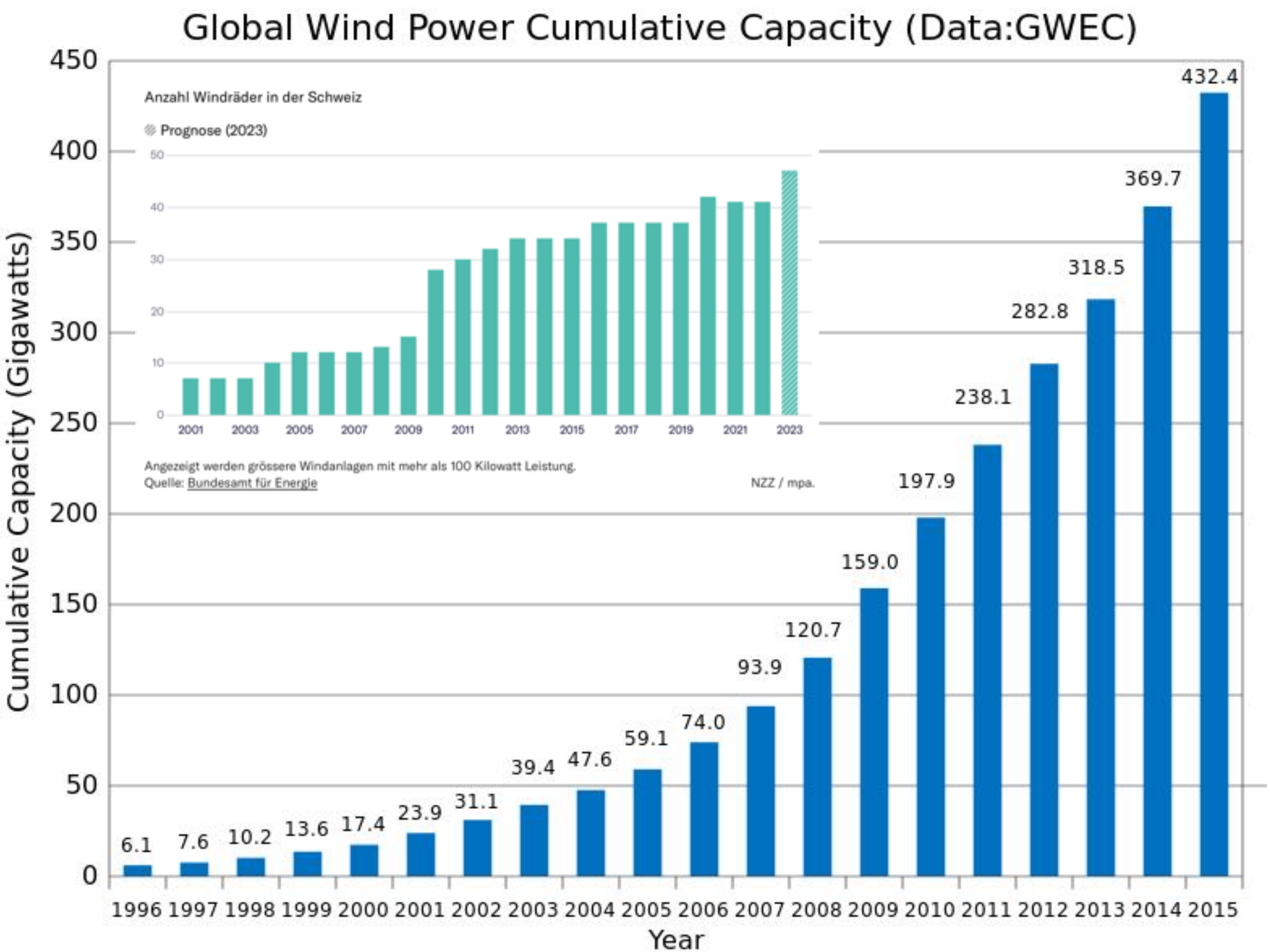
10.7.2. 760 POTENTIAL WIND TURBINES



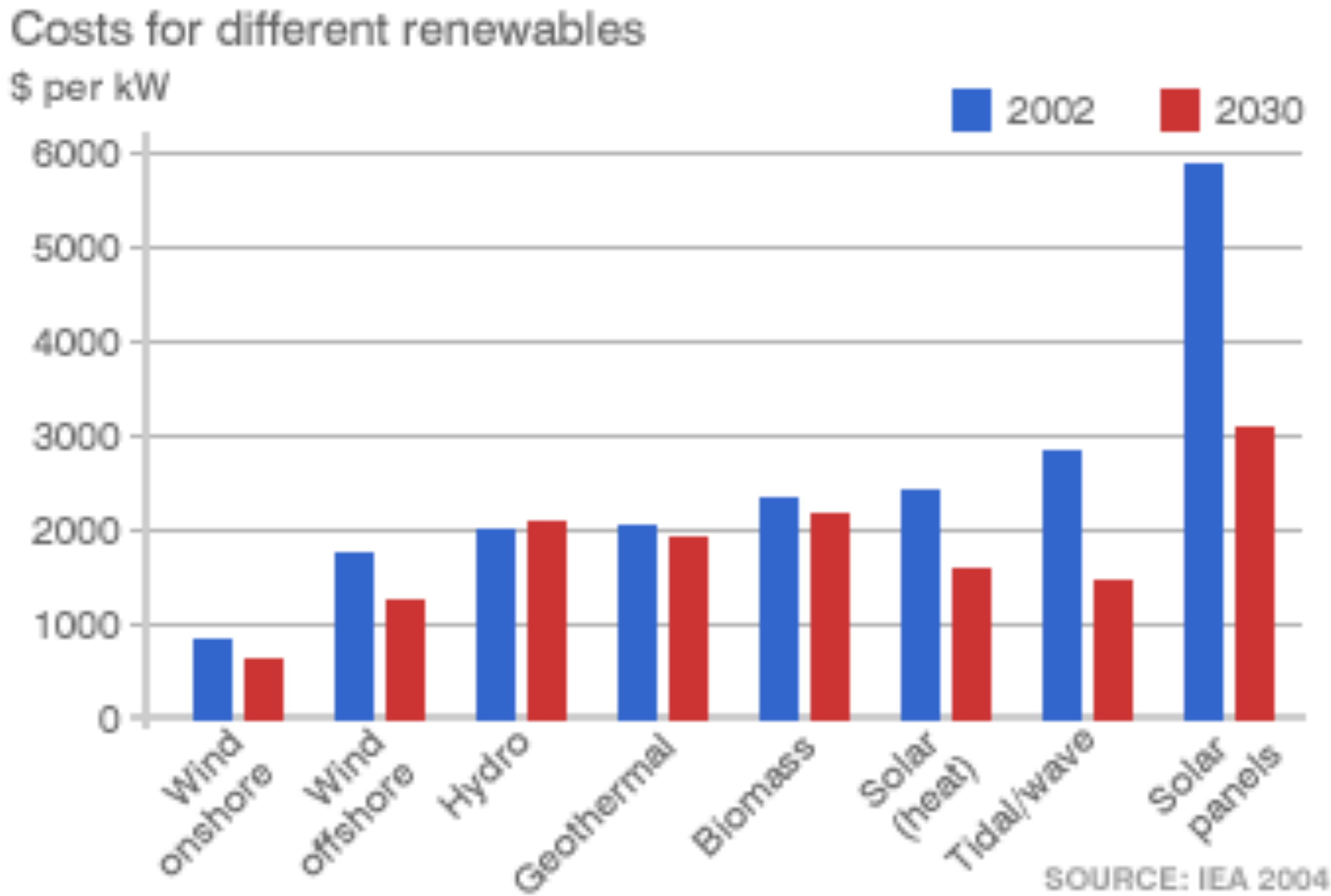
Producing 4.3 TWh/y

Ref.: https://ethz.ch/de/news-und-veranstaltungen/eth-news/news/2023/03/wo-sollen-windraeder-in-der-schweiz-stehen.html

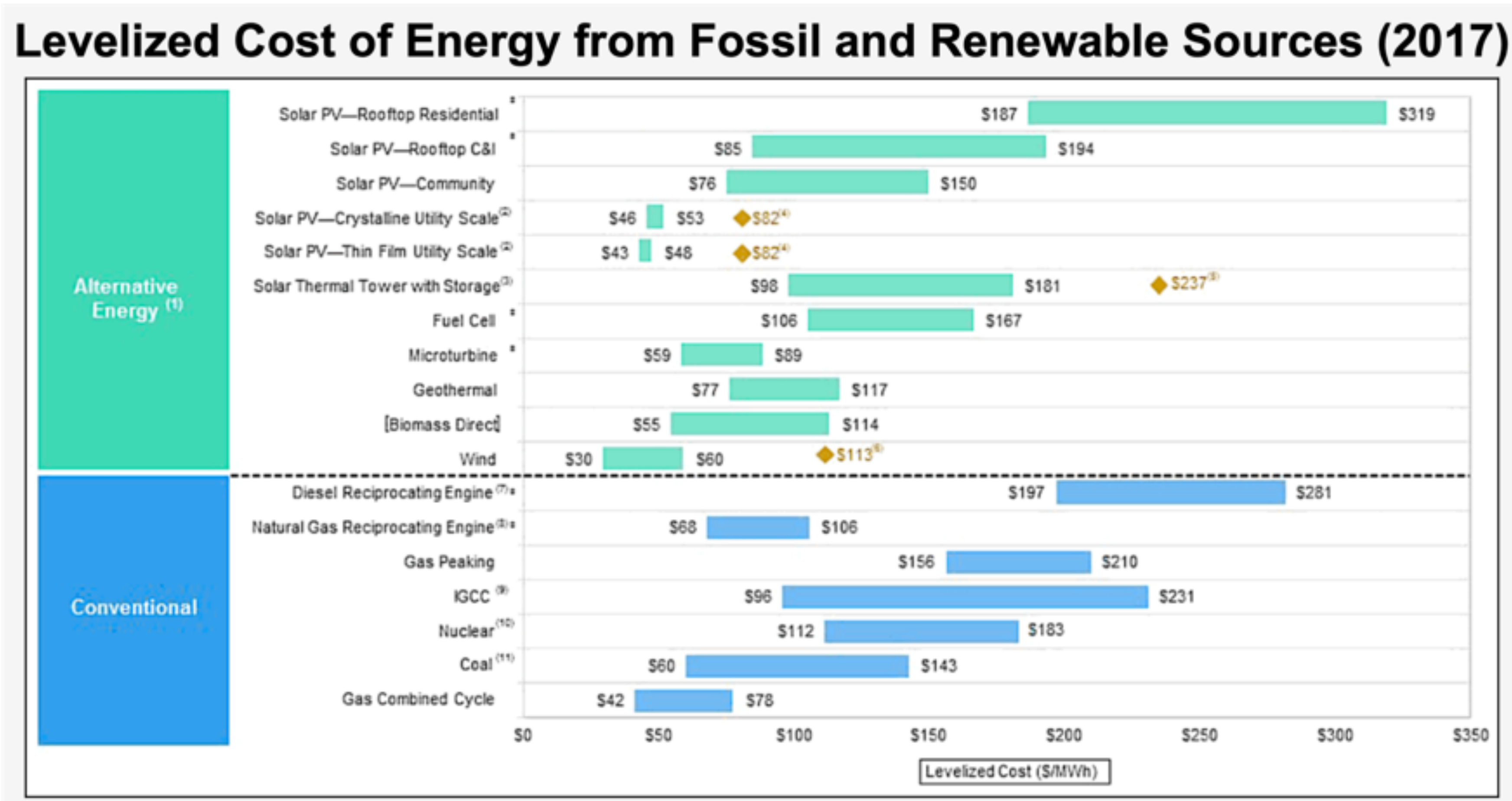
10.7.3. GLOBAL INSTALLED WIND POWER



10.7.4. CAPITAL COST OF RENEWABLE ENERGY CONVERTERS



10.7.5. LEVELIZED COST OF ENERGY



The "Levelized Cost of Energy" (LCOE) is an apples-to-apples comparison of the cost of new electricity generation from different sources. LCOE is the all-in lifetime cost of generating electricity divided by the total amount of electricity produced during the generator's lifetime, expressed in $/MWh (dollars per megawatt-hour). These are wholesale costs, but for reference, the average residential retail electricity rate in Colorado is about $120/MWh. (Figure: Lazard)

Ref.: https://energyfreedomco.org/f3-LCOE.php

EXERCICES

1) Calculate the power of the wind for disc of 1 m and 100 m diameter for a wind speed of 15 km/h and 30 km/h.

2) What is the minimum distance between wind rotors?

3) What is the size of a wind rotor in order to cover the average electricity consumption per person in Switzerland?

4) Extrapolate the installed wind power to the future and estimate, when it would cover the world energy demand.

5) Estimate the cost of a 2MW wind turbine and the pay back time if the electricity is sold for 0.05 CHF/kWh at no operation cost.