Physics and engineering of wind power systems

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- **Present status of wind energy use**
- Physical and meteorological basics
- Techniques of wind converters
- Market introduction and problems

Structure of my presentation

Wind energy use – a good idea since a lot of years

Wind energy use worldwide (values rounded)

	Rated Capacity [GW]	Share worldwide [%]
	2019	2019
China	236,40	36,3
USA	105,57	16,2
Germany	61,4	9,4
India	37,51	5,8
United Kingdom	23,34	3,6
France	16,64	2,6
Brazil	15,45	2,4
Canada	13,41	2,1
Sweden	8,8	1,4
Remaining countries	132,12	20
total	**~ 651**	**~ 100**

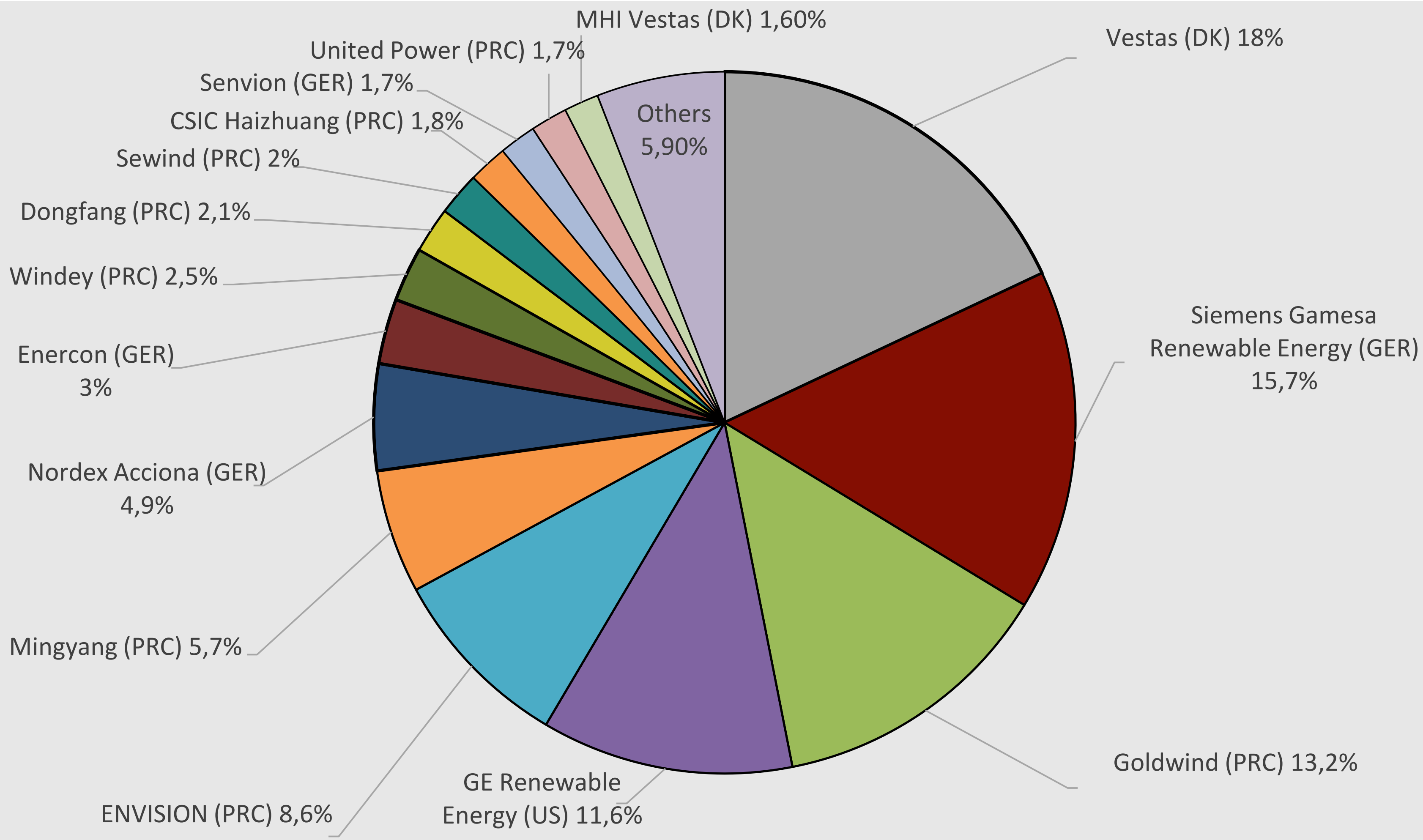
In 2021 4 GW of offshore wind power will be added across europe – in Germany only 3,1 GW by 2025.

Germany detailed: ~ 53 GW & Onshore ~ 8 GW Offshore (2019)

Compared to Germany in 2003: only 14,6 GW Onshore

Sources: https://www.volker-quaschning.de/datserv/windinst/index.php

Worldwide wind use – present status



New erected capacity 2019:

63 GW

Source: https://gwec.net/wind-turbine-sizes-keep-growing-as-industry-consolidation-continues/

Shares of the suppliers in the world market in 2019

- Present status of wind energy use
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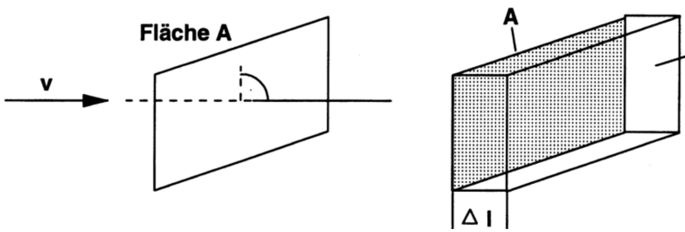
Structure of my presentation

For Germany

Derivative of the equation with steady velocity of wind v



$$\Delta V = A \cdot \Delta l$$

$$v = \frac{\Delta l}{\Delta t}$$

$$\Delta V = A \cdot v \cdot \Delta t$$

Kinetic energy E of a mass element Δ m

$$\Delta E = \tfrac{1}{2} \Delta m \, v^2$$

$$\Delta m = \Delta V \cdot \rho_L$$

$$\Delta E = \tfrac{1}{2} \cdot A \cdot \rho_L \cdot v^3 \, \Delta t$$

$$E = \tfrac{1}{2} A \, \rho_L \cdot v^3 \cdot t$$

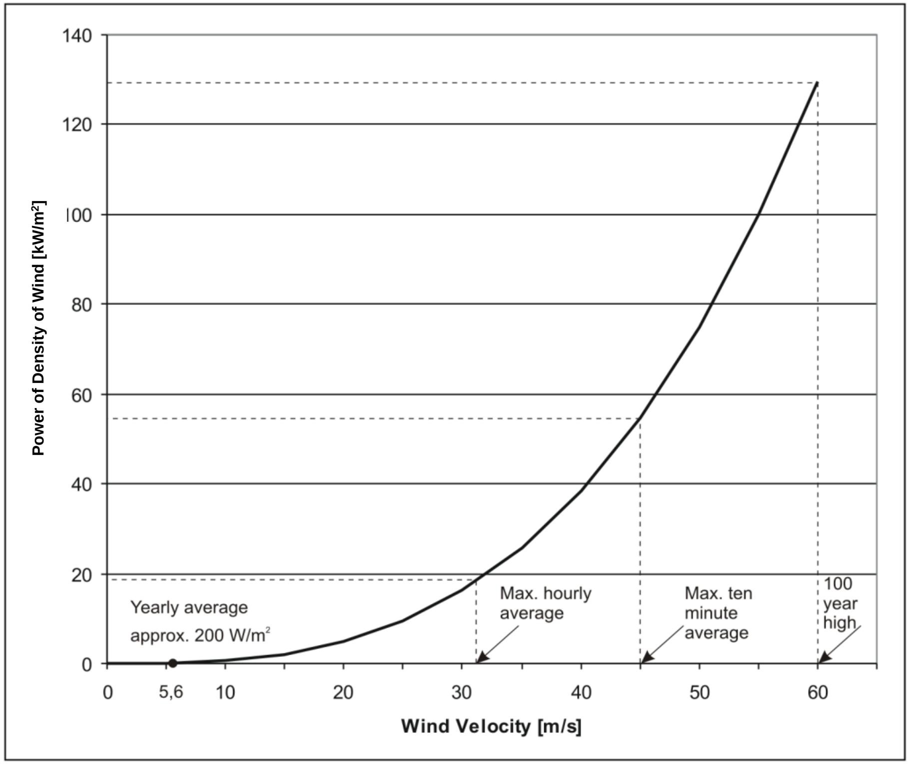
$$P = \frac{E}{t} = \tfrac{1}{2} \cdot A \cdot \rho_L \cdot v^3$$

V = volume

ρ_L = density of air = 1,2 kg/m³

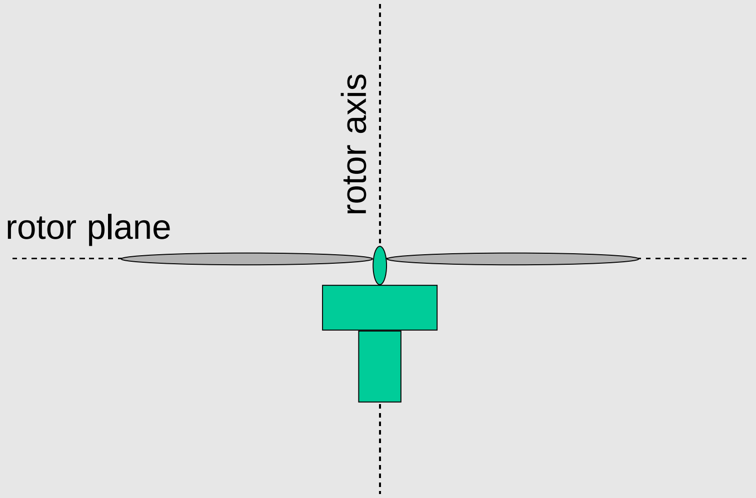
Efficiency

$$\eta = \frac{P_{el}}{\tfrac{1}{2} \cdot \rho_L \cdot A \cdot v^3}$$



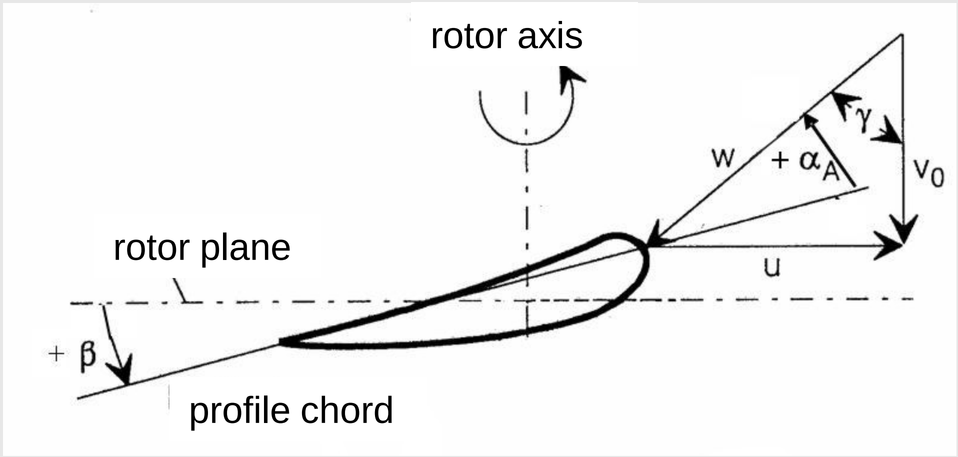
Energy and power density of wind

Bird‘s eye view of horizontally positioned rotor blades



a_A	= angle of attack (angle between profile chord and relative approach velocity)
β	= pitch angle
α	= angle between wind velocity and approach velocity
u	= circumferential velocity
v_0	= wind velocity in the rotor axis
w	= relative approach velocity

Bird‘s eye view of vertically positioned rotor blades

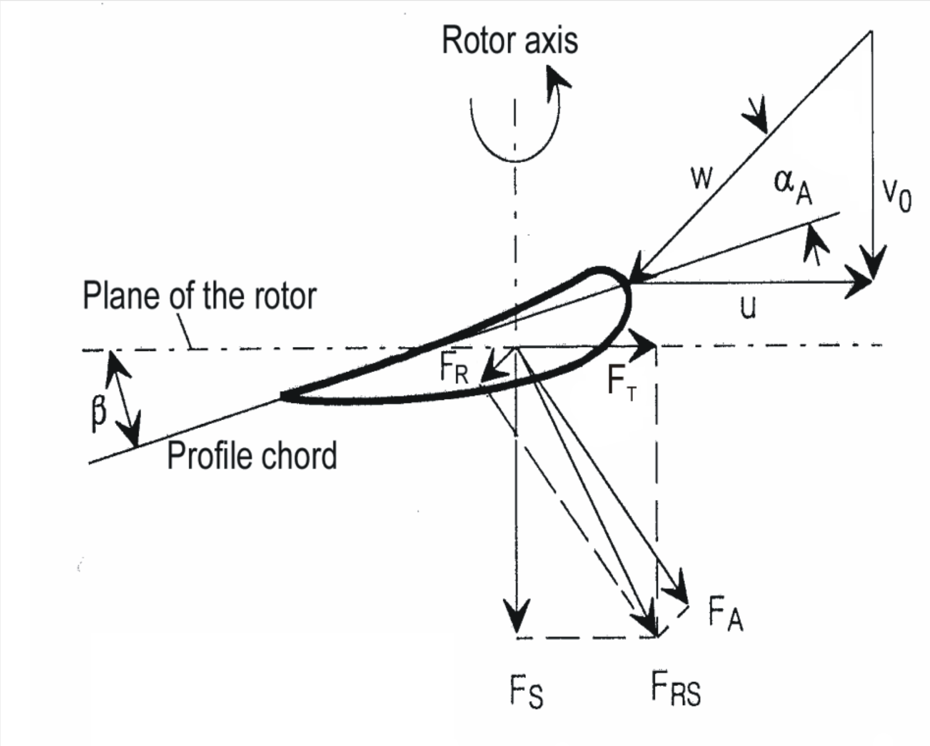


for the pitch angle applies:

α_A should be optimal, besides use b as a set variable in accordance to v_0 and u (revolution)

$$\alpha_A = f(\beta, v_0, u) = \arctan(v_0/u) - b$$

Velocity triangle at the rotor blade

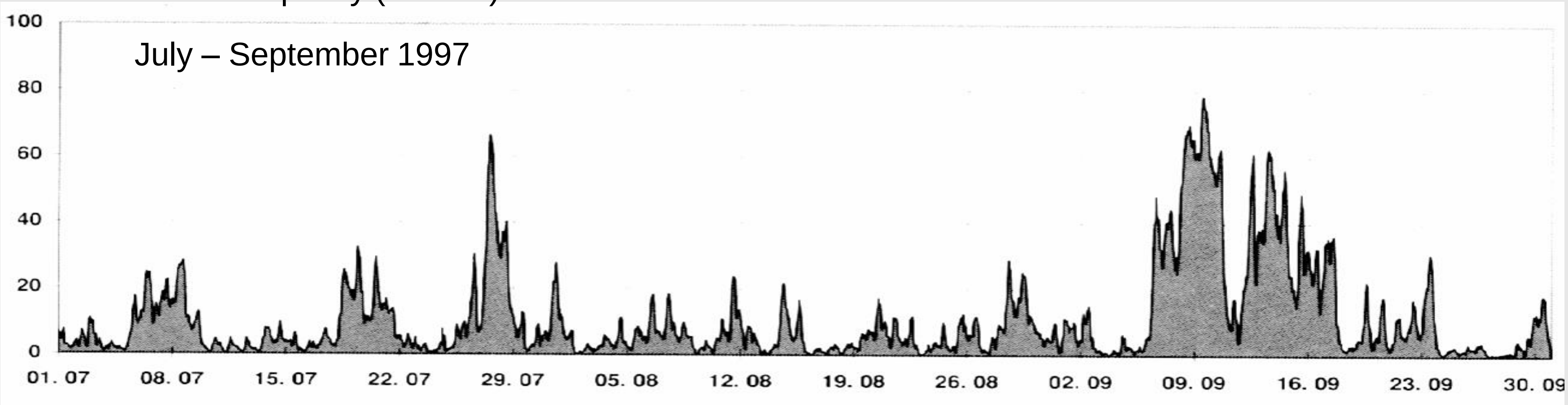


α_A = Angle of attack
β = Pitch Angle
u = Average circumferential velocity
v_n = Wind velocity in the rotor plane
w = Relative approach velocity
F_R = Drag force
F_A = Lift force
F_{RS} = Resulant force
F_T = Tangential component
F_S = Axial component

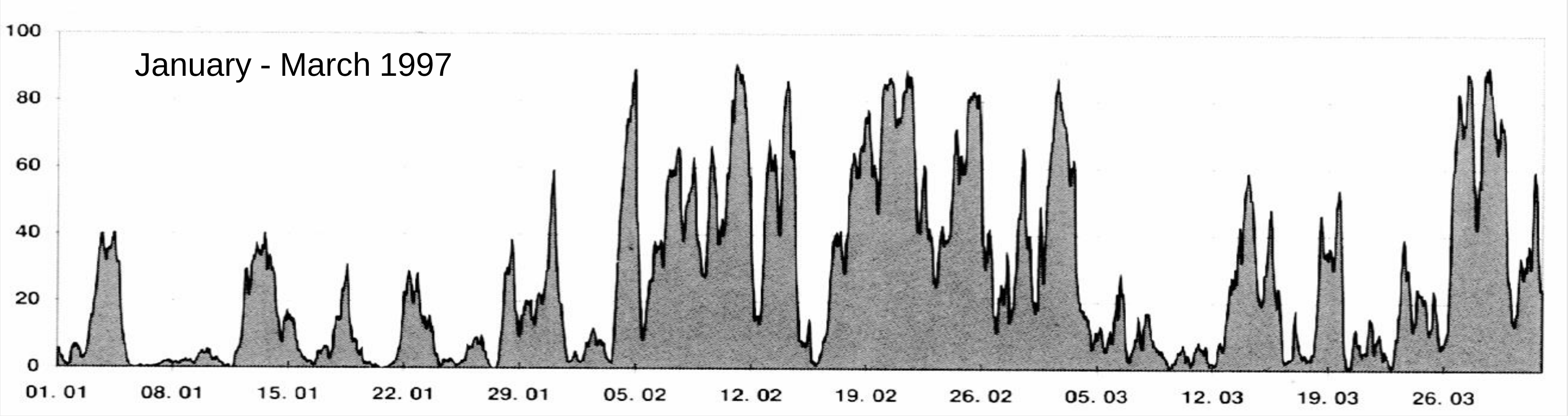
The velocities and forces acting on a blade

Pitch angle β of a blade section

Percent of total capacity (28 MW)



Percent of total capacity (28 MW)



Source: 250 MW-Auswertebericht: zitiert nach M. Kleemann, FZ Jülich, Vortrag Dehli Januar 2002

Load distribution – Measurement 250 MW program on land in Germany

- Present status of wind energy use
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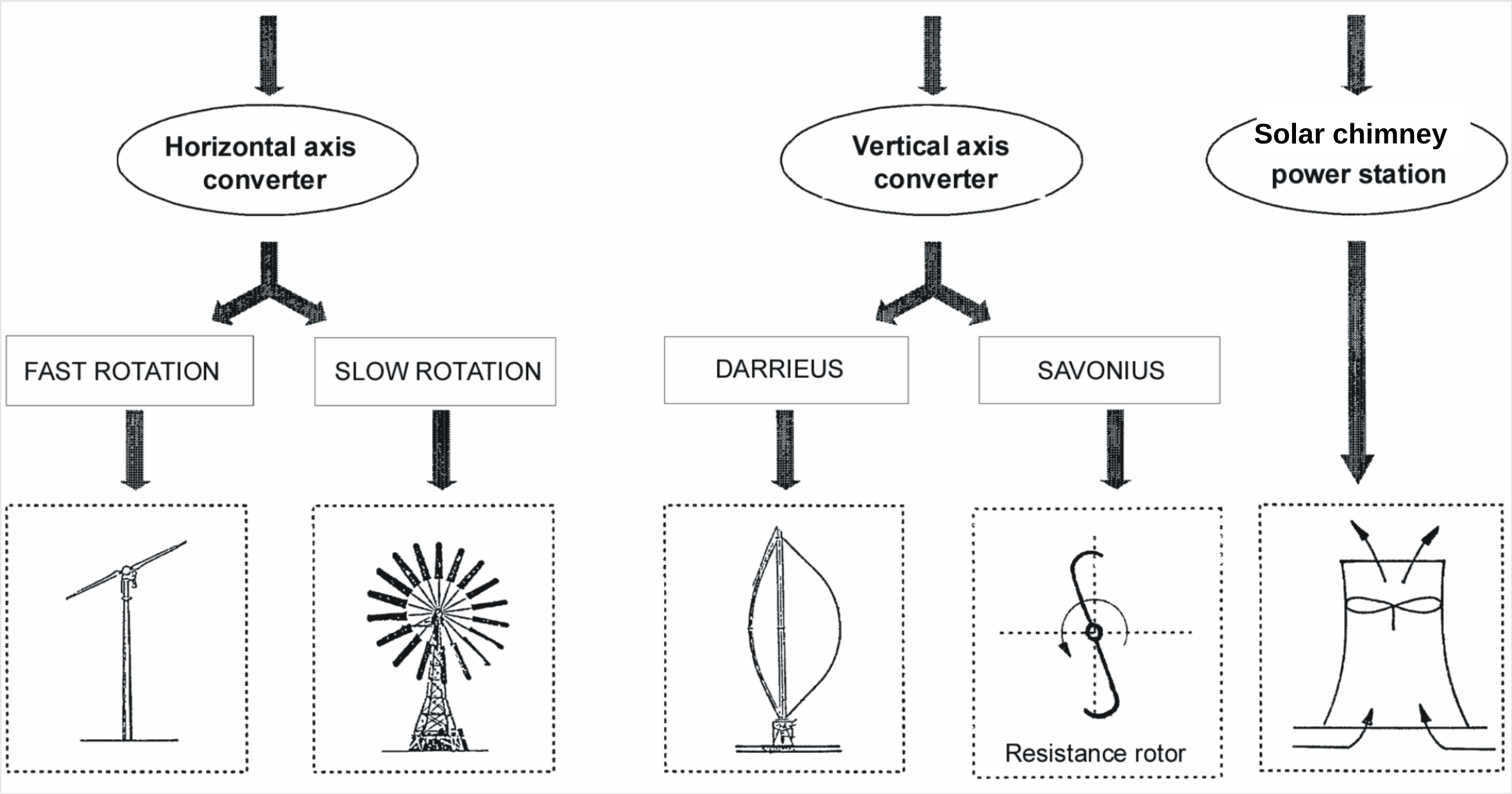
- **Techniques of wind converters**
- Market introduction and problems

Structure of my presentation



Different types of realised wind energy converters (Solar chimney only 1 prototype)

Source: www.reuk.co.uk

- Electrical power: 4 MW
- Height: 96 m
- Rotor diameter: 10 - 65 m

Vertical axis of “Darrieus” wind turbine

Definition of the rotor power

$P = 0,5 \cdot c_p \cdot \rho \cdot A \cdot v^3$

v = wind velocity

A = rotor circular area = $\pi \, l^2$ with l = rotor length

ρ = air density

c_p = power coefficient

The theoretical maximal power coefficient is 0,593 (Betz-number)

Dependence of the power coefficient c_p

c_p interdepends with three factors:

1. Blade design, i.e. ratio of buoyancy factor to friction factor = glide ratio.
   The glide ratio affects the tip speed ratio strongly.

2. Ratio blade tip velocity to wind velocity = tip speed ratio λ
   Dutchmen windmills: λ = 2 -4
   Modern 3-blade conversion systems: λ = 3 -12
   Limitation of the tip speed ratio in practice due to sound emissions (blade tip velocity contributes to sound emissions with the power of six)

3. Ratio of the sum of all blade areas to the rotor circular area A = solidity ratio.
   which is simplified the number of rotor blades.

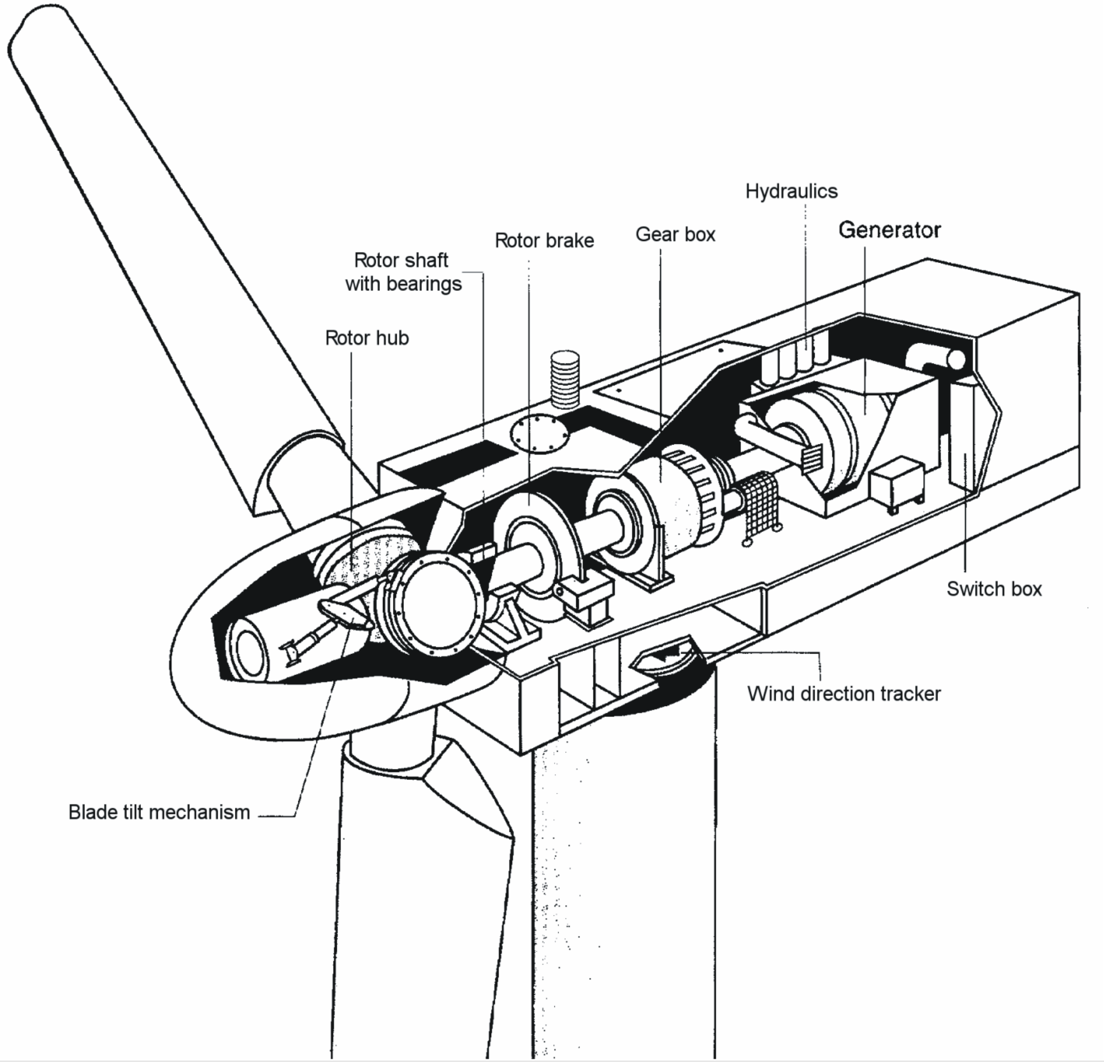
„Cooking recipes“
for dimensioning of wind energy conversion systems

1. High glide ratios lead to high tip speed ratios and therefore to a large power coefficient c_p
   → Modern converters with good aerodynamic profiles rotate quickly.

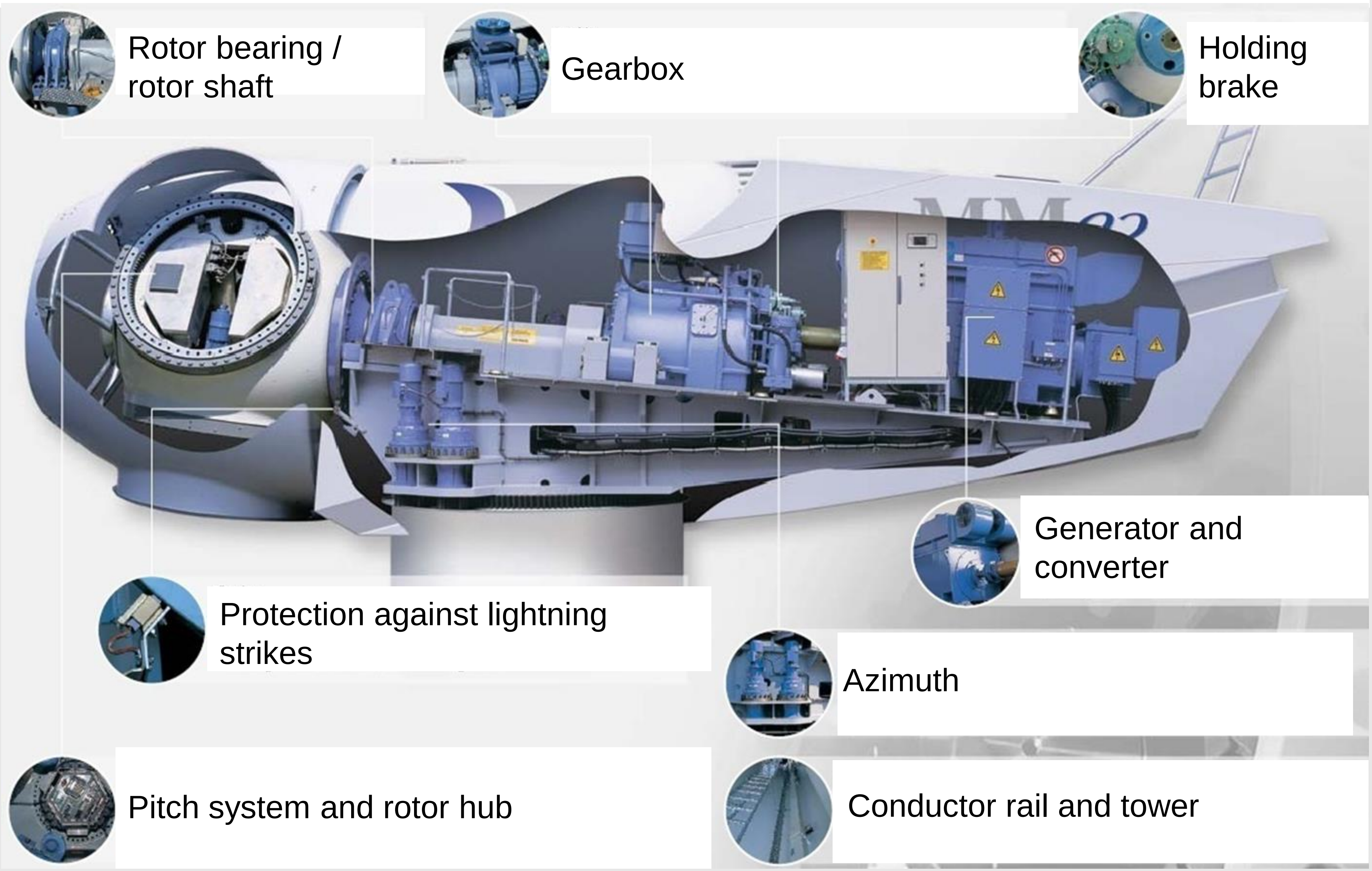
2. Simple profiles with a smaller glide ratio have smaller tip speed ratios. Therefore is a large solidity ratio required to achieve an increase of the power coefficient.
   → Slow rotating converters have poor aerodynamic profiles and a high number of blades

3. Glide ratio and tip speed ratio have a larger influence on the power coefficient than the solidity ratio.
   → Number of blades for fast rotating converters has a secondary relevance (in practice mostly 2-3).

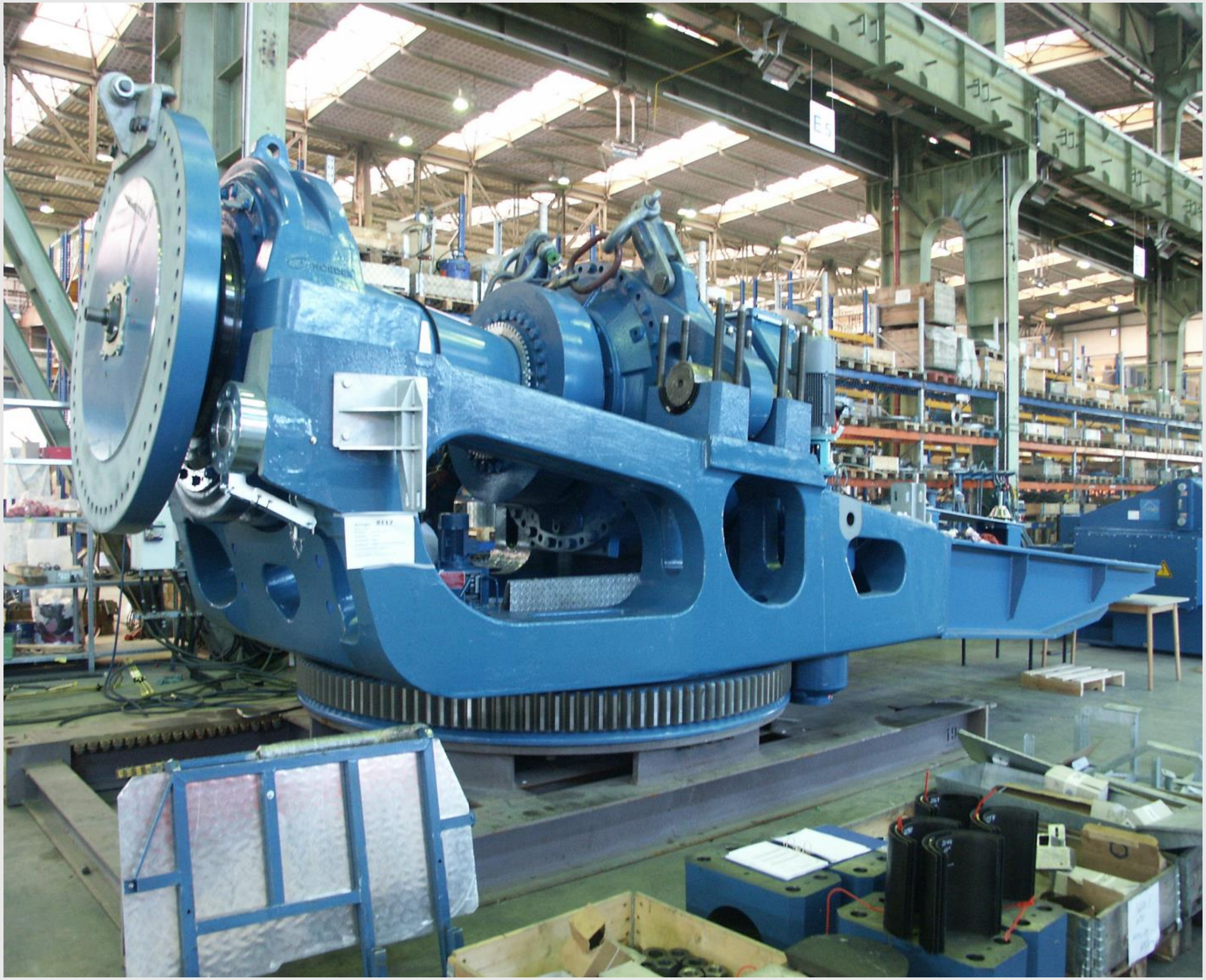
Dimensioning of wind energy conversion systems



Constructional type of a WECS with „classical“ power train

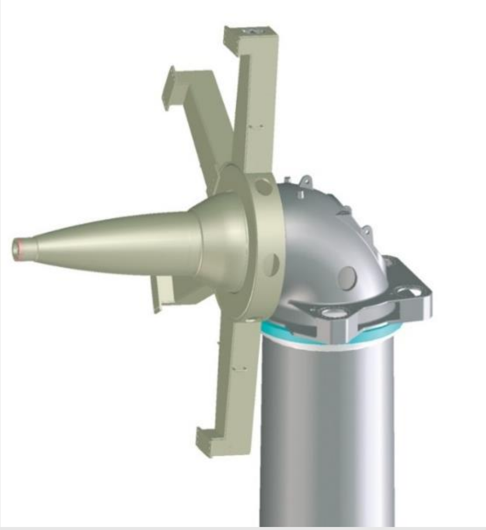


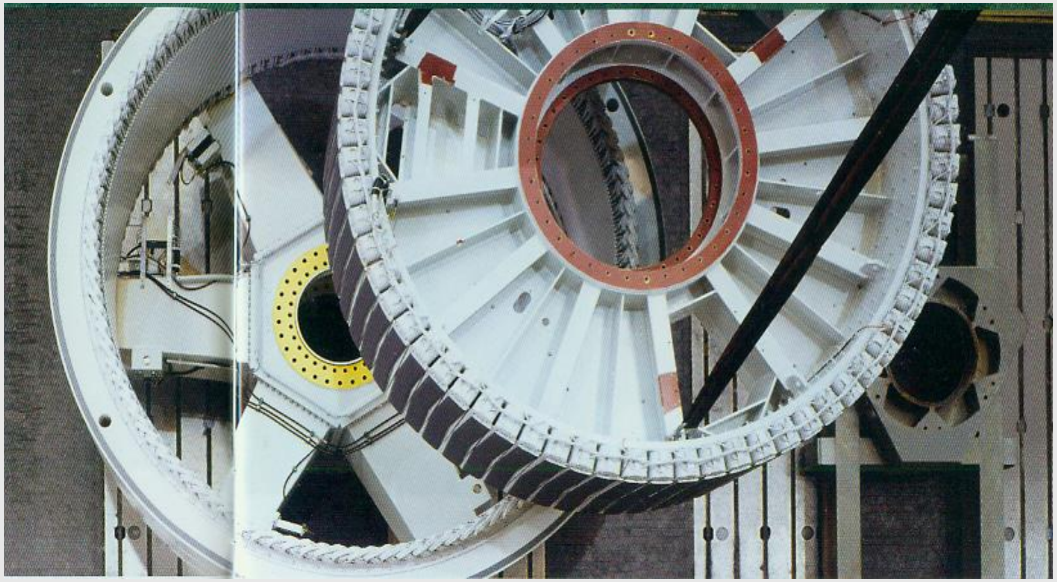
Nacelle of a 2 MW wind turbine with gearbox (by Repower Systems)

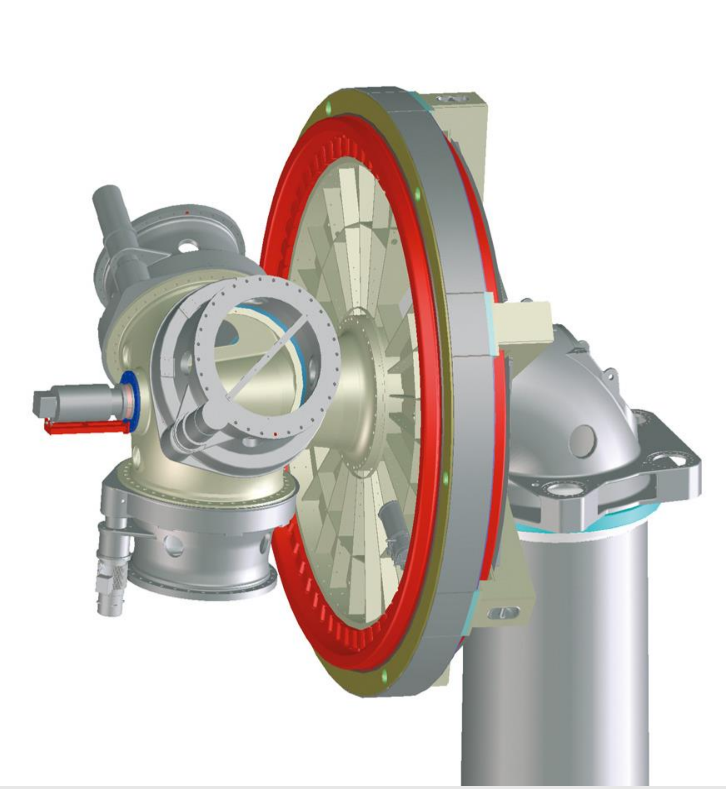


Source: Nordex AG

Assembling of a wind converter by Nordex AG with gearbox

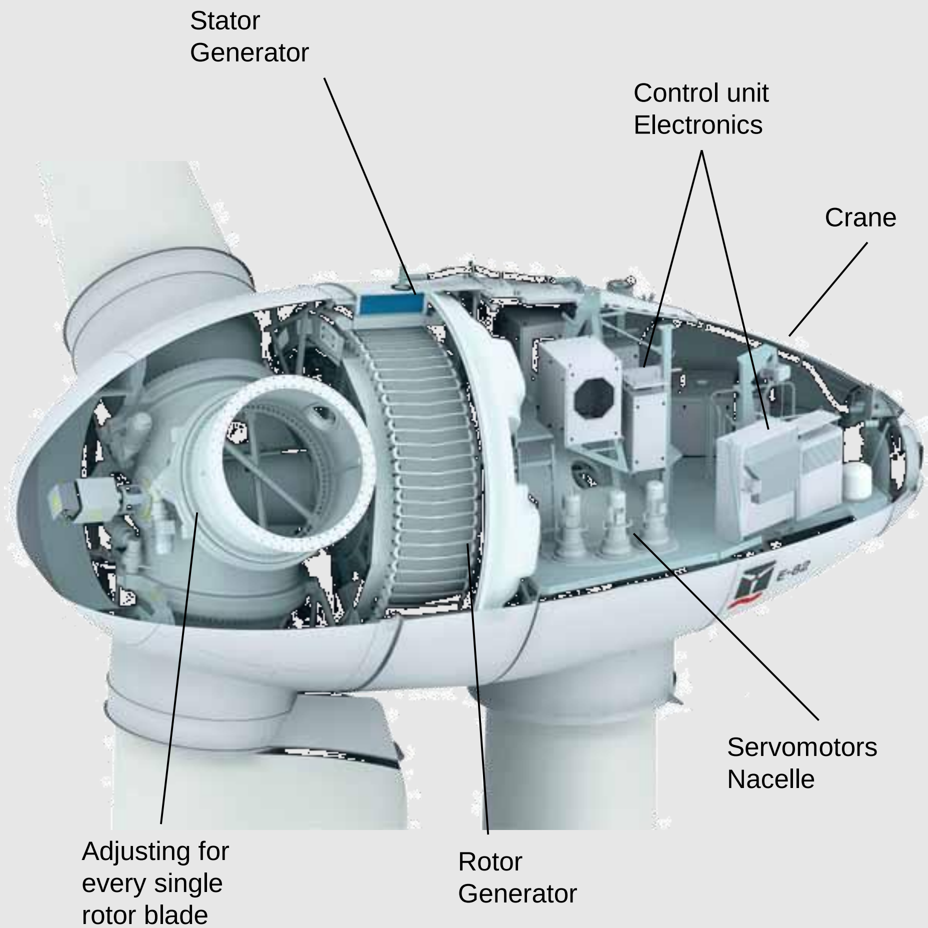




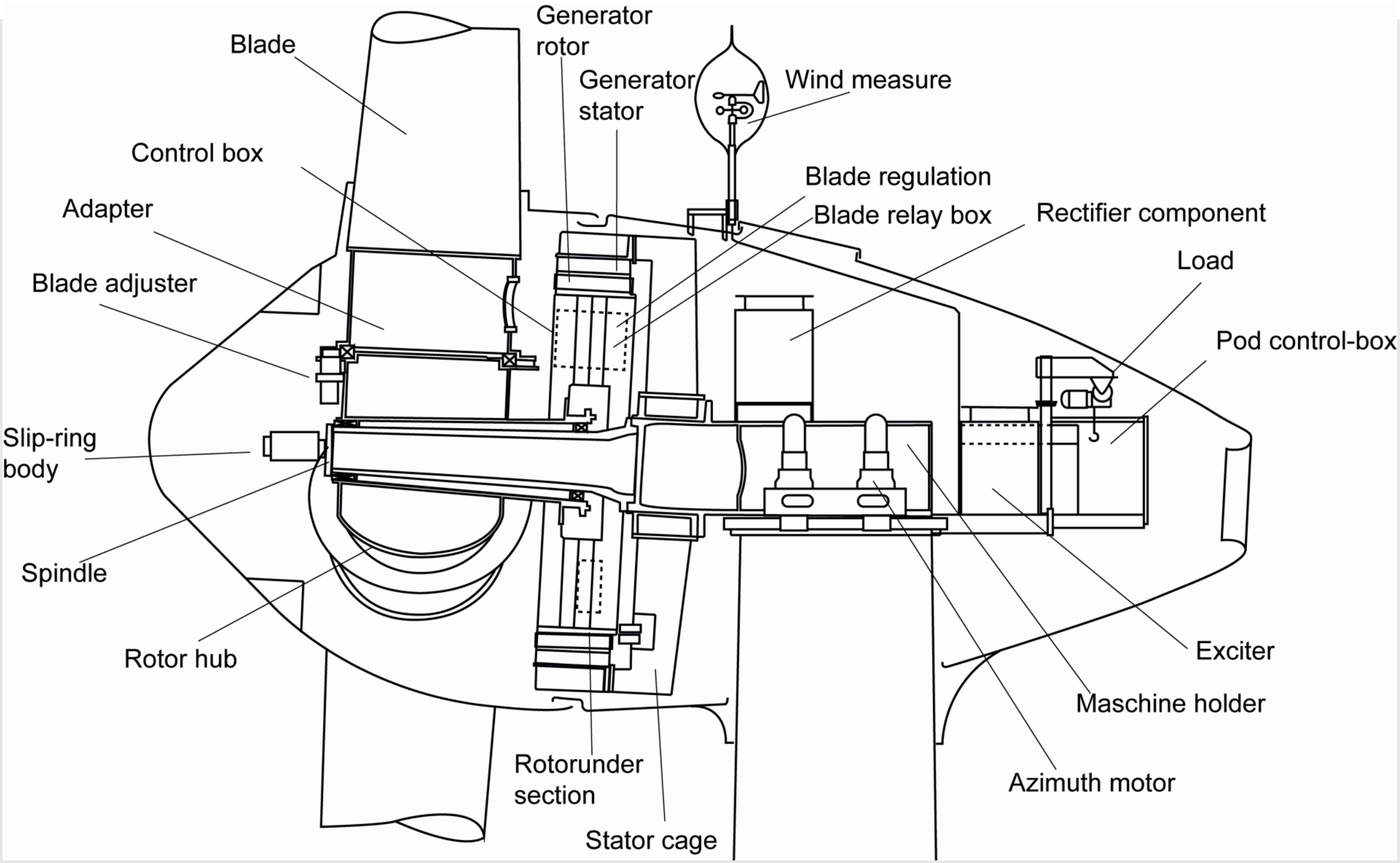


Source: ENERCON GmbH

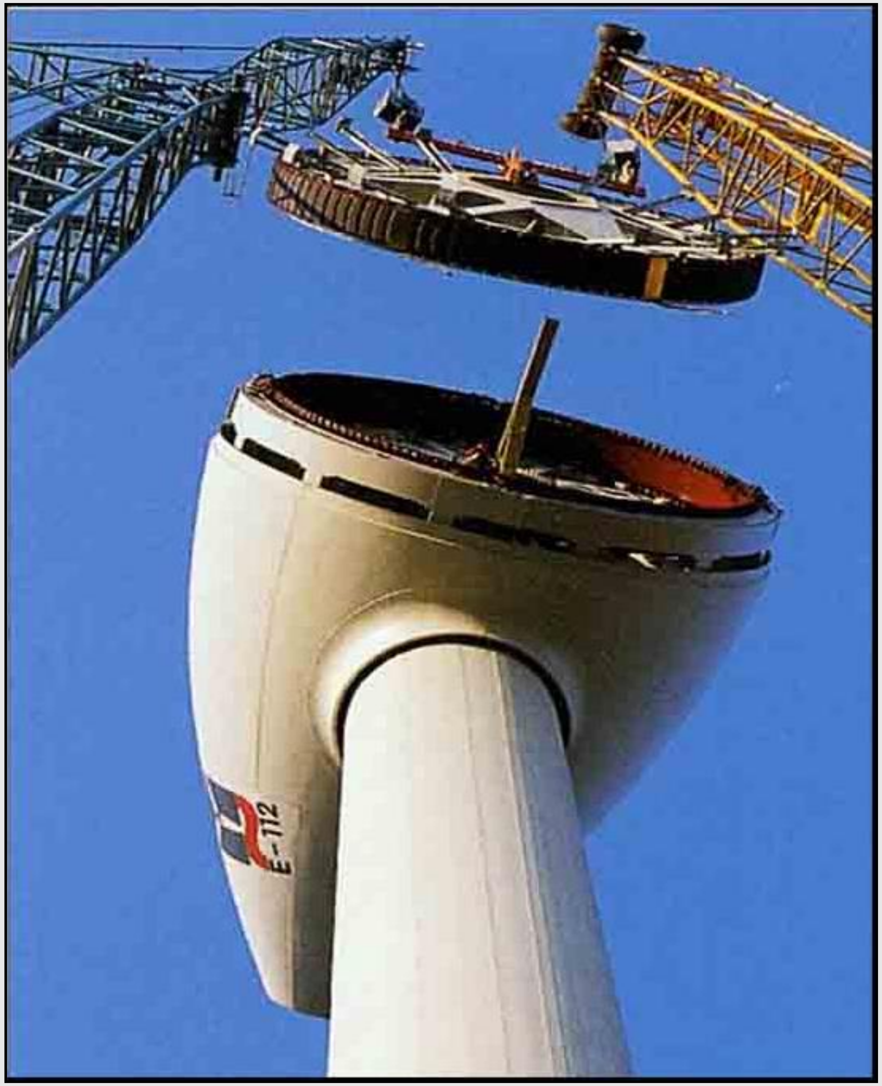
Wind energy converter without gear box



Sectional view of a wind turbine without gearbox (by ENERCON)



Constructional type of the WEC Enercon-66 without gearbox



Installation of the generator by a wind mill without gearboxes

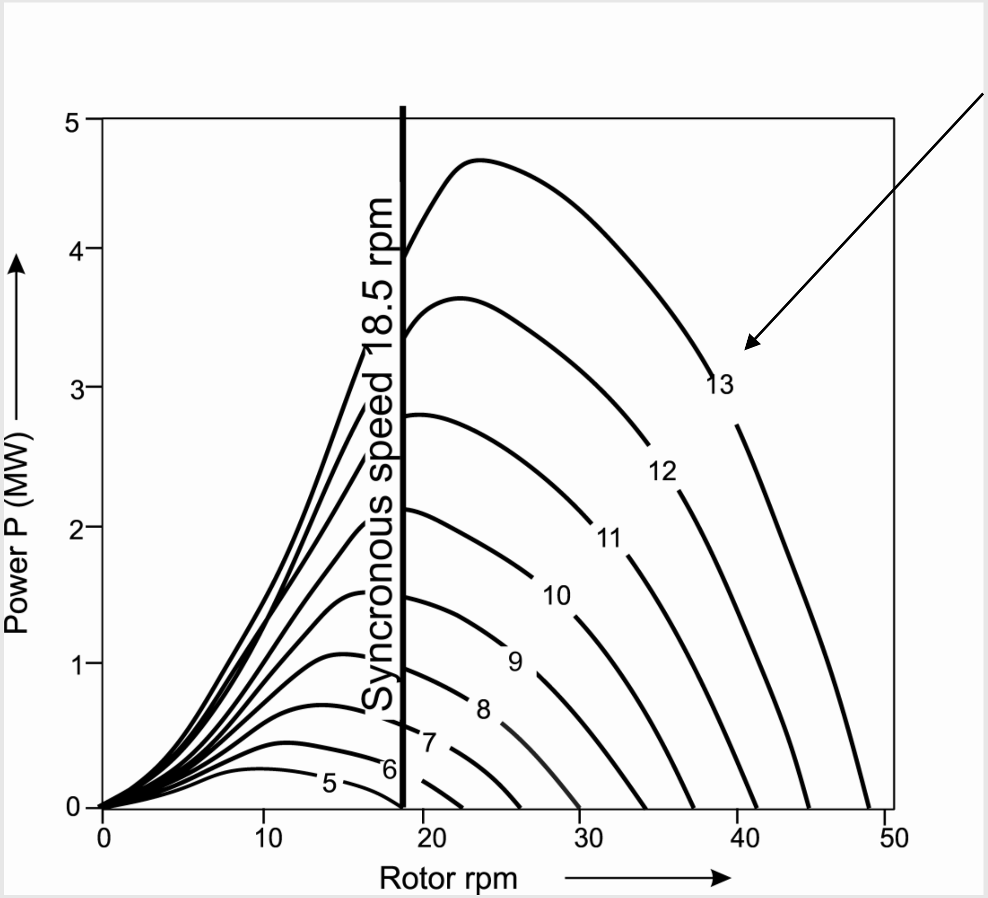
Both designs (*gearbox* and *multipole generator / without gearbox*) have one disadvantage each:

- The design *with gearbox* has the disadvantage of losses during transmission of power and high speed drive required for connecting the generator
- The design *without a gearbox* has the disadvantage of increased weight of the nacelle due to an increased number of poles
- Possible solution -> combination between a special gearbox and a multipole generator

Design with Gearbox and Multipole Generator

	Enercon E-182 E3	REpower 3,2 MW
Design	without gearbox	with gearbox
Hub height	80 - 130 m (onshore)	100 - 130 m (onshore)
No. of blades	3	3
Rotor speed	6-18 rpm	6.7 -12 rpm
Rotor diameter	82 m	114 m
Material of blade	Fibreglass (reinforced epoxy)	Fibreglass (reinforced epoxy)
Blade regulation	Pitch	Pitch
Rated power	3 MW	3.2 MW
Transmission ratio of gearbox	None	approx. 99
Generator	Multi-pole	Asynchronous, few poles
Grid connection	Via frequency converters	Via frequency converters

The technical figures of two different multi-megawatt wind turbines for onshore

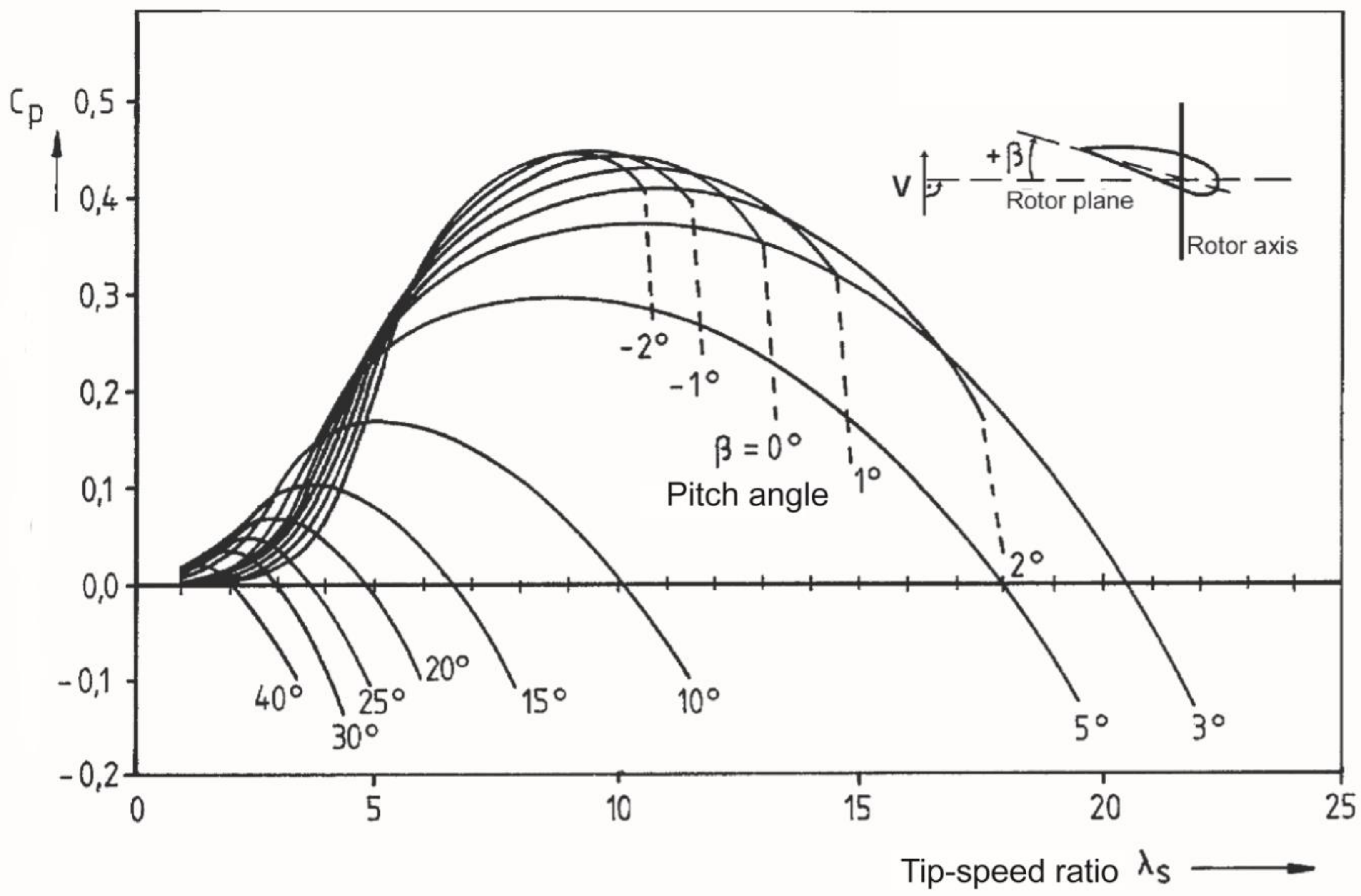


v_{wind} [m/s]

Adjusting of the revolutions and the line frequency with:

- controllable gearing or
- changeable number of pole pairs (electrical gearing) or
- asynchronous generator with extended slip or
- intermediate direct currency link

Curve family of a fast rotating rotor development of wind velocity



Example of the relationship between the power coefficient and the tip-speed ratio

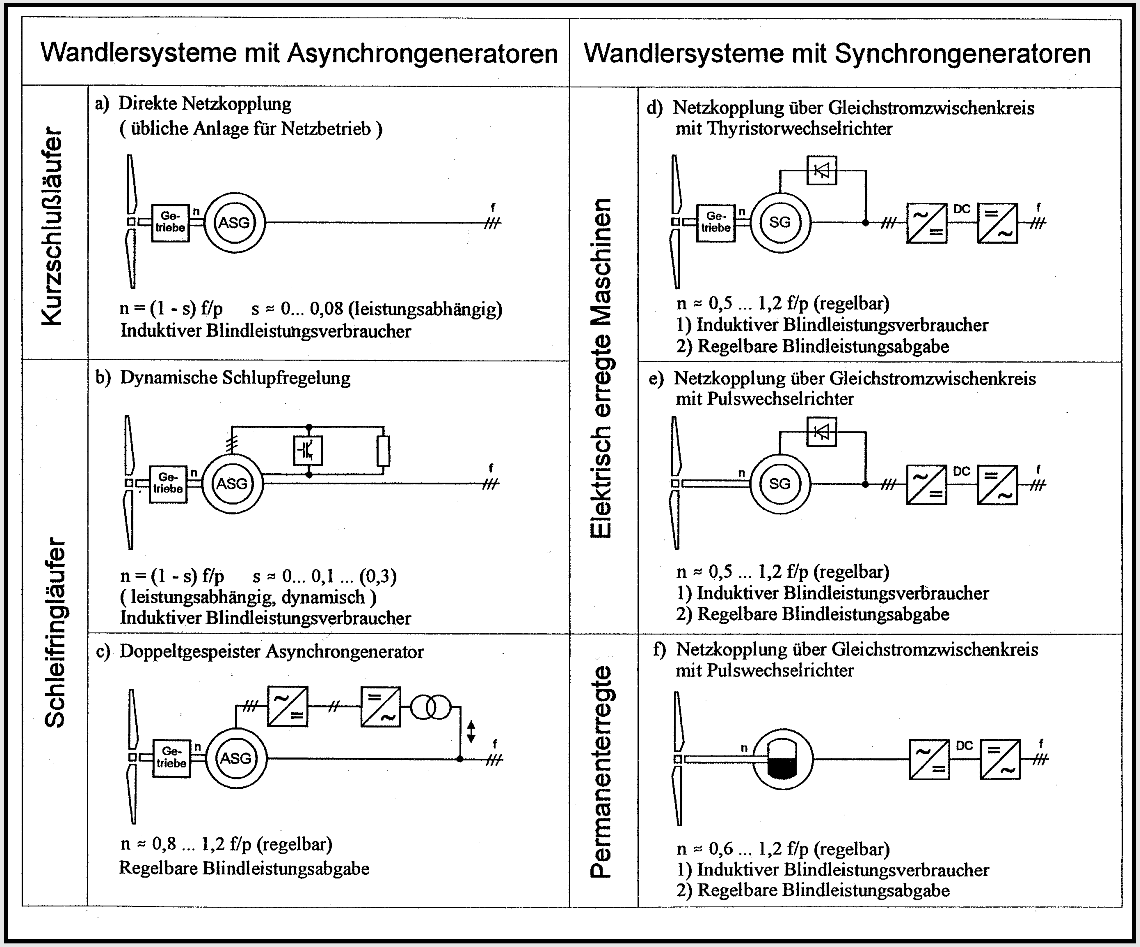
Systems with asynchronous generators

Systems with synchronous generators and permanent magnetes

Direct grid connection

Dynamic slip control

Double excited asynchronous generator



Synchronous generator with gear box

Synchronous generator without gear box

Synchronous generator with permanent magnetes

Graphic source: Forschungsverband Sonnenenergie 96/97 & Prof. Wagner

Grid connection of converter systems with synchronous and asynchronous generators

New devices need testing: Problems with gear boxes in previous years

Image: http://ais.badische-zeitung.de/piece/04/81/34/f7/75576567.jpg

Safety - Burned off wind power station in Lahr/ Germany

Source: Jörg Sarbach; SonneWind&Wärme, ISSN 1861-2741 H 2607, Stand 04/2017

Fallen concrete fundament of wind turbine after 10 Mio load changes

Source: mdr.de

95 m high wind turbine twisted by a storm at the wind park „Sitten/Bockelwitz“ (Germany, 29th of december 2016)

Generators	-Copper? Permanent Magnet? -Rare earths? -Superconductors?
Rotor Blades	-Cost reduction? -Utilization? -Legal situation? -Active control elements in rotor blades?
Operations Monitoring	-Drive train monitoring (CMS) for onshore plants? -Tower- and foundations vibrations – Number of Sensors, also Onshore? -Periodic Inspections- Scope, Number?
Technical Uncertainties	-Handling of new developments?
Offshore Foundations technologies	-Steel? Concrete? -Gravity Foundations? -Environment, under water noise protection during the piling for the foundation?

Technical developments in Wind Turbines

Source: http://www.siemens.com/press/pool/de/pressebilder/2012/photonews/300dpi/PN201209/PN201209-01_300dpi.jpg

Montage of a rotor blade

Source of the graphic: Trianel Borkum
http://www.trianel-borkum.de/bilder/errichtung-wea/

Windpark „Trianel II“ at Borkum – with financial support of the „Stadtwerke Bochum“.
The ship is able to change height and connect the blades to the tower.

A construction ship with rotor blades

Source: http://www.siemens.com/press/pool/de/pressebilder/2012/photonews/300dpi/PN201204/PN201204-06e_300dpi.jpg

Size of rotor blades of a 6 MW windturbine

- Present status of wind energy use
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Structure of my presentation

Investment plan	Costs [€/kW]	
Hub height	< 120 m	> 120 m
Wind power station, transport, installation	1150	1340
Foundation	70	
Grid connection	70	
Site development (lanes)	40	
Planning, environmental measures, concession, others	190	
Total	**1520**	**1710**

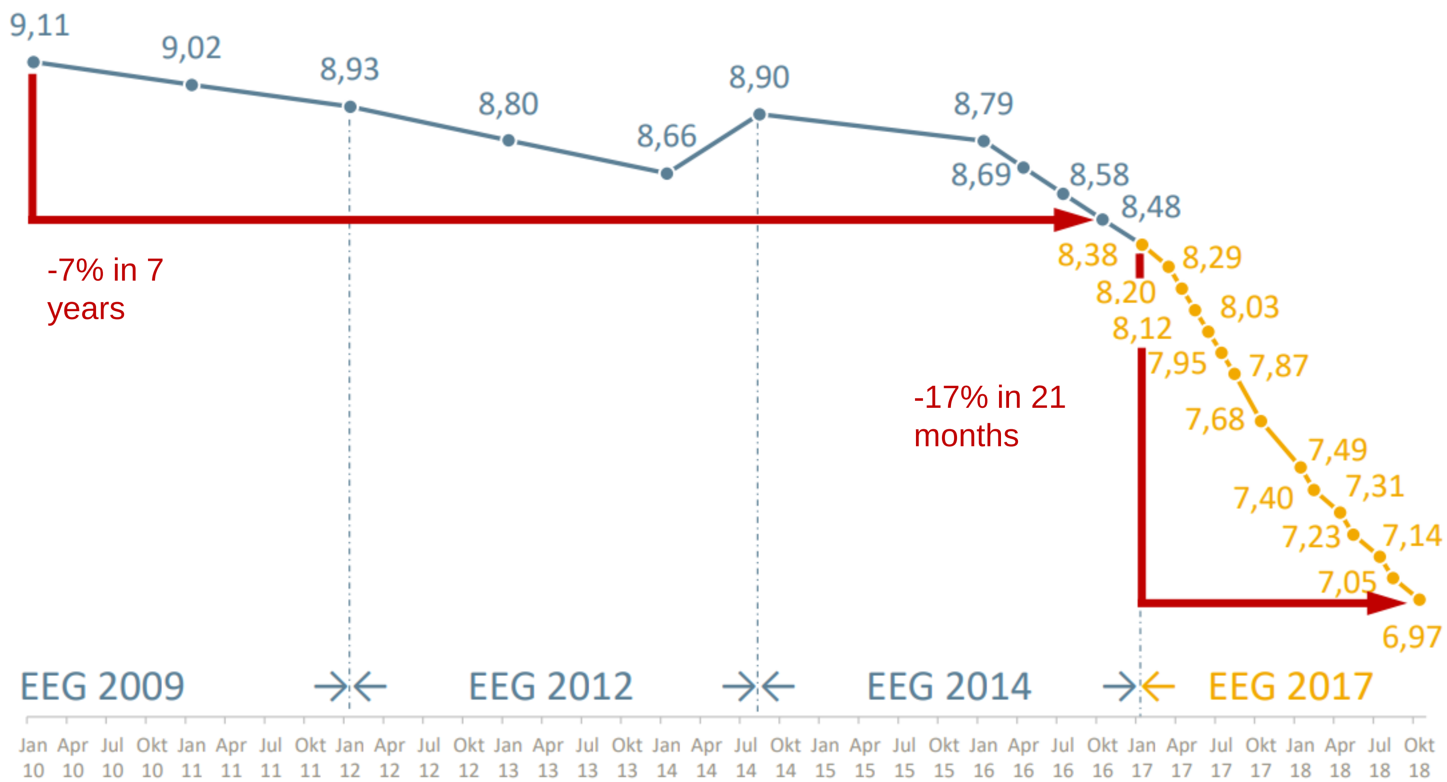
Operating costs: 5,1 ct/kWh (Average over 20 years operating time)	
Service, reparation, others	50 %
Rent	20 %
Management (technical and business)	20 %
Reserve for unforeseen events	5 %
Insurance	5 %

Source: Deutsche WindGuard GmbH; Kostensituation der Windenergie an Land in Deutschland, Stand 2013

Costs of a 2 MW onshore wind power station in Germany

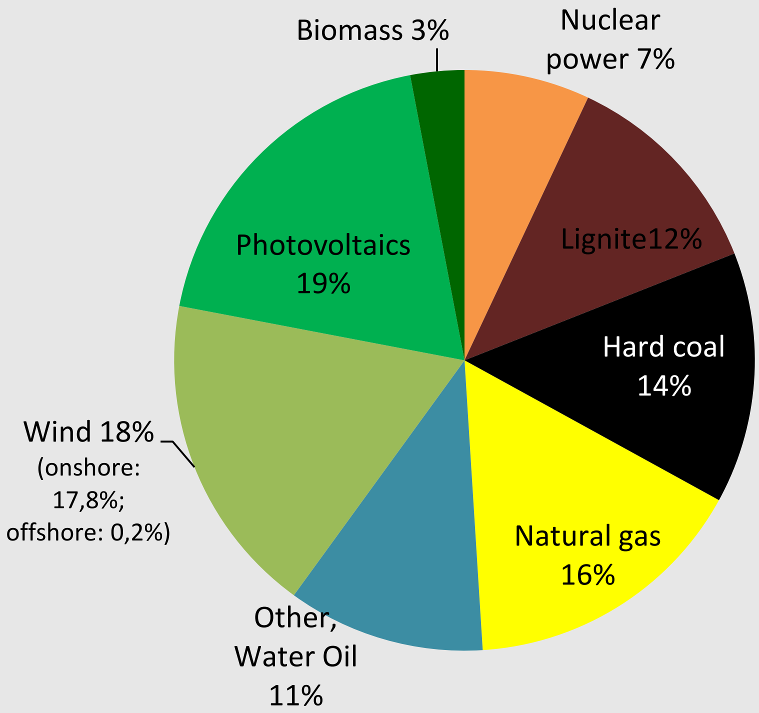
Remuneration rates for electricity from onshore wind

[Initial remuneration in ct./kWh]

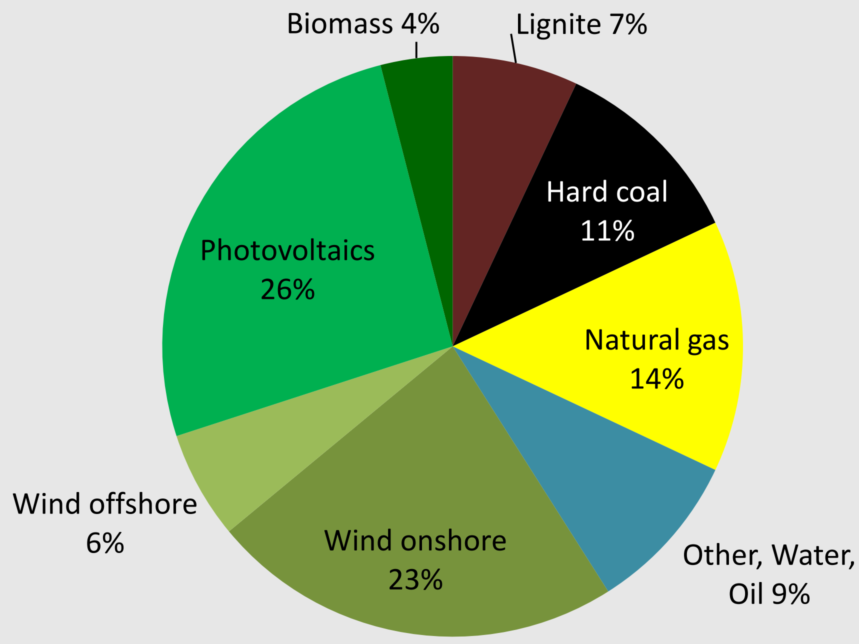


Graphic source: Fachagentur Windenergie an Land – Loccumer Finanztage (online) Mai 2020

Remuneration rates for electricity from onshore wind in Germany



2012
Statistical value (175 GW)

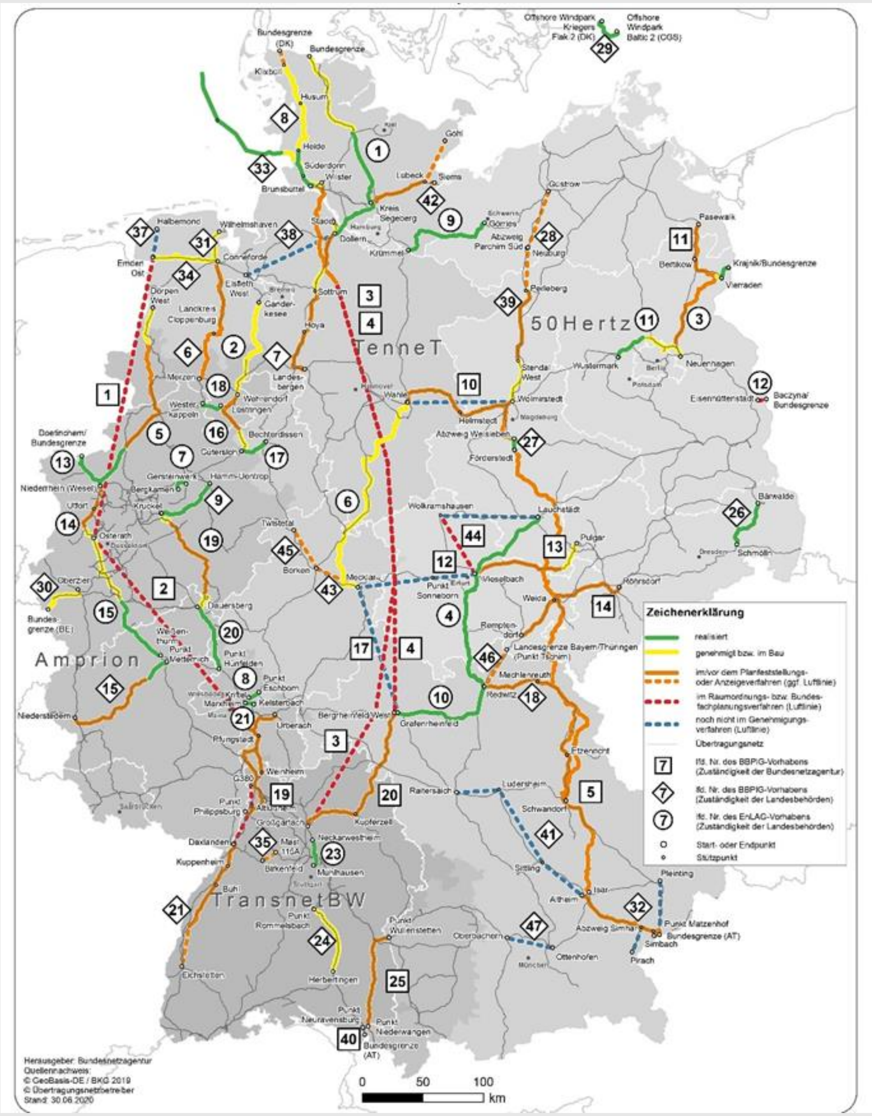


(Nuclear power: 0,0%)

2024
Objective of government (225 GW)
(Scenario B)

Objective power station capacities in Germany 2024

Renewables and liberalisation require the grid extension europeanwide

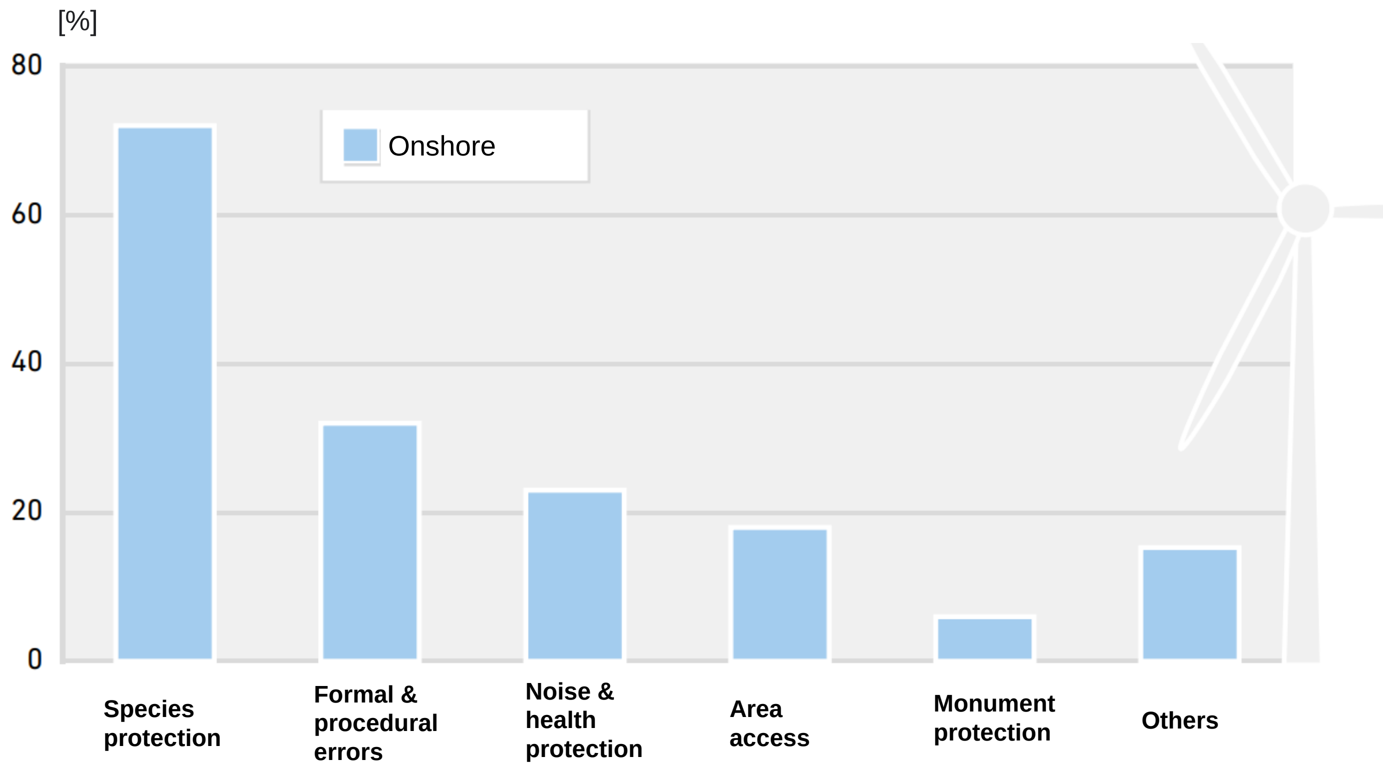


Source:
https://www.netzausbau.de/leitungsvorhaben/de.html

Network development plan for the german electricity system (2020)

Most common reasons for complaints against onshore wind turbines

Species protection may be the clearly dominant cause of complaint; however - a remarkably high proportion is also attributable to formal and procedural errors



Quelle: Branchenumfrage der Fachagentur Wind an Land, eigene Berechnungen, n=325 Anlagen, Stand: Q2/2019

Source (graphic): Renews Spezial Nr. 90 / April 2020

Most complains include more than one reason.

Main cause of actions against onshore wind turbines

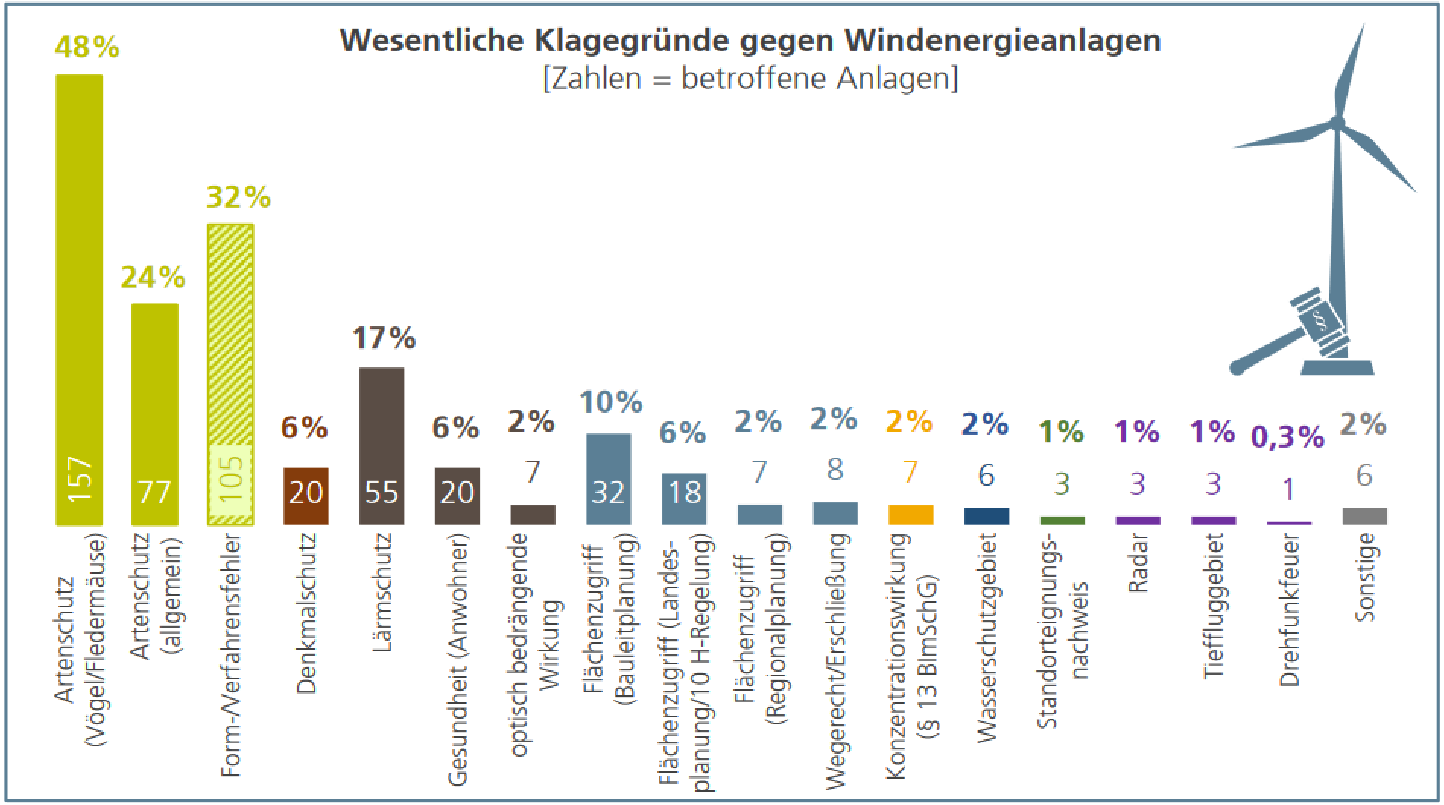


Abbildung 1: Klagegründe und Zahl der betroffenen WEA mit Mehrfachnennungen [n = 325 WEA]; Daten und Grafik: FA Wind (Stand Q2/2019)

Top 3 reasons people complaining about wind power: species protection (especially birds), process and manifacturing defects, noise level

Source: Fachagentur Windenergie an Land, Umfrage, „Hemmnisse beim Ausbau der Windenergie in Deutschland, Juli 2019

Pleas against wind power in Germany

Source: http://bilder3.n-tv.de/img/incoming/origs4135986/4292739368-w1000-h960/2zsw0118.jpg

Upward lightning strikes on rotor blades of wind turbines

Bild: http://www.cpmax.com/tl_files/content/leistungen/inspektionen/galerie/100629%20097_klein.jpg