Renewable Energy from Wind and Ocean

Jianning Dong
Assistant Professor Electromechanics
Delft University of Technology
The Netherlands

DCE&S
DC systems, Energy conversion & Storage

TU Delft

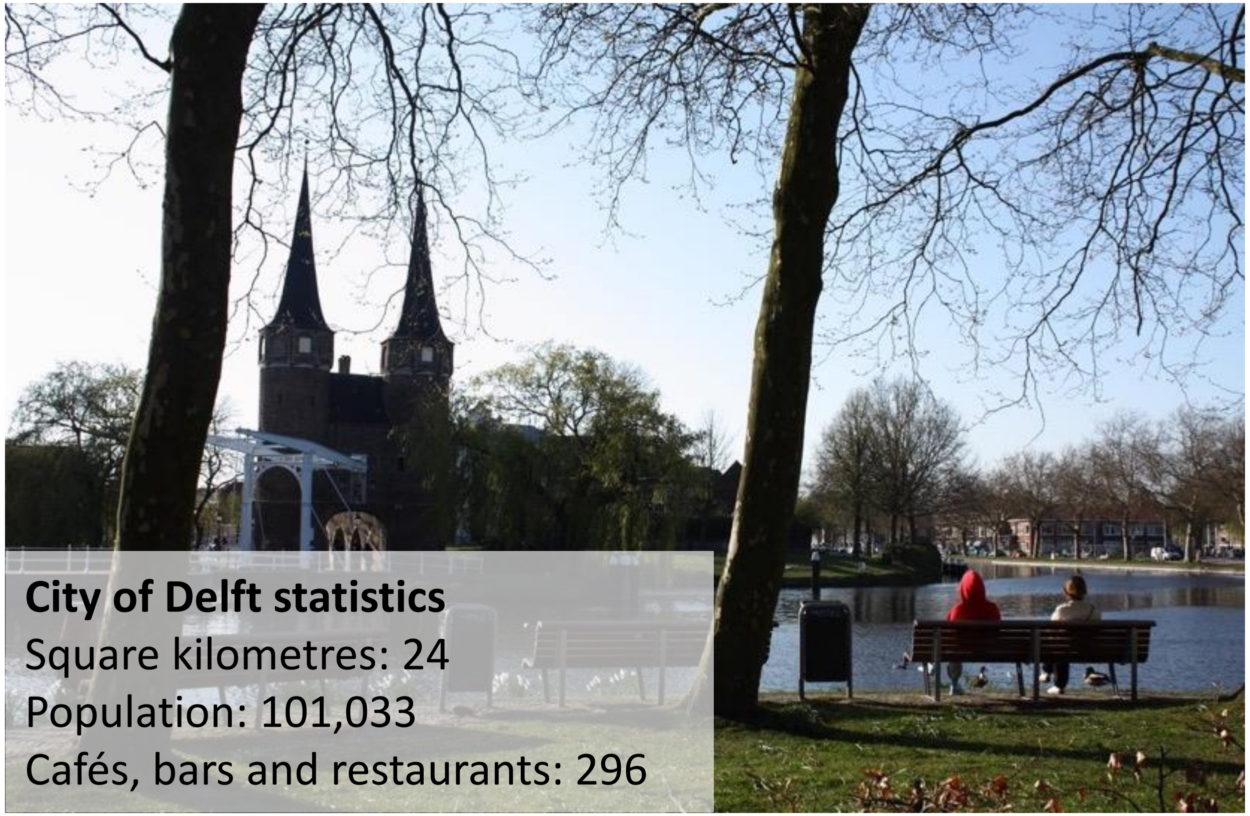
About me

Jianning Dong

2016.10-now, Assistant Professor, Electromechanics, TU Delft
2016.01-2016.09, Postdoc, Electric Vehicle, McMaster University, Hamilton, Canada
2010-2015, Ph.D., Electrical Engineering, *Southeast University*, Nanjing, China

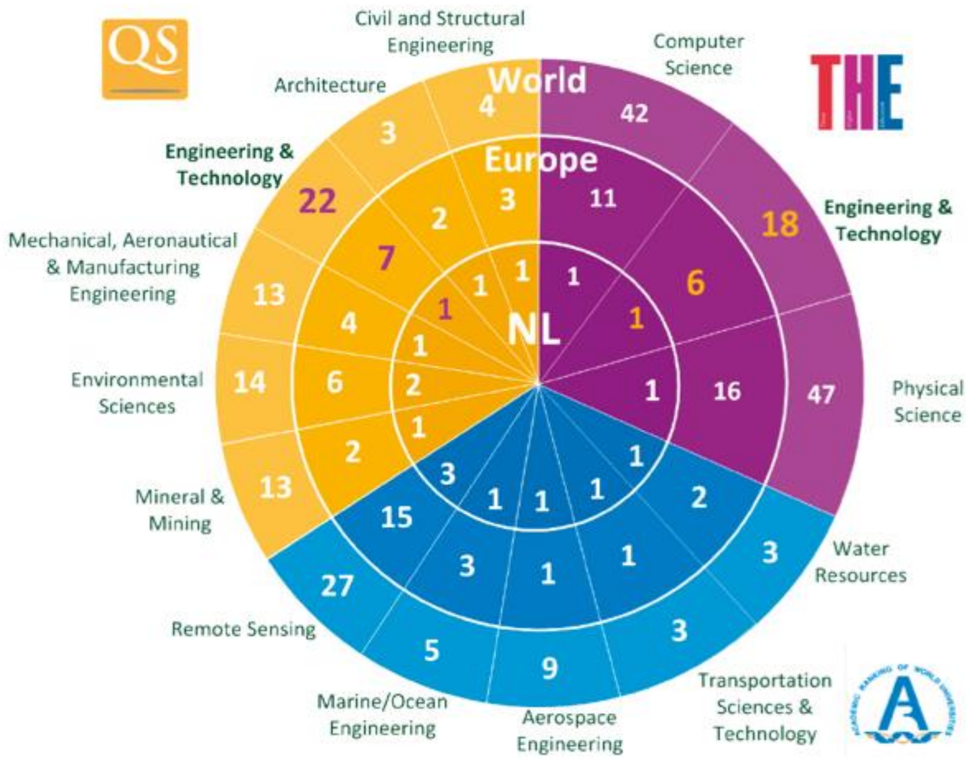
Research

- Generators for renewable energy: wind, tidal, waste heat
- High speed electrical machines
- Acoustic noise and vibration of electrical machines
- E-mobility
- Contactless charging, induction heating



City of Delft statistics
Square kilometres: 24
Population: 101,033
Cafés, bars and restaurants: 296

Position TU Delft in Subject Rankings



Learning objectives

After taking the lectures, students should be able to

describe and explain:

- Background and developments in wind/ocean energy
- Basic aerodynamics/hydrodynamics relations in wind/tidal turbines
- Structure of wind/tidal turbine and requirements on generation system
- Generator system solutions
- Advantages and disadvantages of different choices

do basic calculations on

- Torque, speed, power in renewable generator systems based on electrical machine related courses

Important concepts will be highlighted in RED BOX!
Keywords will be highlighted in BLUE TEXT, difficult terminology will be given in Chinese.
Questions will be highlighted in RED TEXT!

Interrupt me if anything are not clear

- I often assume something are familiar to you, but it might not be the case.
- Tower of Babel: languages might affect communication.
- Asking questions is a good way to keep focused (and prevent sleeping).

- You may either raise your hand/type in chat or unmute yourself and shout out.

Contents

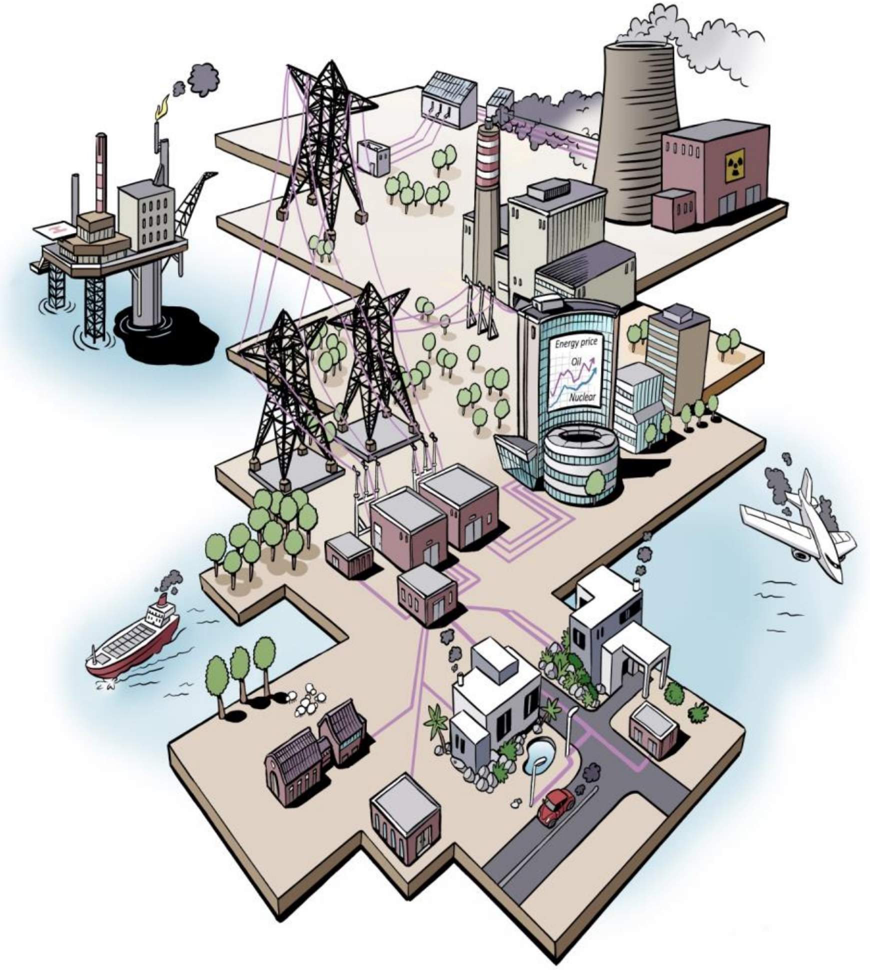
- Introduction to wind and ocean energy
- Energy conversion system topology and turbine drivetrain structure
- Basic principles: fluid dynamics and electromechanics
- Requirements of renewable generation system
- Overview of generator system solutions
- Comparison of system choices
- Current challenges and issues

Introduction to

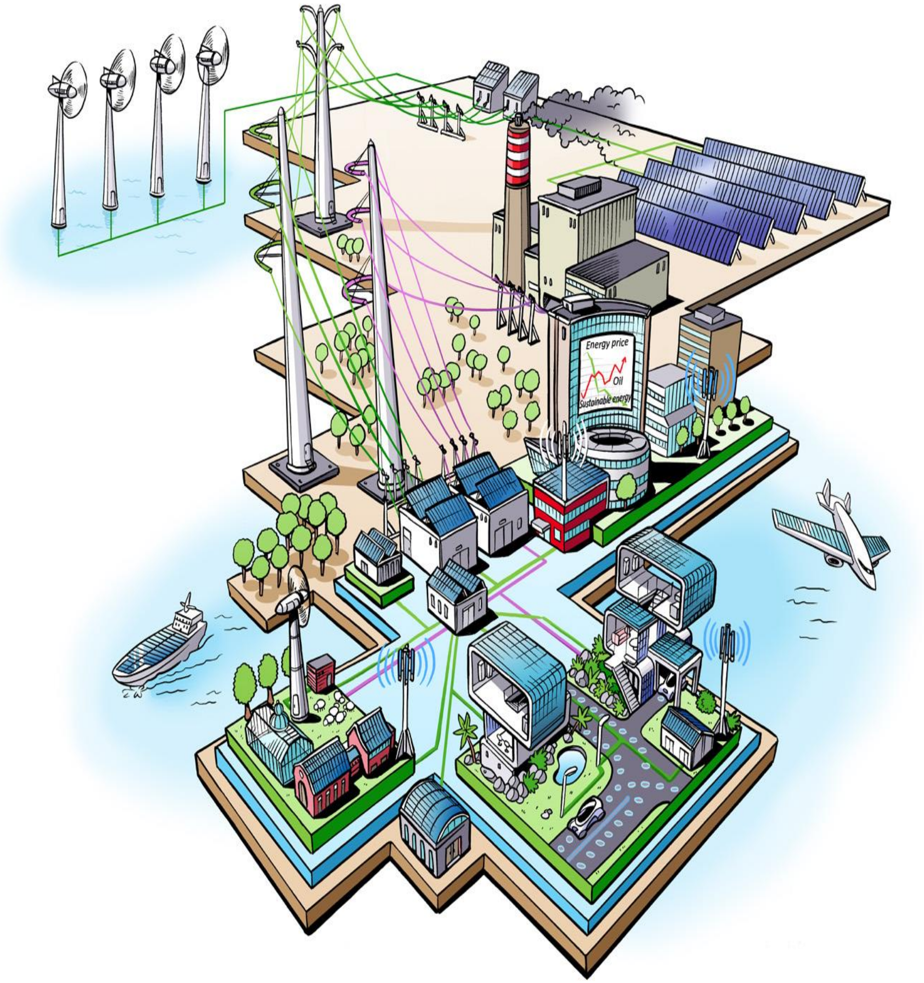
wind and ocean energy

Motivation

A green and sustainable future

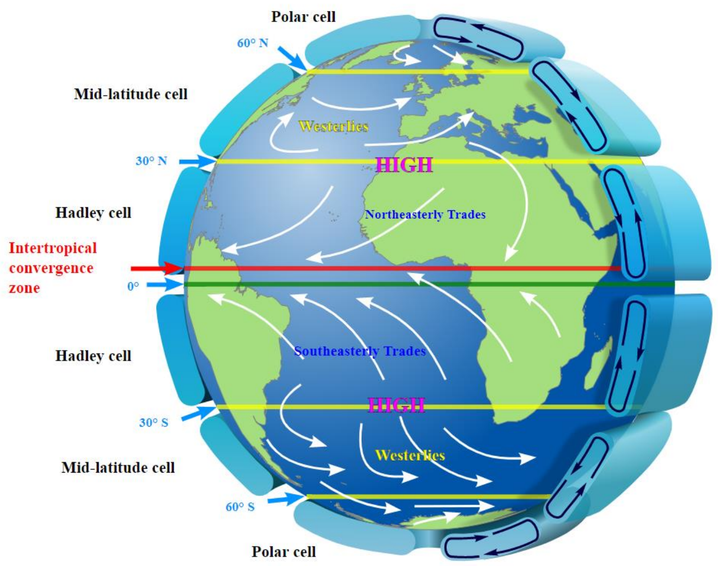


- More renewable energy
- More efficient conversion



Source: inaugural lecture P. Bauer

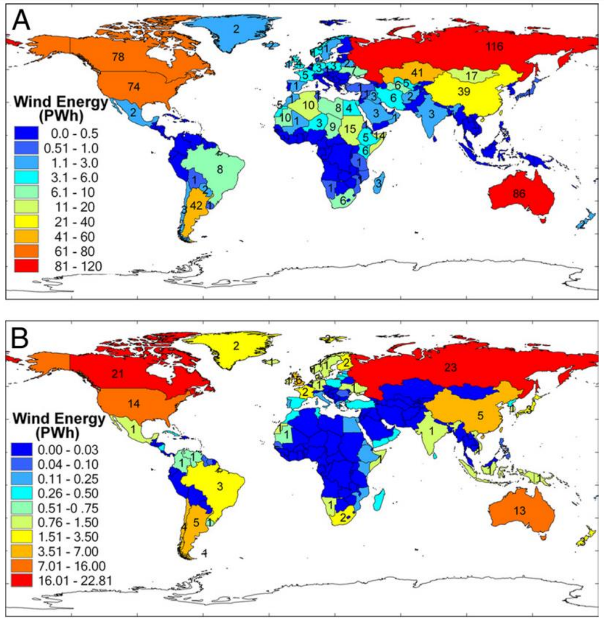
TU Delft

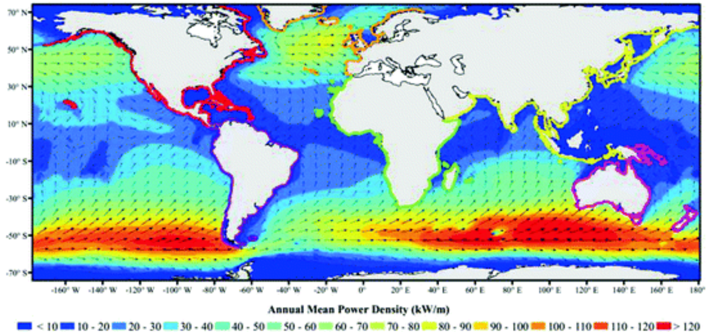


Atmosphere circulation, source: Wikipedia.org

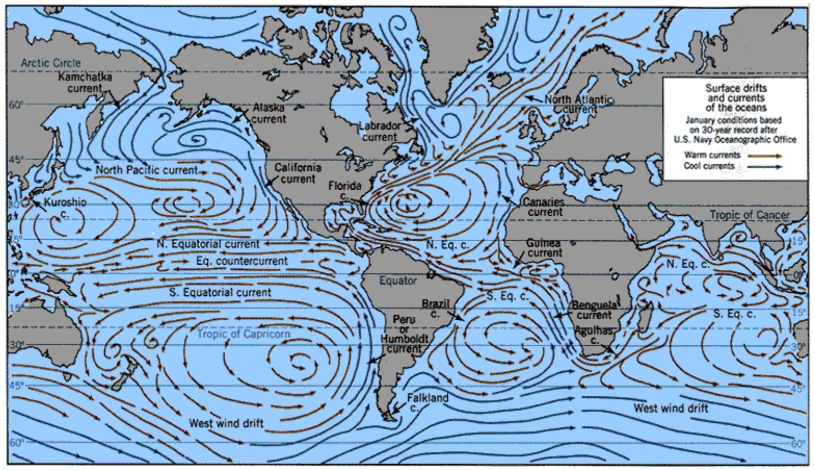
- The earth is covered by the atmosphere;
- Oceans cover 71% of the Earth's surface;
- Atmosphere and oceans are constantly flowing.

A huge potential for electricity generation





Global wave energy density
Source: Gunn K., Stock-Williams C., Quantifying the global wave power resource. Renew. Energy vol. 40, no. 0, 2012.



Ocean circulation, source: nasa.gov

Annual wind energy potential by country
(A: onshore, B: offshore)
Source: Lu X., McElroy M. B., and Kiviluoma J., Global potential for wind generated electricity, PNAS, vol. 106, no. 27, 2009.

Resources: wind energy utilisation

Wind energy: an ancient but modern story

- Virtual axis
- Horizontal axis
- Airborne (高空)
- Bladeless

Vertical axis wind turbine,
Panemone windmill,
700-900 AD

Small power vertical wind turbine
Early 2000s – now

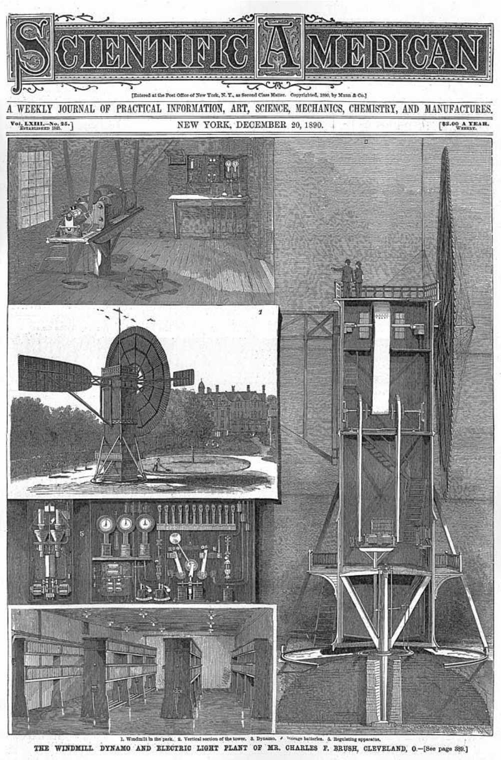
Wind turbines in Shanghai Tower,
source: skyscraper.org
2018

Resources: wind energy utilisation

Wind energy: an ancient but modern story

- Virtual axis
- Horizontal axis
- Airborne (高空)
- Bladeless

Horizontal axis wind turbine
14th century – now



First wind turbine for electricity generation
12 kW, source: http://xn--drmstrre-64ad.dk/
1890

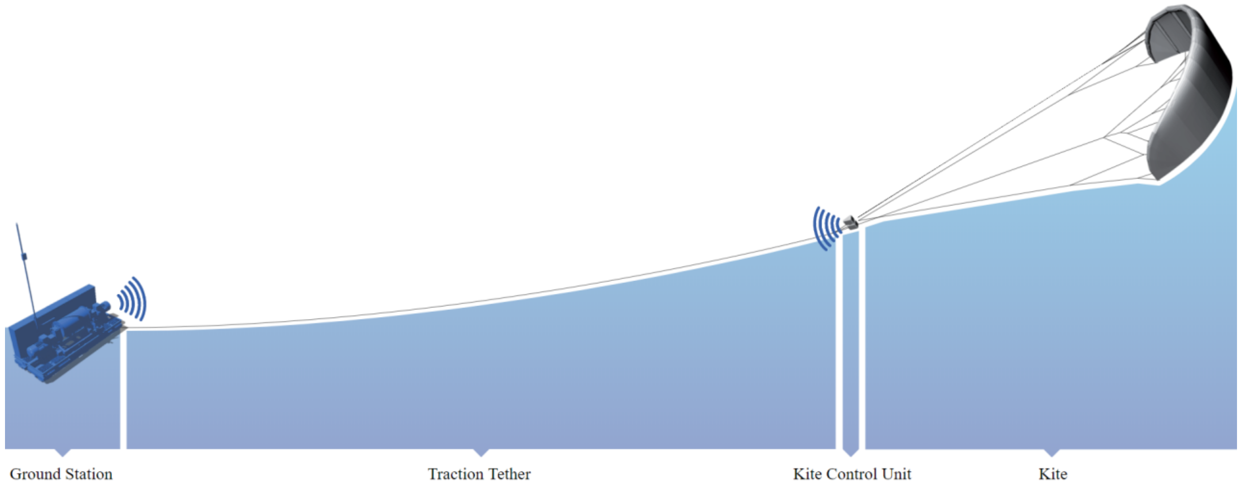
GE Haliade-X 12 MW
wind turbine
2019

Resources: wind energy utilisation

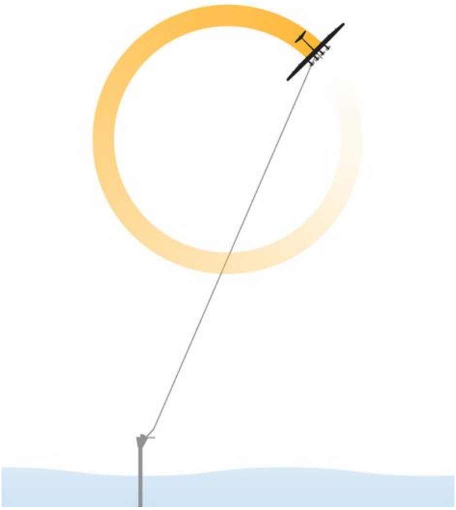
TUDelft

Wind energy: an ancient but modern story

- Virtual axis
- Horizontal axis
- Airborne (高空)
- Bladeless



Airborne wind energy, ground based generator
Source: Kitepower, a startup of TU Delft, https://kitepower.nl/



Airborne wind turbine, onboard generators
Source: Makani, https://makanipower.com

Resources: wind energy utilisation

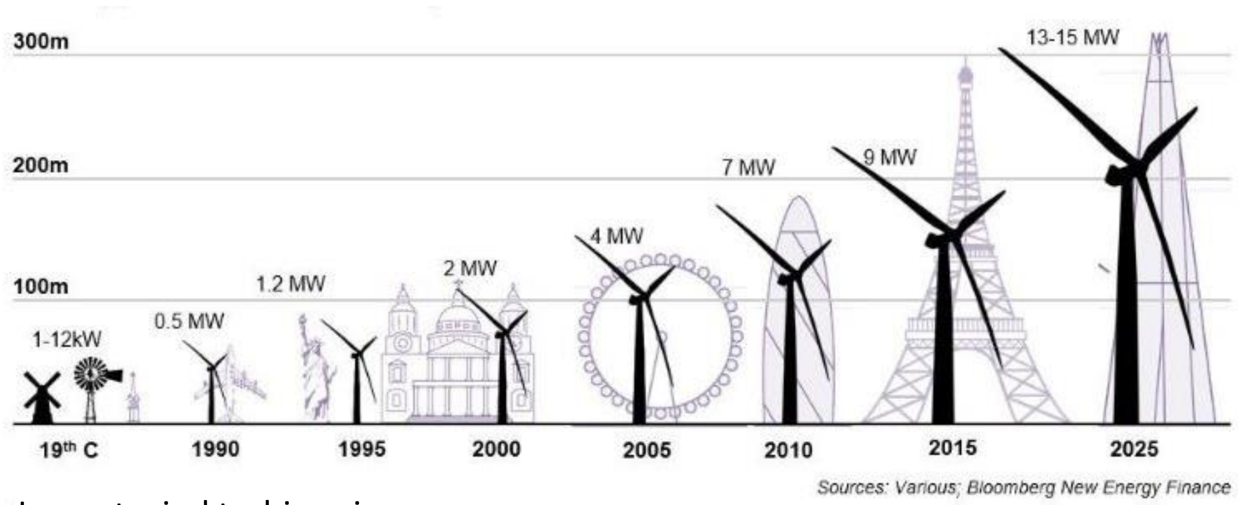
Wind energy: an ancient but modern story

- Virtual axis
- Horizontal axis
- Airborne (高空)
- Bladeless

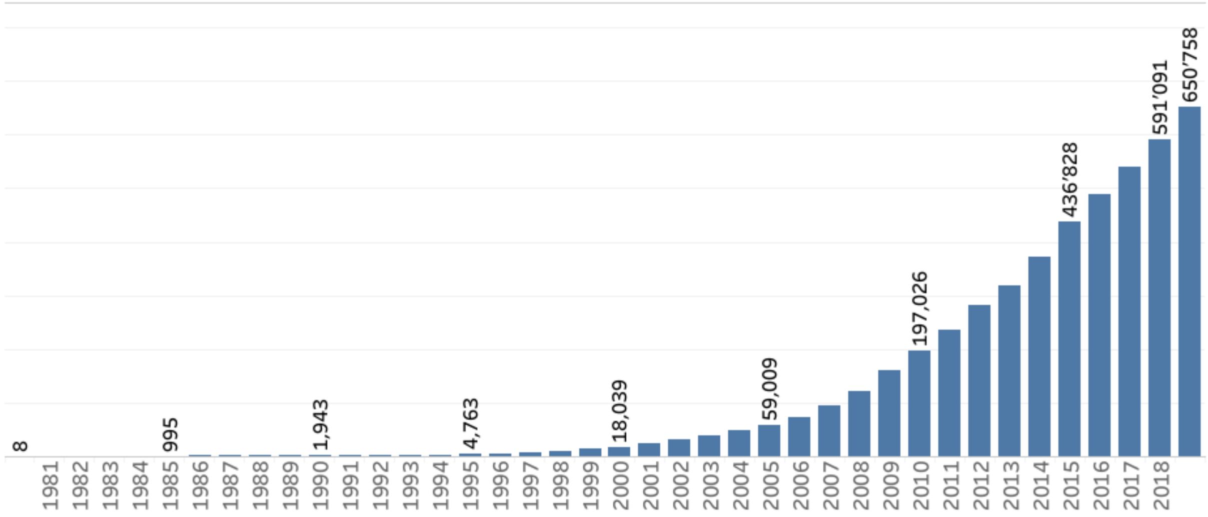
Bladeless wind turbines
Source: Makani, https://www.theverge.com/

Bird friendly?

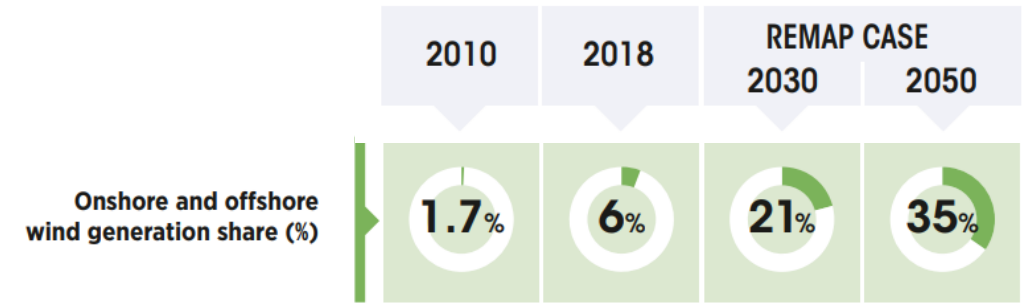
Resources: wind energy utilisation overview



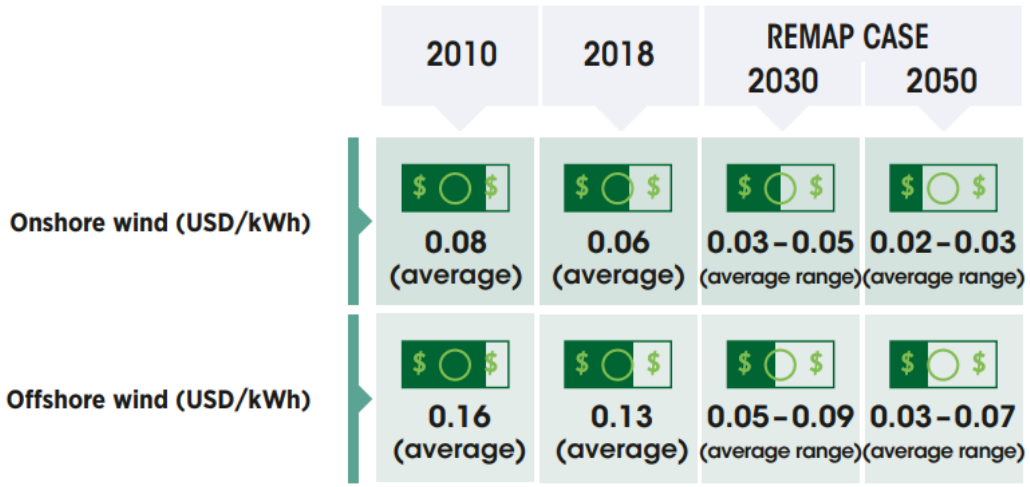
Largest wind turbine size



Global total installed capacity (MW),
50-60 GW annual installation in last 10 years.



Levelised cost of electricity (LCoE) outlook

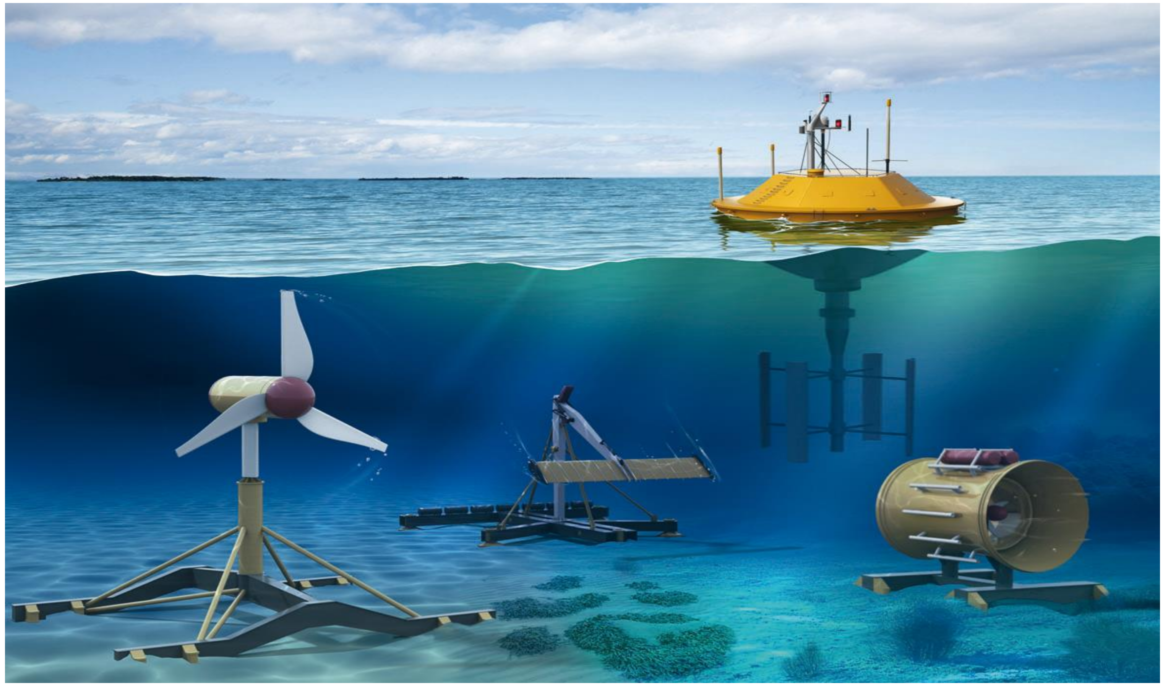


Global wind generation share outlook (%)
Source: IRENA, Future of Wind, 2019.

Resources: ocean energy utilisation

Ocean energy: higher mass density enables more possibilities

- Tidal energy
- Ocean wave energy
- Ocean thermal energy conversion
- Ocean biomass: biofuel - chemical energy
- Blue energy – salinity gradient: electro-chemistry

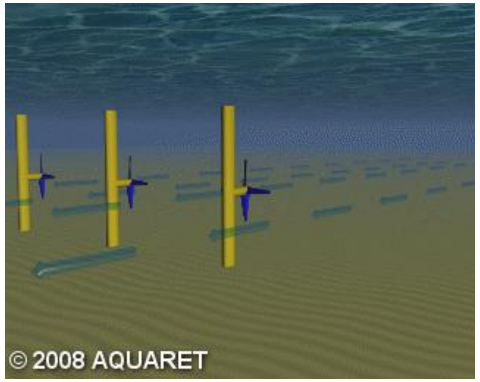


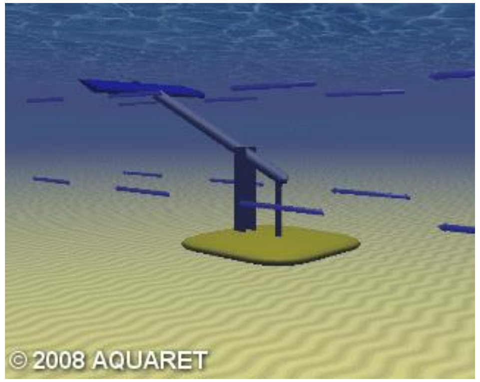
Source: Xpodence Research

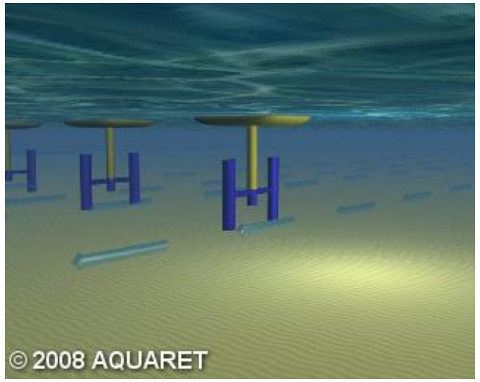
Resources: ocean energy utilisation

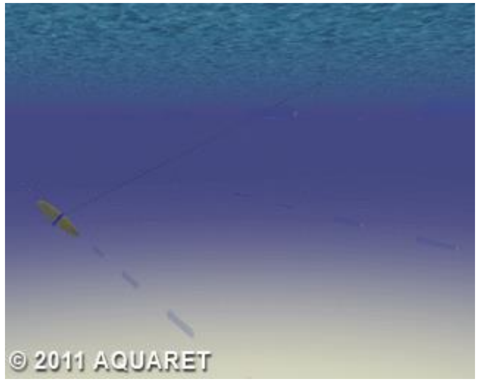
Ocean energy: higher mass density enables more possibilities

- Tidal energy (潮汐)
- Ocean wave energy
- Ocean thermal energy conversion
- Ocean biomass: biofuel - chemical energy
- Blue energy – salinity gradient: electro-chemistry









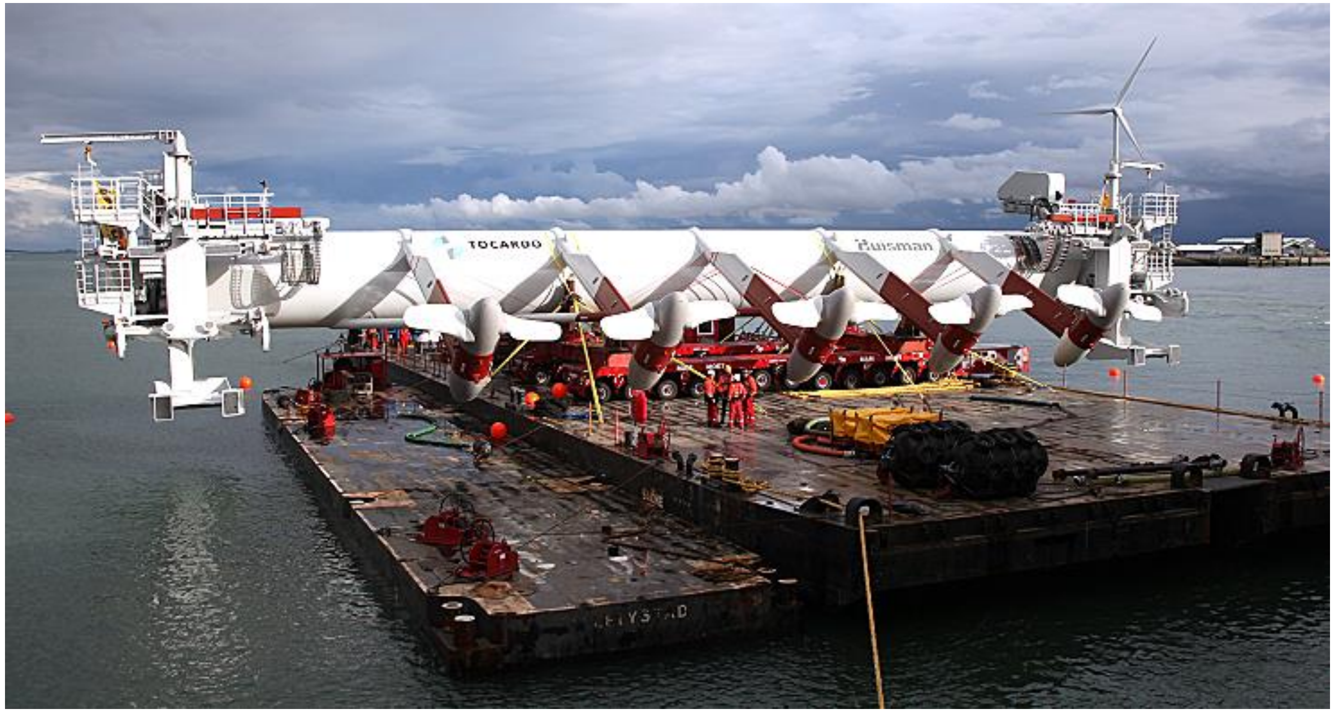
Source: aquaret.com

Resources: ocean energy utilisation

TUDelft

Ocean energy: higher mass density enables more possibilities

- Tidal energy
- Ocean wave energy
- Ocean thermal energy conversion
- Ocean biomass: biofuel - chemical energy
- Blue energy – salinity gradient: electro-chemistry

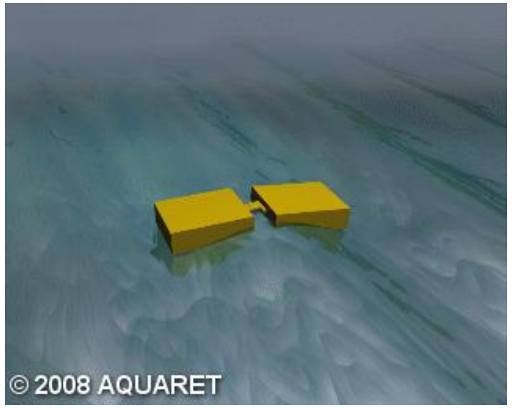


Source: Tocardo: the Dutch Tidal Power Company, tocardo.com

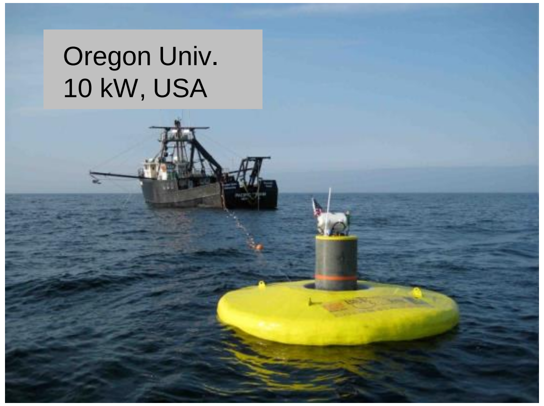
Resources: ocean energy utilisation

Ocean energy: higher mass density enables more possibilities

- Tidal energy
- Ocean wave energy (海浪)
- Ocean thermal energy conversion
- Ocean biomass: biofuel - chemical energy
- Blue energy – salinity gradient: electro-chemistry



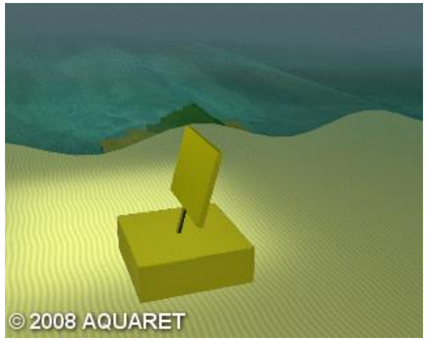
Attenuator / Point absorber
Source: aquaret.com

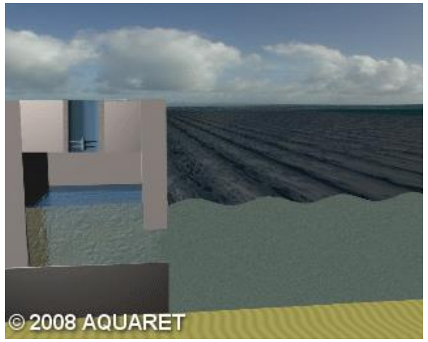


Resources: ocean energy utilisation

Ocean energy: higher mass density enables more possibilities

- Tidal energy
- Ocean wave energy
- Ocean thermal energy conversion
- Ocean biomass: biofuel - chemical energy
- Blue energy – salinity gradient: electro-chemistry



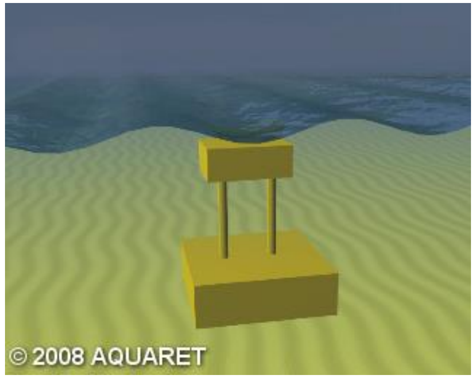


Oscillating wave surge converter / oscillating water column (water to air flow)
Source: aquaret.com

Resources: ocean energy utilisation

Ocean energy: higher mass density enables more possibilities

- Tidal energy
- Ocean wave energy
- Ocean thermal energy conversion
- Ocean biomass: biofuel - chemical energy
- Blue energy – salinity gradient: electro-chemistry



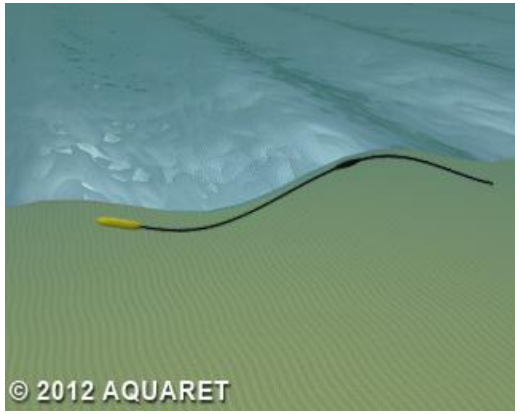
Overtopping device (water reservoir) / Submerged pressure differential device
Source: aquaret.com

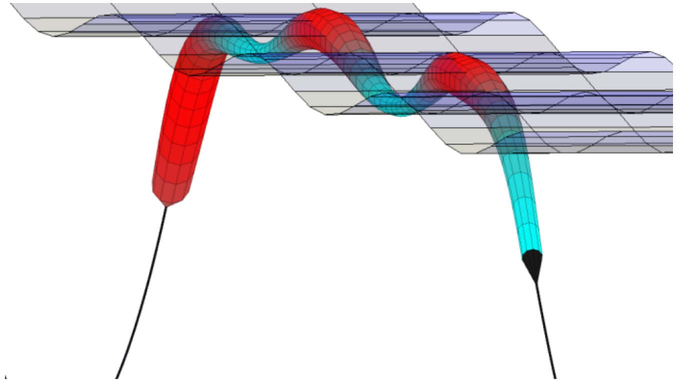
Source: Polinder H., Damen, M. E. C. and Gardner F., Linear PM generator system for wave energy conversion in the AWS, IEEE Trans. Engr. Conv., vol. 19, no. 3, 2004.

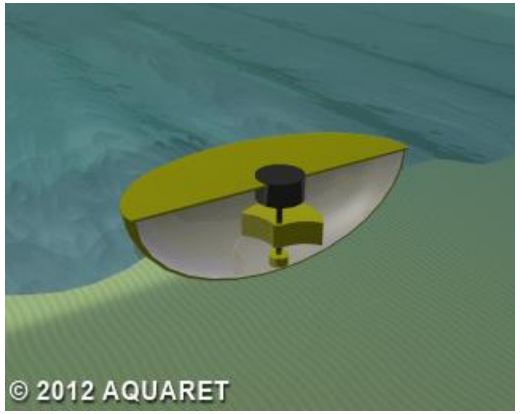
Resources: ocean energy utilisation

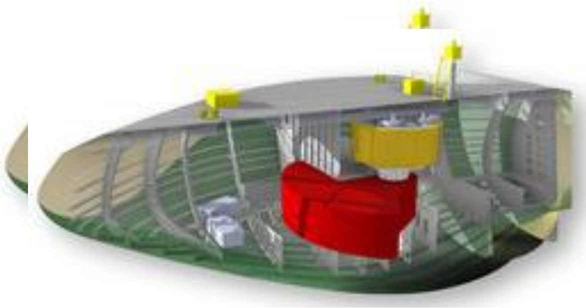
Ocean energy: higher mass density enables more possibilities

- Tidal energy
- Ocean wave energy
- Ocean thermal energy conversion
- Ocean biomass: biofuel - chemical energy
- Blue energy – salinity gradient: electro-chemistry







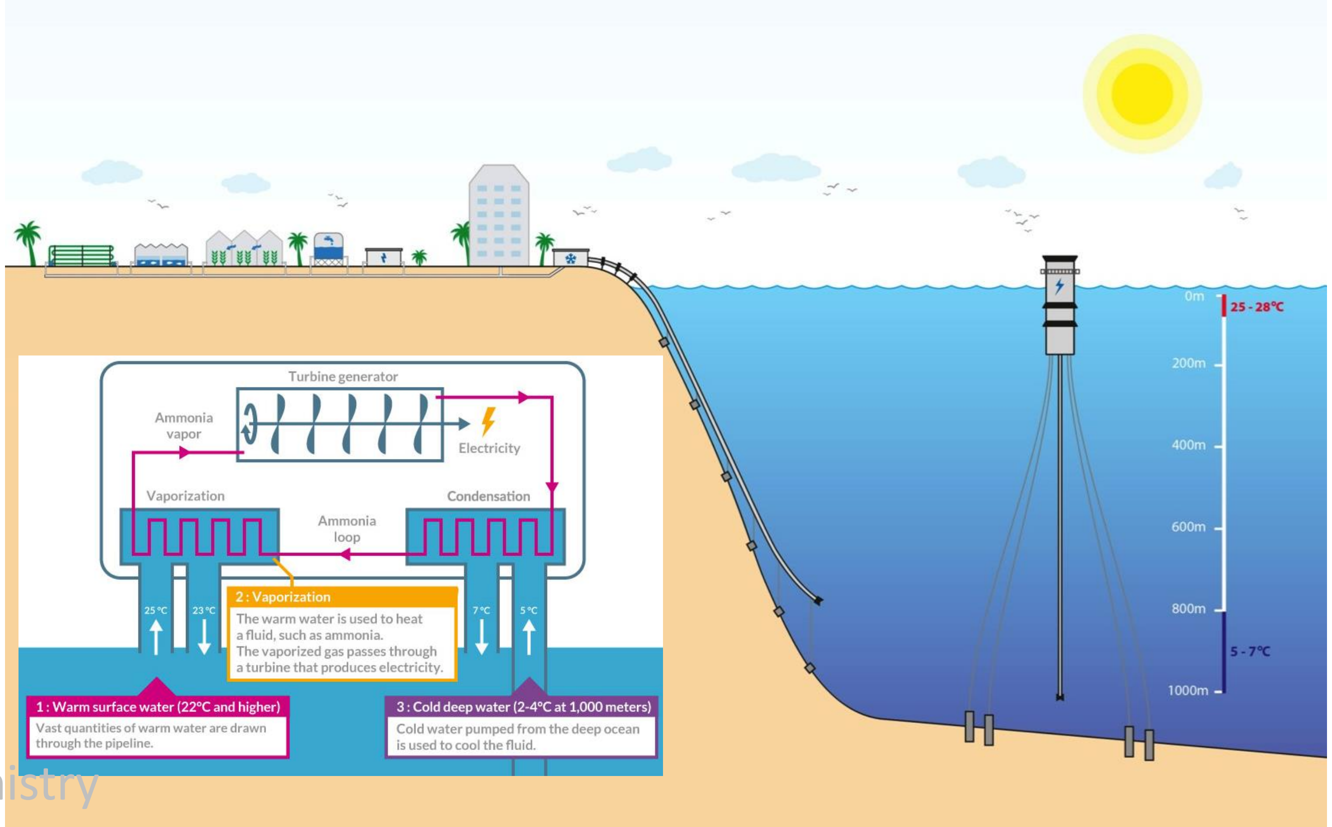


Bulge wave / Rotating mass
Source: aquaret.com

Resources: ocean energy utilisation

Ocean energy: higher mass density enables more possibilities

- Tidal energy
- Ocean wave energy
- Ocean thermal energy conversion
- Ocean biomass: biofuel - chemical energy
- Blue energy – salinity gradient: electro-chemistry



Source: planete-energies.com

Resources: ocean energy utilisation

Ocean energy: higher mass density enables more possibilities

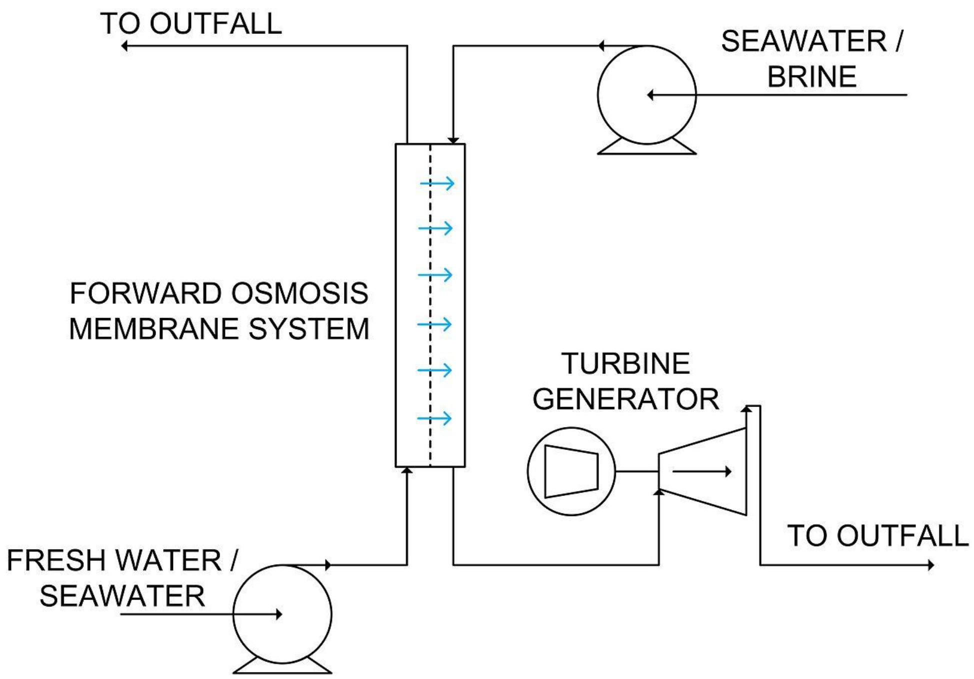
- Tidal energy
- Ocean wave energy
- Ocean thermal energy conversion
- Ocean biomass: biofuel - chemical energy
- Blue energy – salinity gradient: electro-chemistry

Dunaliella salina Algae (杜氏盐藻)
Source: Wikipedia.org

Resources: ocean energy utilisation

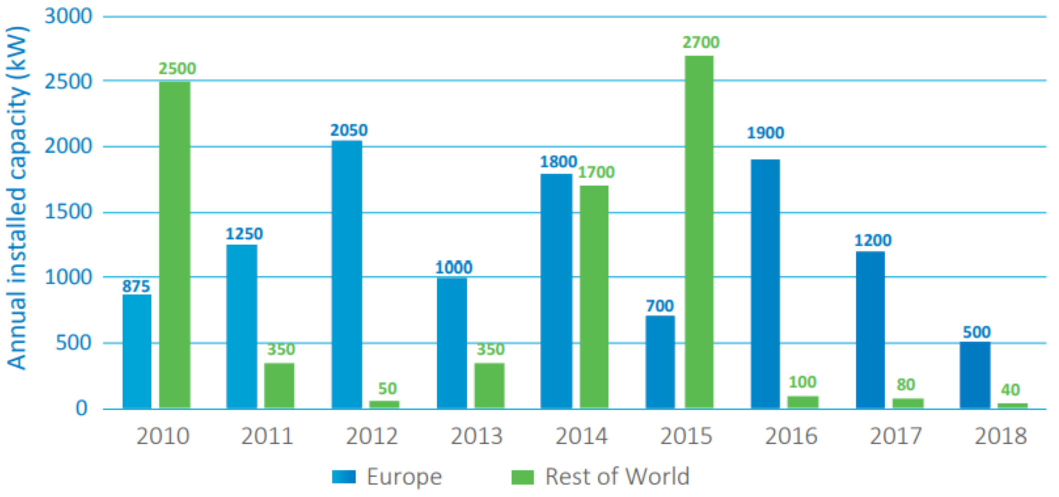
Ocean energy: higher mass density enables more possibilities

- Tidal energy
- Ocean wave energy
- Ocean thermal energy conversion
- Ocean biomass: biofuel - chemical energy
- Blue energy – salinity (盐度) gradient: electro-chemistry

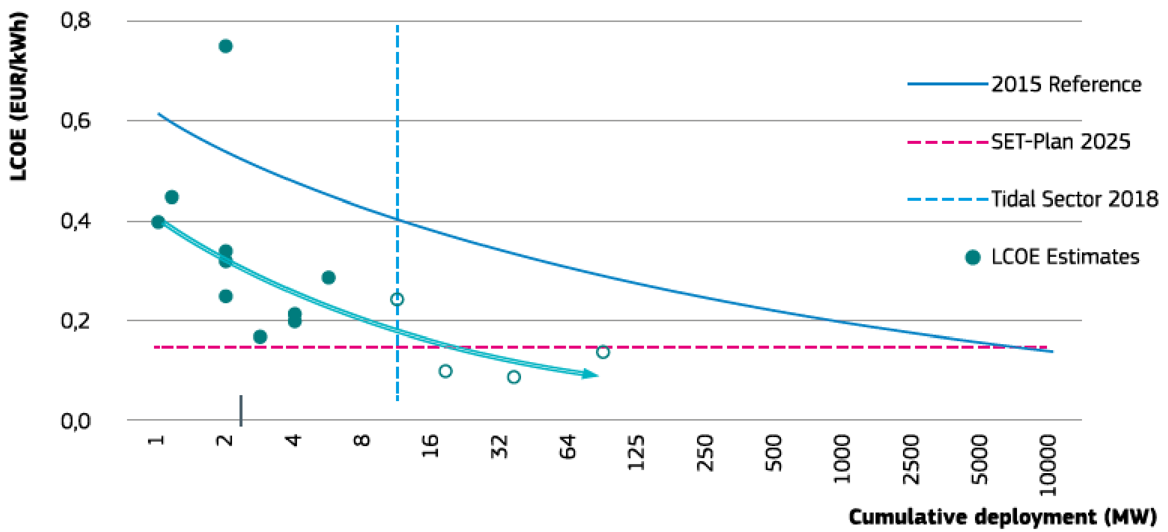


Pressure-retarded osmosis based process
Source: Wikipedia.org

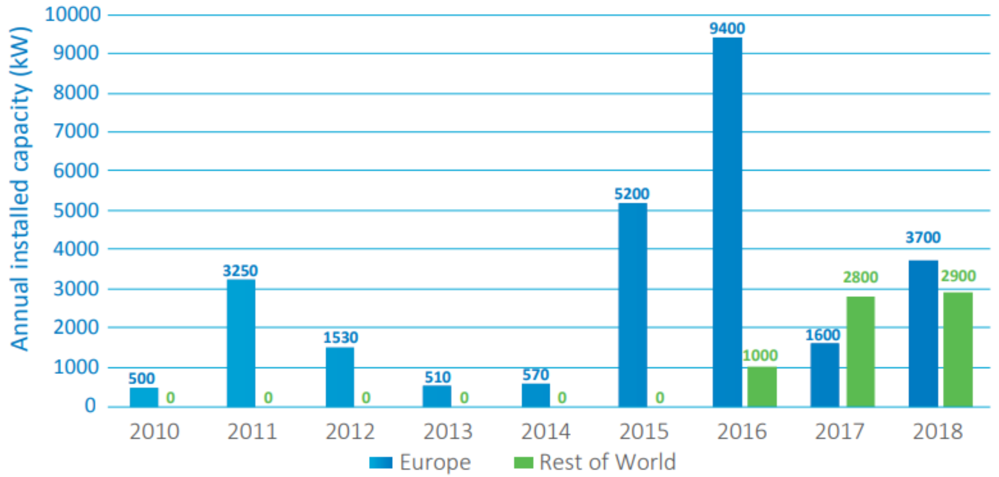
Resources: ocean energy utilisation overview



Annual wave energy installation Europe vs. rest of world



LCoE reduction target set by The European Strategic Energy Technology (SET) Plan
Solid dots: existing projects; hollow dots: new project estimation.
Source: SETIS magazine, no. 20 - May 2019

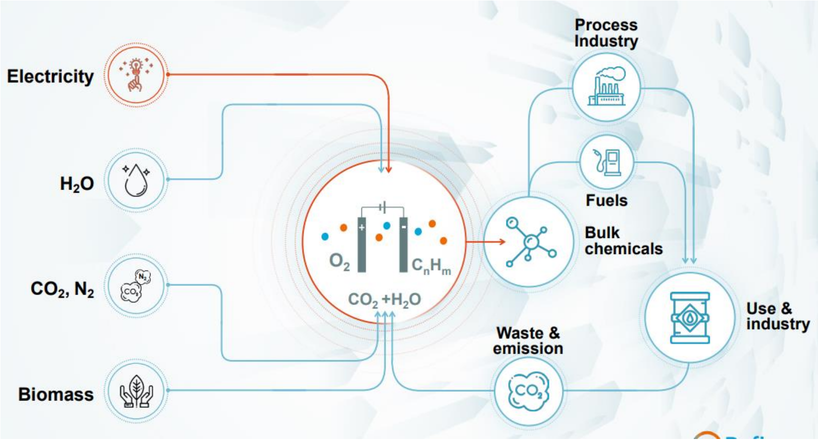


Annual tidal energy installation Europe vs. rest of world
Source: ocean energy Europe

- More diverse solutions than wind.
- Global installation is even far less than a wind farm.
- Technology is evolving, but high cost of generated electricity is still an issue.
- Reliability of the generator system is another issue: high salinity water/air, undersea converters/generators.

Resources: offshore wind and electrochemical energy

Sustainable productions of fuels and chemicals: electric refinery (电炼油)

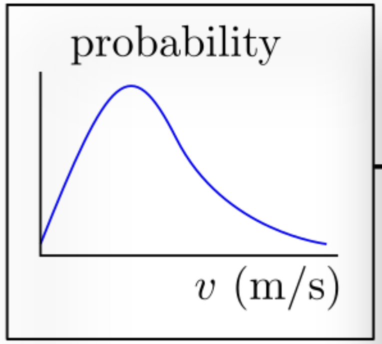


reaction	n	$E°/V^a$
$CO_2 \rightleftharpoons CO + 0.5O_2$	2	−1.33
$CO_2 + H_2O \rightleftharpoons HCOOH + 0.5O_2$	2	−1.43
$CO_2 + 2H_2O \rightleftharpoons CH_3OH + 1.5O_2$	6	−1.21
$CO_2 + 2H_2O \rightleftharpoons CH_4 + 2O_2$	8	−1.06
$2CO_2 + 3H_2O \rightleftharpoons C_2H_5OH + 3O_2$	12	−1.14
$2CO_2 + 2H_2O \rightleftharpoons C_2H_4 + 3O_2$	12	−1.15
$3CO_2 + 4H_2O \rightleftharpoons C_3H_7OH + 4.5O_2$	18	−1.13

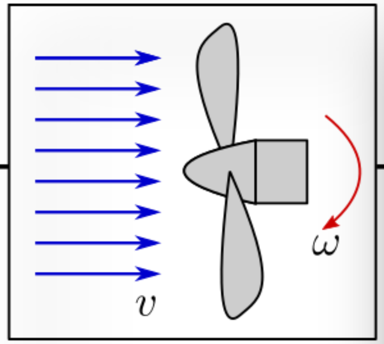
Energy conversion system topology

Energy conversion system

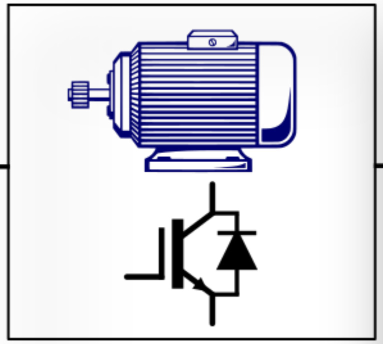
System overview



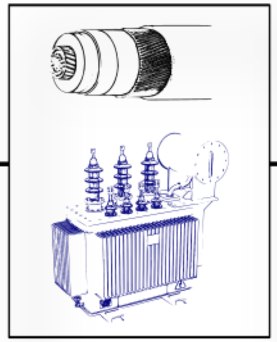
Source properties



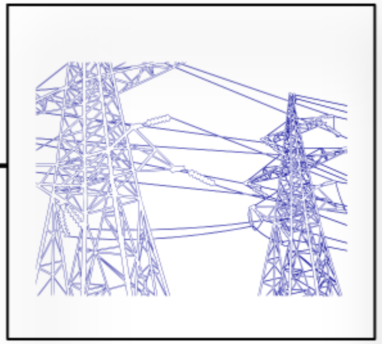
Primary conversion



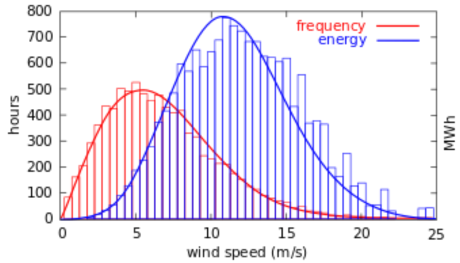
Secondary conversion

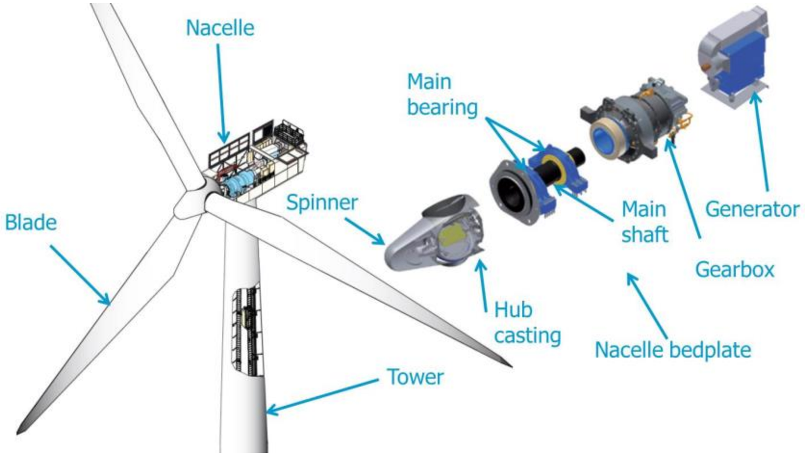


Power collection and transmission

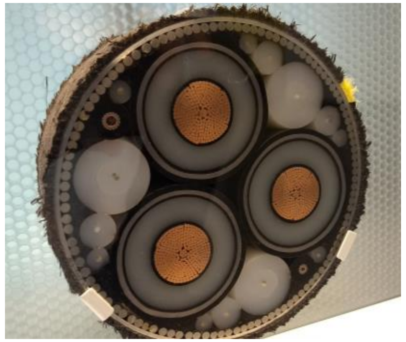


Power grid





Source: http://www.kentwindenergy.co.uk



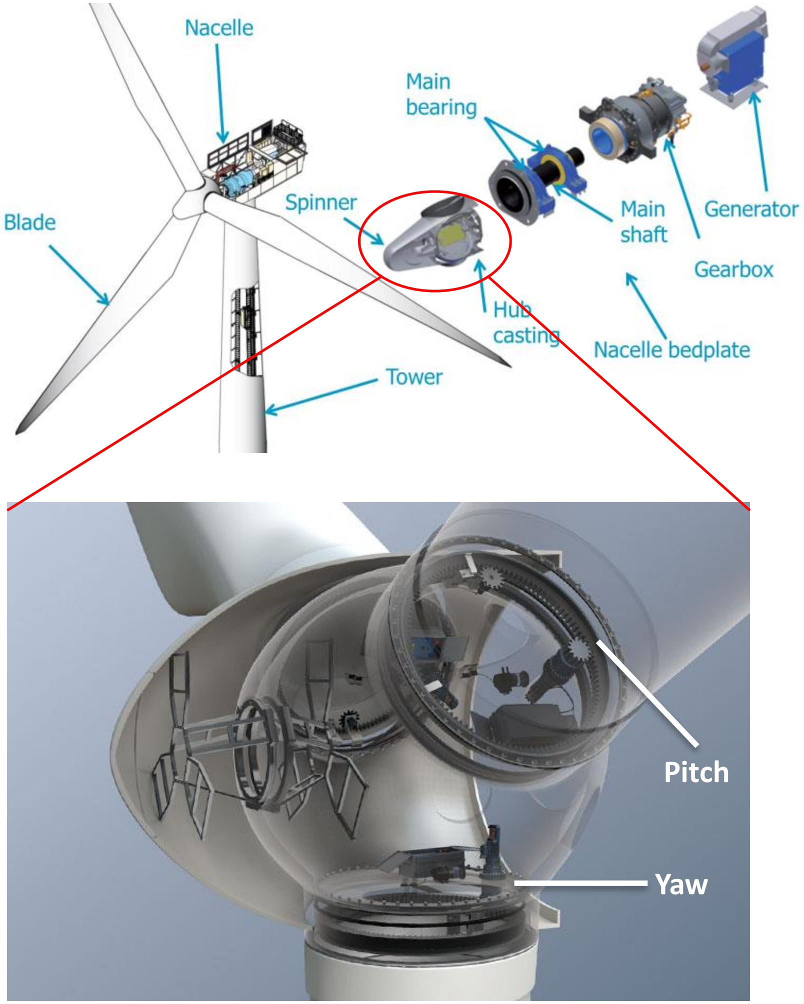
150 kV,
3-phase submarine cable

Offshore wind substation
Source: offshorewindindustry.com

Turbine drivetrain structure

Turine drive train

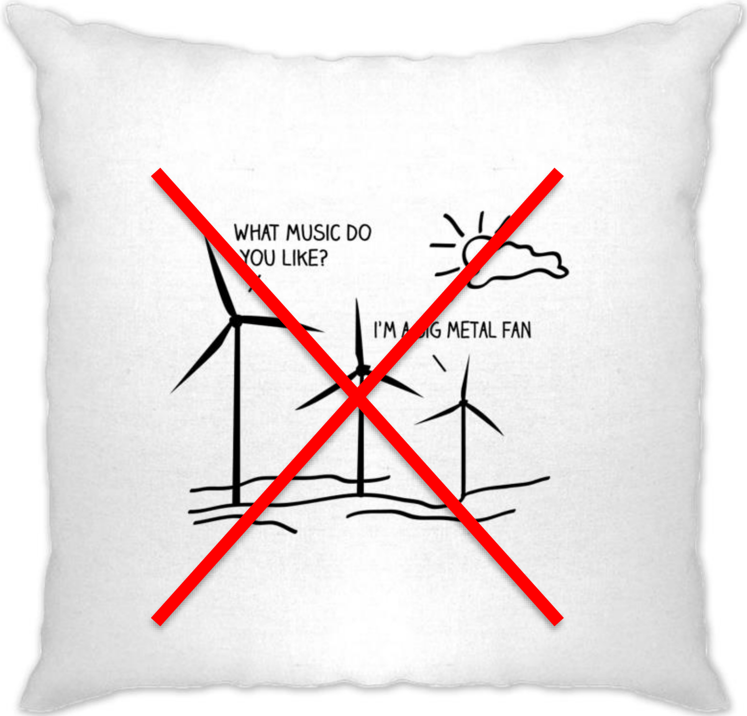
Drivetrain: an overview



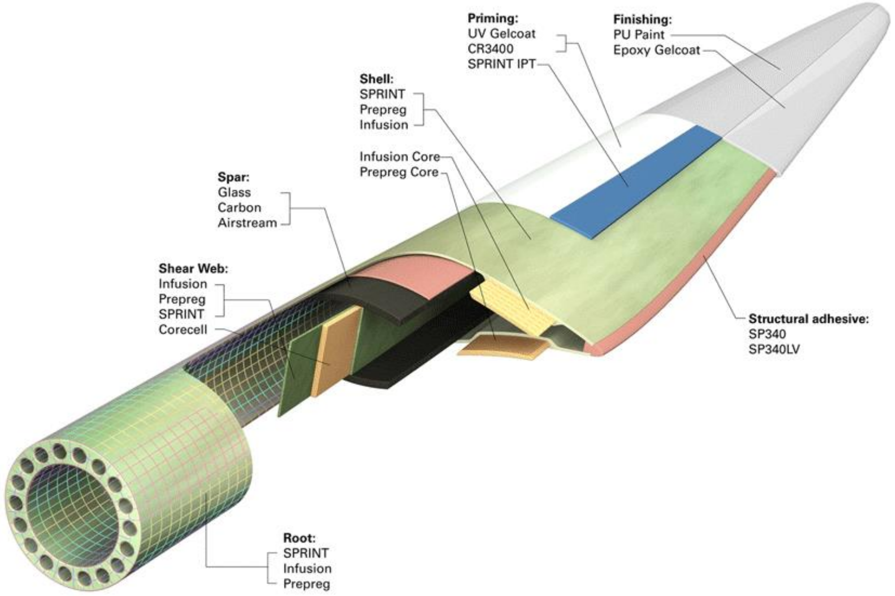
Source: http://www.ifm.com

- Gearbox is removed if direct-drive generator is used
- Pitch (变桨) and yaw (偏航) mechanism to utilize wind efficiently and sufficiently
- Brake is essential, why?
- Power converter
- Cooling system
- Other auxiliaries: various sensors, lubricant system, hydraulic system, lift

Big metal fan?



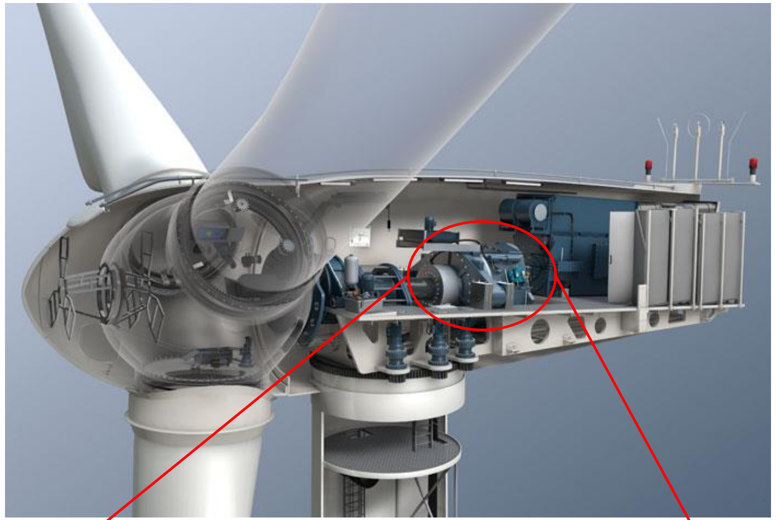
Blades are made of composite materials



and more non-metal materials will be used…

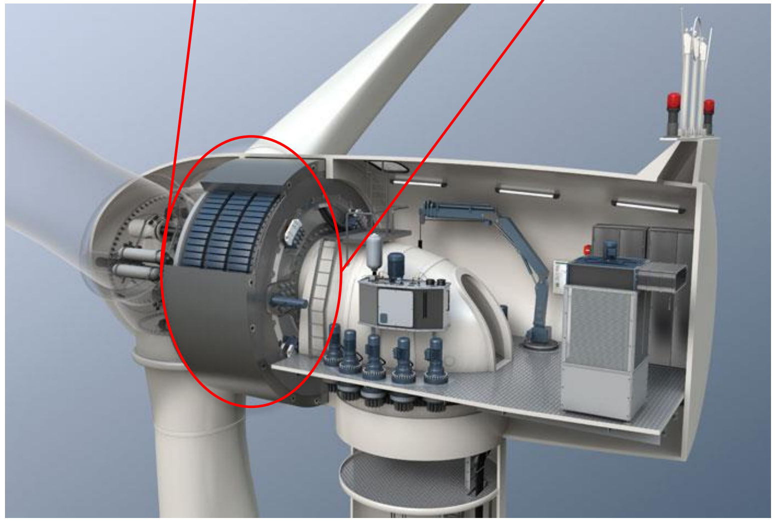
Gearbox: pros and cons

Direct drive vs. geared drivetrain



Gearbox

Direct-drive generator

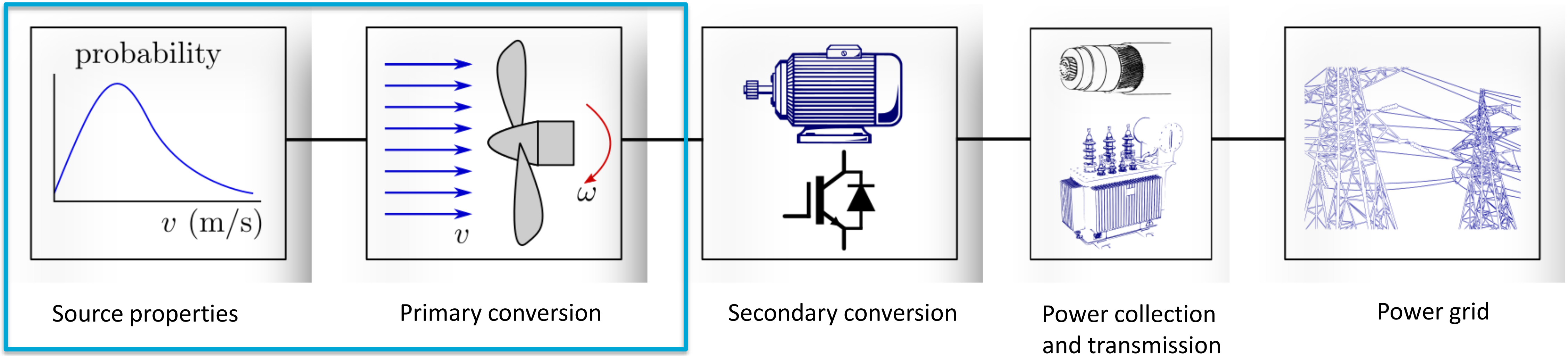


Basic principles:

fluid dynamics and electromechanical

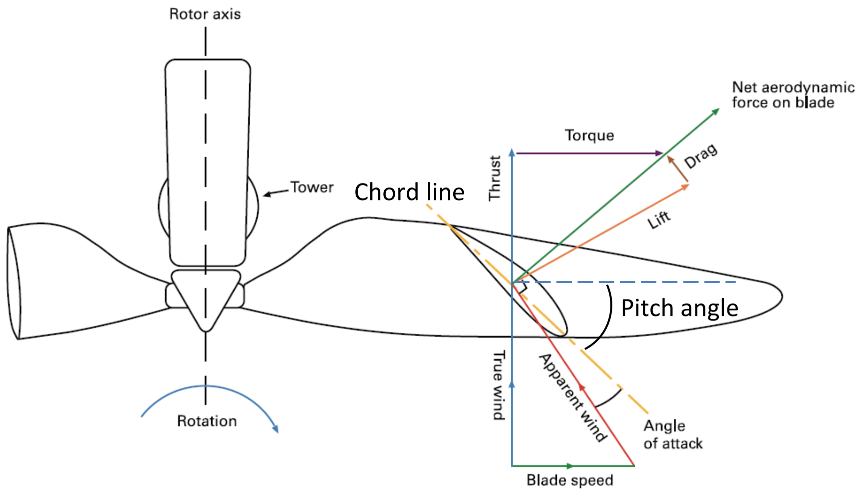
Energy conversion system

System overview

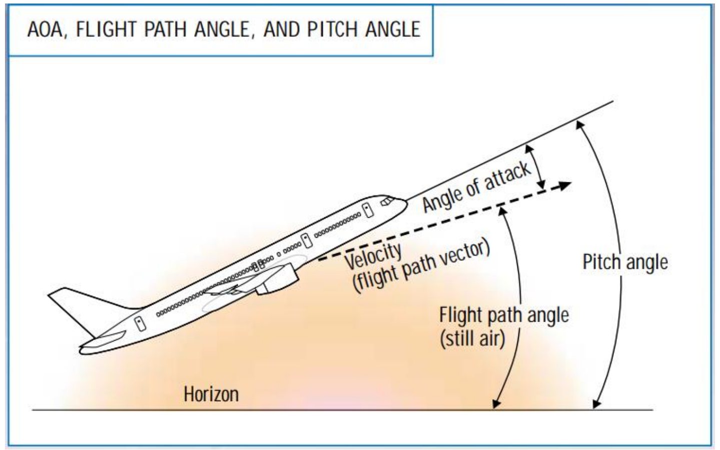


Lift and drag

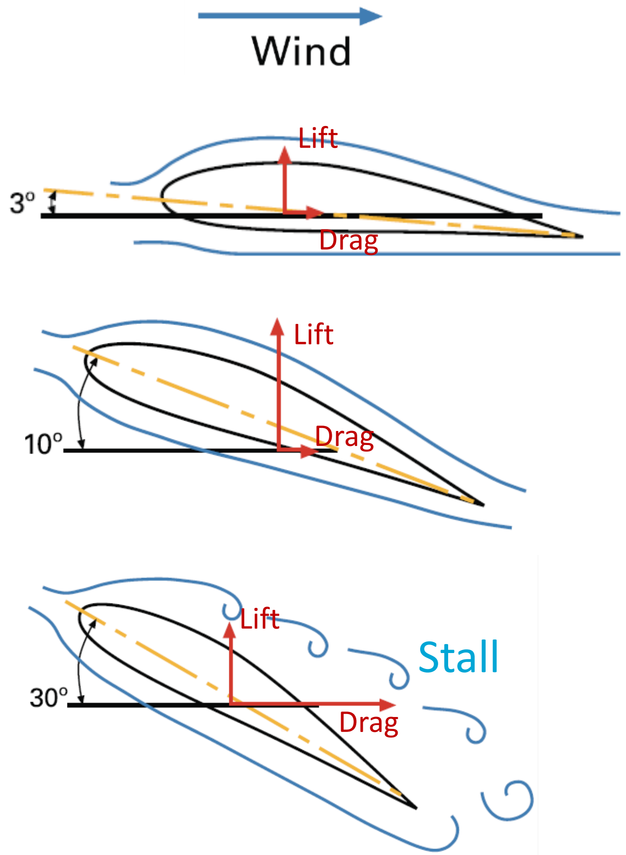
Angle of attack



Sectional view of balde tilted 90° into the paper



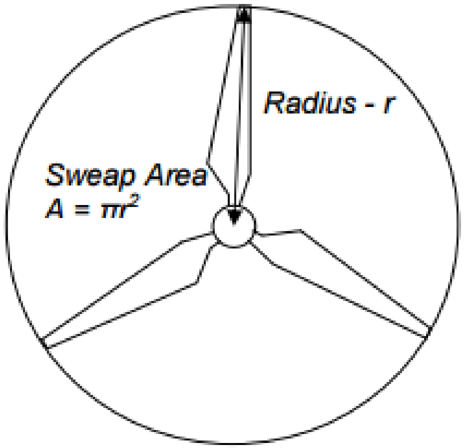
An airplane analogy
Source: Boeing



- Angle of attack (AoA, 攻角) changes with pitch angle (俯仰角)
- Force to rotate the blades can be controlled by pitching (变桨)
- Large AoA will lead to stall (失速) because of turbulence on the back

Basic aerodynamic relations

Performance coefficient



Available wind power is calculated from change rate of kinetic energy:

$$P = \frac{\mathrm{d}E}{\mathrm{d}t} = \frac{1}{2}\frac{\mathrm{d}m}{\mathrm{d}t}v^2 = \frac{1}{2}\rho_{fluid} A v^3$$

Performance coefficient (利用系数), or power coefficient, describes the ratio of power extracted:

$$C_p(\lambda, \theta) = \frac{\text{utilized energy}}{\text{total available energy}}$$

is a function of pitch angle and

$$\lambda = \frac{v_r}{v} = \frac{\omega_r r}{v}$$

Rotor tip speed

Fluid speed

Tip speed ratio (叶尖速比)

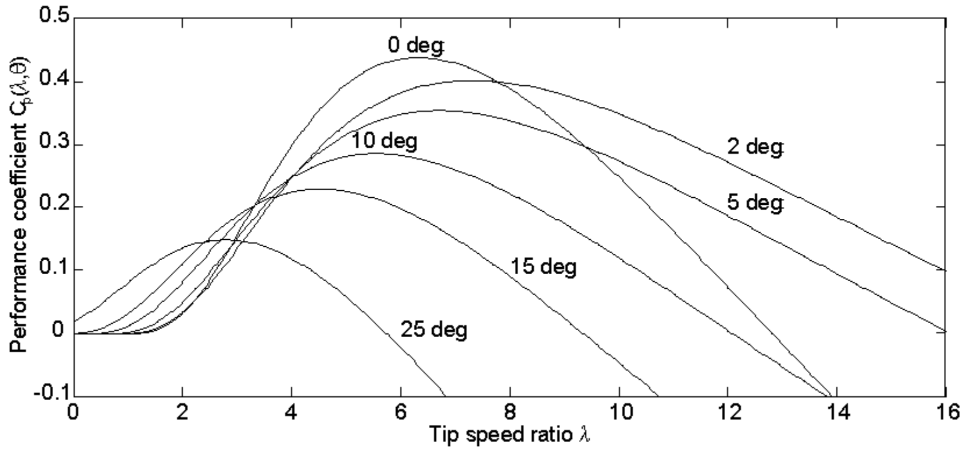
The extracted power is:

$$P = \frac{1}{2}\rho_{fluid} C_p A v^3 = \frac{1}{2}\rho_{fluid} C_p(\lambda, \theta)\pi r^2 v^3$$

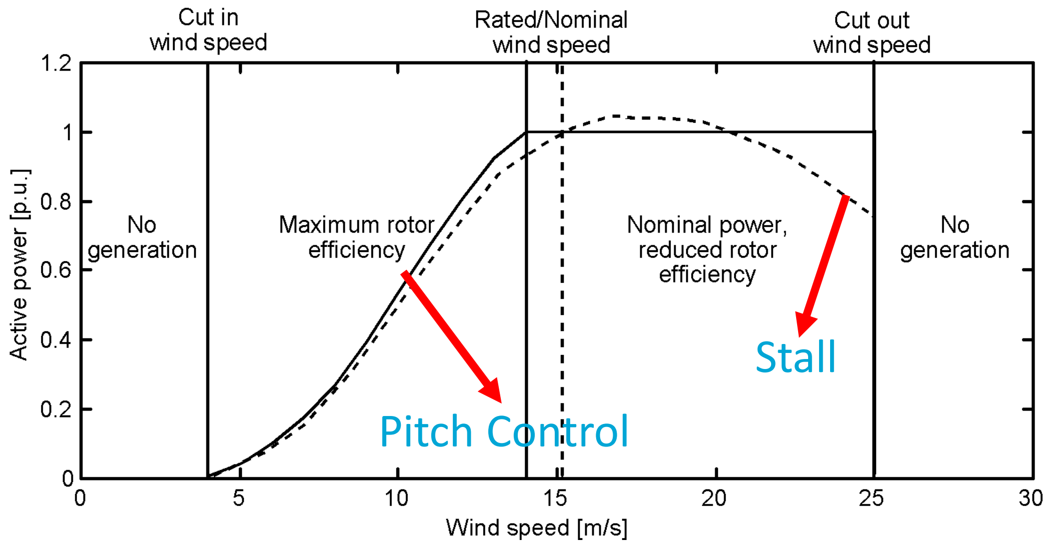
Draw some conclusions here?

Power regulation: C_p Curves

Stall control and pitch control



C_p curves as functions of pitch angle and tip speed



Power curves of pitch controlled and stall controlled wind turbines

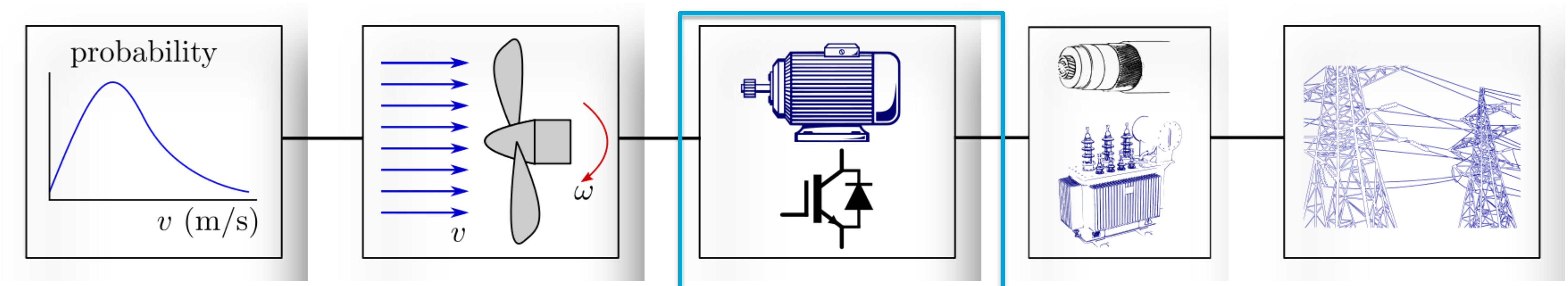
Pitch controlled wind turbine:

- C_p is actively controllable through pitching
- Optimal pitch angle at different speeds
- At very high speed, the rotor is stopped: “cut-out” wind speed (切出风速)

Stall controlled turbine:

- No pitching mechanism
- Fluid dynamically designed blade to stall at high speed
- C_p is not optimal

System overview



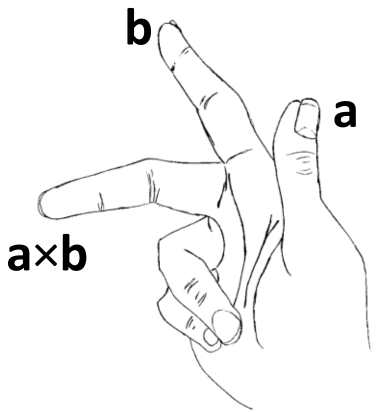
Source properties — Primary conversion — Secondary conversion — Power collection and transmission — Power grid

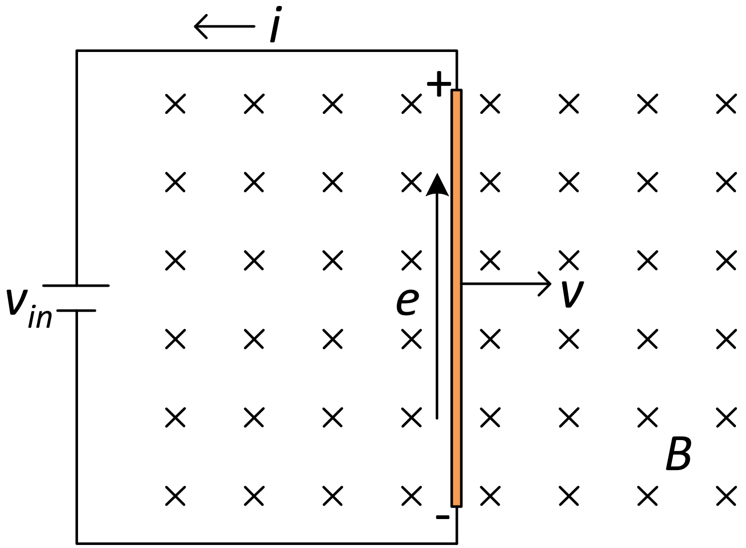
Electromechanics: induced voltage

Faraday's Law

$$e = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$
$$= |\mathbf{v}||\mathbf{B}|\sin(\theta)\hat{\mathbf{n}} \cdot \mathbf{l}$$

$$\boxed{e = Blv}$$





Delivered electrical power

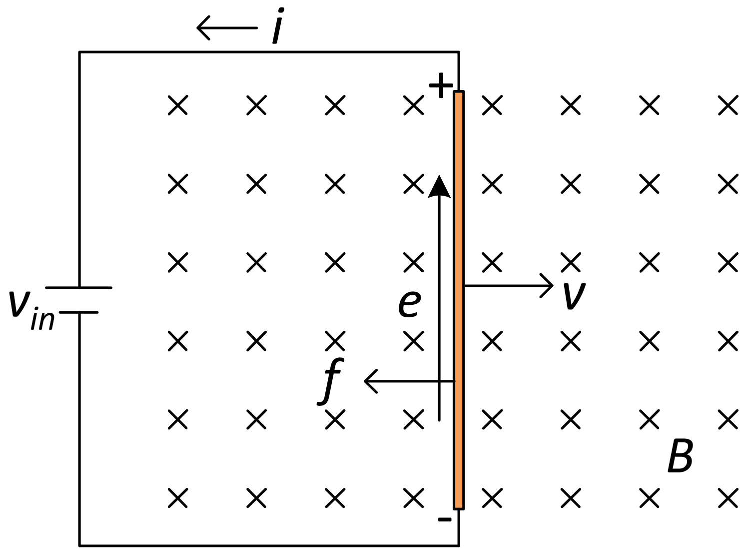
$$p = ei = Blvi$$

Electromechanics: force production

Lorentz Force

$$
\begin{aligned}
f &= i(\mathbf{l} \times \mathbf{B}) \\
&= |\,\mathbf{l}\,||\,\mathbf{B}\,| \sin(\theta)\hat{\mathbf{n}}
\end{aligned}
$$

$$\boxed{F = Bli}$$

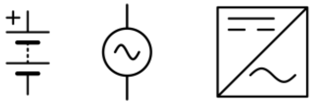


Converted mechanical power

$$p = Fv = Bliv$$

Anatomy of electric machines

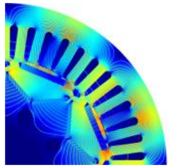
Electrical terminal



$$e = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$

- DC machine
- AC machine

Magnetic field



- Permanent magnet machine
- Electrically excited machine

$$f = i(\mathbf{l} \times \mathbf{B})$$

Mechanical terminal

- Linear machine
- Rotational machine

Coils to support *i* and *e* : armature

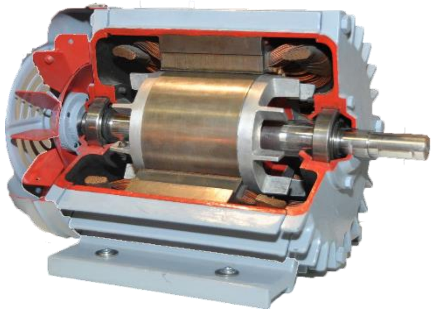
Components to create the field *B* : field winding

or permanent magnet

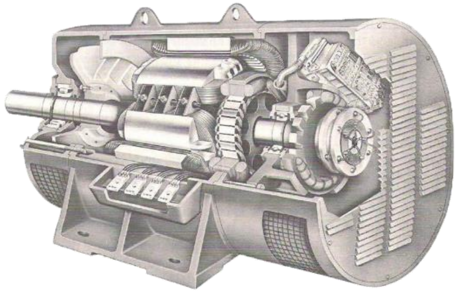
Machine type	Winding	Function	Locatio n	Current
DC Machine	Armature	Input/output	Rotor	AC in coils, DC at brushes
	Field	Magnetizing	Stator	DC
Synchronous machine	Armature	Input/output	Stator	AC
	Field	Magnetizing	Rotor	DC
Induction machine	Input	Primary	Stator	AC
	Output	Secondary	Rotor	AC

No purely DC machine!

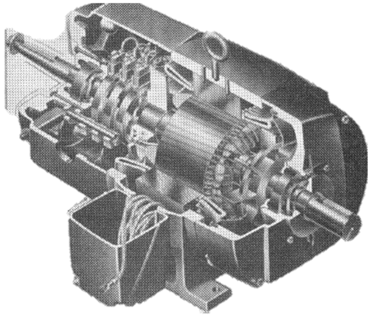
Main-stream generators for renewable energy



Squirrel cage induction machine



Wound field synchronous machine



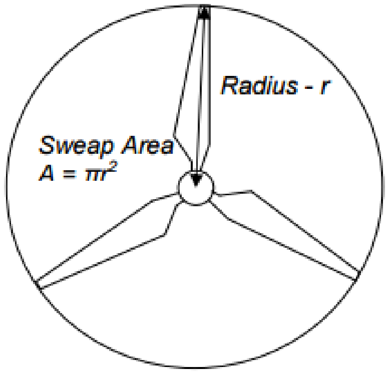
Doubly fed induction machine

Permanent Magnet synchronous machine

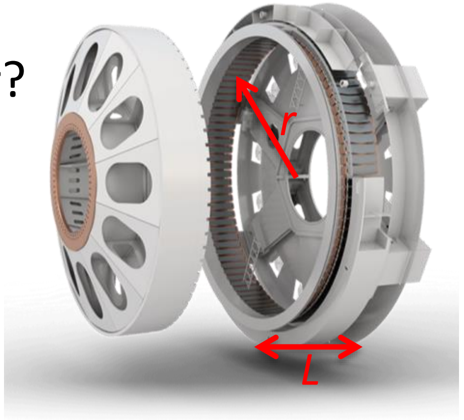
Why DC generator is not used?

Electrical generator: sizing

How large the generator should be?



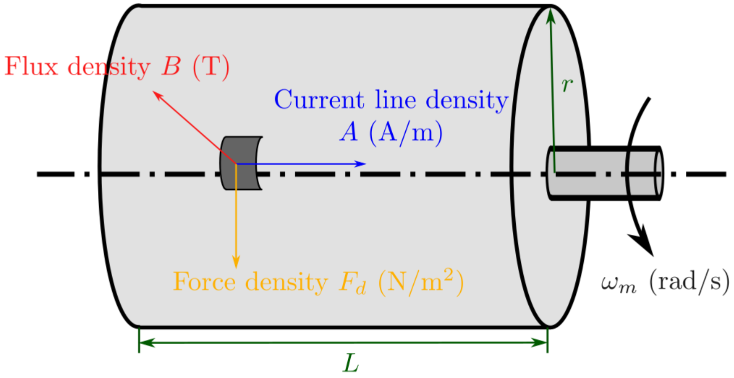
- We know $P = \frac{1}{2}\rho_{fluid} C_p A v_w^3 = \frac{1}{2}\rho_{fluid} C_p(\lambda,\theta)\pi r^2 v_{fluid}^3$ for blades
- How about the generator?



- Force density in the air-gap (the gap between rotor and stator):

$$F_d = B_g A$$

$$F_d \approx 30 - 60\ \mathrm{kN/m^2}$$

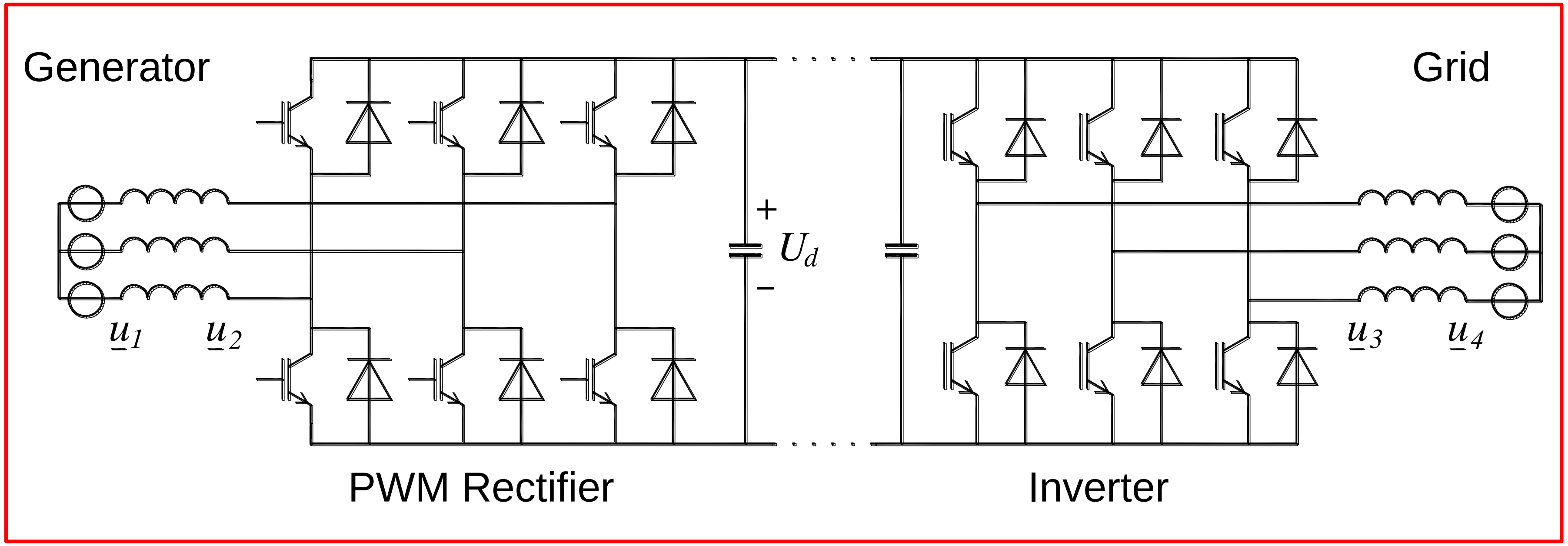


- Rather constant because
  - Saturation limits B_g
  - Losses limit *i*

$$P = \omega_m T = \omega_m r F = \omega_m r(2\pi r) L F_d = 2\omega_m V_r F_d$$

When generator can't work alone …

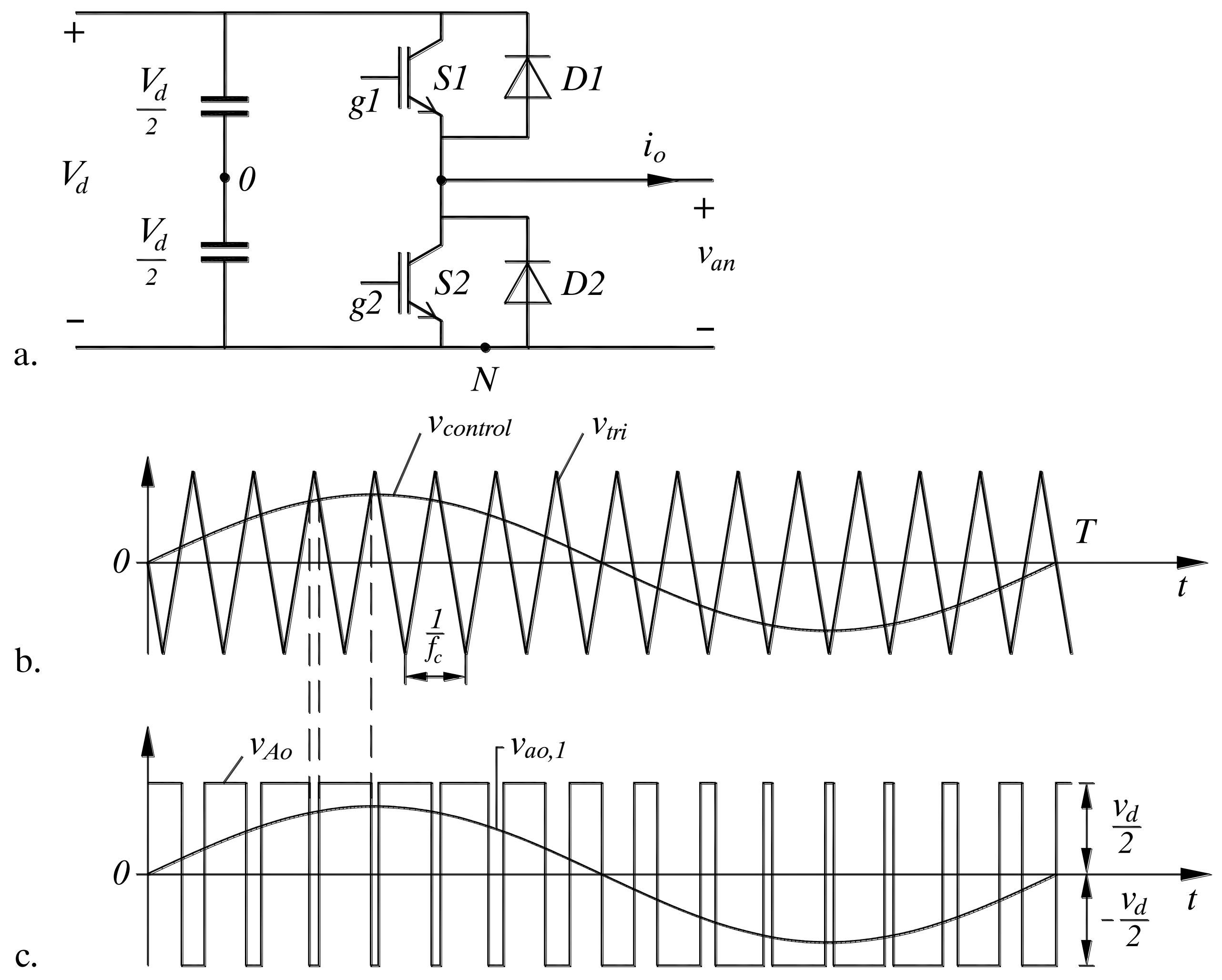
Power converters



Back-to-back converter

Principle of voltage source inverter

Pulse width modulation



Phase leg of Voltage Source Converter (电压源型变换器)

=

Basic building block of modern power electronics

PWM: average output voltage is a replica of $v_{control}$

TUDelft

Requirements of renewable generation system

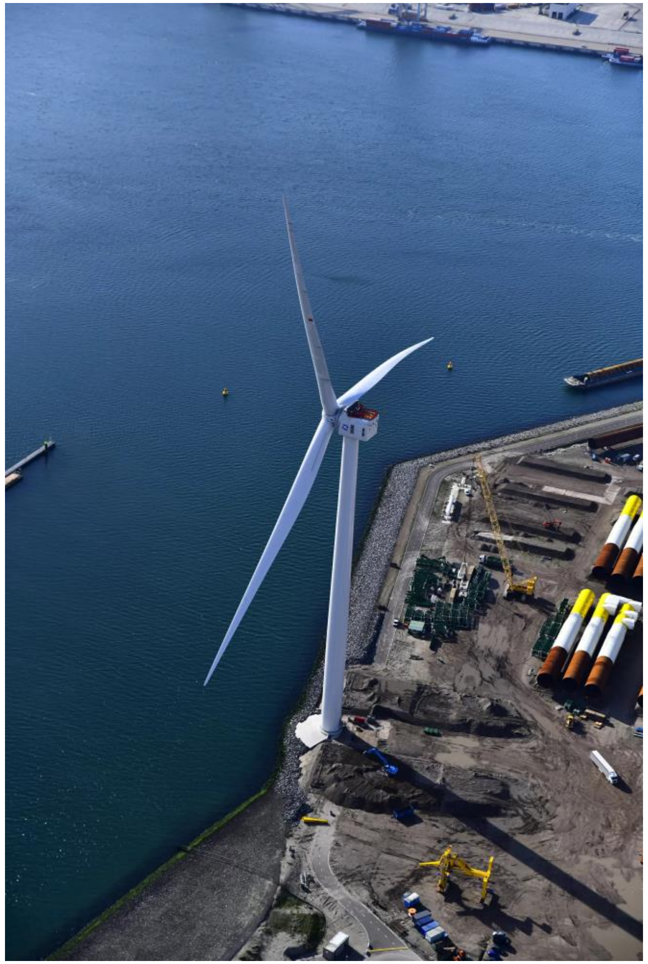
TUDelft

An example

GE Haliade-X

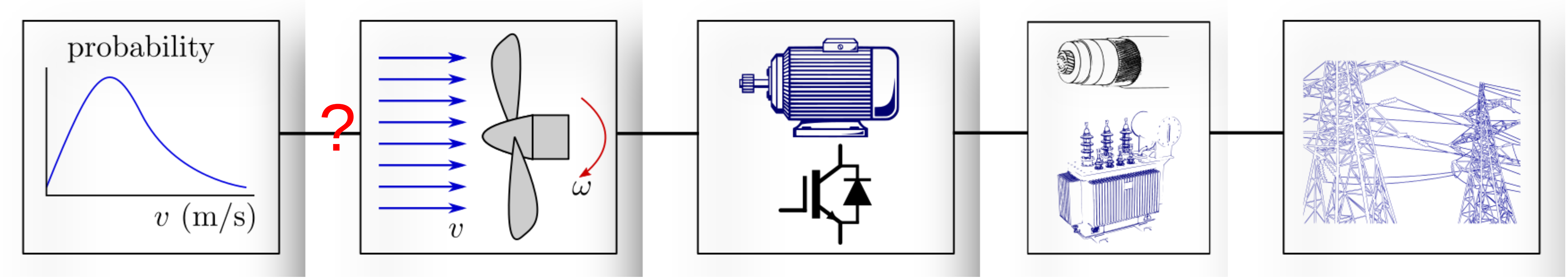
- Diameter 220 m
- Rotor speed 7.81 rpm
- Tip speed 89.2 m/s

- What lead to such design?
- What are important requirements?



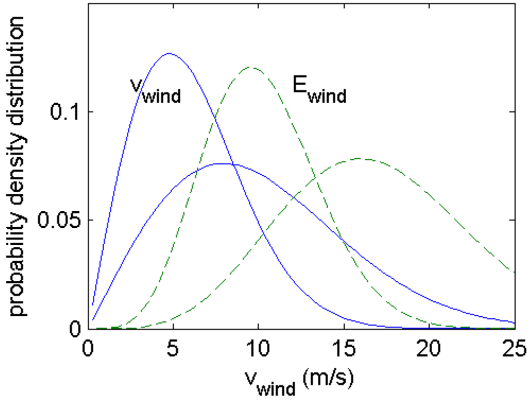
GE Haliade-X 12 MW wind turbine, Rotterdam Port.

Requirements: primary conversion



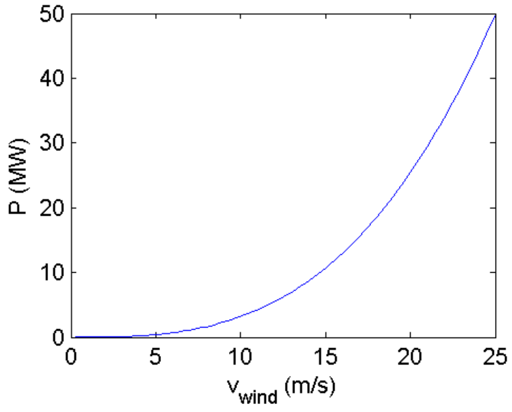
Rated wind speed and power: Weibull distribution (韦伯分布)

- Wind and energy probability distribution for average wind speeds of 6 and 10 m/s



- Power vs. wind speed

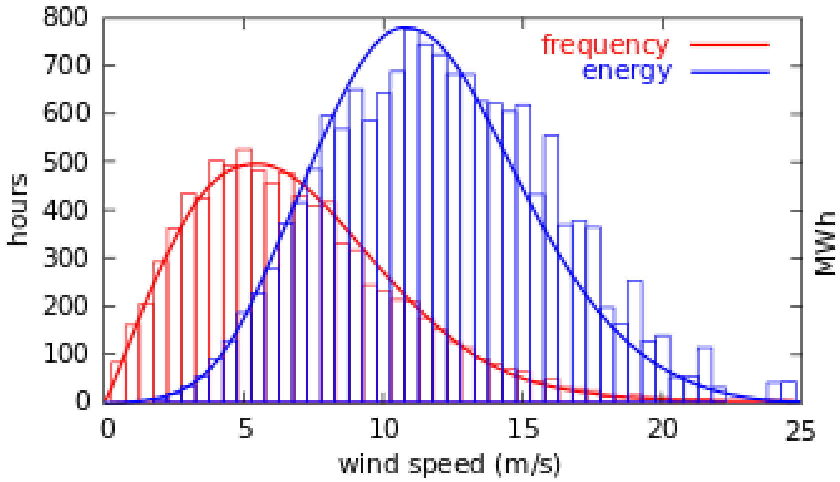
$$P = \frac{1}{2}\rho_{air} C_p(\lambda,\theta)\pi r_r^2 v_w^3$$

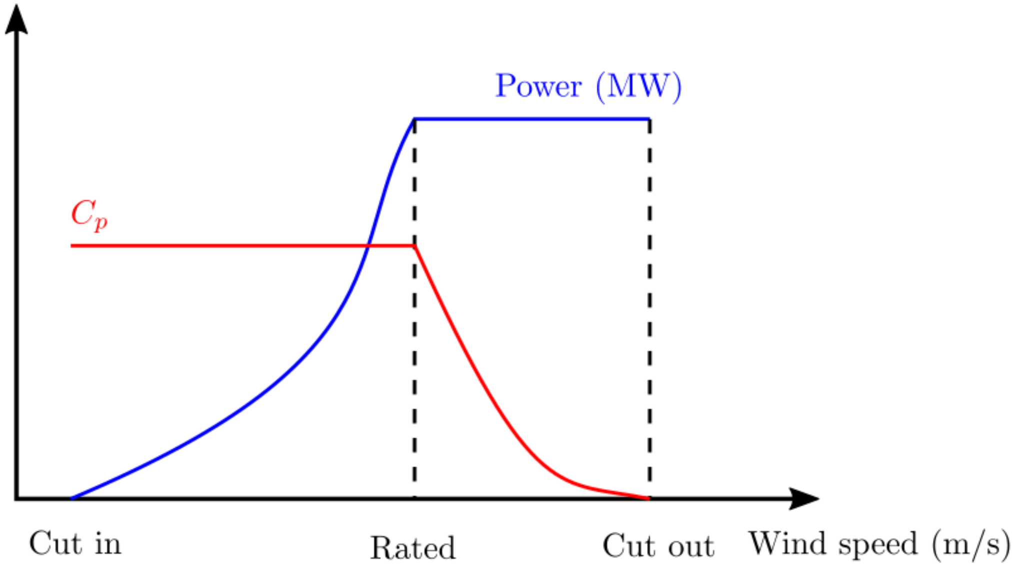


Rated wind speed

A probability problem

$$P = \frac{1}{2}\rho_{fluid} C_p A v^3 = \frac{1}{2}\rho_{fluid} C_p(\lambda,\theta)\pi r^2 v^3$$



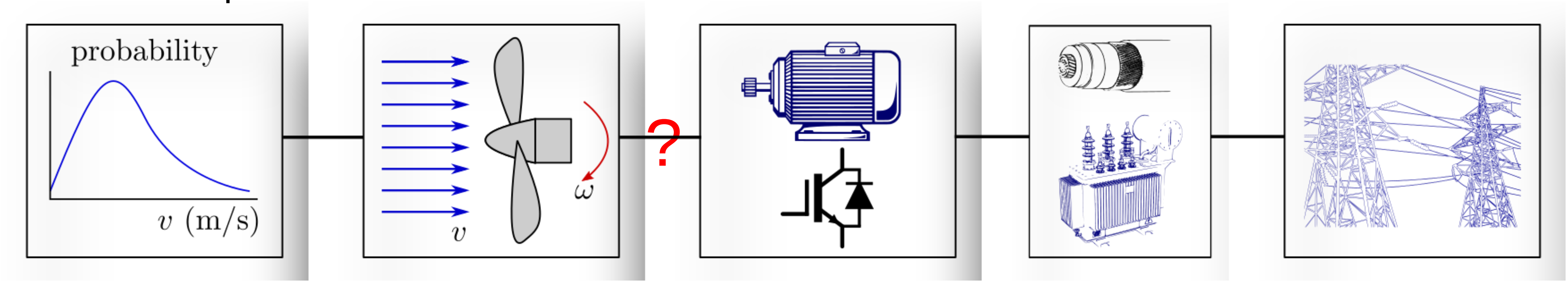


Where shall we set the rated wind speed? Why?

- ~6 m/s
- ~11 m/s
- ~14 m/s ⇦

Rated rotor speed

A mechanical problem



$$P = \frac{1}{2}\rho_{air} C_p(\lambda,\theta)\pi r^2 v_w^3$$

$$P_{rated} \propto r^2$$

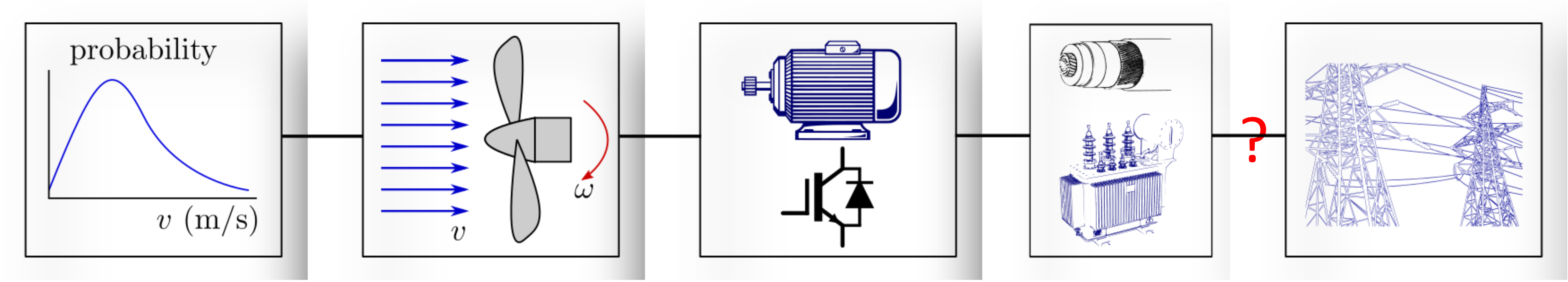
Rated speed limited because of noise production by high blade tip speed:

$$n_{rated} = 60 f_m = 60\frac{\omega_m}{2\pi} = \frac{60}{2\pi}\frac{v_{trated}}{r} \propto \frac{1}{\sqrt{P_{rated}}}$$

- The higher the power, the lower the rotor speed;
- Higher speeds possible for offshore wind, why?

Requirements: grid side

Voltage, frequency, power, fault?



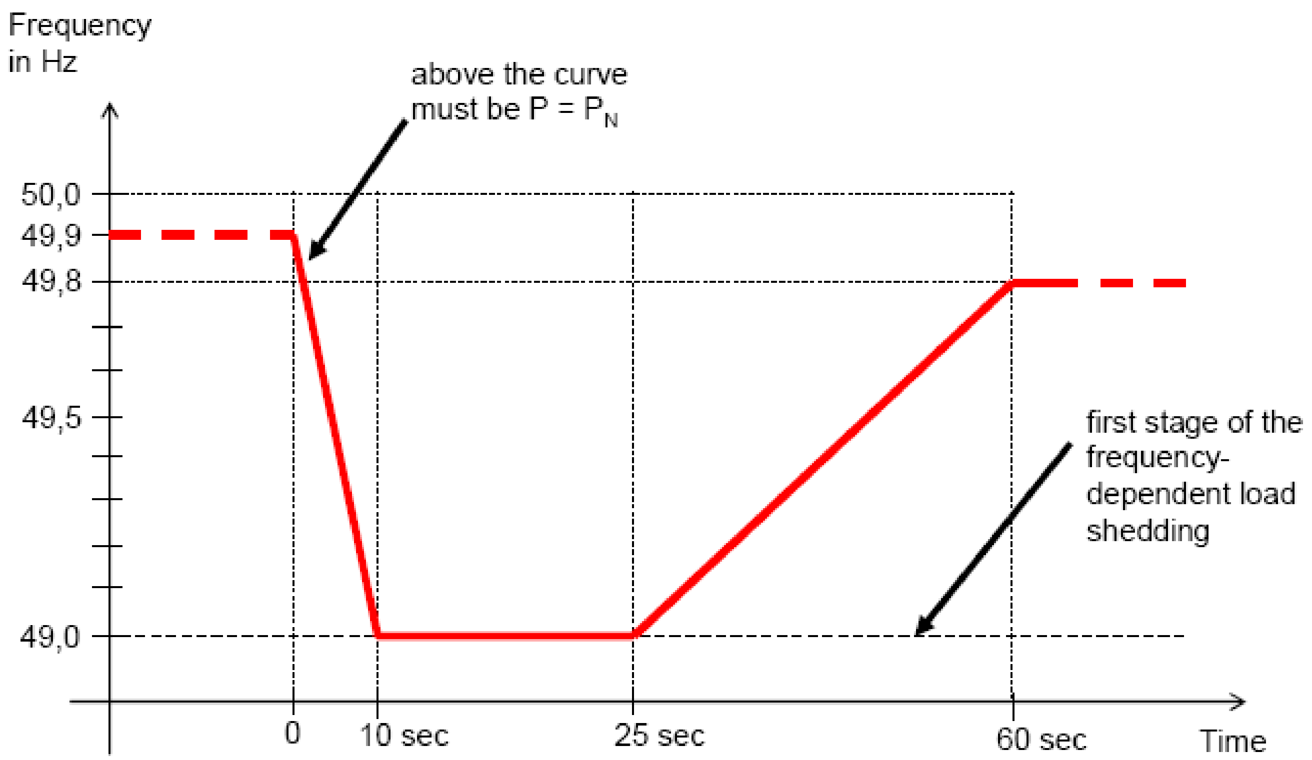
- Grid voltage e.g. 10 kV
- Grid frequency e.g. 50 Hz
- Collection and transmission
- Grid fault ride through requirements
- Power factor requirements
- Contribution to grid control

Real power and frequency control

Frequency regulation

- Real power should not decrease above the red line

- Real power should increase to recover power balance

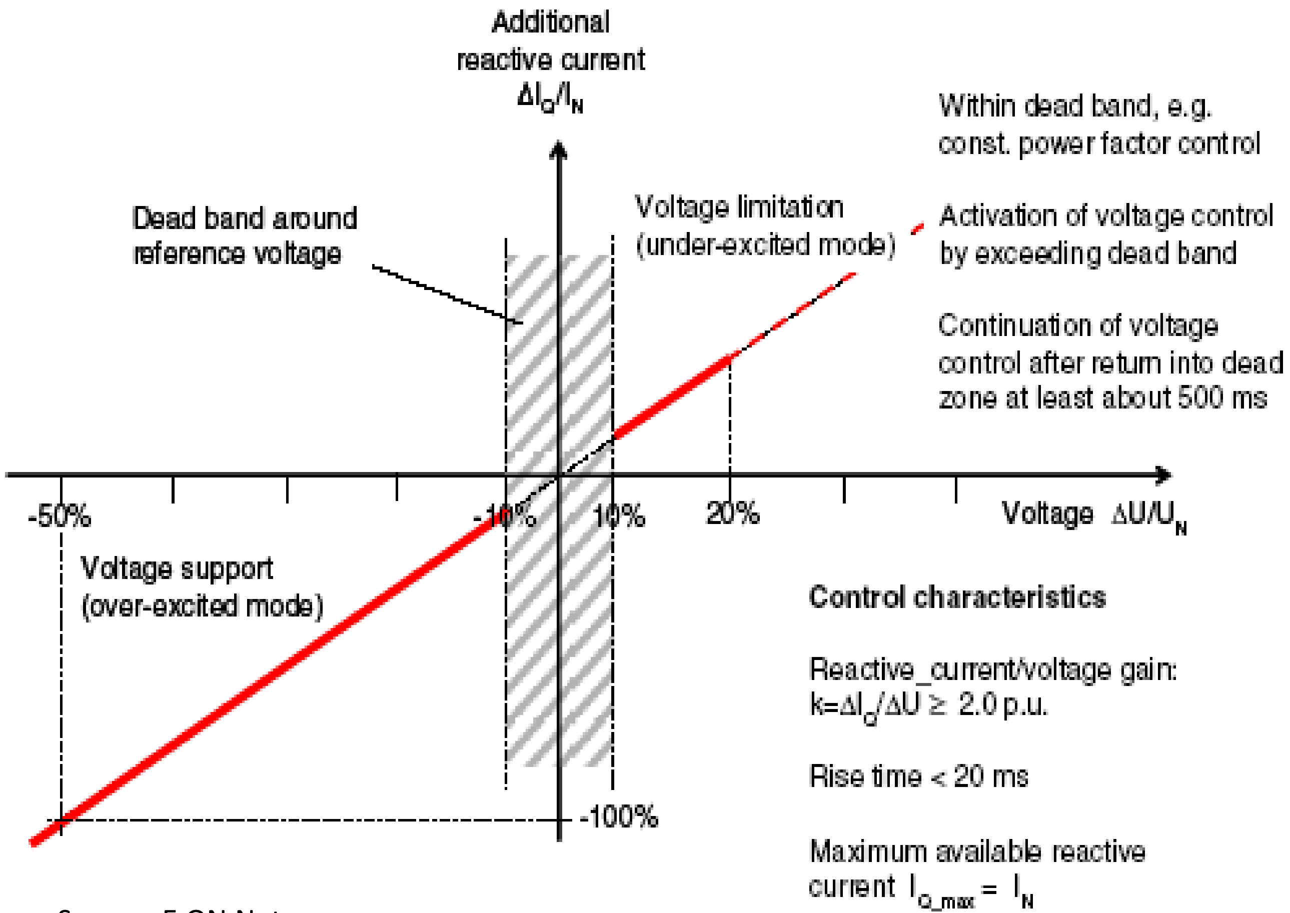


Source: E.ON Netz

Reactive power and voltage control

Voltage regulation

Reactive power should be generated or absorbed when voltage deviates from nominal value.



Source: E.ON Netz

Grid fault tolerance

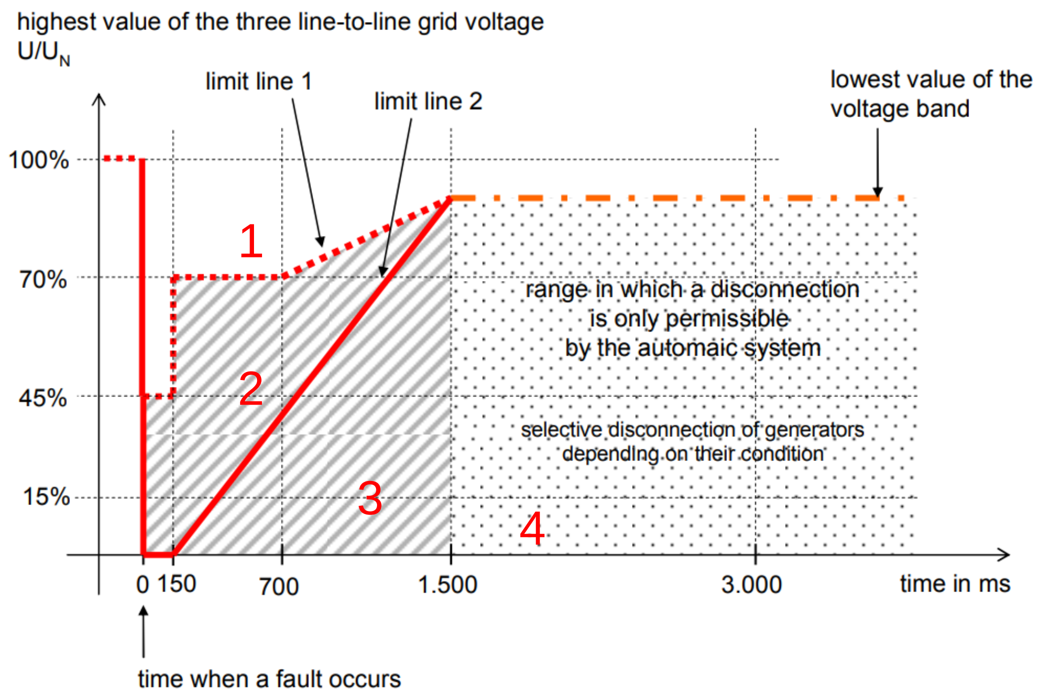
Low voltage ride through

Generator system should experience fault without disconnection for certain interval.

E.ON Netz FRT requirements

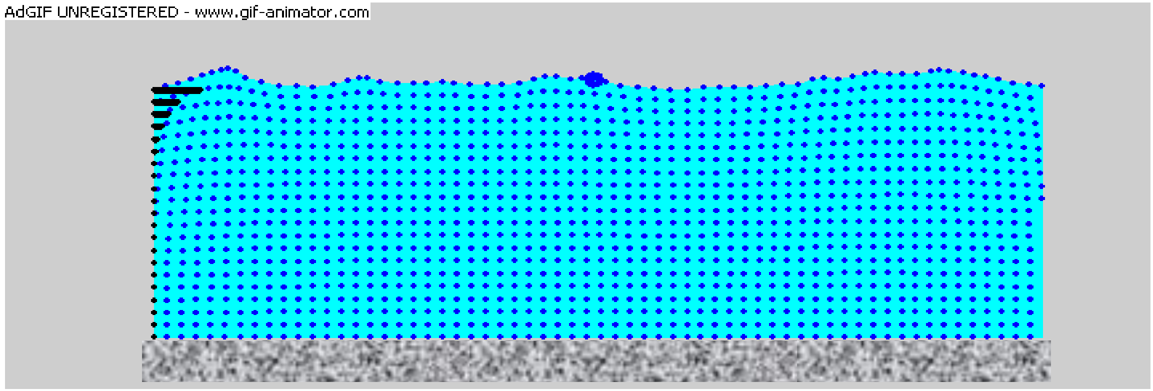
- Region 1: No tripping (跳闸)
- Region 2: No tripping
  - STI allowed < 0.3 s.
- Region 3: STI allowed < 2 s.
- Region 4: Resynchronisation in 2 s.

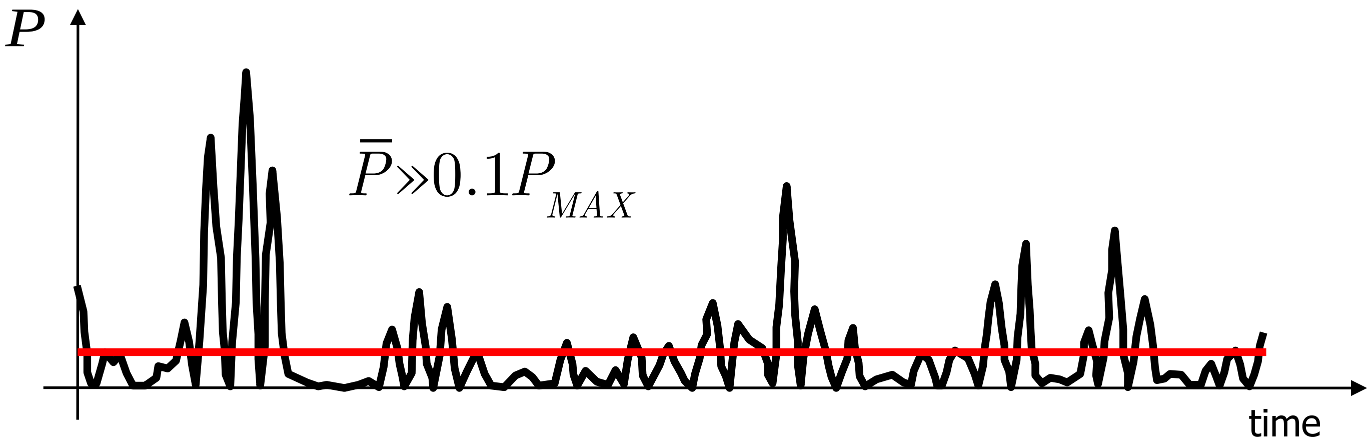
STI: short term interruption



Source: E.ON Netz

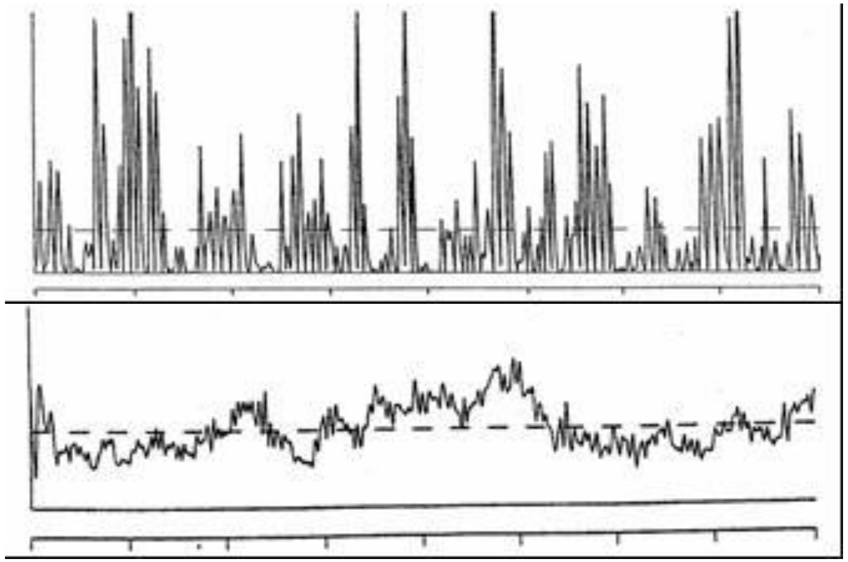
Flickr in wave energy



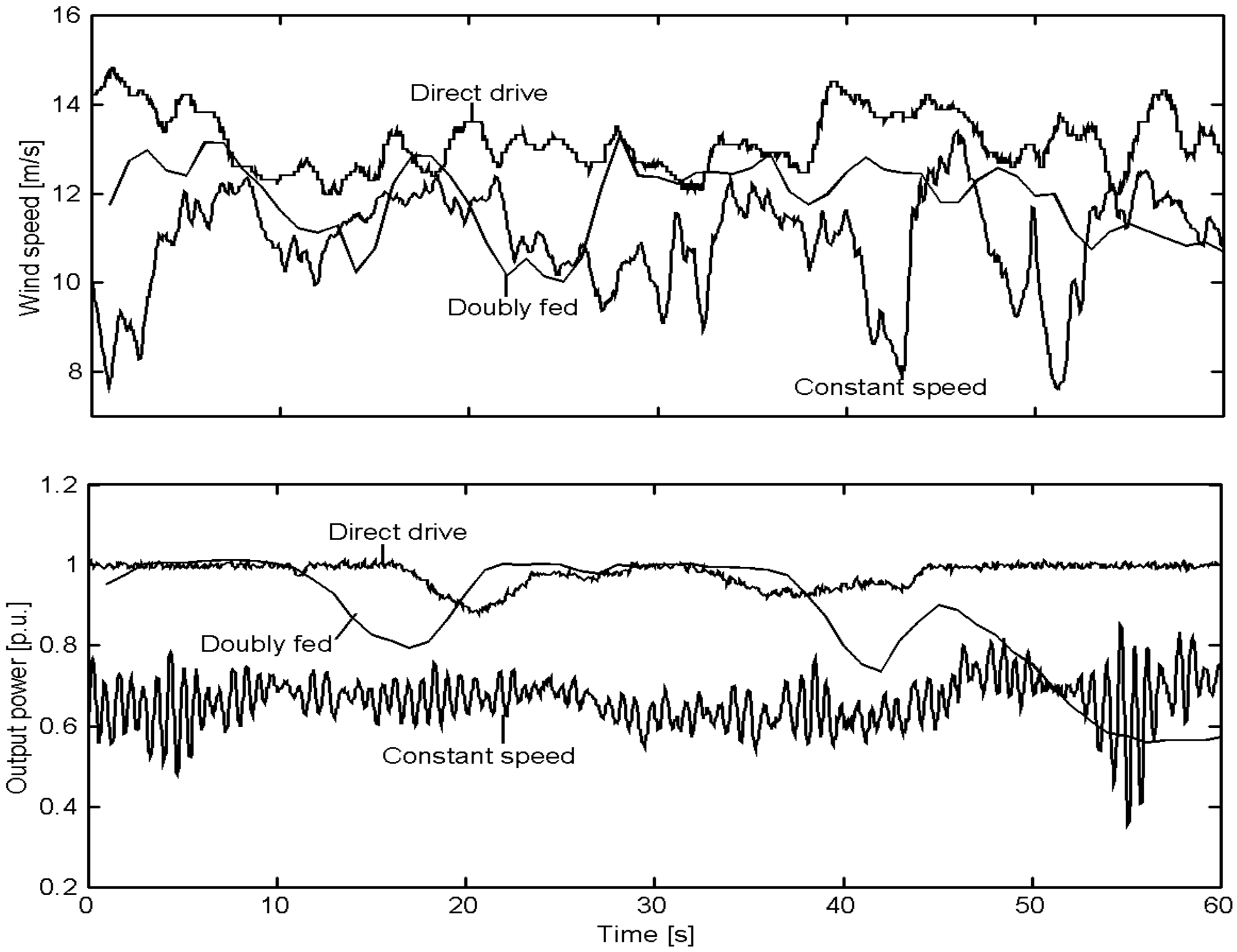


How to solve the problem?

Superposition: from 1 to 64 generators

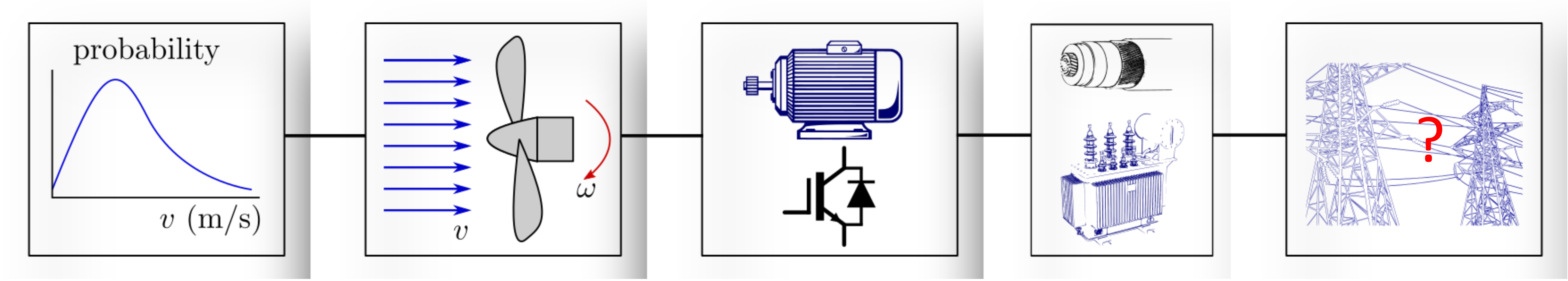


Output power of wind generator



Collection and transmission

Power lines/cables



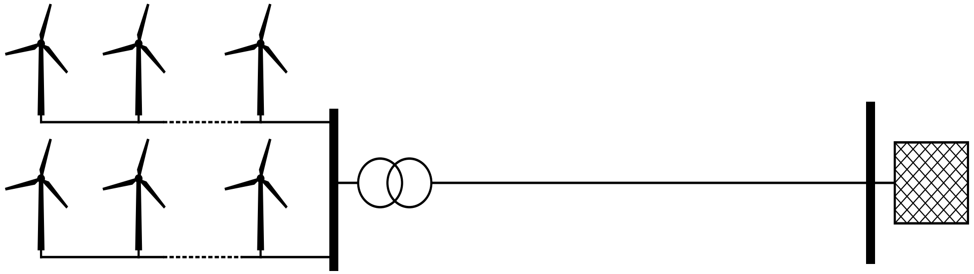
- Overhead lines
- HVAC (standard) three-core cable
- HVDC (two single-core cables)
  - high laying costs
  - buried at 1-2 m depth or more (currents, anchors)
  - mostly XLPE cables (='low cost')

Three wind farms in the Netherlands

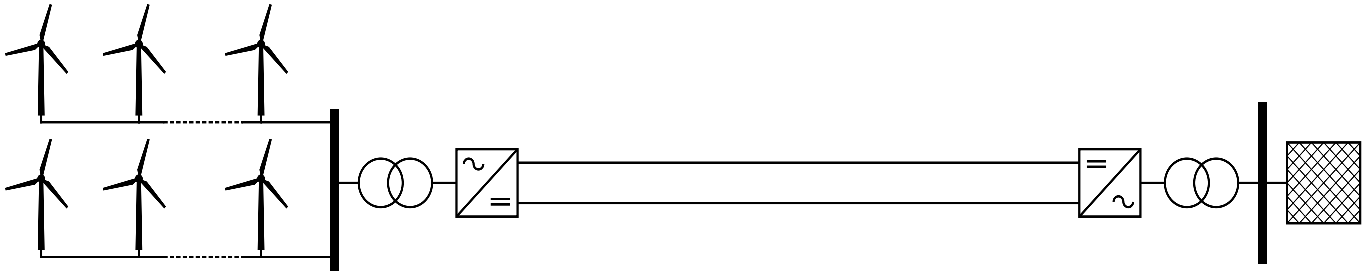
- OWEZ
  - 10 km, 108 MW
  - No offshore substation

Why different choices?

- Princess Amalia
  - 23 km, 120MW
  - Offshore substation



- Butendiek
  - 34 km, 288 MW
  - Offshore substation



System requirements: a summary

TUDelft

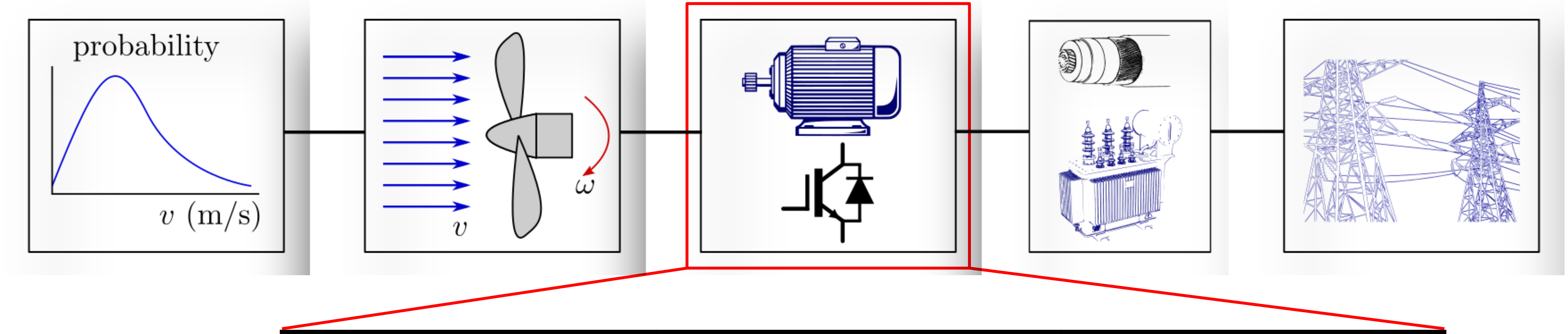
• Power level	12 MW
• Speed	7.81 rpm rated, 4-11.5 rpm variable
• Torque	12/(2π7.81/60) MNm = 14.7 MNm
• Grid voltage	e.g. 10 kV
• Grid frequency	e.g. 50 Hz

- Grid fault ride through requirements
- Power factor requirements
- Contribution to grid control
- Availability (reliability, reparability, protection)
- Efficiency
- Transportation
- Assembly
- Onshore/offshore
- Other…

Overview of generator system solutions

Possible system choices

Secondary system



Mechanical conversion	Electromechanical conversion – generator	Electrical conversion – frequency
• Direct drive • Gearbox (n-stage) • Hydraulic torque converter	• Induction • Synchronous • Permanent magnet (Direct current)	• Direct connection • Voltage source inverter

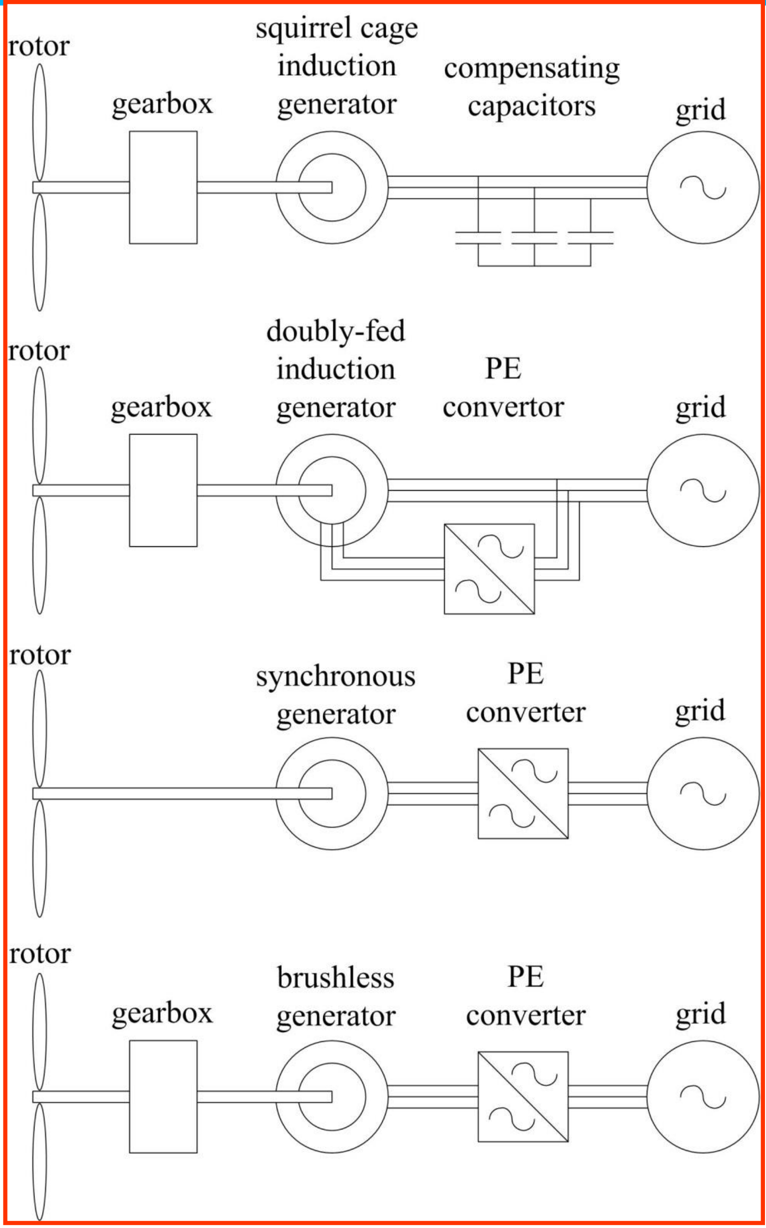
Generator systems

Constant speed stall (CS)
- Mainly before 2000, low power
- Squirrel cage induction generator

Variable speed with gear pitch (DFIG)
- Since 1998, >1 MW
- Doubly-fed induction generator

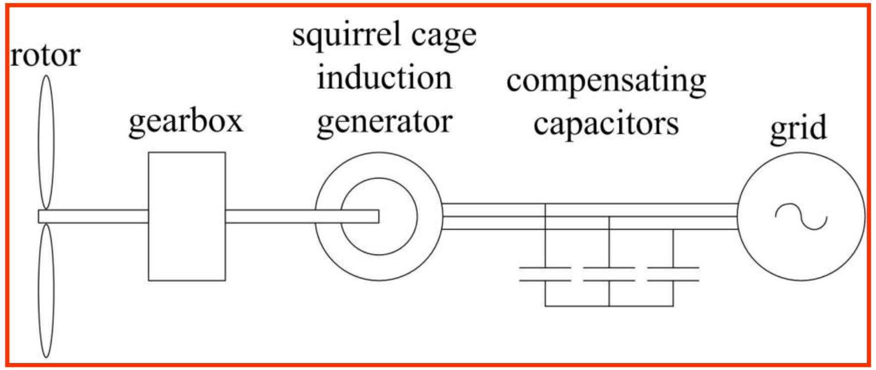
Variable speed direct drive pitch (DD)
- Since 1992
- Synchronous generator

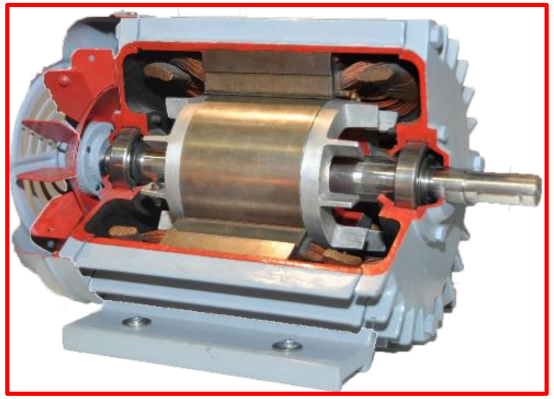
Variable speed with gear pitch (GFC)
- Since 2010, > 2 MW
- Brushless generator (mainly IM or PM)



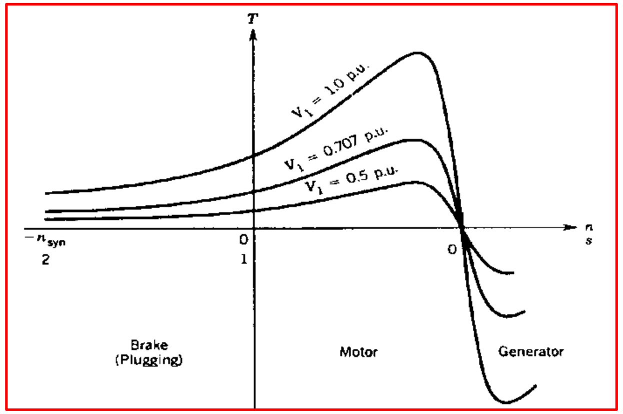
Constant speed stall regulated (CS)

Constant speed squirrel caged induction generator



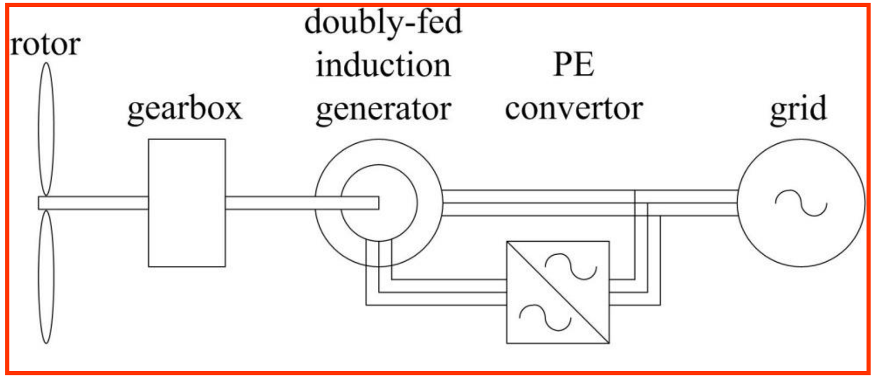


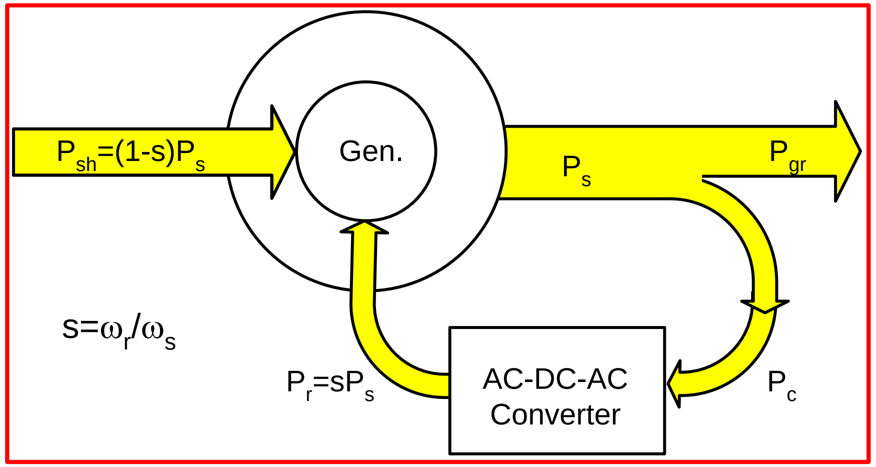
- Blades are aerodynamically designed to stall above rated wind speed;
- Direct online, no PE converter required;
- Reactive power provided by capacitor bank;
- Operates in generation (over-synchronous) regime;
- ~90:1 gearbox.

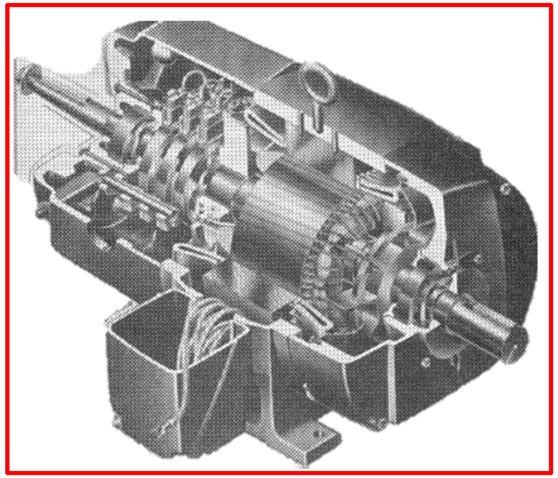


Variable speed with gear, pitch regulated (DFIG)

Variable speed doubly fed induction generator



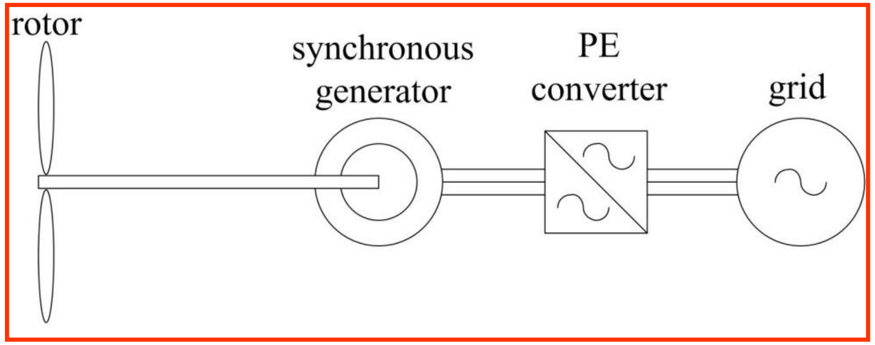




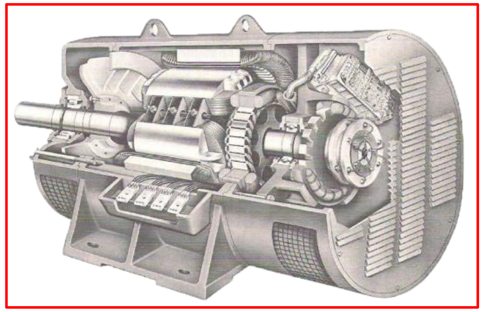
- Partial power converter (25%)
- Control rotor frequency to compensate rotor speed variation

Variable speed direct drive, pitch regulated (DD)

Variable speed direct drive generator

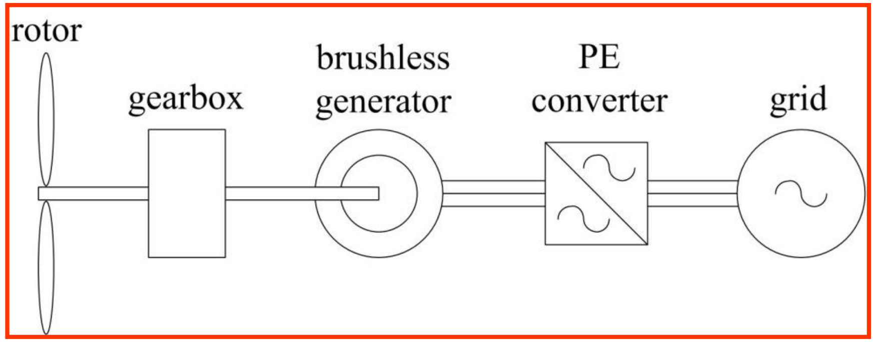


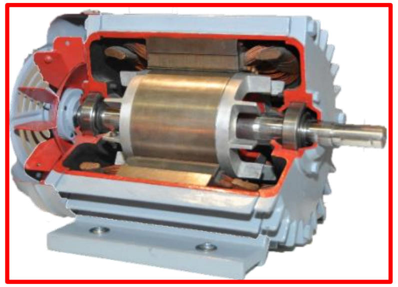
- Full power converter (100%)
- Regulate stator frequency to meet grid
- Gearless, low speed, large torque
- Permanent magnet generator
  or wound rotor generator



Variable speed with gear, pitch regulated (GFC)

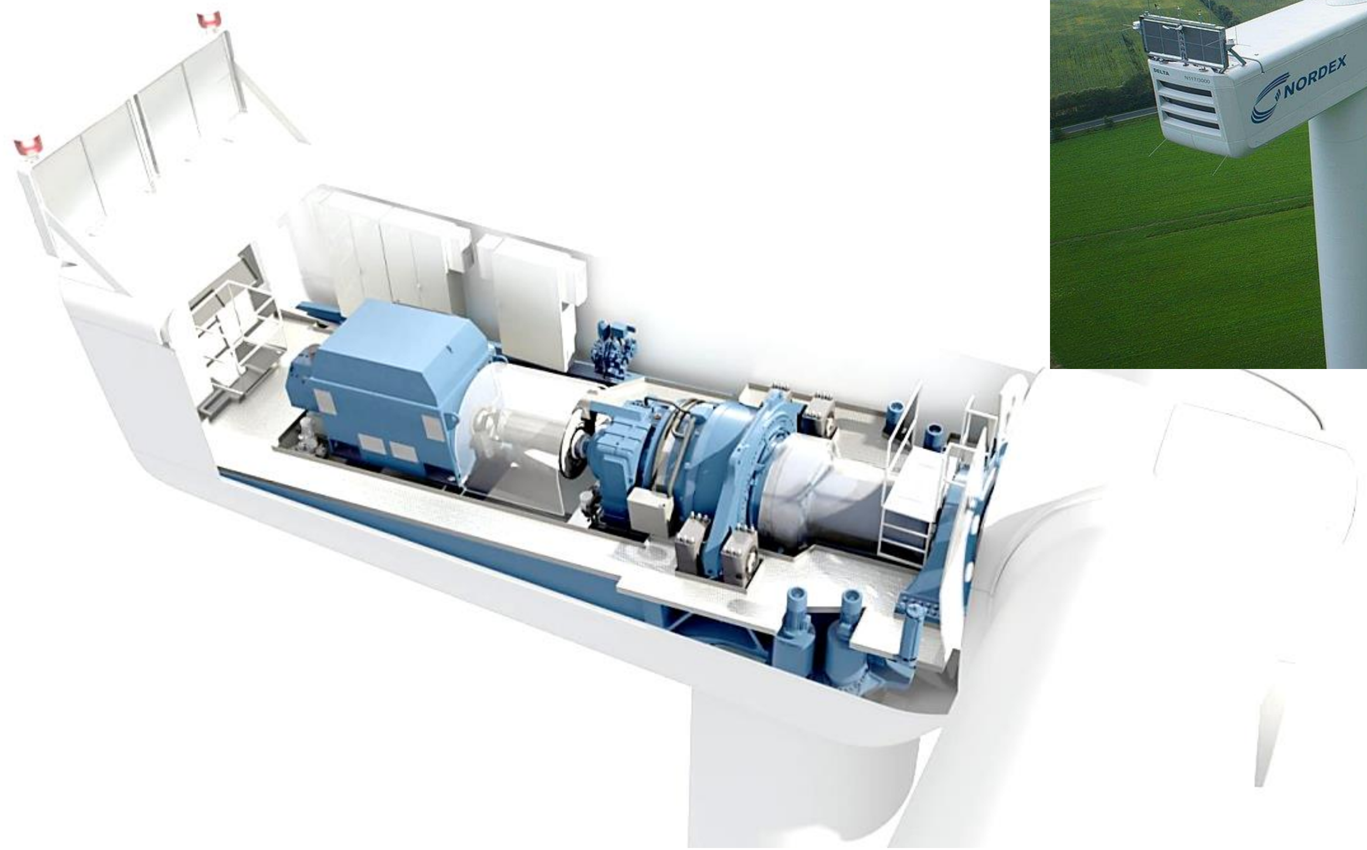
Geared generator with full power converter





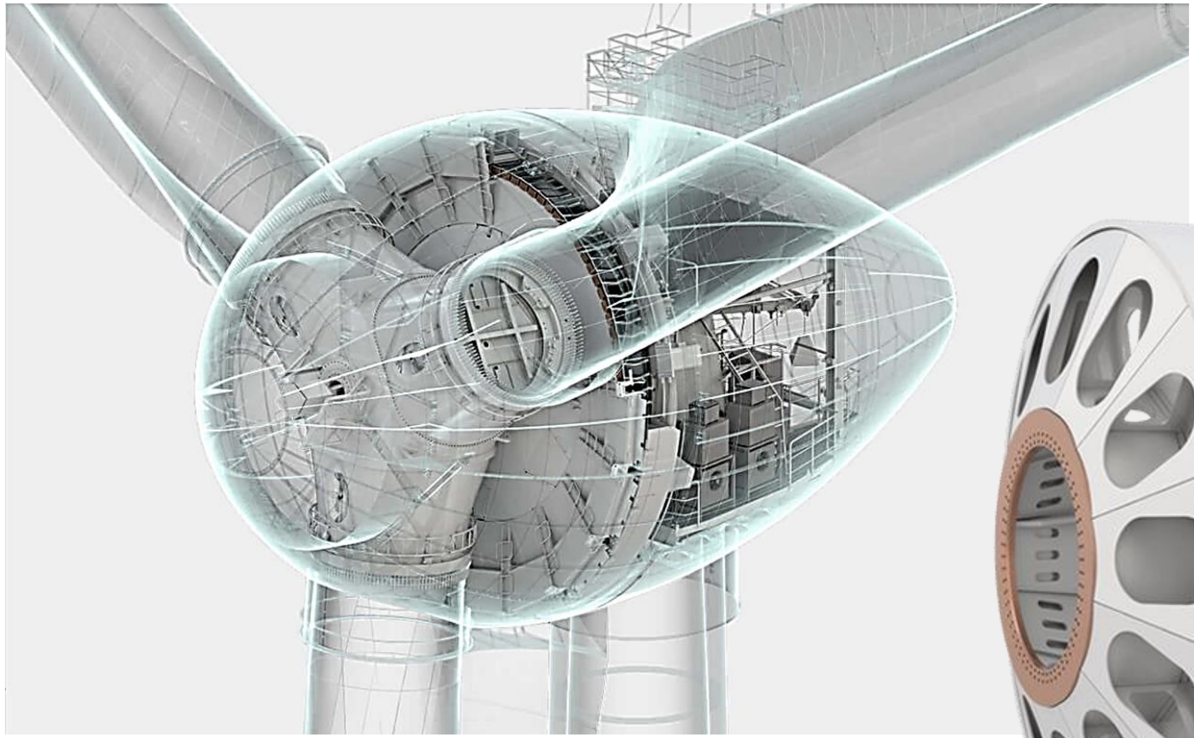
- Full power converter (100%)
- 1/2 stage gear, ~30:1 gear ratio or lower
- Brushless machine:
  - Squirrel cage induction machine
  - Permanent magnet synchronous machine

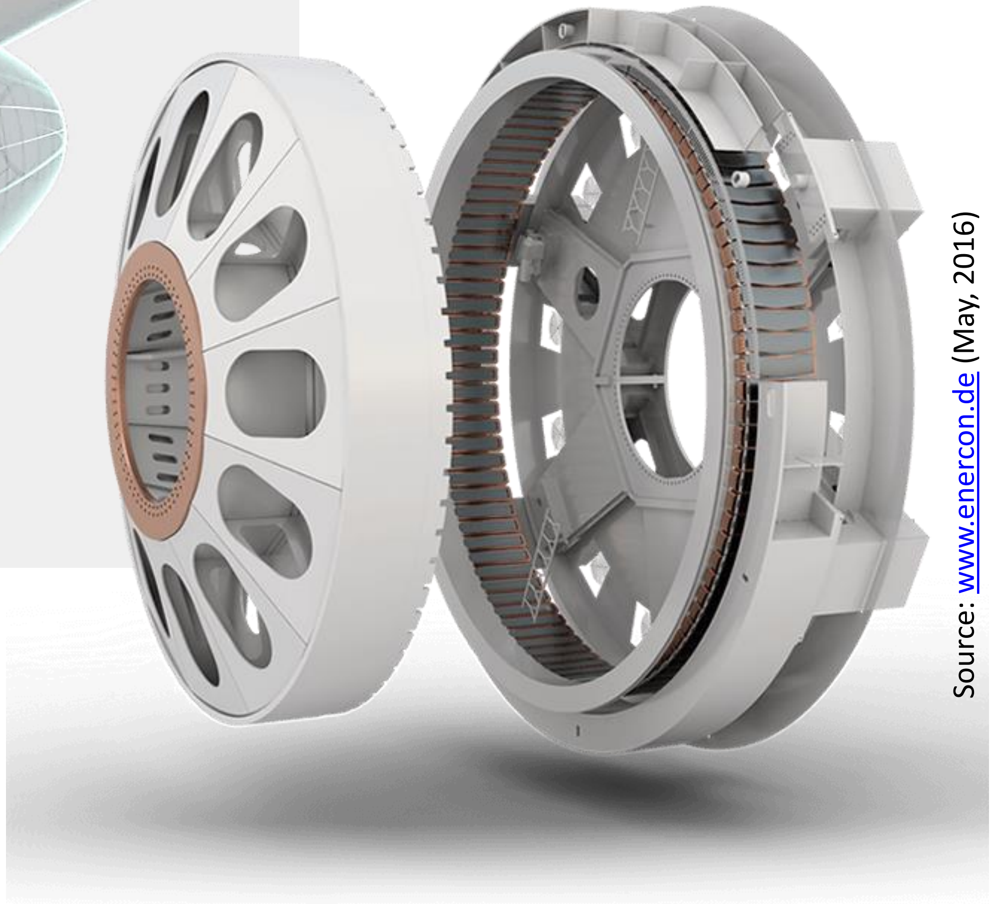
DFIG: Nordex N117/3000 3 MW



1. Source: https://www.wind-energy-market.com(May, 2016), courtesy Nordex.
2. Source: www.nordex-online.com (May, 2016).

Direct drive: Enercon E-126 7.6 MW



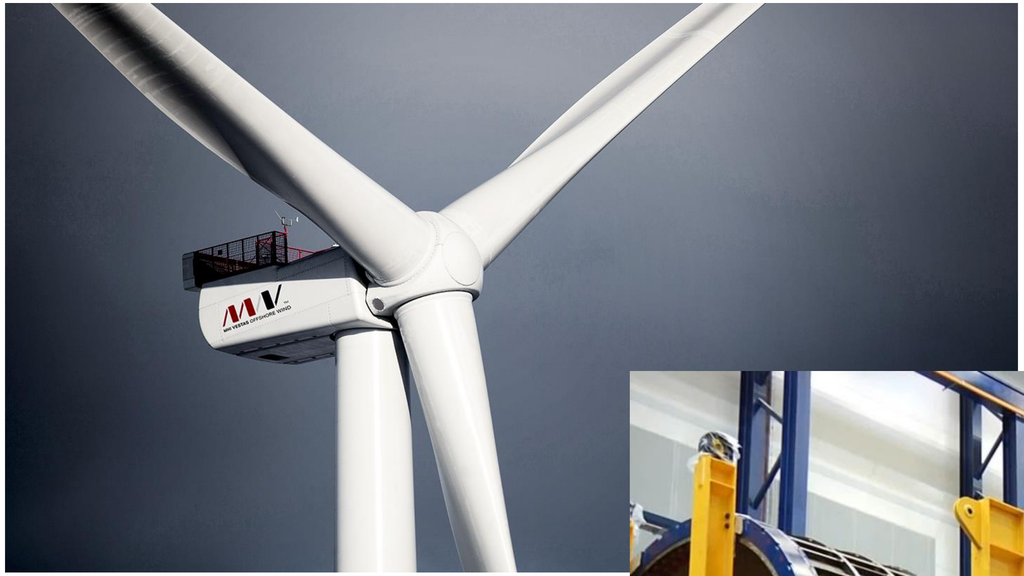


Source: www.enercon.de (May, 2016)

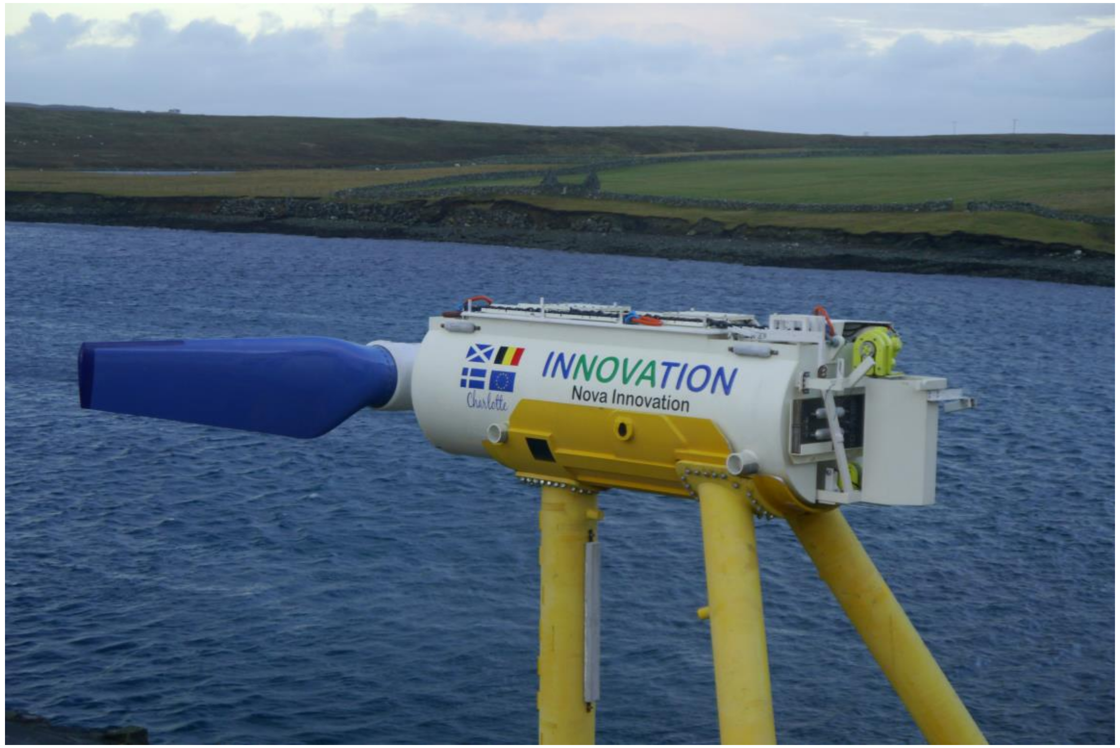
GFC: MHI Vestas V164-8.0

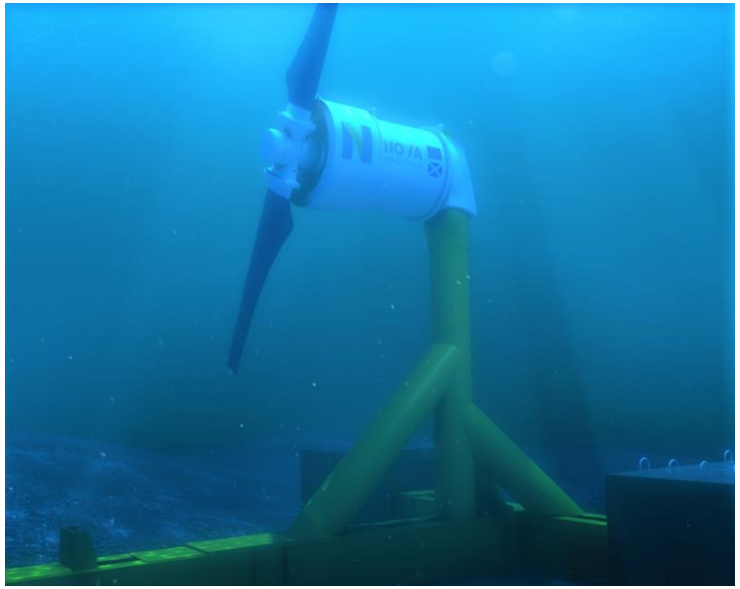
8 MW Permanent Magnet Generator with gearbox

Source: http://www.mhivestasoffshore.com (April, 2018)



Nova Innovation DD tidal turbine





Source: https://www.novainnovation.com/nova-m100
https://www.tipa-h2020.eu/tipa-project-exceeds-expectations/

Turbines of large manufacturers by installation in 2019

Manufacturer	GW	Concept	Diameter (m)	Power (MW)
Vestas (Denmark)	9.6	DFIG GFC	90 – 120 105 – 162	2 – 2.2 3.45 – 5.6
Siemens Gamesa (Spain)	8.79	DFIG DD PM	114 – 170 154 – 222	2.1 – 5.8 6 – 14
Goldwind (China)	8.25	DD PM	121 – 184	2.5 – 8
General Energy (US)	7.37	DFIG DD PM	87 – 158 150 – 220	1.7 – 5.3 6 – 12
Envision (China)	5.78	DFIG GFC IM	82 – 141 130 – 161	1.5 – 3.6 4.2 – 5.2
Ming Yang (China)	4.5	DFIG GFC	77 – 121 112 – 158	1.5 – 2 2.5 – 7.25
Windey (China)	2.06	DFIG GFC	103 – 160 130 – 139	2 – 4.5 5
Nordex (Germany)	1.96	DFIG	117 – 148	3 – 5.5
Shanghai Electric (China)	1.71	GFC IM DD	130 – 155 154 – 172	3 – 5 6 – 8
CSSC Haizhuang (China)	1.46	DFIG DD	87 – 131 151 – 210	2.5 – 3.3 5 – 10

Summary and trend

Summary

- A large variety of generator types;
- DFIG is popular up to 3.5 MW;
- GFC and DD are dominant in 5 MW and higher;
- Rotor diameter varies even with the same power level: geographical reasons;
- Market is dominated by big players;
- 6 of the top 10 are Chinese manufacturers.

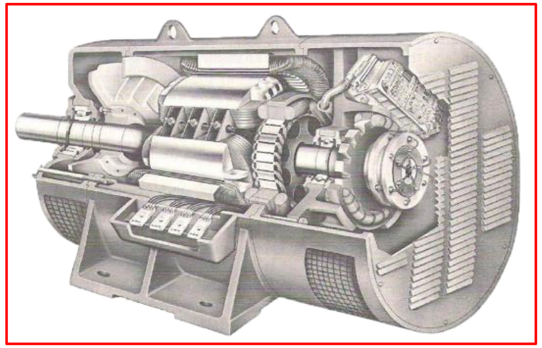
Trend

- No fixed speed turbines after 1998;
- 1998 – 2008: rise of DFIG;
- 2005 – now: gearbox + IM/PM + full power converter emerges (5 out of 10);
- Future: 12+ MW giant wind turbines.

Comparison of generator system choices

PM vs electrical excitation

A material problem



Advantages of PM excitation

- Higher efficiency
- Significant reduction in mass of active materials
- Cost issues: rare earth PM

Advantages of electrical excitation

- Controllable field
  - High speed
  - Low wind speed
- No risk of demagnetization

GFC over DFIG?

A power problem

Advantages:

- Better grid-fault ride through capabilities
- Simpler control
- Brushless generator
- Suitable for both 50 Hz and 60 Hz
- Cheaper generator if IM or SM with electrical excitation

Disadvantages:

- More expensive converter
- Less efficient converter

GFC vs. DD

A size problem

$$P = \omega_m T = \omega_m r F = \omega_m r (2\pi r) L F_d = 2\omega_m V_r F_d$$

- Direct drive machines are HUGE
- Efficiency of DD machines is limited

- low speed - high torque
- limited efficiency
  - Induced voltage $\vec{E}_{ind} = \vec{B} \times \vec{v} \approx 4\text{V/m}$
  - Resistive voltage drop $\vec{E}_R = \rho_{Cu} \vec{J} \approx 0.1\text{V/m}$

Why efficiency is limited for low speed generator?

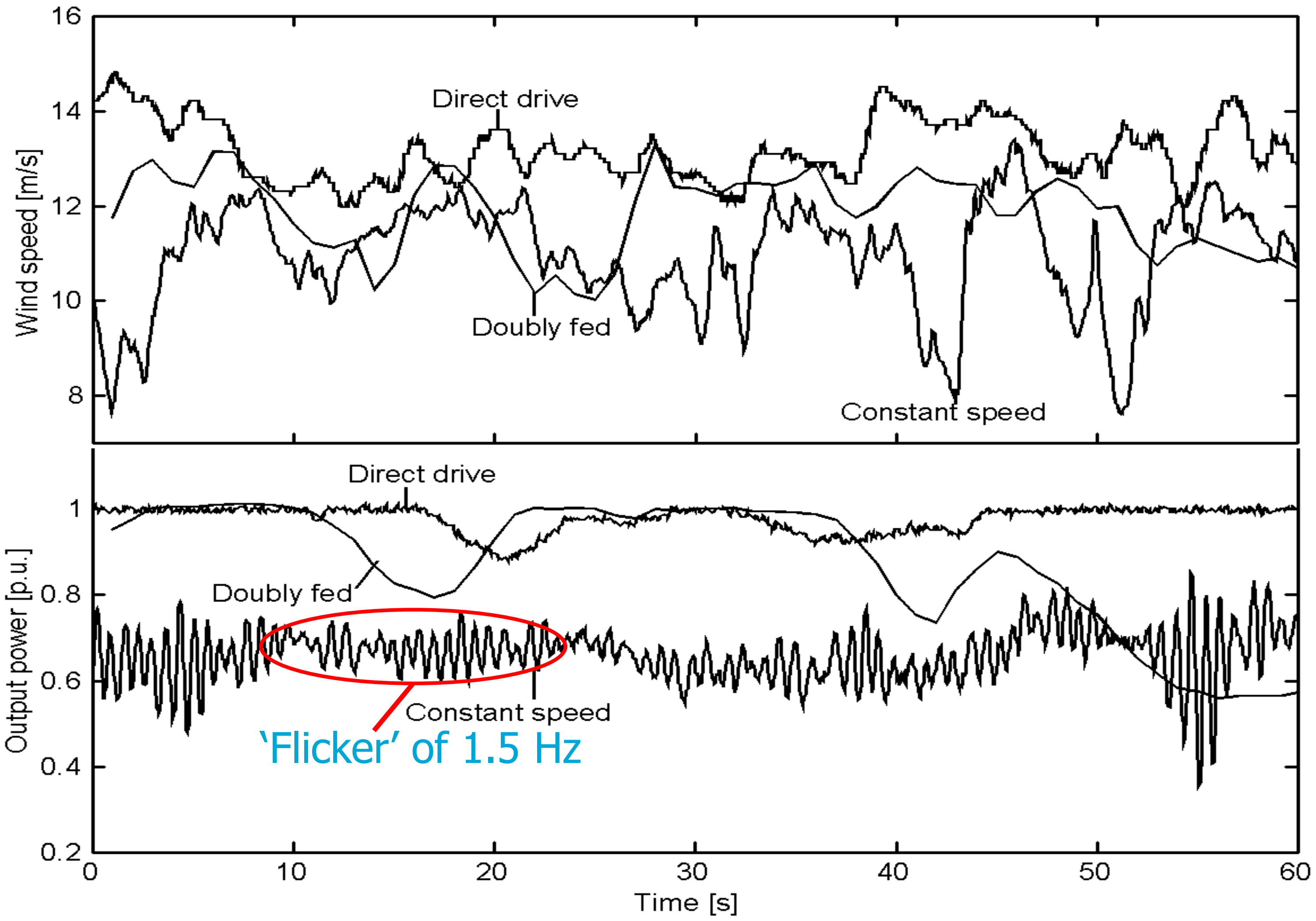
But,

- Gearbox may fail
- Gearbox reduces efficiency

Comparison of system choices

		CS	DFIG	GFC	DD
Cost, size and weight		+	+/-	+/-	-
50/60 Hz grid frequency		-	-	+	+
Audible noise of blades		-	+	+	+
Energy yield	Variable speed	-	+	+	+
	Gearbox	-	-	-	+
	Generator	+	+	+	-
	Converter	+	+/-	-	-
Reliability and maintenance	Brushes	+	-	+	-(PM+)
	Gearbox	-	-	-	+
	Mechanical loads	-	+	+	+
	Complexity	+	-	-	+/-
Power Quality	Harmonics	+	-	-	-
	'Flicker'	-	+	+	+
	V&f control	-	+	+	+
Grid faults	Fault currents	+	+/-	-	-
	Fault ride through	+	+/-	+	+
	Restoring voltage	-	+/-	+	+

Output power of generator systems



Why there are zig-zags around 1.5 Hz on the constant speed waveform?

Challenges and issues

Availability

Onshore -> offshore -> subsea

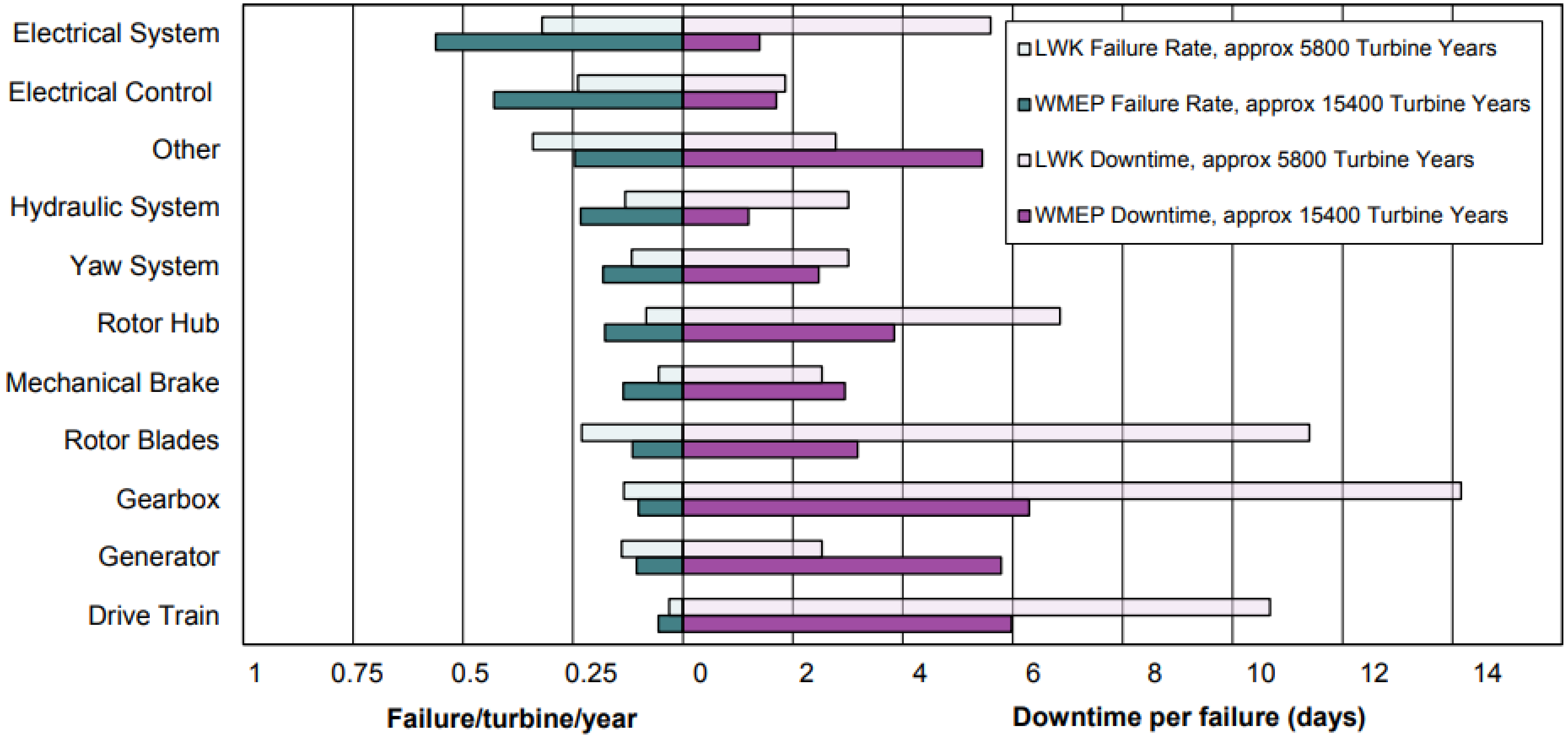
$$\text{Time-based availability} = \frac{\text{Time available (in hours)}}{\text{Total time in consideration (in hours)}}$$

$$\text{Production-based availability} = \frac{\text{Energy actually produced (in kWh)}}{\text{Energy potentially expected (in kWh)}}$$

- Not just an extrapolation of on shore!!
- Aggressive environment
  - Coatings against corrosion
  - Enclosed equipment
  - Conditioned air
- Focus on availability and maintenance
  - Reliability statistics
  - Logistics planning
- Condition monitoring
  - Condition based maintenance
  - Condition based control

Failure rate and downtime

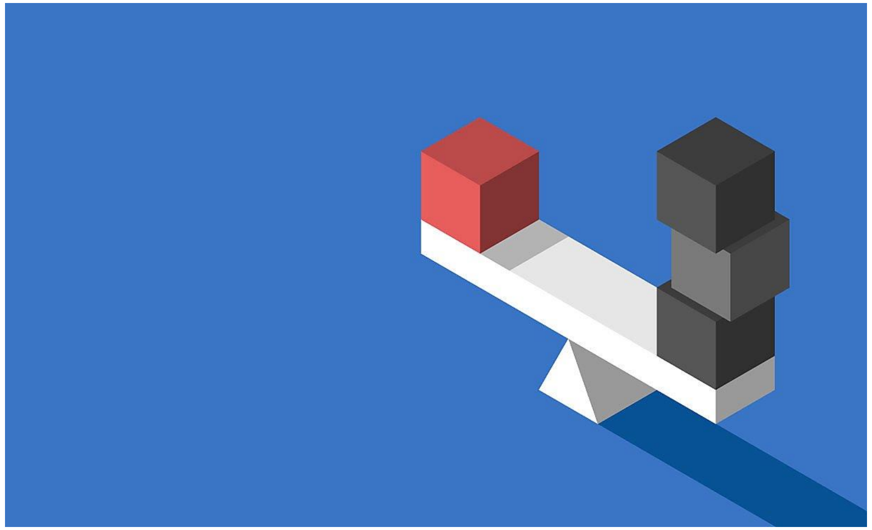
High failure rate ≠ higher downtime

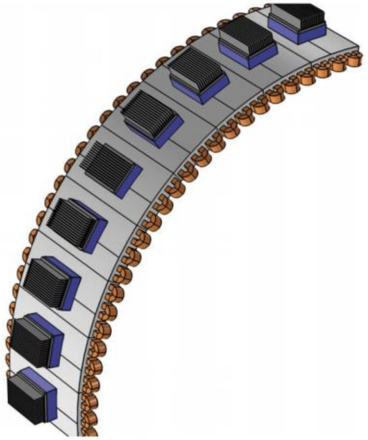


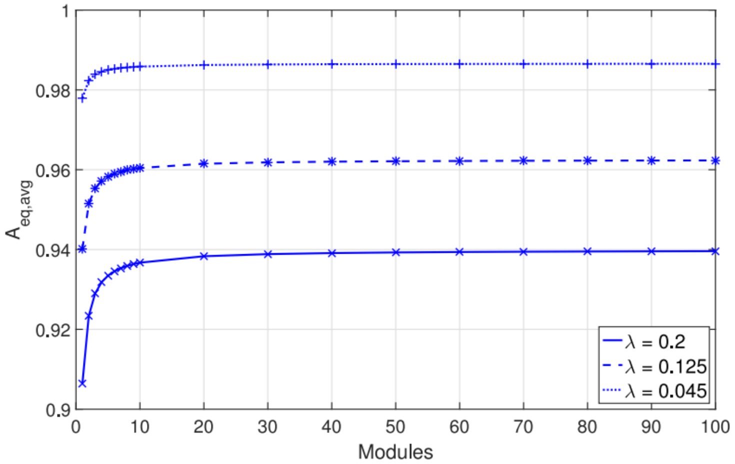
Source: NREL.gov, Report on wind turbine subsystem reliability, 2013.

Improving reliability

- Tradeoff between CAPEX and OPEX
- Fault prevention or avoidance
- Fault detection and mitigation
- Fault forecasting and fault evasion
  - Condition monitoring
  - Condition based control
  - Condition based maintenance
- Fault tolerance? Modularity?







Source: Shipurkar et al., Availability of wind turbine converters with extreme modularity, 2018.

Availability of PM materials

- Rare-earth elements in PM: Neodymium, Samarium, Yttrium, Dysprosium, Terbium
- Between 1990 and 2005, magnet prices dropped by roughly a factor of 10, because of China entering the market.
- The permanent magnet crisis (2010/2011)
  - Over 95% of rare earth materials mined in China
  - Large demand
    - Renewable energy generation
    - Electric mobility
  - China protects market and environment
- Long term
  - Materials also found at other places
  - Mining is being developed
  - Superconducting?

Pollution caused by rare-earth mining in China
Source: BBC

Summary

Contents

- Introduction to wind and ocean energy
- Energy conversion system topology and turbine drivetrain structure
- Basic principles: fluid dynamics and electromechanics
- Requirements of renewable generation system
- Overview of generator system solutions
- Comparison of system choices
- Current challenges and issues

Summary

- Wind and ocean provide abundant renewable energy sources;
- Turbine based rotational electromechanical energy conversion is dominant in wind/ocean energy;
- Design of the turbine drivetrain should consider requirements from both primary source and power grid;
- There are a large variety of generation system choices with their pros/cons;
- Current challenges: improve availability and reduce cost of energy.

European Wind Energy Master Program

A FEW WORDS

From Our Graduates

"The most leading universities in wind energy."

"Very challenging programme."

"You really learn how to cope with people with different backgrounds, different cultures and from different nationalities."

2 MSC. DEGREES	4 UNIVERSITIES
45 PARTNERS	43 NATIONALITIES

For more details:
https://ewem.tudelft.nl/