Wind power course summary lecture

PHYS-E6572 Advanced Wind Power Technology

Hannele Holttinen

02.12.2022

Lecture	Content	Lecturer
7.9.22	Introduction to the course and wind power. Wind power globally and in Finland, status, development and market forecasts.	Hannele Holttinen, Recognis
16.9.22	Wind power meteorology. What is wind – profiles, distributions, turbulence. Temperature, stability, icing. Estimating wind resources, wind measurements.	Hannele Holttinen, Recognis
23.9.22	Wind turbines. Wind turbine aerodynamics. Wind turbine systems: Drive train. Yaw system. Pitch system. Electrical system.	Timo Karlsson, VTT
30.9.22	Loads & Control. Design load cases. Certification and Standards. Components: Hub, Nacelle, Tower	Timo Karlsson, VTT
7.10.22	Wind power project I – resource estimation and planning	Esa Holttinen, AFRY
14.10.22	Wind power project II – economy and financing; building process	Esa Holttinen, AFRY
28.10.22	Wind power project: planning procedures and environmental impacts	Mattias Järvinen, wpd
4.11.22	Arctic wind power. Measurements. Condition monitoring, Reliability. Operation & Maintenance.	Timo Karlsson, VTT
11.11.22	Wind turbine noise: measurements, modeling, and annoyance	Valtteri Hongisto, Turku AMK
25.11.22	Network connection of wind farms (Sähköverkkoon liittäminen)	Sanna Uski, Despro
30.11..22	Wind power impacts on energy systems: variability & uncertainty; impacts on balancing, stability and capacity adequacy	Hannele Holttinen, Recognis
2.12.22	Wind turbine upscaling. The square-cube law. Wind turbine trends, Grand challenge of Wind energy science. Summary of the course - main take-aways	Hannele Holttinen, Recognis

Materials

- Lectures contain all that is needed for passing the course
  - Some lectures have some material also to give a bit more information
- Background materials: these are not compulsory, only if you find the lectures difficult to follow and need some basic information
  - ''Wind Energy Engineering'' by Letcher-2016
  - ''Wind Energy-Renewable Energy and the Environment'' by Nelson-2009

Exam

- 7.12.2022. Students will find the correct hall listed in the bulletin board at the main entrance to Otakaari 1 in the morning of the exam. In any case, your exam will be in one of the halls A,B or C
- Retake Feb 2023
- No formulas/exercises. Terminology and important concepts, from viewpoint of a wind power project

Contents for summary lecture

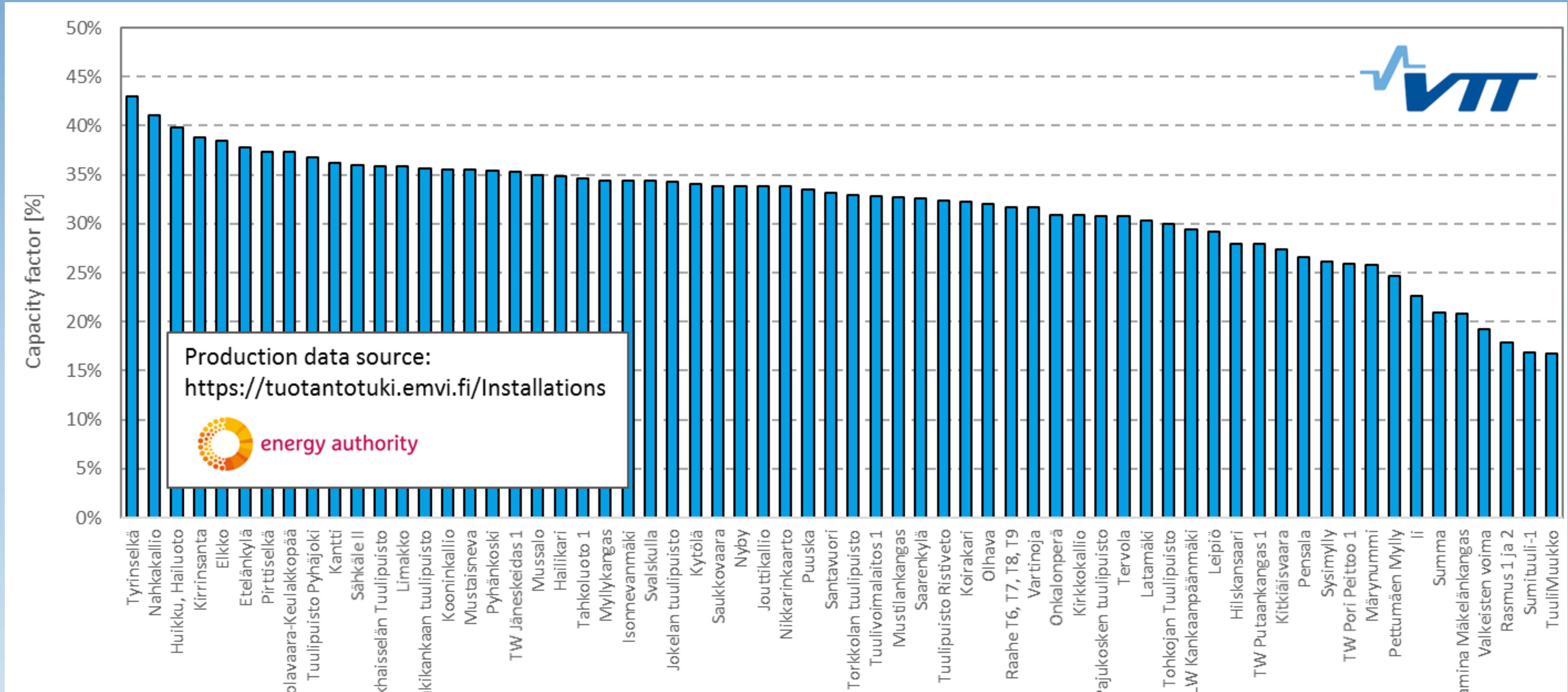
- Intro – drivers and barriers
- Meteorology
- Turbine technology and components (2 lectures)
- Wind power project (3 lectures)
- Noise
- Connection to network
- Energy systems
- Arctic. O&M
- Technology trends

Drivers and barriers

- Drivers/positive sides of wind power:
  - Positive environmental impacts: CO_2 reduction targets
  - Decreasing dependence on fossil fuels
    - also hedge to increasing gas and oil prices
  - Increasing employment (in remote areas)
  - Property tax to municipalities where wind built
- Barriers/negative sides of wind power:
  - Planning, acquiring site permits: public acceptance, “NIMBY”
  - In some countries also grid permits has or is becoming a barrier
  - Negative environmental impacts of wind power
  - **Cost of energy** (CoE) has been higher than with conventional generation THIS HAS CHANGED TO BEING THE CHEAPEST NEW ELECTRICITY GENERATION TECHNOLOGY IN MANY MARKETS

Terminology: Comparing production from different turbines

- Capacity factor (average power relative to rated power) (20-45 %)
- Full load hours (huipunkäyttöaika) h/a, **theoretical figure** expressing how many hours in the year needed to achieve yearly production if producing only at full power (2000-4000 h/a)
- Production relative to rotor swept area (> 900 kWh/m^2)



What impacts wind generation / capacity factor?

Wind resource:
-site /resource and wake losses
-year /resource
-height above ground

Technology:
-technology /rotor size versus capacity
-technical availability /faults

Grid/market:
-curtailments (grid congestion or spot price negative)

Source VTT 2017 Wind power statistics

Wind Energy: why do we need to know about the wind? and what?

- MAXIMIZE WIND POWER PRODUCTION
- MINIMIZE TURBINE LOADS

Estimating average wind power production for life time
Forecasting next day production for markets

Other met variables to assess: temperature, humidity, air pressure

What is wind:

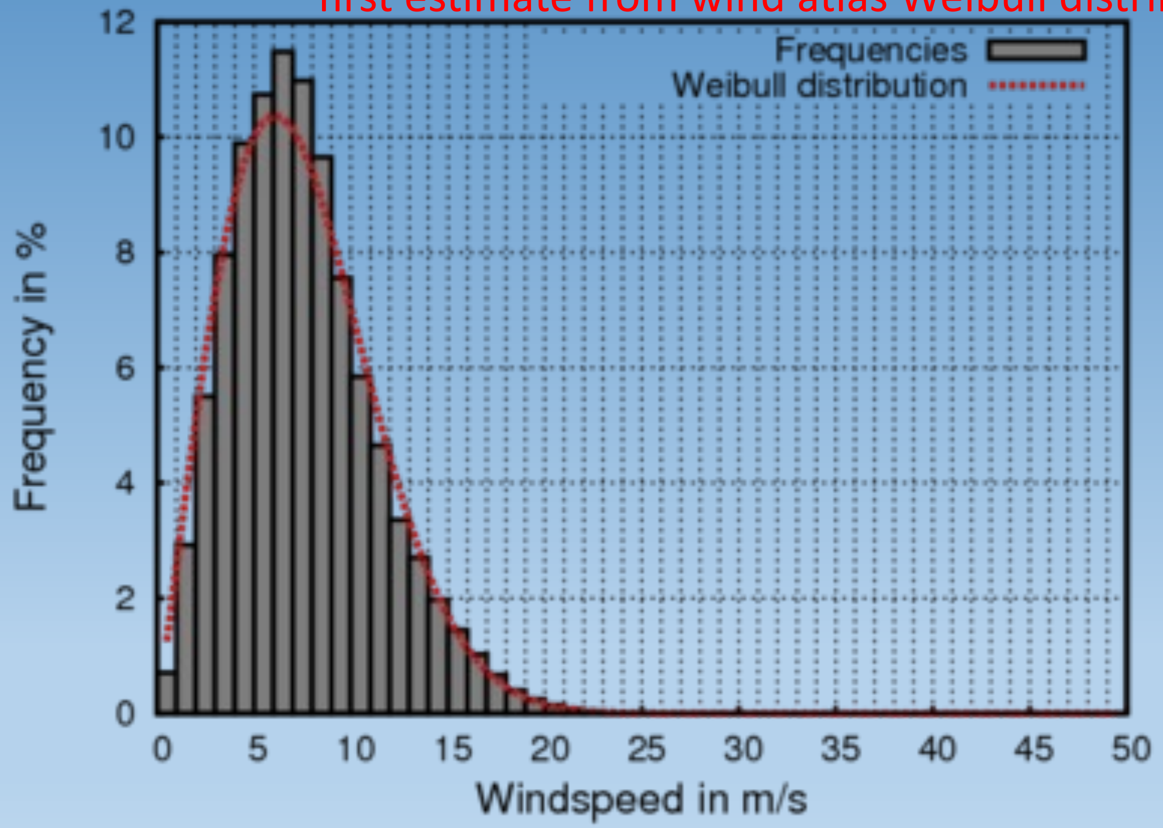
Simple models based on terrain roughness
not taking into account stability

Average/max wind speeds, turbulence, gusts, extremes

Wind directions/wind rose, wind shear /profile, distributions

Predicting long term wind energy production: From wind speed distribution to wind energy

first estimate from wind atlas Weibull distribution



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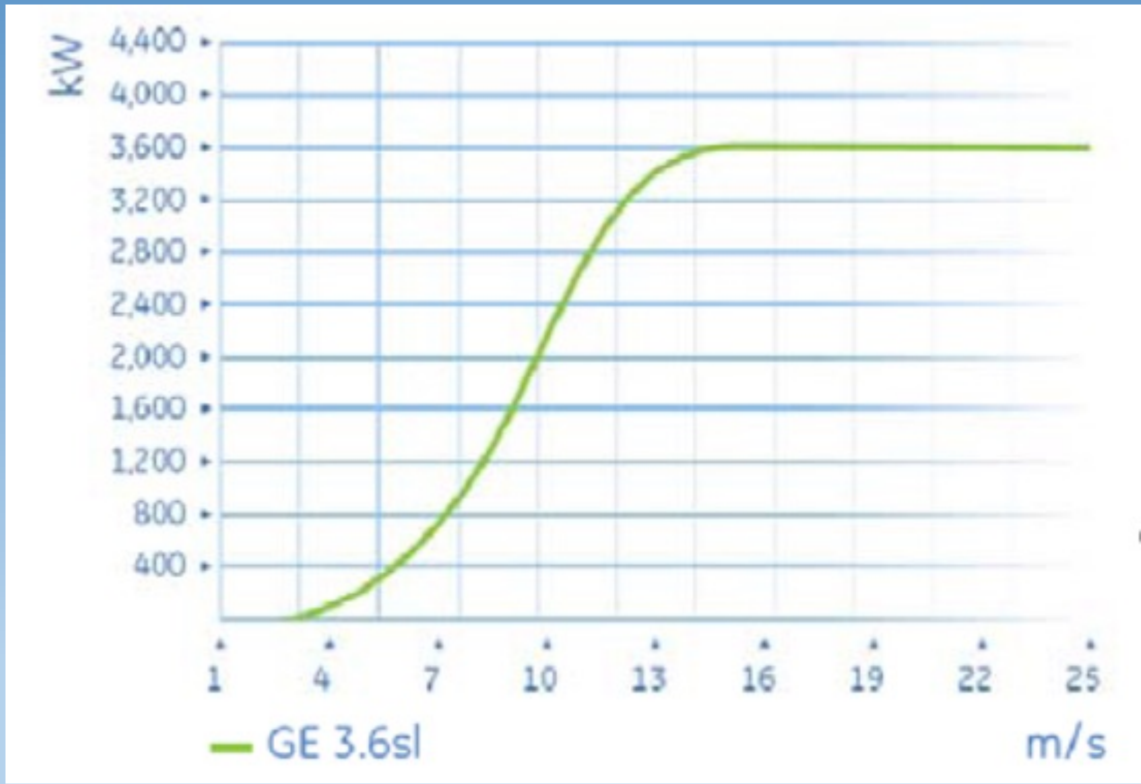


measurements, accuracy/uncertainty

turbine type – specific rating

Wind measurements, and accuracy

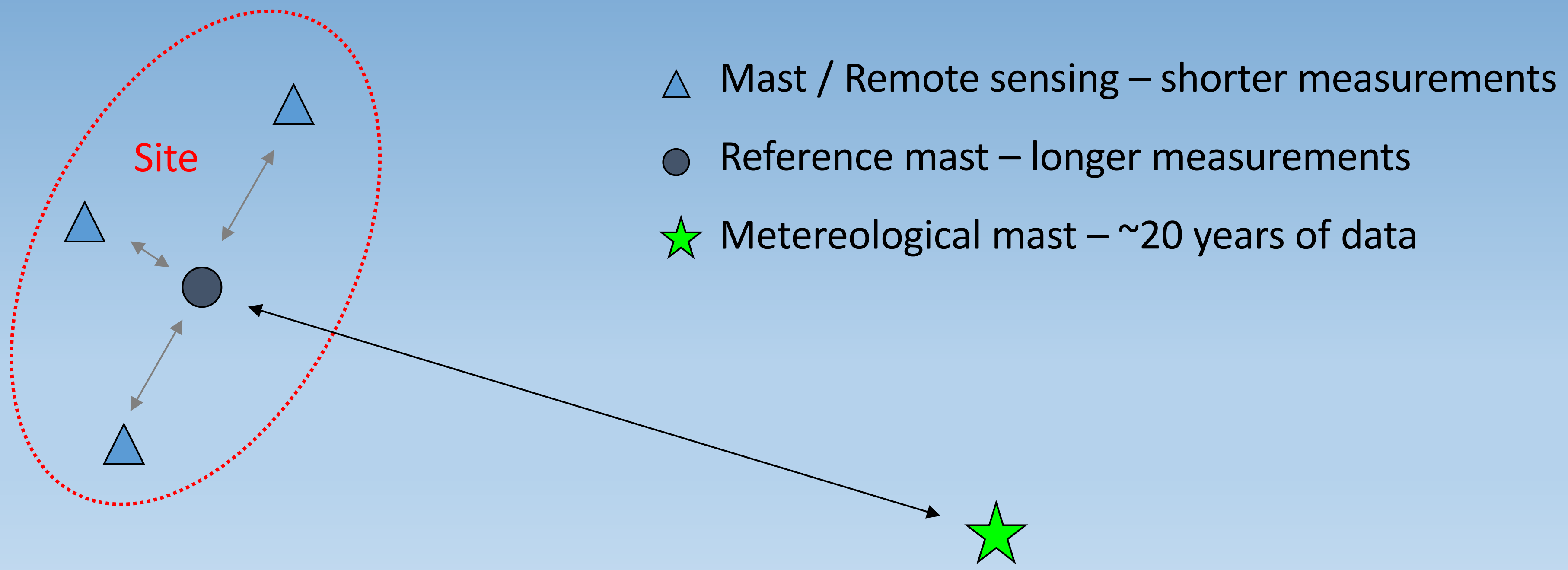
- IEC 61400-12-1 compliant
- Near hub height masts
- Classified anemometers
- Sufficiently heated anemometers for icing conditions
- High quality sensors
- Calibrated sensors
- Good mounting
- Good data acquisition
- Experienced data analysis

…and as a support:

- Remote sensing (Lidars, Sodars)
- Modeling (MCP, CFD, WAsP)

From short term measurements to long term estimate of wind energy produced during the life time

MCP: Measure-Correlate-Predict technique can be used between the reference mast and other measurement points



Aerodynamics - terminology

- An airfoil is a 2D geometrical shape designed to generate a fluid dynamic force (**Lift**) perpendicular to the direction of the incoming flow.

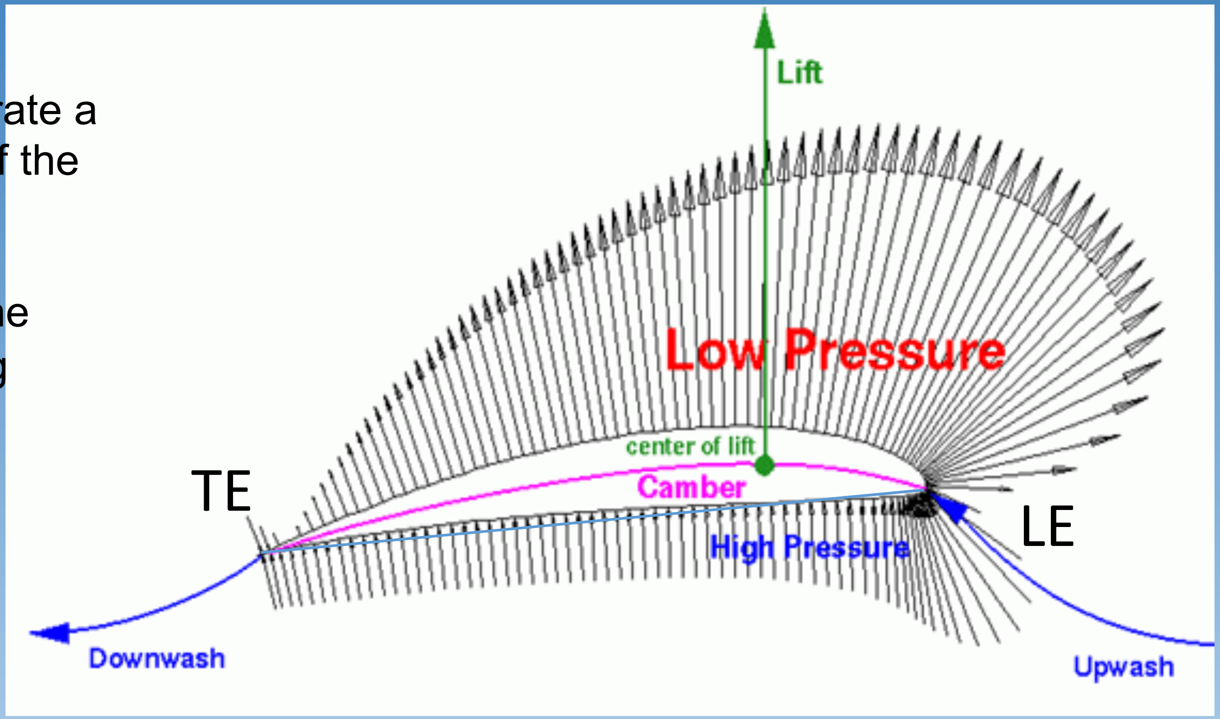
- The **chord** is the line between the **trailing edge** and the **leading edge** (point of the airfoil farthest from the trailing edge).

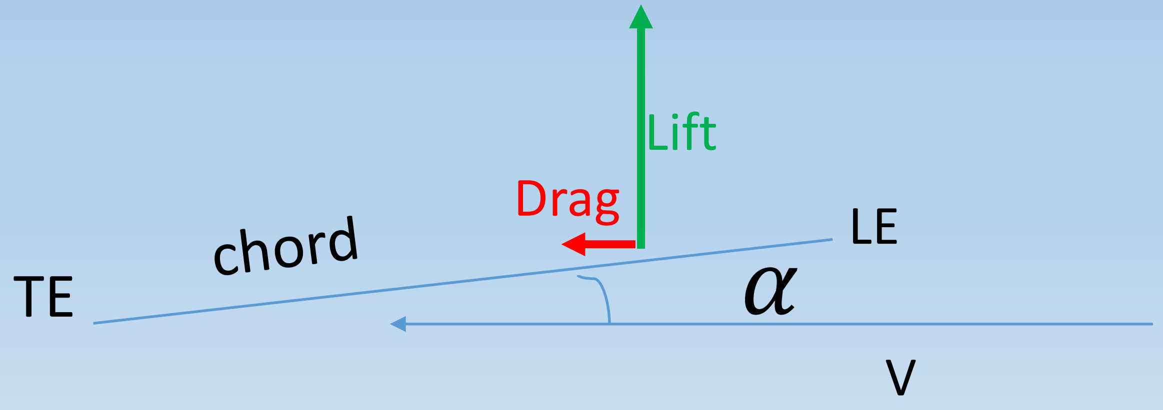
- The angle between the chord and the flow velocity upstream **V** is called **angle of attack α**

- Lift and Drag are functions of α

- The combination of curvature (**camber**) and **angle of attack** , generates the lift due to the assimetric distribution of air pressure in the airfoil surface.

- The **Drag**, is an undesirable fluid dynamic force in the direction of the upstream velocity. It is produced by the resultant of pressure forces in the airfoil and tangential forces due to friction between the fluid and the airfoil surface.





Wind turbine performance

Abrupt cutout is now replaced by gliding cutout, ramping down from 20 to 30 m/sec softly G

- Currently, utility scale wind turbines are HAWTs with **variable-speed** operation
- The **power curve** provides the wind turbine electric power as a function of wind speed
- It takes into account power losses as an **efficiency factor η** (mechanical, electrical, and ancillary consumption)

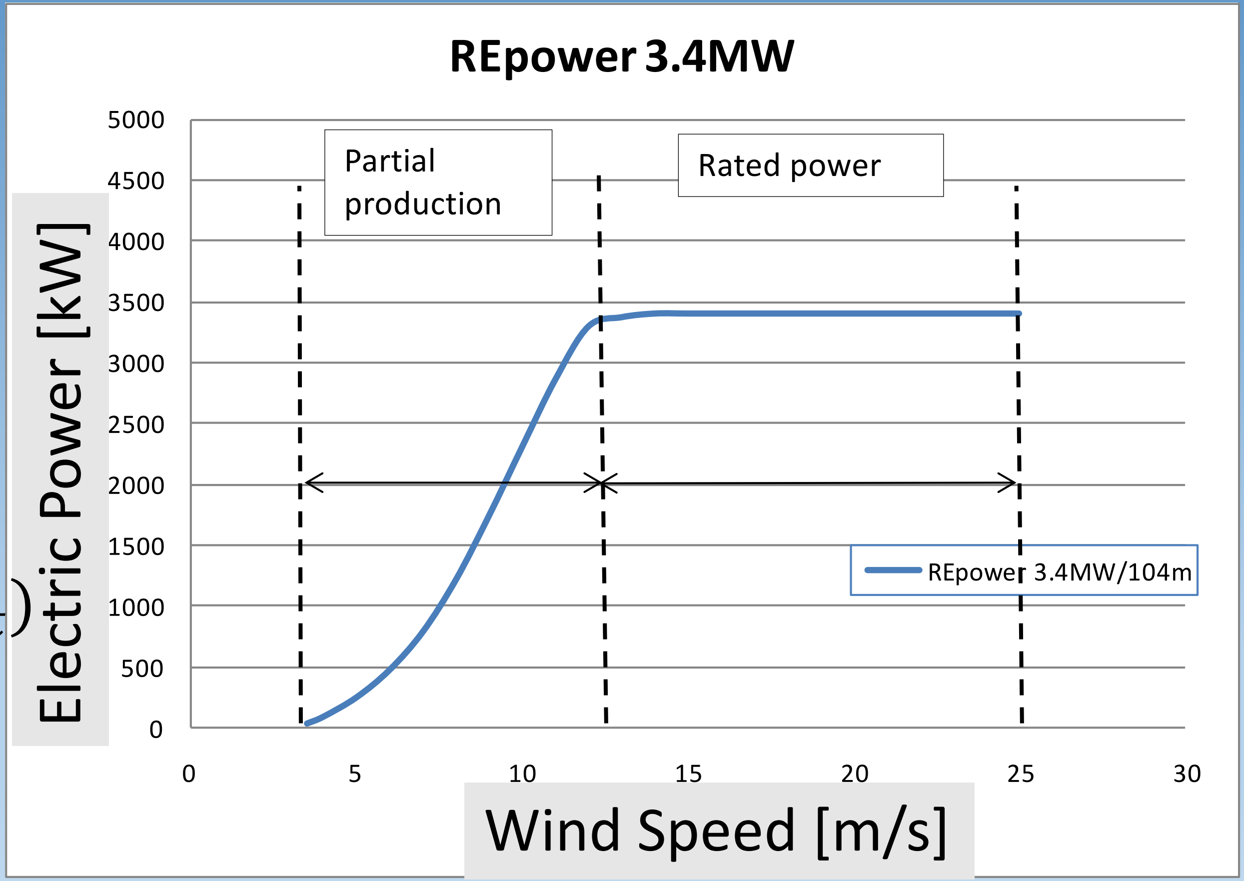
$$P_{elec} = P_{aero} . \eta$$

- There are two main regions in the power curve:
  - **Partial production** (P < Prated) : In this region the angular speed of the rotor is controlled through the **Generator Torque** in order to maintain the optimal tip speed ratio

$$P_{elec} = \eta . \frac{1}{2} . \rho . A . V^3 . Cp(\lambda_{opt}, \vartheta_{opt})$$

  - **Rated power** (P=Prated) : In this region the angular speed of the rotor is **constant**, and the pitch angle changes dependign on wind speed in order to maintain constant P=Prated

$$P_{elec} = P_{rated}$$



Wind Turbine Specific Rating (I)

Class IEC	I	II	III
Vref [m/s]	50	42,5	37,5
Vave [m/s]	10	8,5	7,5

- The **specific rating [kW/m2]** measures the **rated capacity** of the generator to the **swept area** of the rotor.

- For the same wind class, a lower specific rating means:
  - larger rotor, higher energy yield and design loads
  - The Cost of Energy (COE) will depend on the trade-off between energy yield and the cost of the wind turbine

- Higher **IEC class** (lower wind) favours lower machine ratings (chart in the right)

- Technological improvement allows increased rotor sizes for the same class, therefore reducing the specific rating

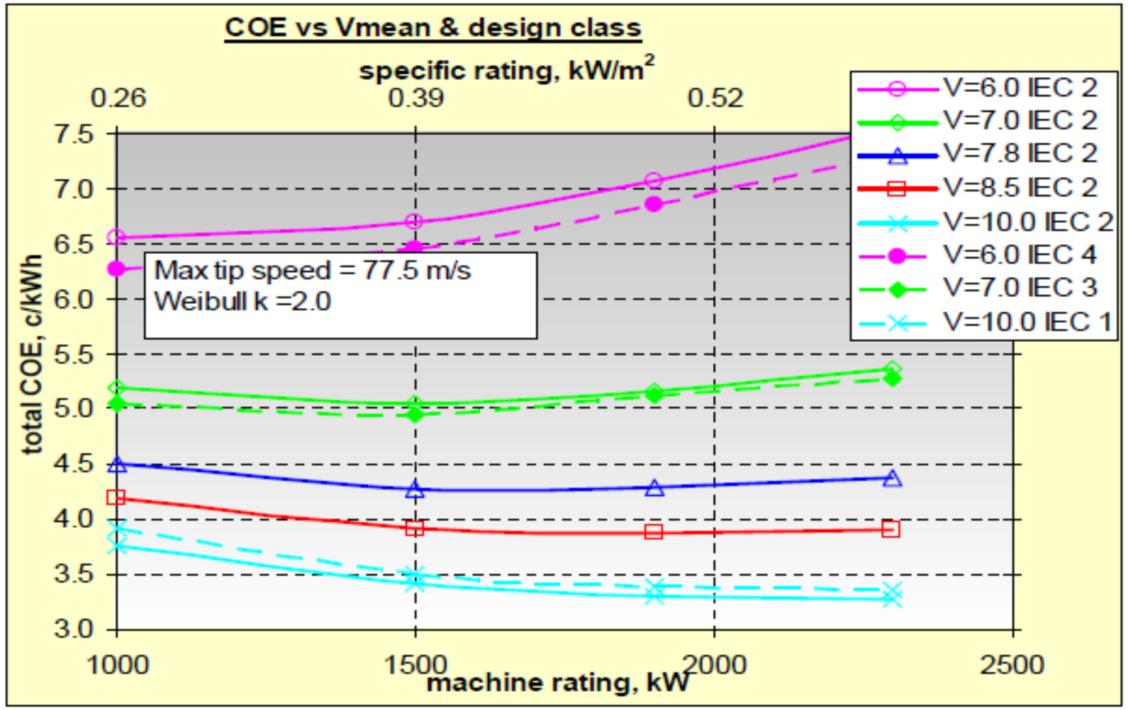
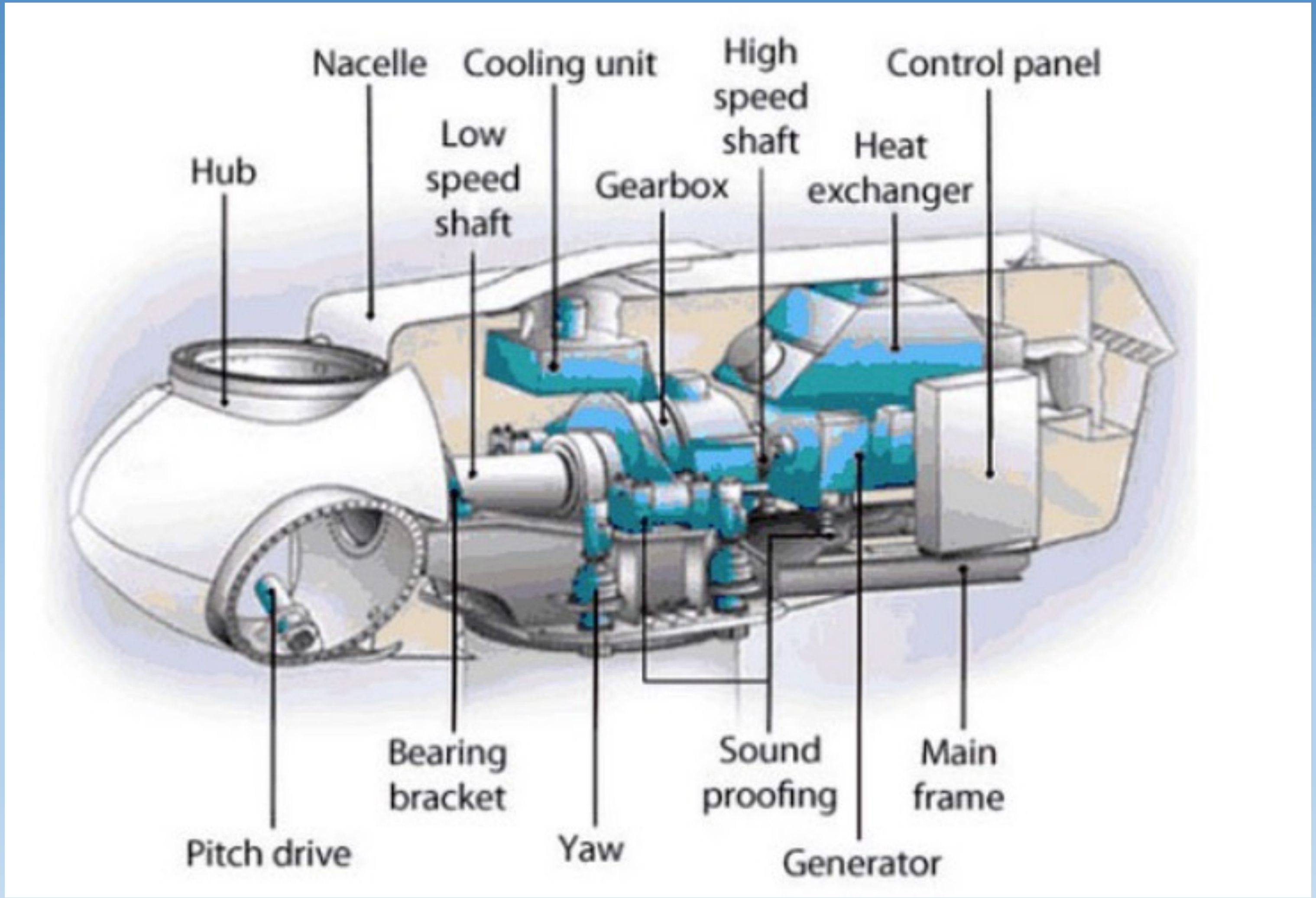


Figure 4-14. Effect on COE of mean wind speed and design class.

Source: WindPACT Turbine Rotor Design, Specific Rating Study, NREL, 2003

Wind turbine components

- A classical layout in a wind turbine nacelle is shown below

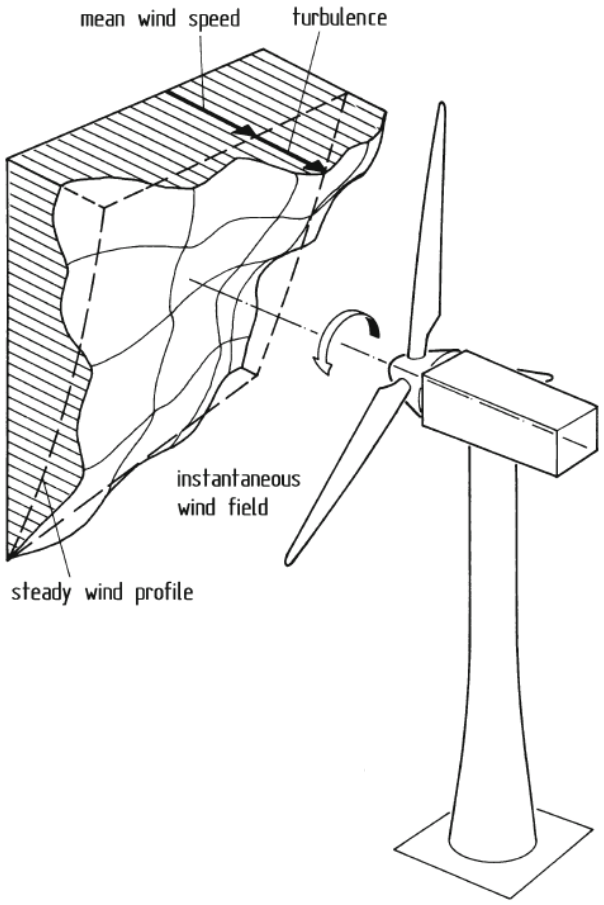


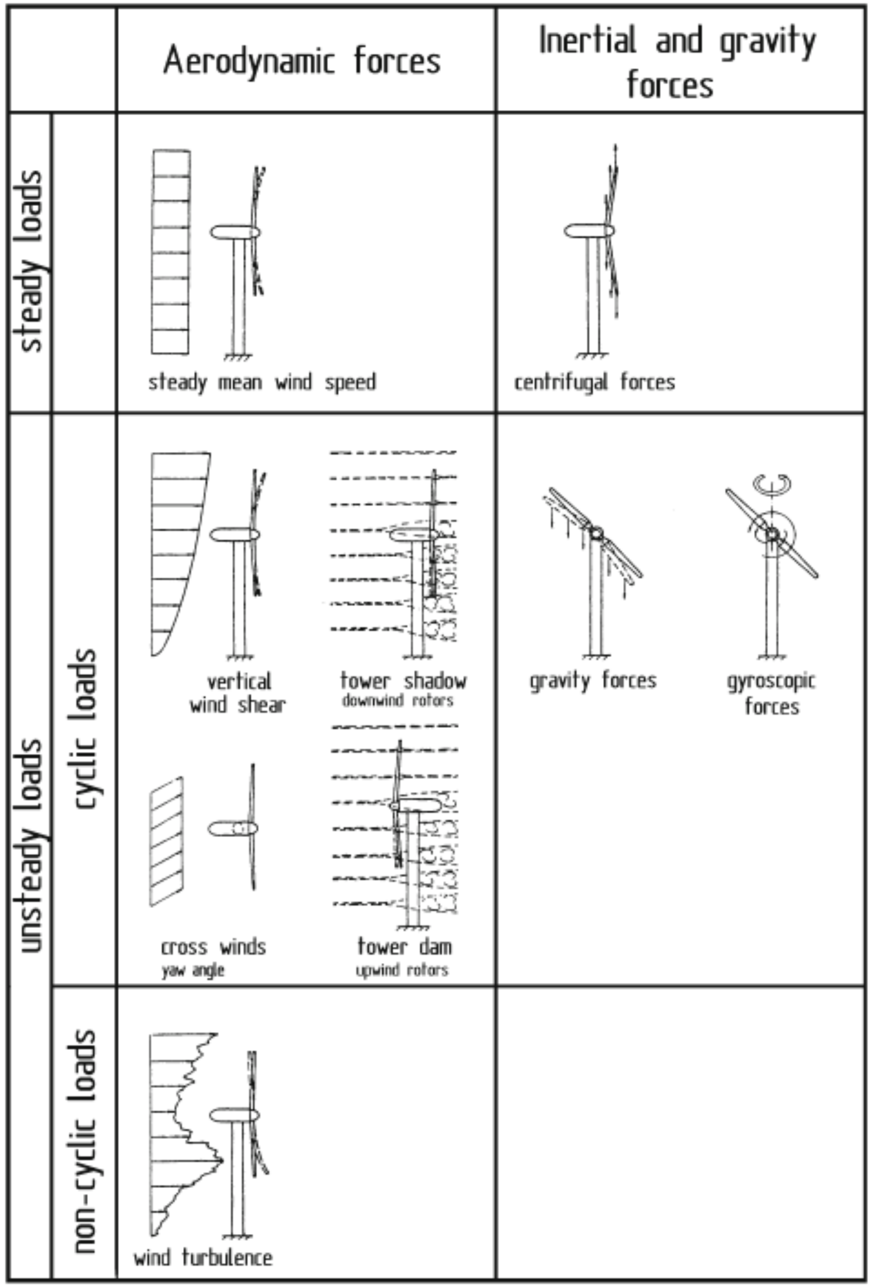
Source: https://www.e-education.psu.edu/earth104/node/923

List of of wind turbine systems
Rotor hub (cast, slip ring)
Pitch system
Rotor bearings
Blade pitch bearings
Blades
Nacelle
Main frame
Drive train - gearbox
Generator
Generator switching system
Converter
Compensator
Transformer
Control system (sensor array + industrial pc)
Supervisory Control & Protection / SCADA
Yaw system
Tower
Tower inner support structure
Foundation structure
Lubrication
Hydraulic
Cooling
Air conditioning /Air circulation
Electrical Auxiliary Power Supply
Earthing / Lightning Protection System
Obstacle Warning System
Fire extinguishing
Personnel Rescue System
Service lights
Lifting equipment (cranes, elevators)
IT Network & telephone
Process monitoring (fire alarm, video monitoring, environmental measurement)

Wind turbine loads (I)

- During operation a wind turbine experiences a combination of steady and unsteady loads, caused by wind, gravity and inertia.





Turbine classes for different sites

Source: Erich Hau "Wind Turbines" Ed 3.

Wind turbine control (I)

- Goals:
  - Power regulation
  - Maximize energy capture
  - Maintain loads under acceptable limits
  - Noise control
  - Power quality in compliance with grid code
  - Operate in coordination with other turbines in the wind farm (Wind farm control)
- Challenges:
  - Challenging environment: Fluctuating wind, challenging to measure, wake flows
  - Large inertias, heavy and flexible components
  - Avoiding structure natural frequencies
  - Robust control (simulation model vs ”reality”)

Typical time frame and budget

is it a suitable location?

- Site identification
- Pre-study / Show-stoppers — 1 – 3 months, 10 – 40 k€
- Securing of land (lease / purchase) — 3 – 12 months, 20 – 100 k€
- Technical & financial assessment; Technical design; EIA & Permit procedures; Contract negotiations — 2 – 5 years, 400 k€...2 M€
- ”Package ready” for financing — 4 – 6 months, 200 – 1000 k€
- ”Point of no return”
- Construction — 1 – 2 years, 10 – 300 M€

How to succeed as Project Developer?

- Find the right sites
  - Feasibility in terms of both technoeconomic and environmental/social issues

- Recognise the showstoppers of each project early on, and react accordingly
- Invest in right things at the right time
  - Avoid upfront spending when risks and uncertainties are still high
  - Maximise the added value of the new information you acquire at each stage

- Make sure the interplay between technical, environmental and contractual work functions at all times
  - Keep on the flow (but not overflow!) of information between experts working on different fronts
  - Be prepared for surprises and keep options open; modify project size, relocate turbines, etc.

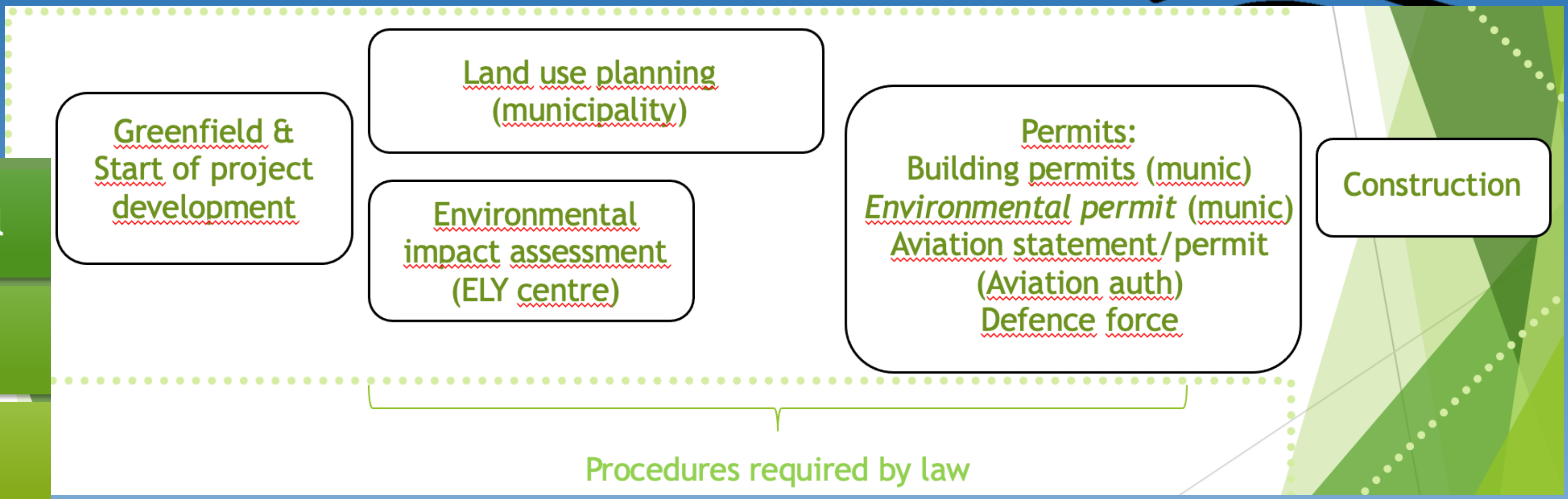
- Report to your financiers and external stakeholders openly and without delay!
- Not all eggs in one basket: Have a healthy mix of projects
  - in different stages of development,
  - in different geographical areas,
  - and in different markets (different legislative / administrative frameworks)

Conclusions on offshore vs. onshore wind

- Challenging physical & environmental conditions
- Big & complex projects, huge investments
- Broad set of special skills required
- Playing field for the big & strong
- Global business

- Underwater geotechnics
- Marine conditions:
  - Waves, sea currents, corroding environment,…
  - Wind-wave interaction & load combinations
  - Ice-infested waters at northern latitudes
- Offshore logistics (construction & maintenance):
  - Handling of big loads at unstable conditions
  - Weather windows; accessibility / waiting times
  - Long distances
  - Complex construction sequence and supply chains
  - Special HSEQ requirements
- Grid connection (and grid impacts) of huge projects
  - Sea cables
  - High voltage levels (HVDC or HVAC) and power levels
  - Offshore substation: design, construction, maintenance
  - Project size vs. design criteria for power systems (”N-1”)
- Special environmental considerations:
  - Impacts on fish & fishing, marine traffic, seabed & benthos, birdlife, sea mammals, underwater noise during construction,…

Permitting and EIA

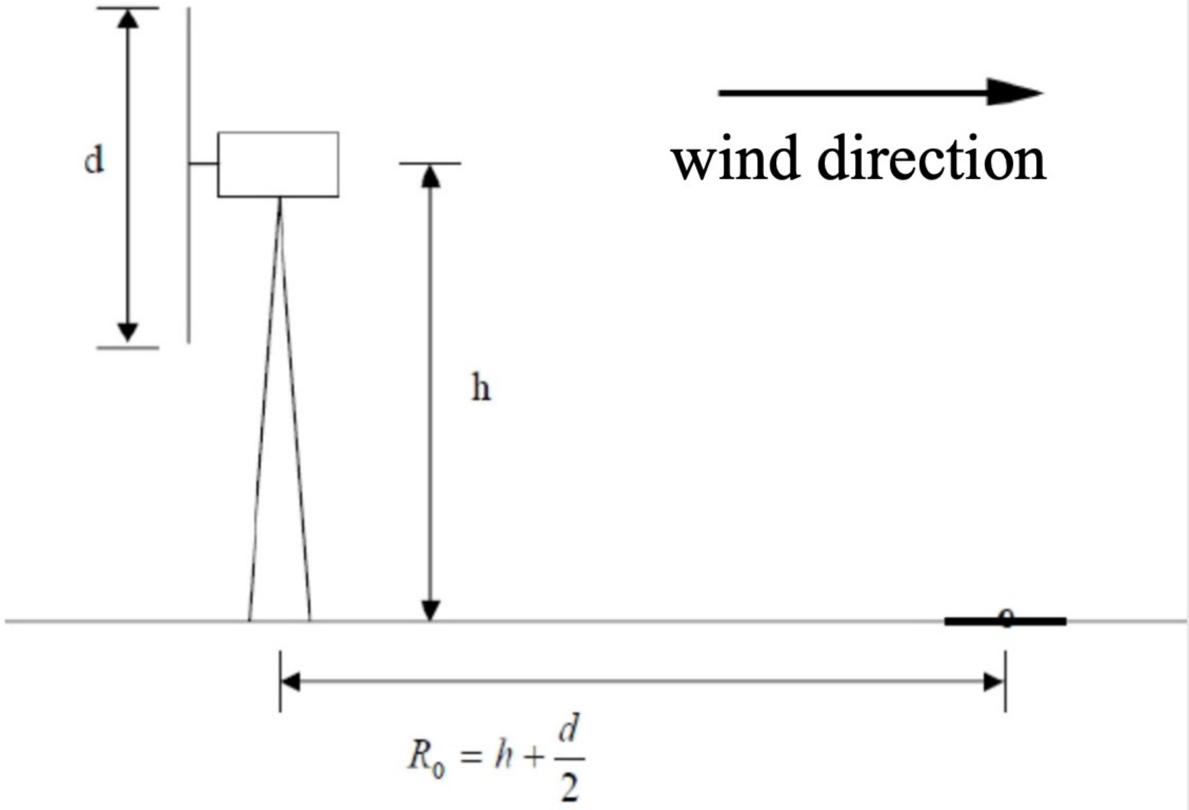


- Abiotic environment
  - **Impacts on the soundscape (noise)**
  - Impacts on light conditions (flicker)
  - **Impacts on air, quality and climate**
  - Impacts on soil, surface and groundwater
- Biotic environment
  - Impacts on vegetation and valuable natural sites
  - **Impacts on birds**
  - Impacts on other fauna
  - Impacts on nature reserves
- Human environment
  - Impacts on land use and the built environment
  - Impacts on traffic
  - **Impacts on the landscape and cultural environment**
  - Impacts on ancient remains
  - Impacts on human health, living conditions and comfort

during construction
during operation

Noise emission measurement

- Measurement distance is R_0
  - ±30 m or ±20% deviation is allowed
- Measurement direction downwind ±15°
- Wind speed measurement at 10 m height
- T [°C], RH [%] and p [Pa] are measured
- The target wind speed is 8 m/s at 10 m height because this wind speed produces typically the maximum energy output in the turbines.
- Typically the measurements are conducted within 6−10 m/s to find better accuracy
- 20−20000 Hz in third octave bands
- Energy output of the wind turbine is recorded
- Noise measurement clock is synchronized with the wind farm clock afterwards.

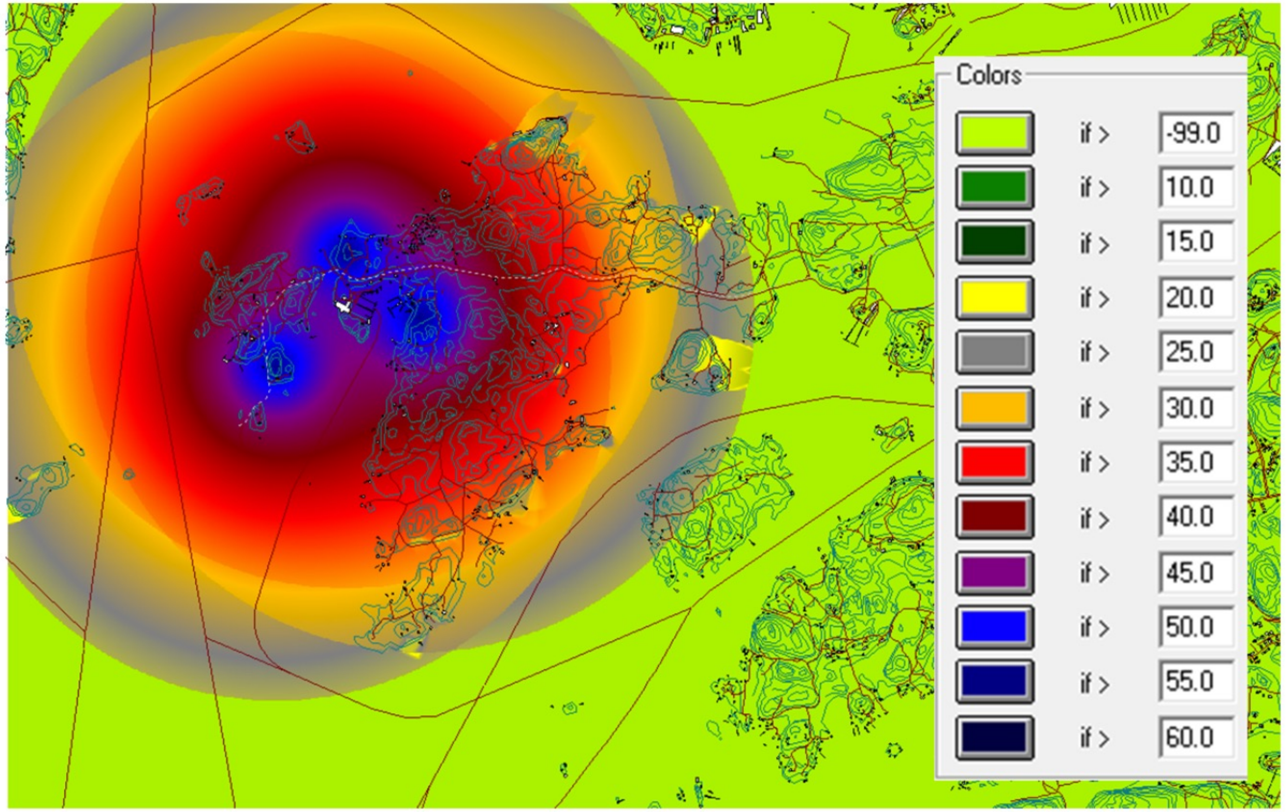


Noise immission measurement

- Immission level means the level of the exposed person
- Short-term measurement: usually ½ hours turbines ON and ½ hours turbines off
- Immission measurements are basically similar than emission measurements
- Since the distance to the tower is nearly always larger than 500 m, the background noise becomes a major challenge.
- The measurement uncertainties are very large, even 7 dB beyond 1 km.
- Reliable measurements are very difficult beyond 1.5 km.

Prediction of wind turbine sound propagation outdoors

- Source type and SWL (emission)
  - Point source
  - Octave band SWL values from 31.5 to 8000 Hz
- In addition:
  - Topography (maps)
  - Athmospheric absorption (T and RH)
  - Ground absorption (0 … 1)
  - Barriers (buildings) close to receivers
  - Vegetation zones (they play very small role)
- Neglegted factors:
  - Temperature gradient
  - Wind gradient
  - Turbulence
- Prediction is usually done with ISO 9613



SWL= sound power level

Wind turbine maintenance activities

Goal: Maximize
Turbine lifetime
Turbine availability
Wind farm revenue

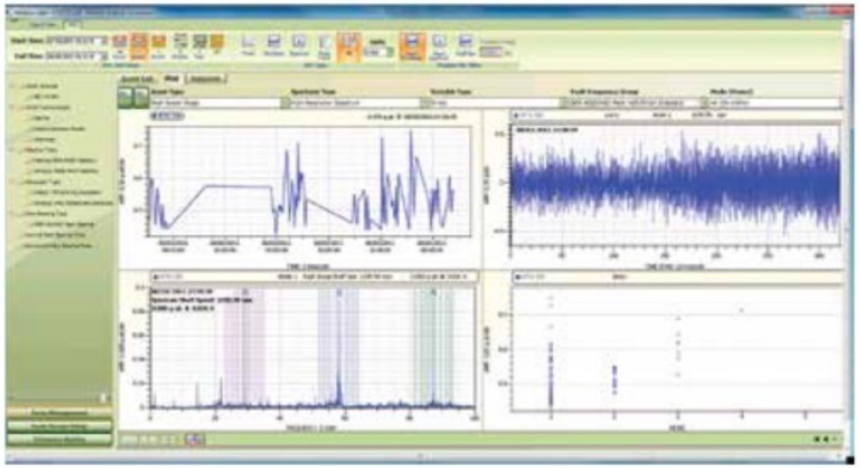
10 – 20 % of lifetime costs onshore are from O&M

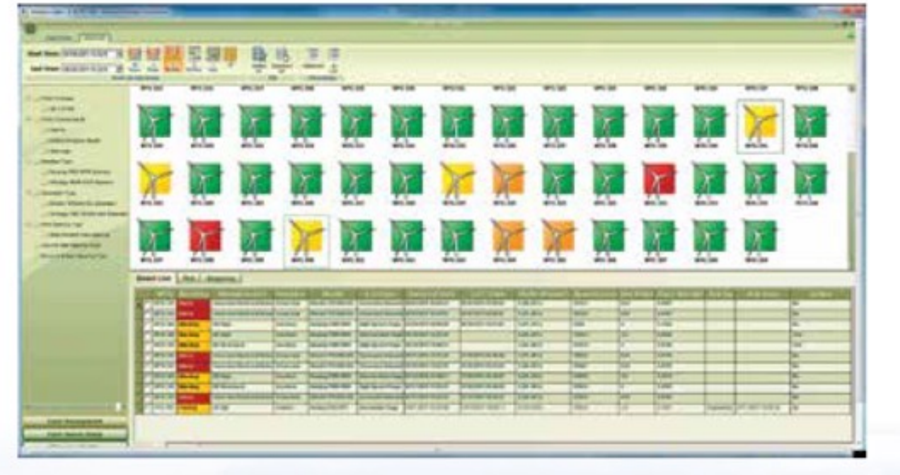
Typical periodic (~yearly) maintenance tasks may include:

- **Bolted connections**: Retightening bolts: tower , gearbox mount, main frame to tower, electric terminal connections, hub pitch drive terminal box. Check pretension in blade root sample bolts, retighten if necessary
- **Gearbox**: Sample of gearbox oil, visual check of oil levels,
- **Hydraulics**: visual inspection of hydraulics pipes/hoses
- **Power cables**: check power cable connections & bus bars, retighten
- **Generator**: check generator alignment, Check electric connections
- **Blades**:
  - Visual inspection for damage,
  - service erosion tape,
  - check lightning protection system electric resistance and status of receptors,
  - check tip drain holes

Condition monitoring system

- Condition monitoring combines **data acquisition** and processing to **diagnose** the status of the system and **prognose** its future status
- It enables a shift from **corrective / scheduled** maintenance towards **predictive or condition based maintenance**
- Typical CMS installed in wind turbines include:
  - Gearbox accelerometers
  - Gearbox oil particle sensors
  - Nacelle accelerometers
  - Signal processing hardware
  - Diagnostic software combining sensors with SCADA data
- Also the following sensors may be included: Temperature of gearbox oil and gearbox bearings

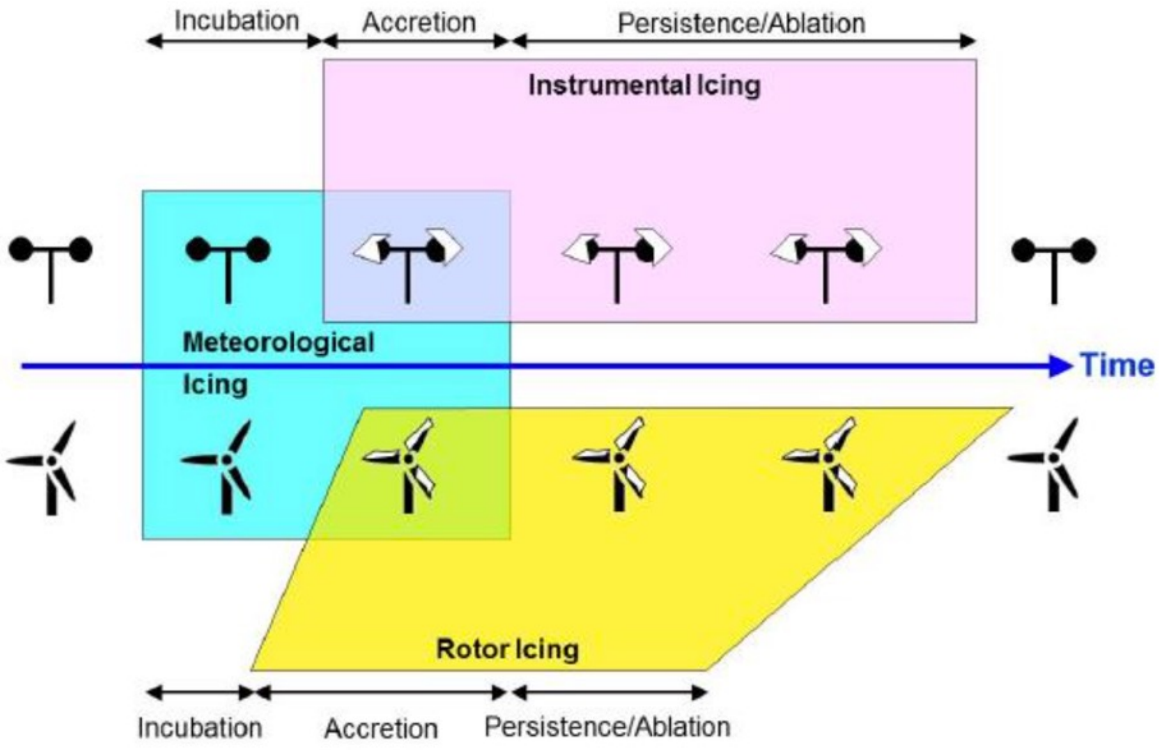




Source: General Electric Measurement

Icing event

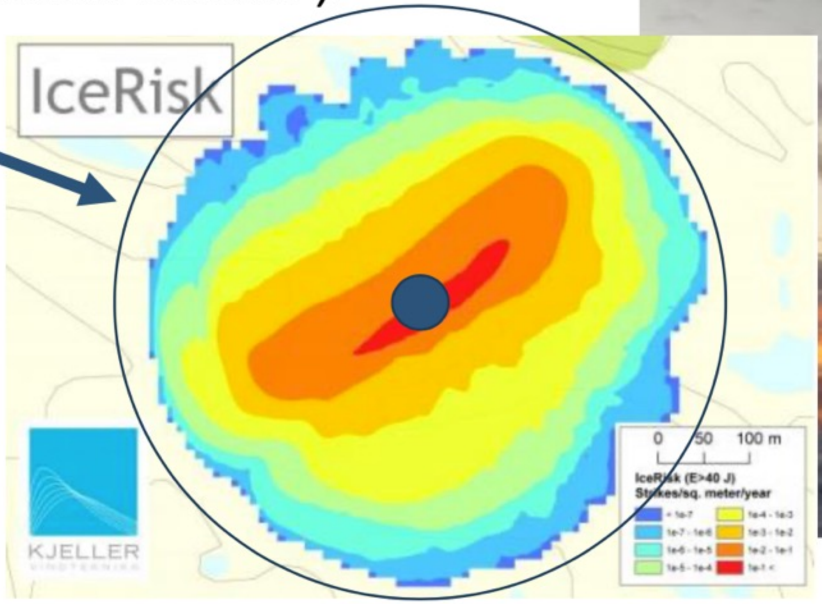
- **Meteorological icing**
  - Period during which the meteorological conditions for ice accretion are favorable (active ice formation)
- **Instrumental icing**
  - Period during which the ice remains at a structure and/or an instrument or a wind turbine is disturbed by ice
  - Typically 2…5 times longer than meteorological icing event
- **Rotor icing**
  - The period during which ice is present on the rotor blade of a wind turbine.
  - Typically, incubation and ablation times for rotor icing are shorter than for instrumental icing.



Source: IEA wind Task 19: Recommended Practices for 13. Wind Energy in Cold Climates, 2 Edition 2017

Ice throw and safety distances

- Industry practices based on
  - Simulations
  - Site surveys used to validate the simulations
- Industry rule of thumb for safety distance ("Seifert-formula"):
  - 1.5 x (hub height + rotor diameter)
  - For example 1.5 x (100 m + 100 m) = 300 m



Plot: Kjeller Vindteknikk

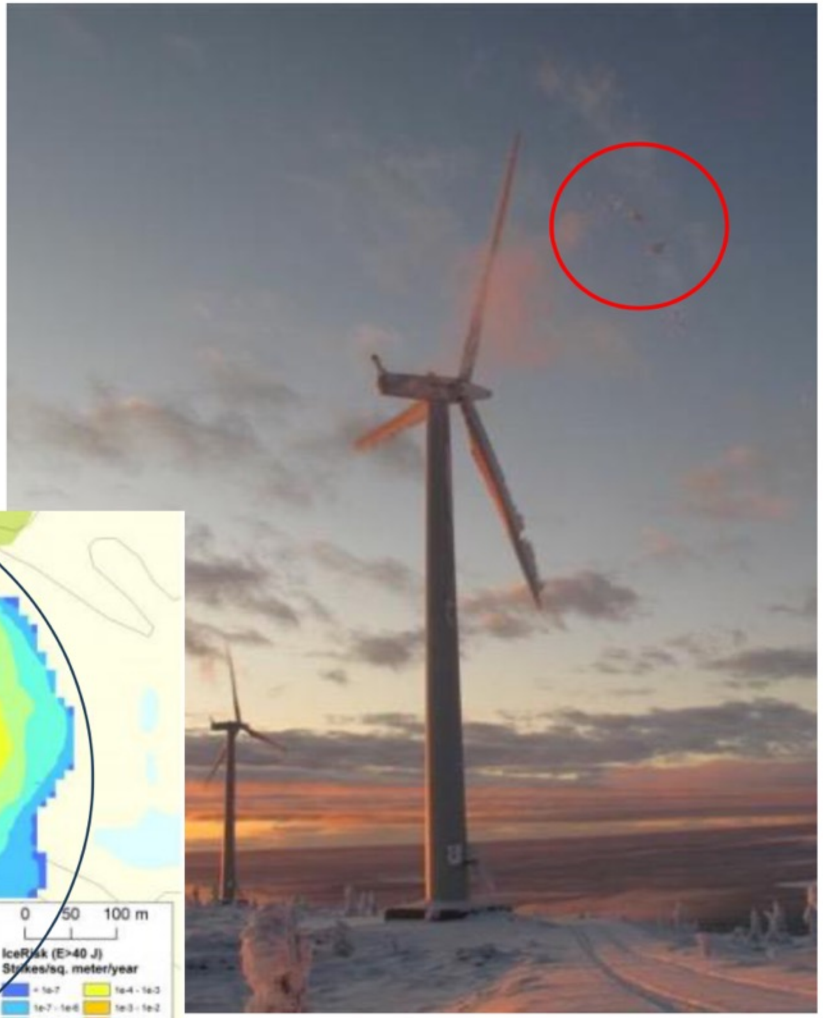


Photo credit: VTT

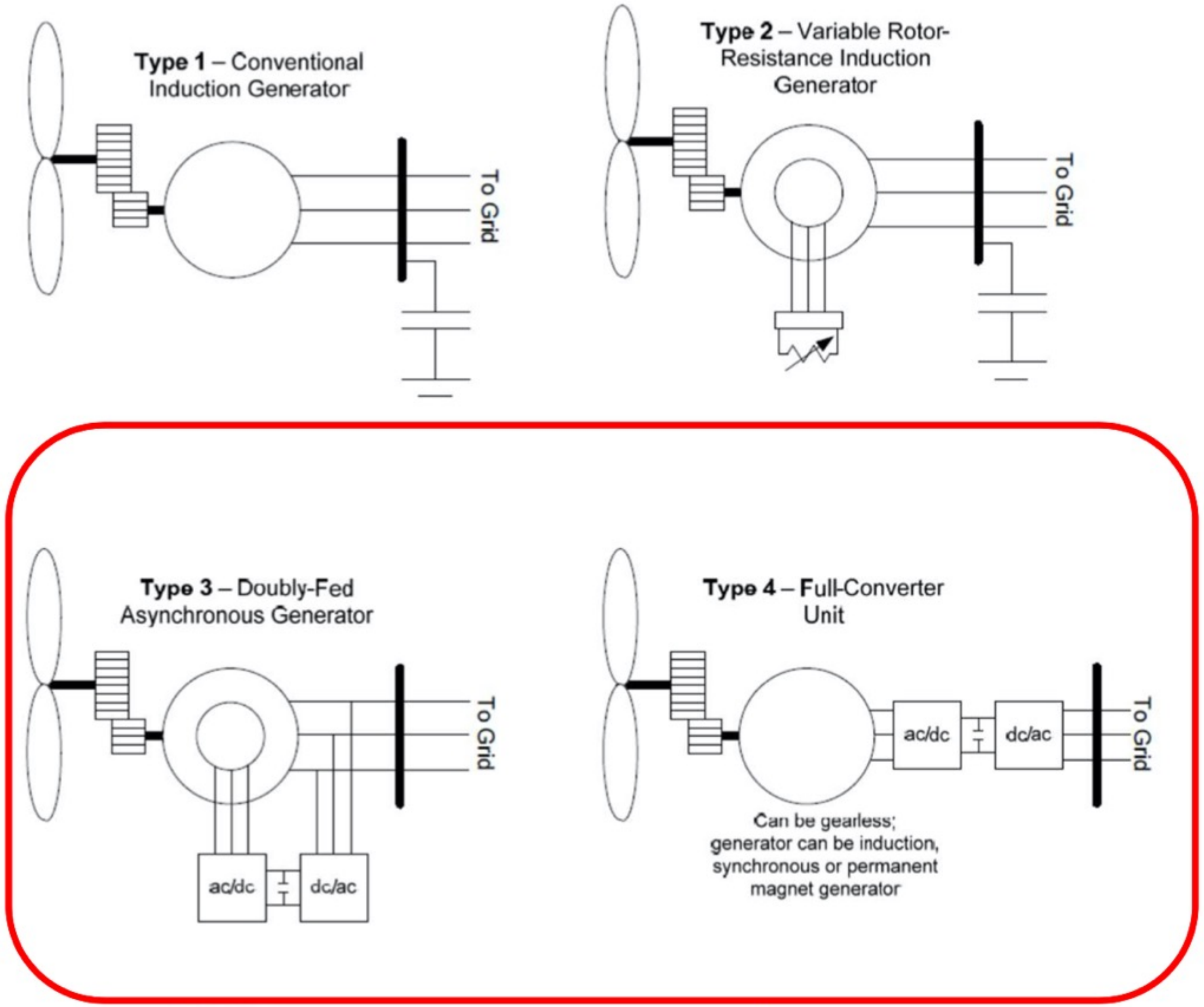
VTT

Qualitative Benefits of Ice Prevention Systems

No system	Hot air / de-icing	Anti-icing with electrothermal heaters
Up to loss 20 % of AEP	Loss of production due start/stops and system use	Loss of production < 1% of AEP (system consumption)
Extensive standstill during wintermonths	Turbine stopped due to system inefficiency	No standstill due to icing or IPS operation
Up to 60% decrease in fatigue design life[1]	Additional stop/start-cycles loading the turbine	Loads close to normal operational conditions
Risk of damage or injury due to ice throw (large ice pieces)	Somewhat reduced risk of damage or injury due to ice throw	Small risk of damage or injury due to ice throw
No need for additional investment	Not proven or available for turbine suppliers	Customizable, opportunity for independent supplier

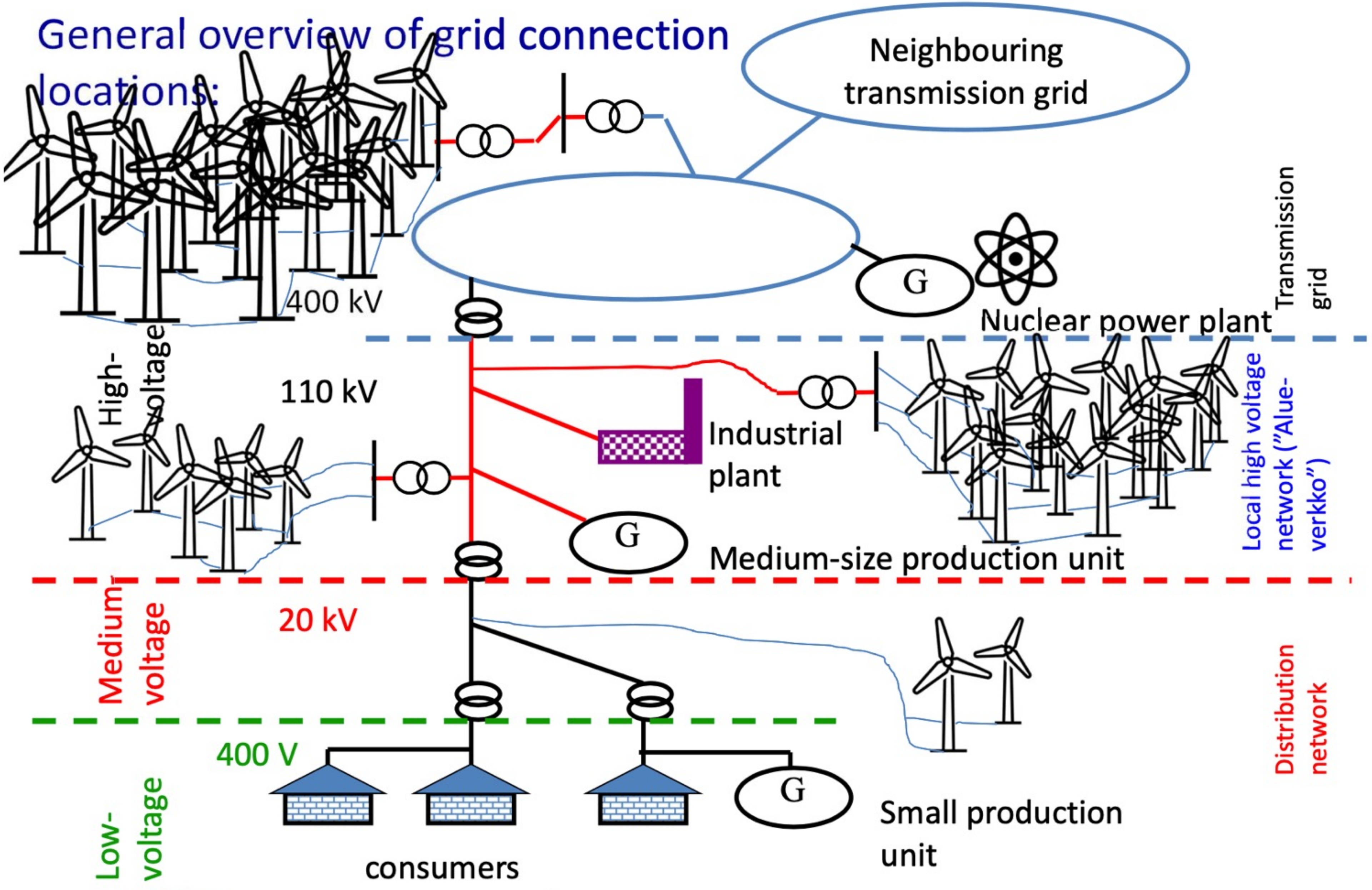
[1]: IcedBlades - Modelling of ice accretion on rotor blades in a coupled wind turbine tool, WinterWind 2012 conference

Wind Turbine Electrical Drive Trains



- three MW-class basic concepts (+ several variations)
  - Type 1: Fixed speed, induction generator connected directly to the network
  - Type 3: Variable speed, doubly-fed induction generator (DFIG) (or rotor resistance control, OptiSlip, Type 2)
  - Type 4: Variable speed, full power converter equipped generator
- Rotor speed slow (~10 rpm 4 MW unit), power system frequency 50 Hz (1500 rpm). There's needed
  - gear
  - or more poles in the generator
  - or power converter
  - or combination of these

General overview of grid connection locations:



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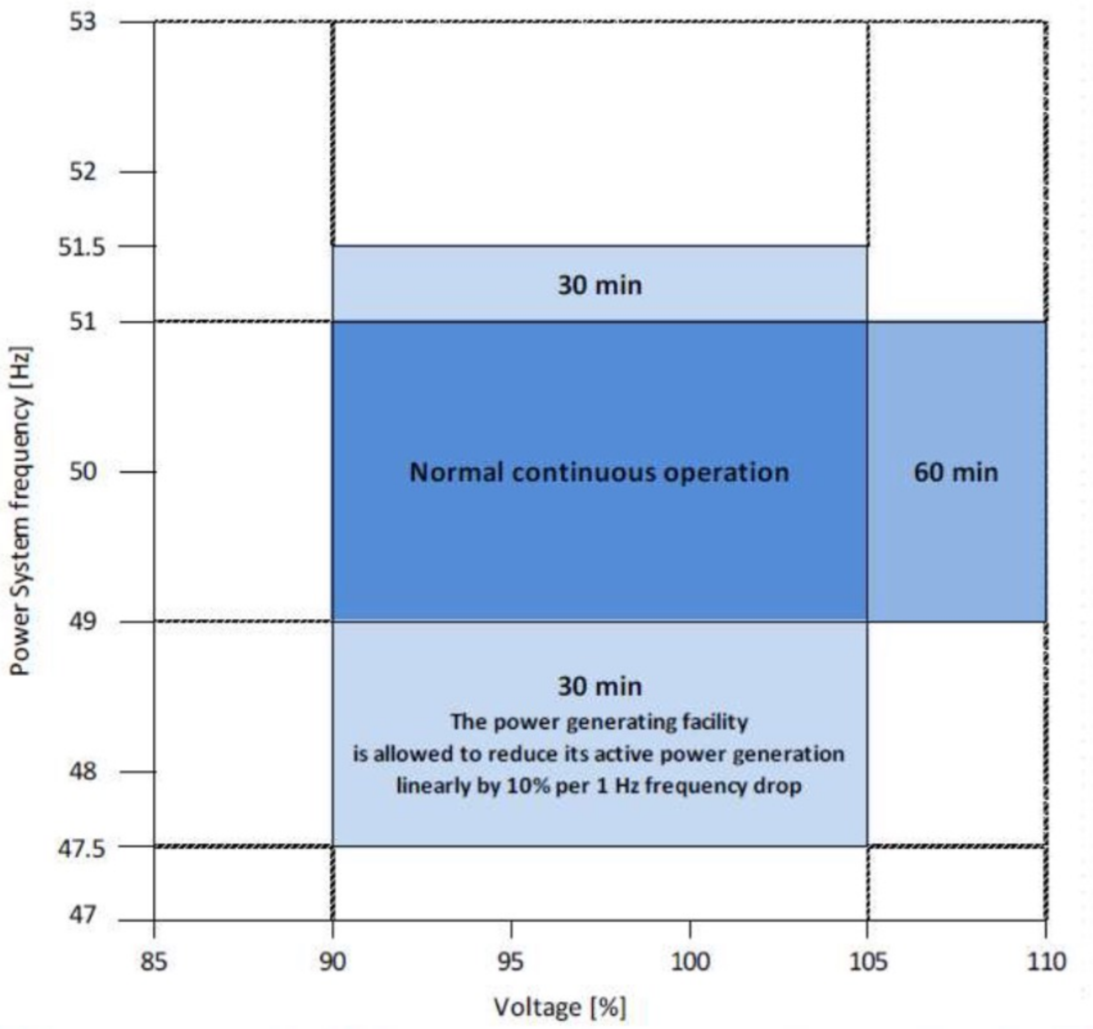
Grid Codes



Main topics in all Grid Codes
Voltage and frequency operating range
Active power / frequency control
Reactive power capability
Voltage / reactive power control
Voltage disturbance events (LVRT/HVRT)
Power quality
Protection, communications etc.
Simulation models
Grid code compliance testing
Compliance process
Others

THE GRID CODE

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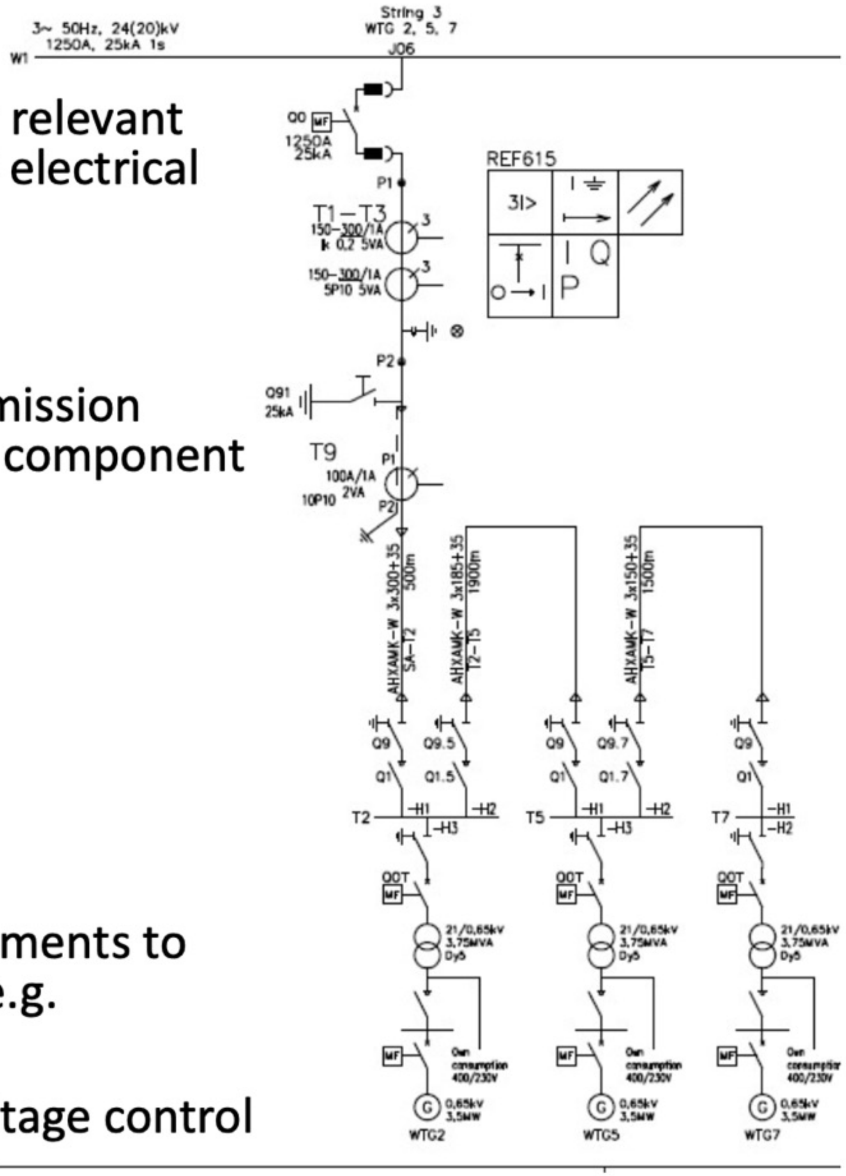
Electrical design of a WPP

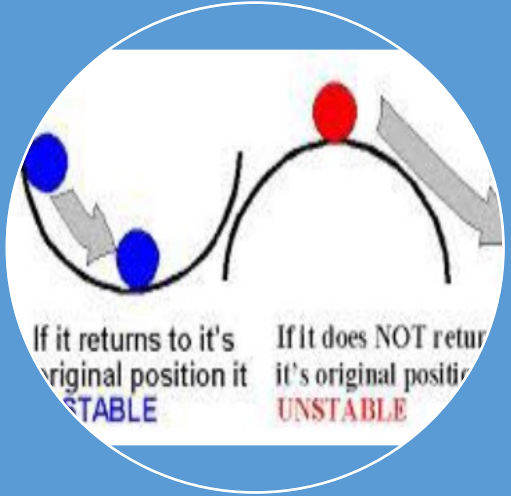
- Consider the grid code requirements and other relevant regulations and standards throughout the WPP electrical planning & design
- Also consider the costs, e.g.
  - Material/component/work expenses
  - Operating costs, e.g. internal power transmission losses, potential loss of production due to component outages
- Electrical design of a WPP consists of, e.g.
  - Cabling dimensioning & design
  - Main transformer selection
  - Instrumentation design & dimensioning
    (e.g. breakers, relays, metering…)
  - Determining the protection settings
  - Design of additional components /arrangements to comply with the grid code requirements, e.g.
    - Capacitor bank
    - Communication arrangements for voltage control



Grid impacts

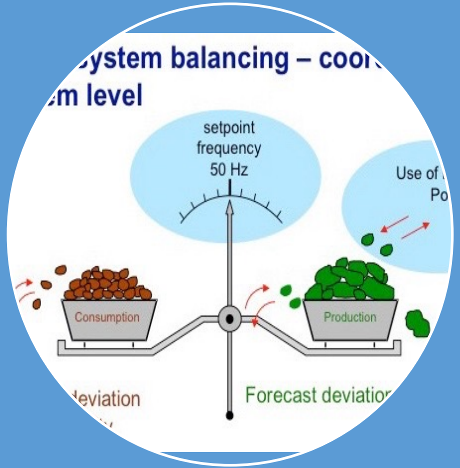
- Grid to connect and transfer the power
  - Currently the grid transferring power from existing units
- Power flows will change
  - Sometimes more, sometimes less losses
  - In some cases, grid bottlenecks will increase and result in part of the generation being lost (curtailed)
  - Grid reinforcement needs may become large if wind power is built far from load centres – usually cost effective to build more interconnectors btw countries and transmission
- Usually transmission grid costs are not allocated to single cause of reinforcement – once the grid is there it will be used by everyone and will increase the security of supply

Future power system challenges



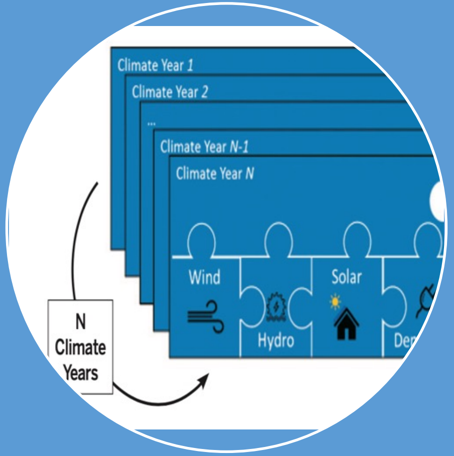
Stability

keep the power system resilient to disturbances and external events; control interactions



Short term balancing

demand and supply in balance – weather impacts like storms



Long term balancing

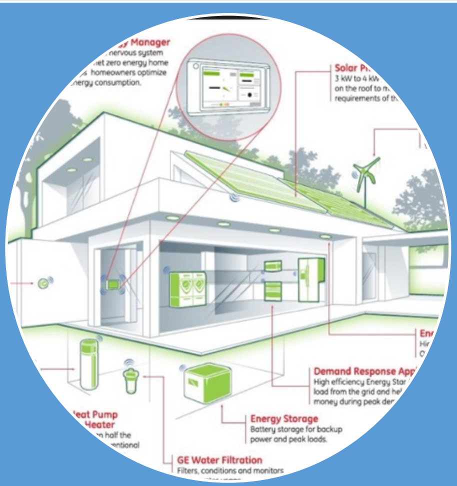
Increased weather dependency, extreme rare events of low wind, solar, hydro resource

seconds, minutes, hours, seasons/years

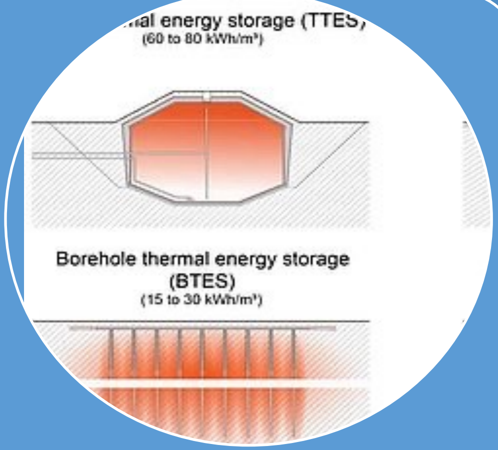
Flexibility and resilience solutions

Stability: How to operate non synchronous system?

How to get resilience from wind, solar, batteries? exploit wider flexibility of inverters, not just replicating synchronous machine features



Short term balancing: technology solutions are there (use demand, wind and solar and storage) - how to incentivise?



Long term balancing:

no more fixed load paradigm, optimise a combination of peakers, storage and demand side. How to incentivise smart sector coupling with all power2X storage options?

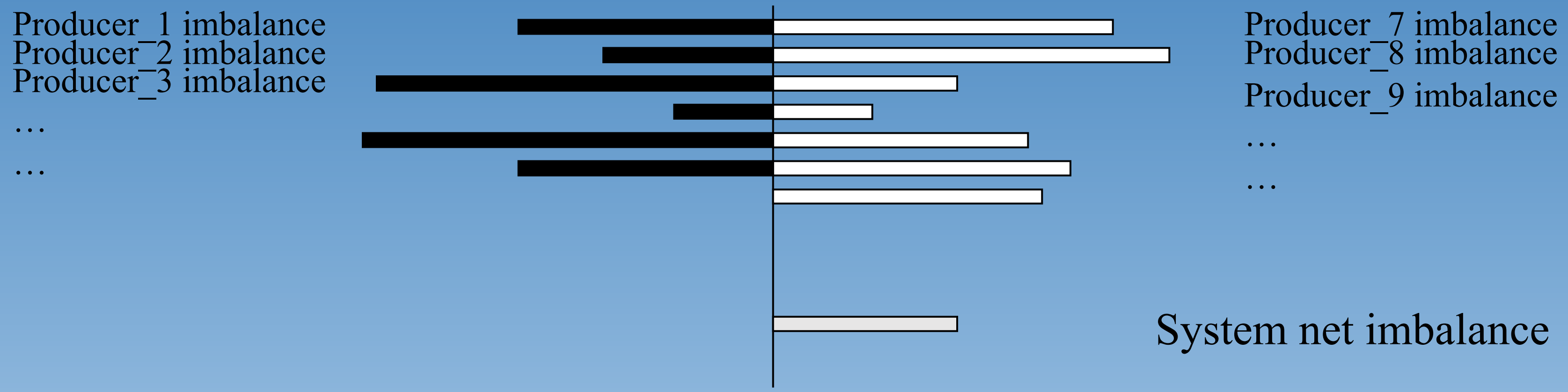
no mass
all brains

large and
fast markets

huge energy systems
power, heat, gas,...

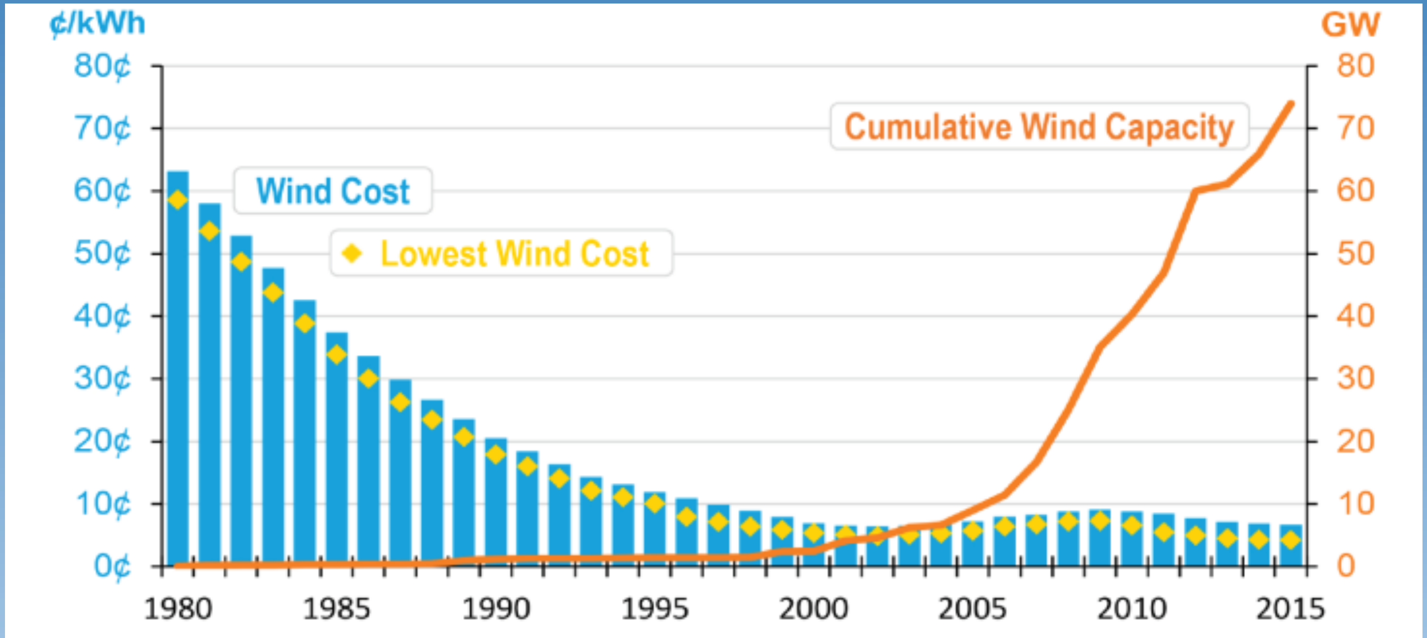
More complexity and amount of data is exploding - digitalisation

System balancing – net imbalances only



- Bids to market – 24 times 1 hour bids the day before – intraday market possibility to correct
- Imbalances are penalised: Transparent and cost reflecting pricing of imbalances
  - Balancing market to cover the system net imbalance → price for imbalances of that hour
- System operator charges regulating power price for imbalances from all producers that have had their imbalance in the same direction as the system need
- The producers that have had their imbalance in the opposite direction:
  - pay/receive the spot market price for the imbalance (two-price model) – no penalty
  - pay/receive the balancing market price (one-price model) – you make profit

Summary of main trends in wind energy



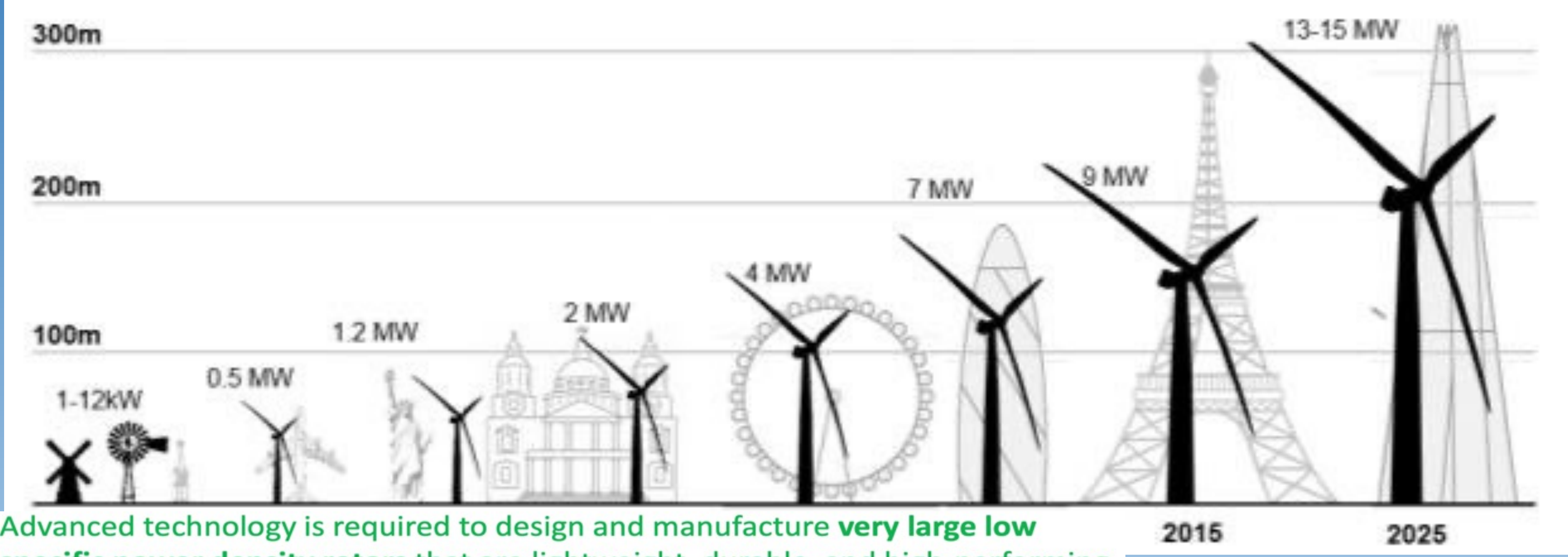
Cost reduction: onshore, offshore, floating

- controls: more energy, less loading, grid support services
- materials, design, manufacturing
- O&M, digitalisation, digital twins

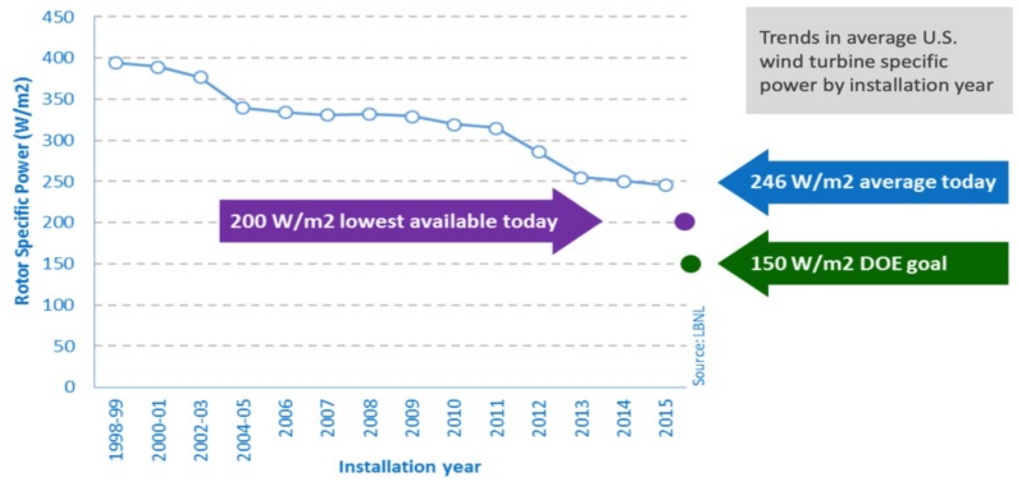
Grand challenges - research:

- physics of resource from the atmosphere to the intra-plant flows
- structural, aero and hydrodynamics coupled with access to material properties
- control of wind power plants to orchestrate wind turbine, plant, and grid forming operations

Larger turbines, rotors, power plants



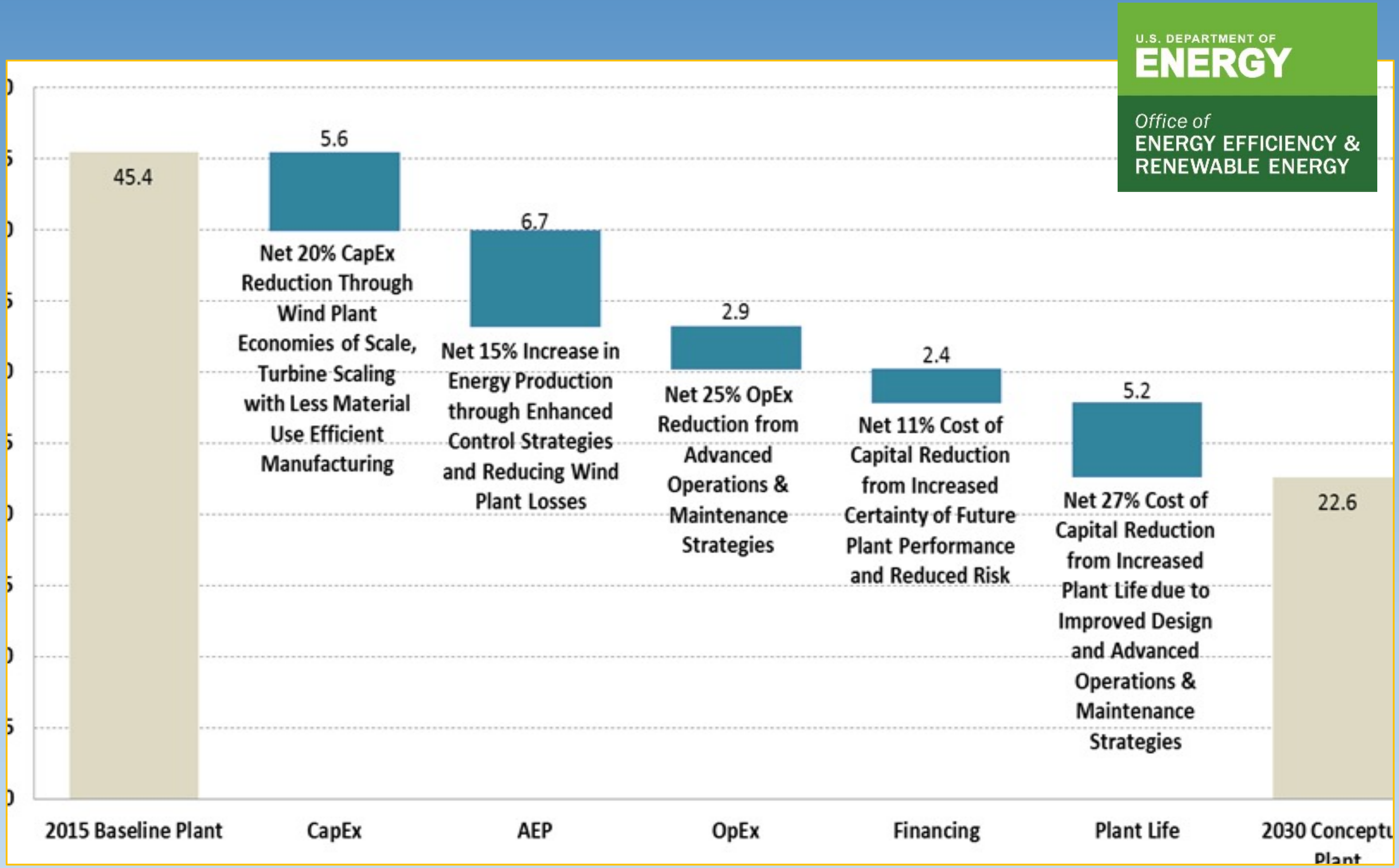
Advanced technology is required to design and manufacture **very large low specific power density rotors** that are lightweight, durable, and high-performing.



- optimal size – Balance of plant impacts how large >5MW would be cost efficient – offshore larger
- Rotor blade technology, cheaper blades impacts low specific rating

Costs, value and sustainability

- Life extension, end of life and repowering
- Recycling - blades
- Sustainable wind power deployment - addressing other than technical challenges like public acceptance
- Beyond LCOE taking into account the value of wind

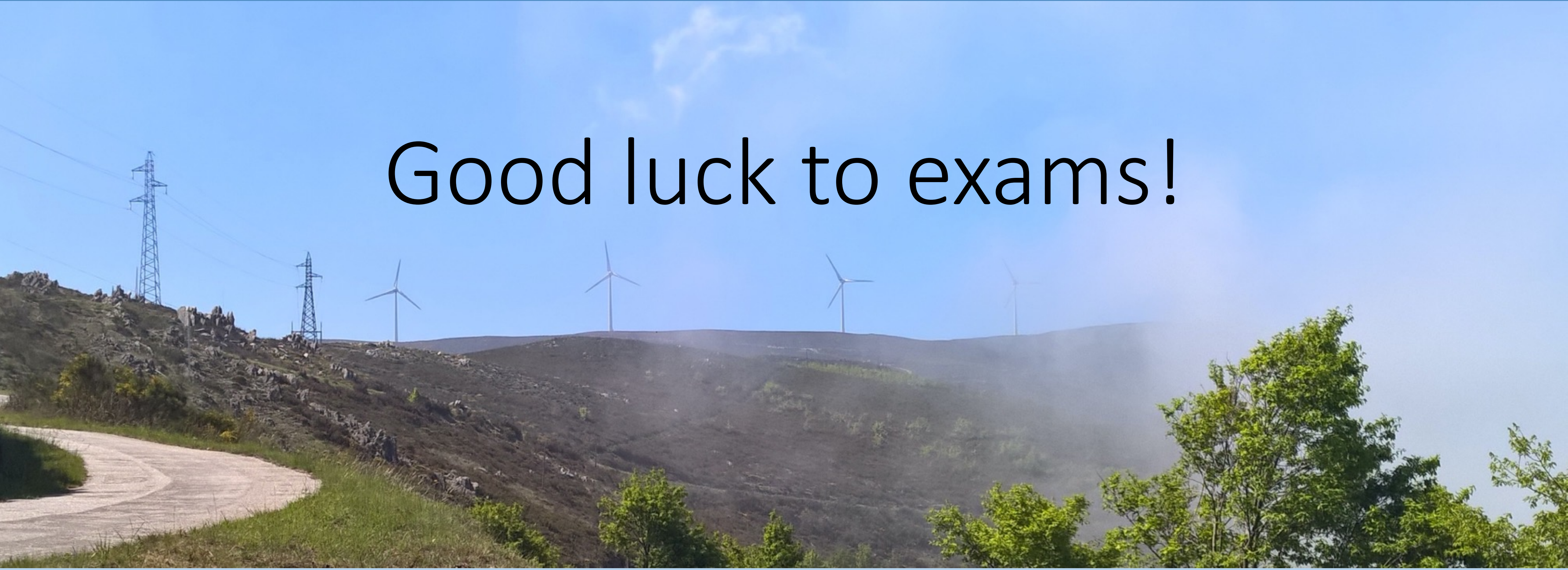


Questions?

Feed-back?

- Was there something you would have liked to hear more about?
- Was there something that was covered in too much detail?
- Would you need background info (of some subject, or all) – slides and presentations enough?

Thank you for your attention



Good luck to exams!

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