Industrial Practice of Wind Turbine Control

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Outline

- Setting the Scope and a bit of History
- Requirements for Modern Wind Turbines
- Control System Hardware
- Control System Architecture
- Future Developments

The Predominant Commercial Turbine Type

- Horizontal axis wind turbine (HAWT)
- Three blades
- Upwind
- With and without gearbox
- Electric generator
  - Permanent magnet, synchronous
  - Doubly-fed induction
  - Asynchronous
- Active Converter

(Source: © 2000 Nordex)

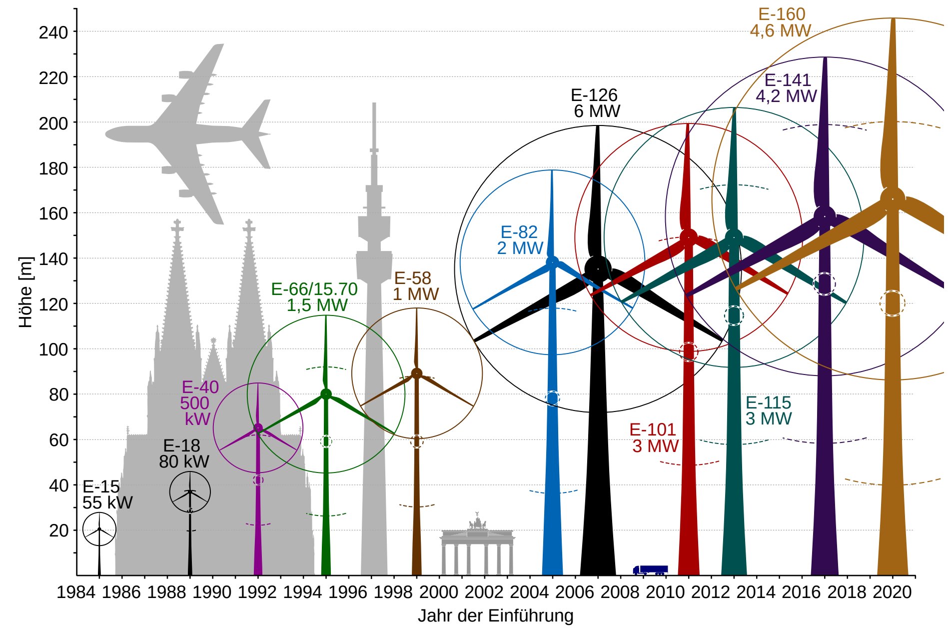
The Ancestor of modern HAWTs

- Wind powered machinery known for millennia
- 1887 first turbine to produce electricity
- The Gedser turbine: prototype for the "Danish Model"
  - 1957 by Johannes Juul
  - 200kW
- Mixed developments followed
- Smaller, mass-produced turbines prevailed
- Evolution in small increments led to today's very uniform turbine design

(Source: Elektrizitätsmuseum, Bjerringbro)

No Controller Necessary

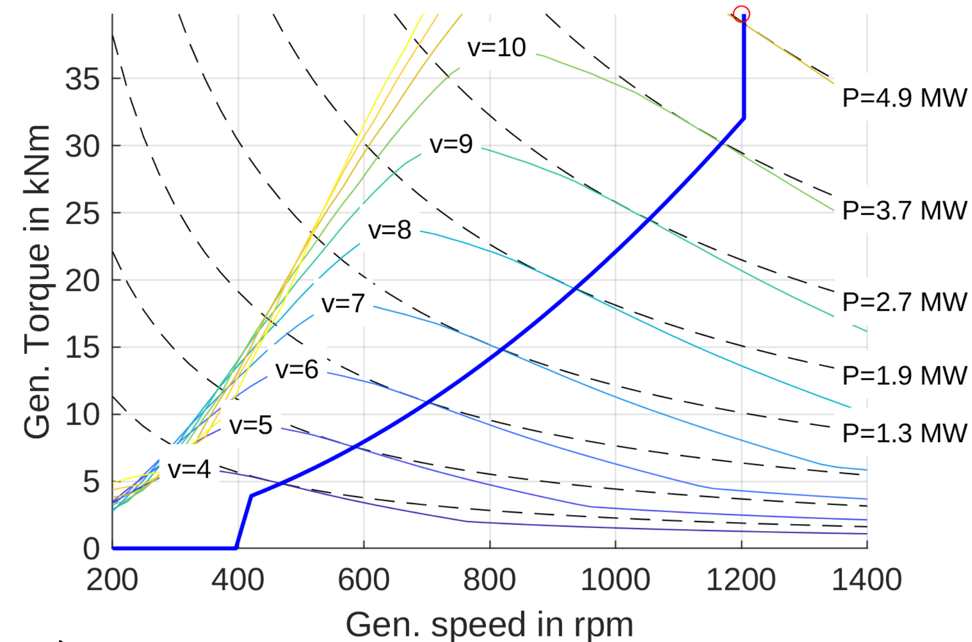
- Control was mostly mechanical or inherent
  - Stall regulated rotor power
  - Implicit torque-speed curve of asynchronous generator
  - Electro-mechanical yaw alignment
  - Aerodynamic tip breaks
- Simplicity and a fail-safe design were drivers of the economic success
- After that, size and technology evolved together



(Source: Jahobr / CC0 2015)

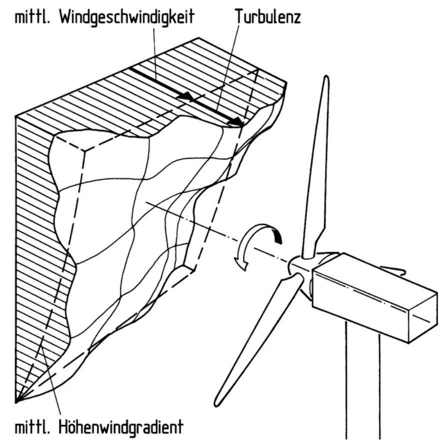
Harvesting Wind

- Partial load (generator control)
  - Minimum wind necessary to startup
  - Variable speed for optimal harvesting
  - Maximum speed for economic design
- Full load (blade angle control)
  - Too much wind must not be harvested
  - Extreme wind shutdown
- Alignment of rotor perpendicular to wind
- Every 0.1% of annual energy production (AEP) counts
- Wind is unknown
- Turbulence is not always the same

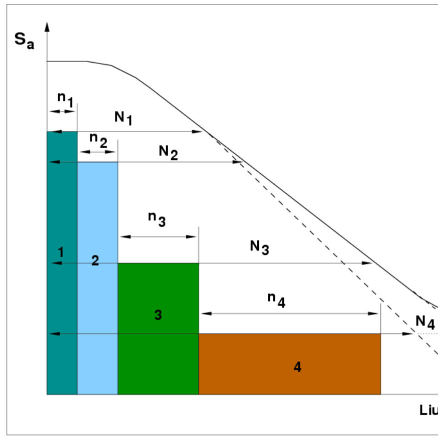


Load Reduction

- Fatigue loads
  - Stochastic excitation
  - Rotational sampling
  - Eigenoscillations
  - Adversarial control action
- Extreme loads
  - Hard to predict but fatal
  - Rare, thus conservative avoidance uneconomical
  - Component faults
- All components are affected
- Torque always goes along with thrust



(Source: Hau, Windkraftanlagen)

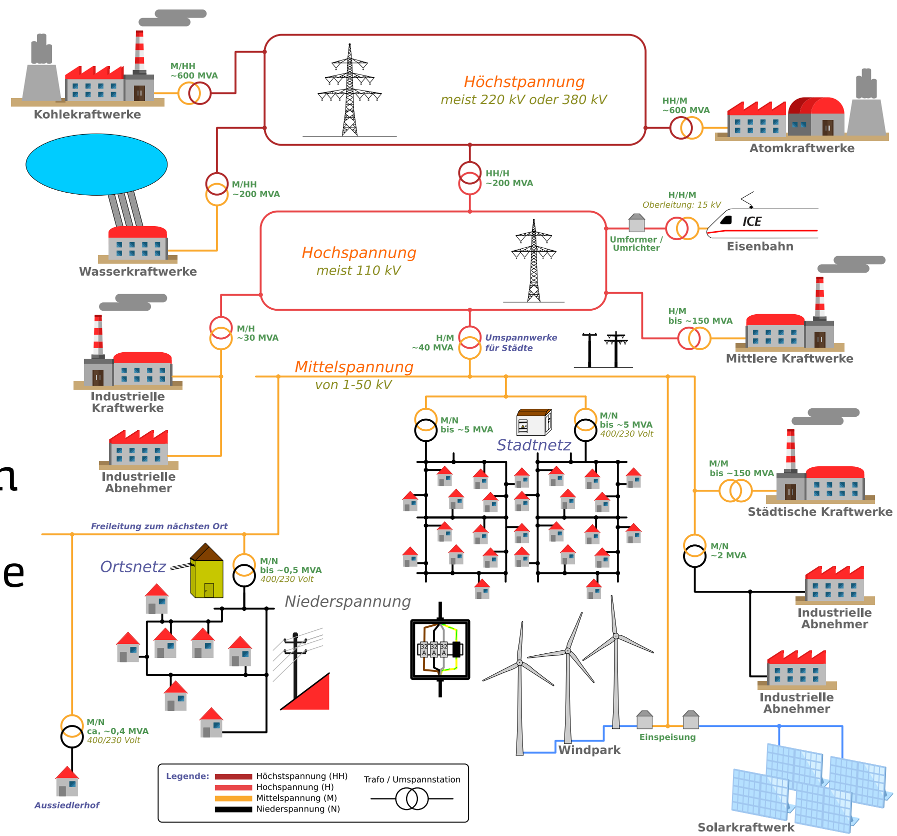


(Source:S. Fischer, CC-BY-SA)

(Source:dpa/Thomas Frey)

Grid Support

- Voltage support
  - Reactive power capability
  - Maybe in conflict with active power production
- Frequency stability
  - Over-frequency requires power reduction
  - Under-frequency requires power increase
- Resilience
  - Frequency deviations
  - Voltage drops (Fault Ride Through)



(Source: Stefan Riepl / Vector: Mrmw / CC0)

Environmental Aspects

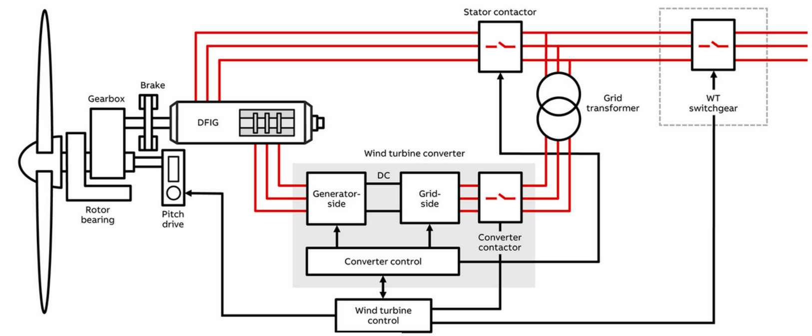
- Outbound
  - Sound and noise immissions
  - Bat protection
  - Radar interference
- Inbound
  - Temperature variations
  - Icing of the blades
  - Sand, dust and rain
  - Terrain, wind-direction and turbine wake
  - General interaction within a wind farm

(Source:DOI: 10.1016/j.rser.2016.06.080)

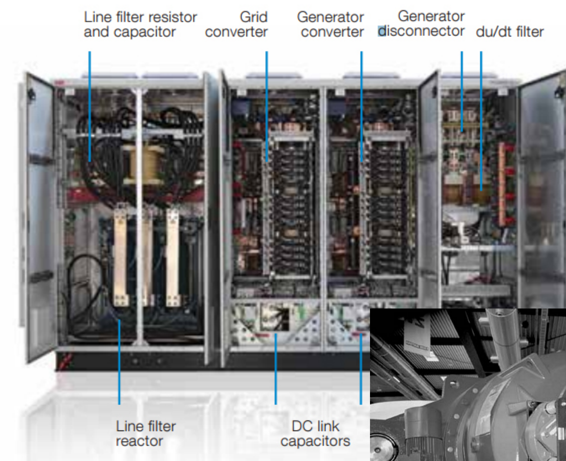
(Source: Mora, 2017: A Transition from ...)

Actuators

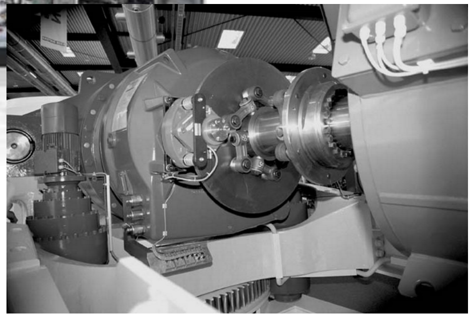
- Individual blade pitch drives
  - DC motors
  - Hydraulic
- Generator torque
- Breaks
- Yaw drives
- (Semi-) active tower dampers
- Auxiliary components



(Source: ABB)



(Source: qats.com)



(Source: Hau, Windkraftanlagen)

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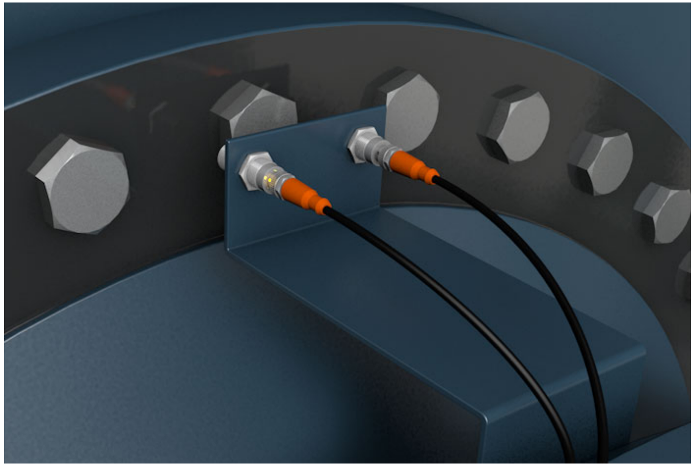
Sensors

- Wind and air
  - Anemometer
  - Wind vane
  - Temperature, Rain, mist, icing, lightning
- Drive train
  - Speed, several, redundant
  - Blade, rotor and yaw position
  - Electrical torque
  - Tower acceleration, Blade bending
- Grid properties
- Many many sensors
  for component supervision

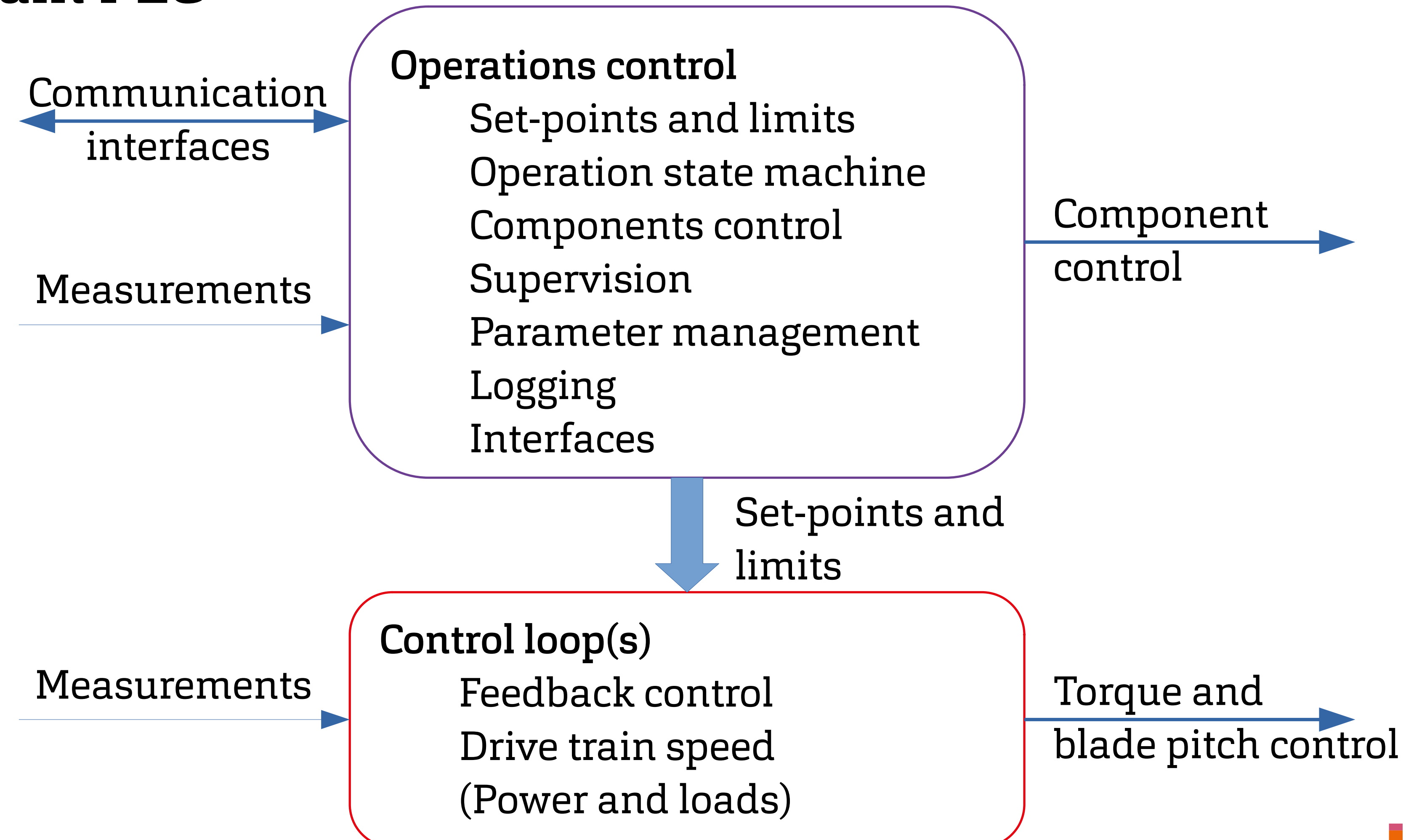
(Source: Getty Images)



(Source: ifm)

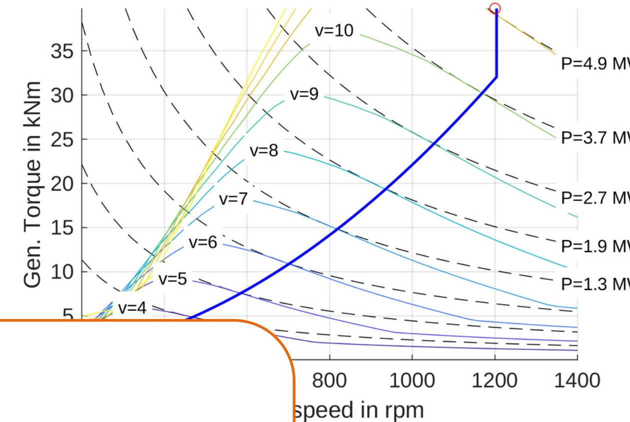
Control System Architecture

Main PLC



Closed Loop Control

- Drive train over actuated
- Pitch and torque: mutually exclusive regions



References →

Measure-ments →

Coordination
- Internal limits
- Feed forward terms
- State machines
- Filtering
- Adaption
- Wind speed estimator

Blade control
- Traditionally PI(D)
- Gain-Scheduling
- Rate limitation
- Over speed protection

→ Pitch angle

Torque control
- PI
- Optimal speed

→ Gen. torque

Many Added Functions for Loads

- Drive train damping via torque
- Tower damping
  - Longitudinal (fore-aft)
  - Lateral (side-side)
  - Via pitch and/or torque
- Individual Pitch control (IPC)
  - Reduce excitation from inhomogeneous wind field
  - Support yawing
- Power and speed reductions according to reference
- Avoid resonances at certain speeds

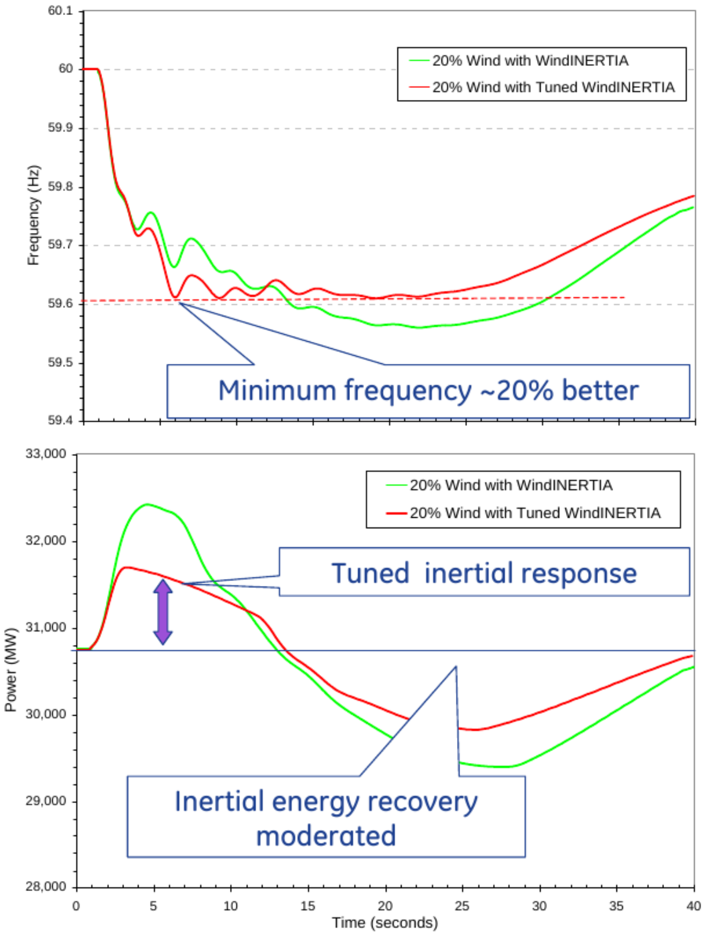
(Source: Hau, Windkraftanlagen)

… and for the Grid

- Low voltage ride through (LVRT)
- Additional power boost for short duration
  - Partial load: power from kinetic energy of rotor
  - Full load: power from wind via pitching in
- Fast active power regulation into and out of curtailments
- High wind ride through

… and the Environment

- Noise reduction: special speed profile
- Avoidance of gear box resonance



(Source: GE, Nicholas Miller)

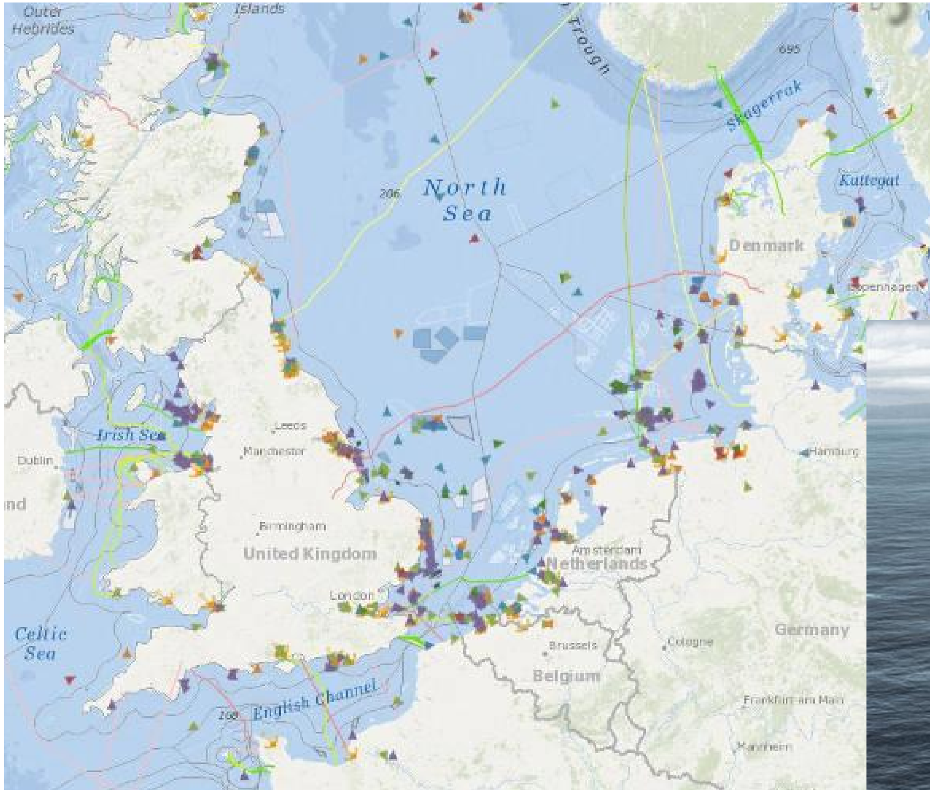
Smarter is better

- Adaption to use every power reserve
  - Turbulence
  - Temperature
  - Grid condition
  - Life time loads
- Learning from data
  - Big (fleet) Data
  - Automatic tuning and calibration
- Improved health
  - Predictive maintenance
  - Digital twin

(Source: windpowerengineering.com)

(Source: GE)

The Future is at Sea



(Source: peakoil.com)

(Source: hexicon.eu)

From Power Source to Power Plant

- **100% renewable energy is not possible**
- **(Without storage)**
- The simplest form of storage is over-capacity
- No individual turbines, only (virtual) power plants
- Coordination of capacities and possibly also consumers
- Paradigm change from “**all you can harvest**” to ”**what the market needs**”

(Source: lifeboat.com)

(Source: nawindpower.com)

Thank You for Your Interest!

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Questions?

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