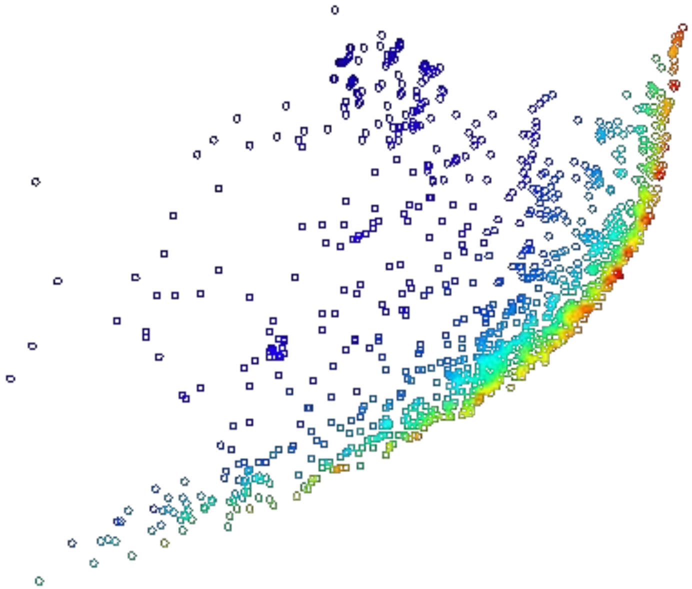
TWIND Course: Design and testing of offshore wind turbines and farms

Lecture 2: Wind Turbine Design



Lecturer: Prof.dr. Dominic von Terzi

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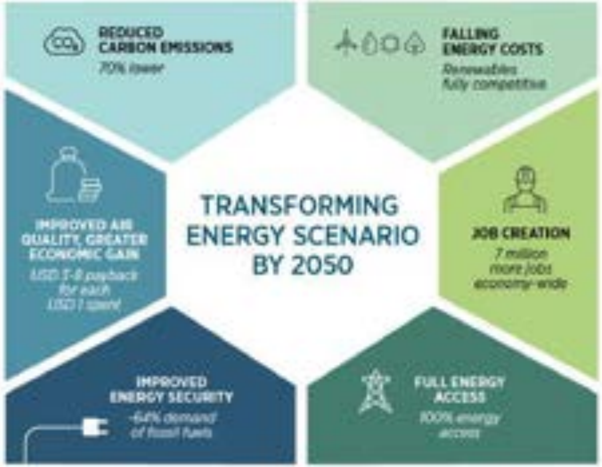
Recap: Why wind energy ?

Key in the world’s **energy transition**:

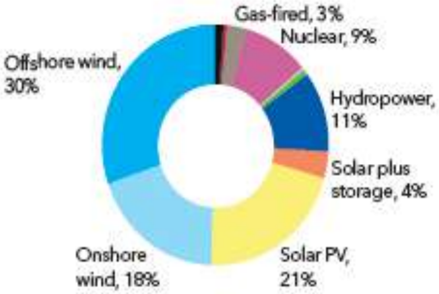
- **Clean, renewable and abundant energy** source
- **Cost competitive** 💡 design objective
  with low operating costs (wind is free)
- Increases **energy security** (no fuel import)
- Creates **jobs**

Challenges:

- **Sufficient electrification** of the energy system
- Energy **system integration** 🔗 design constraints



Example prediction of the benefits of an energy transition with incresead electrification and more wind energy, source: IRENA.



Example prediction of EU energy mix in 2050 , source: DNV-GL

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Recap: Why offshore wind energy ?

- Excellent **wind resource**
- On track to be **cost competitive**
- **Effective use of land**
  close to centers of population
- **Acceptance in society**

design environment
design objective
design constraints

design environment
design constraints

Agenda of this lecture

- Part 1: What is a wind turbine ?
- Part 2: Design objectives
- Part 3: Design process
- Part 4: Design optimization
- Part 5: Constraints and limitations
- Part 6: The role of technology and markets
- Part 7: Current trends

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Part 1: What is a wind turbine ?

GE prototype ECO-Rotr, USA

Nénuphar prototype VertiWind, France

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The wind turbine as energy transformer

Photo source: DoE, GE H-class

- **Wind mill**:
  Generates **mechanical energy** (rotation) **from kinetic energy** of the wind
- **Wind turbine**:
  Generates **electricity from kinetic energy of the wind** using **mechanical energy** (rotation) as intermediate step
- **Gas turbine**:
  Generates **electricity from fossil fuels** using **heat** (combustion) and **mechanical energy** (rotation) as intermediate steps

Recent offshore wind turbines: Giants of the sea

Haliade-X 12 MW	
Output (MW)	12
Rotor Diameter (m)	220
Total Height (m)	260
Frequency (Hz)	50
Gross AEP (GWh)	67
Capacity Factor (%)	63
IEC Wind Class	IB

- Horizontal axis, upwind rotor, direct drive generator, monopile foundation
- World **largest turbine in operation** (rating and rotor size), GE prototype in Maasvlakte, NL, uprated to 14MW in 2021
- **Larger turbines announced** in 2020/21 by SGRE (14MW, 222m), Vestas MHI (15MW, 236m) and MingYang Smart Technology (16MW, 242m)

Wind turbine components

- **Rotor** (with turbine blades) or equivalent: transforming **kinetic energy** of wind (fuel) **into rotational energy**
- **Drive-train** (with generator): transforming **rotational energy into electricity**
- **Support structures** (e.g. towers, foundation, nacelle, main frame etc.) holding components in place
- **Control systems** adjusting operation of turbine and components (passive or active)
- **Transmission system** (with converters) connecting to grid or end-user

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Drive train with gear box

Hub

Main shaft / Low speed shaft

High speed shaft

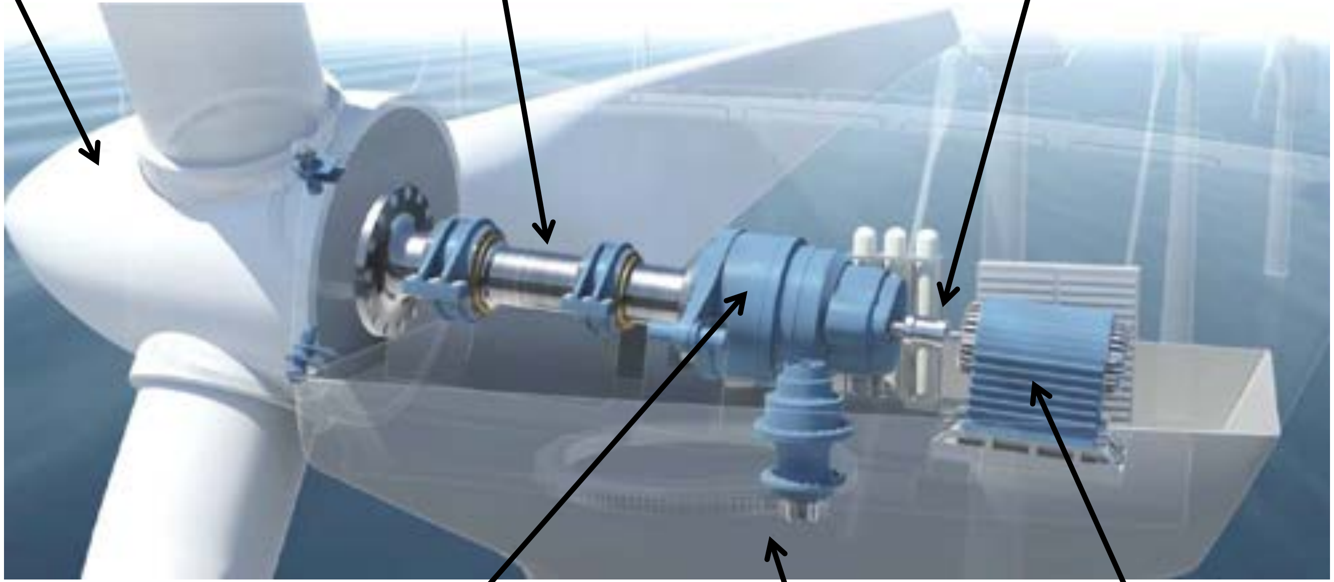

Image: www.schaeffler-fairs.de

Gearbox

Yaw system

Generator

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Drive train without gear box (direct drive)

Image: Lagerwey

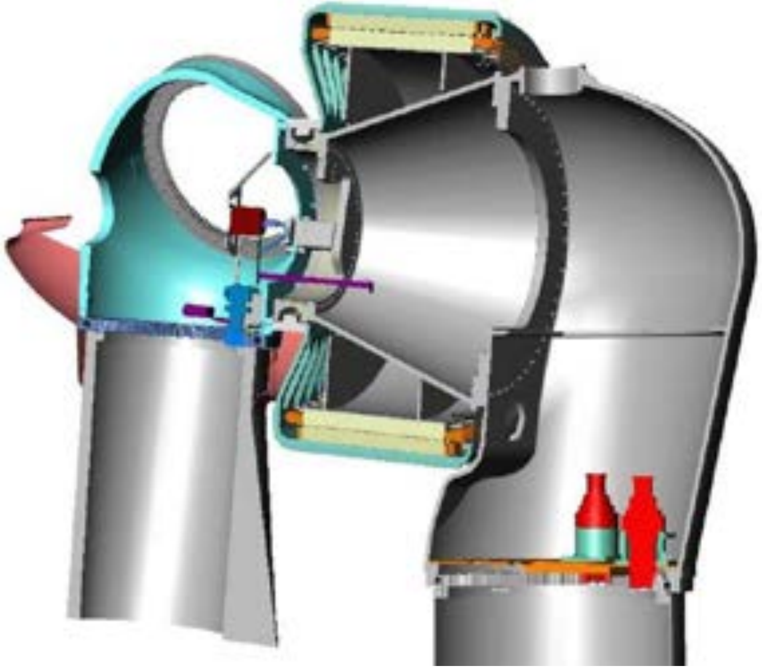

Image: Harakosan Europe

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Visible components

Blade

Hub

Rotor-nacelle assembly { Nacelle, Rotor }

Tower

Sometimes container with transformer

Foundation (not always visible)

direct drive

with gear box

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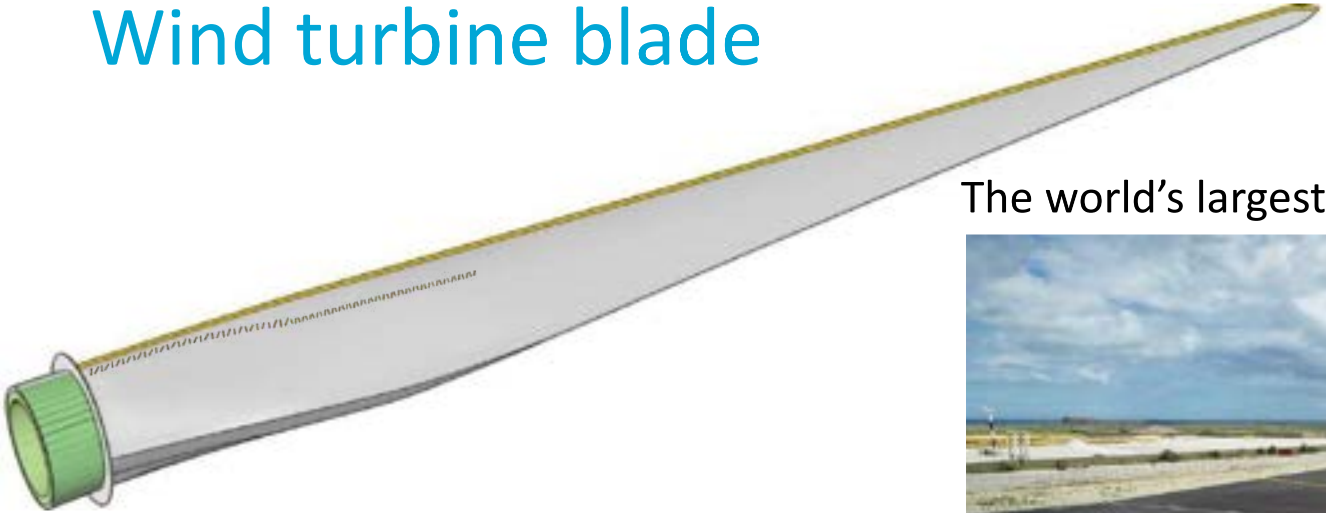
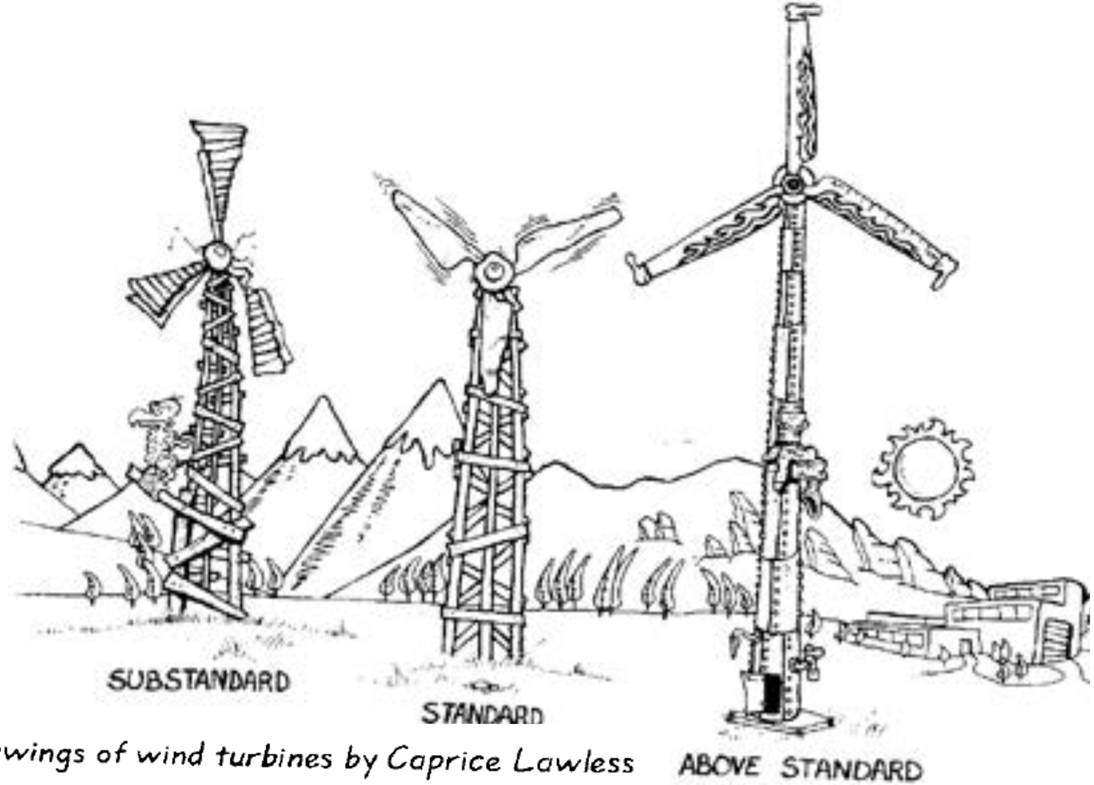
Wind turbine blade



The world's largest blade in 2020: 107m

Photo: LM Wind Power

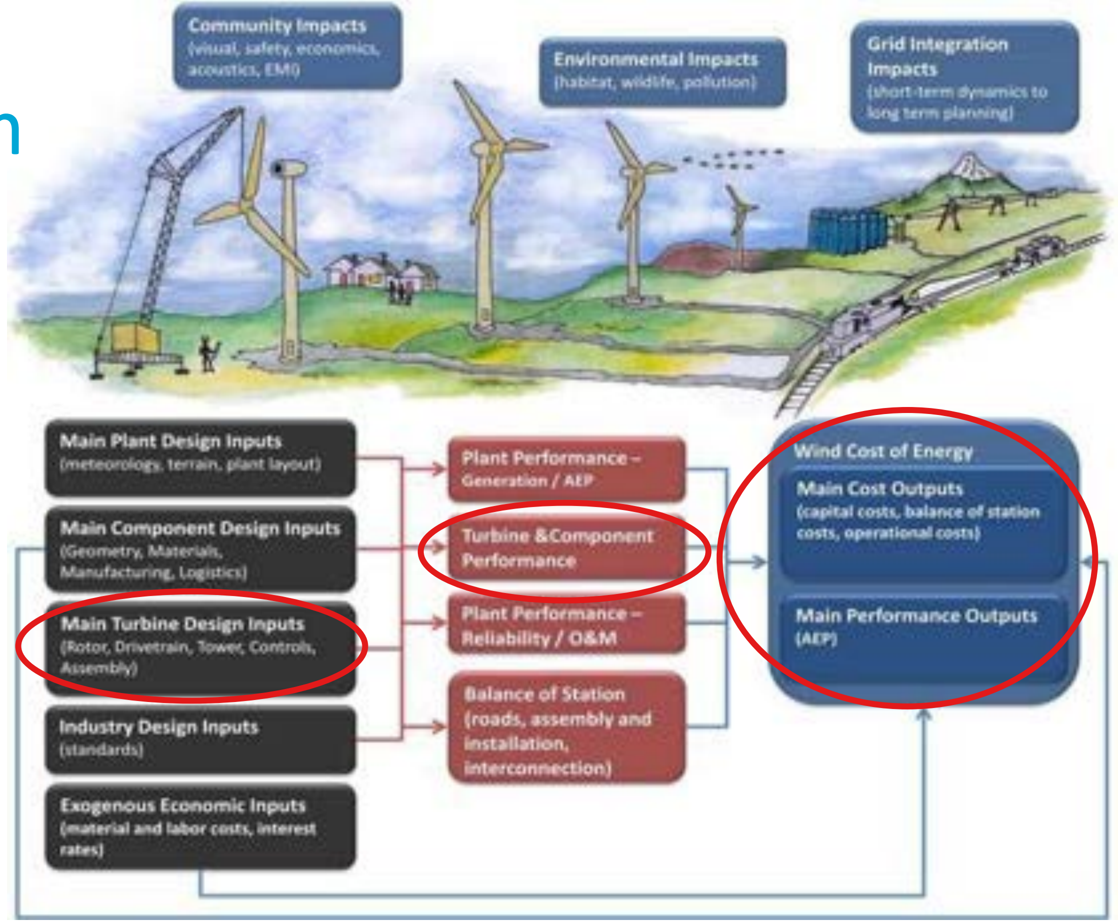
Part 2: Design objectives



Original drawings of wind turbines by Caprice Lawless

Turbine in a system

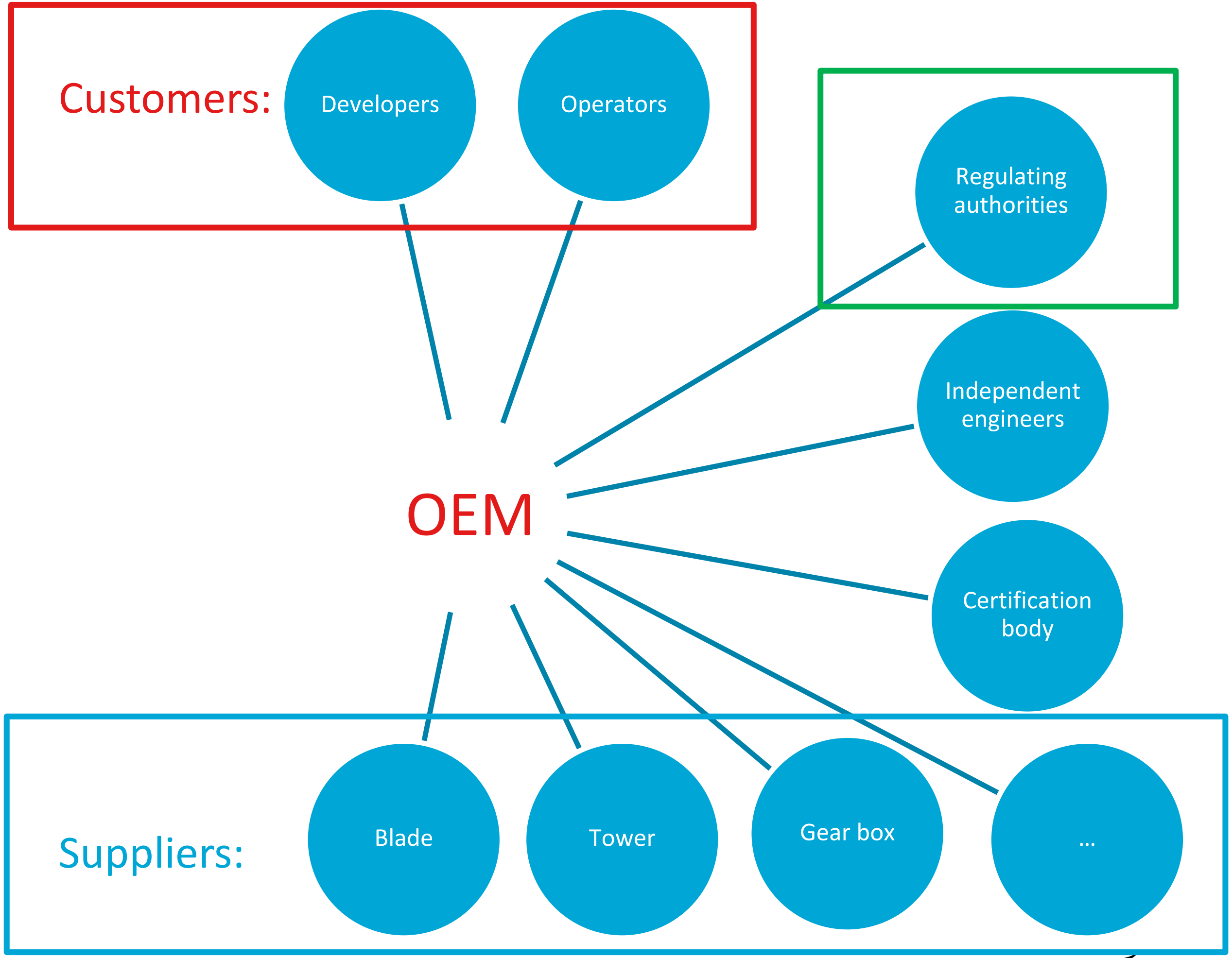
- Wind turbines are **part of a system**
- Turbines often deployed in bundles, i.e. a "**wind farm**"
- **Wind turbine design** needs to be **aware of this system as it sets**
  - **Environment**
  - **Constraints**
  - **Objectives**



From Dykes & Meadows NREL/TP-5000-52616, 2011

OEM view

- **Objectives** are set by **customers**
- **All** can set **constraints**
- **Regulating authorities** set **institutional environment**



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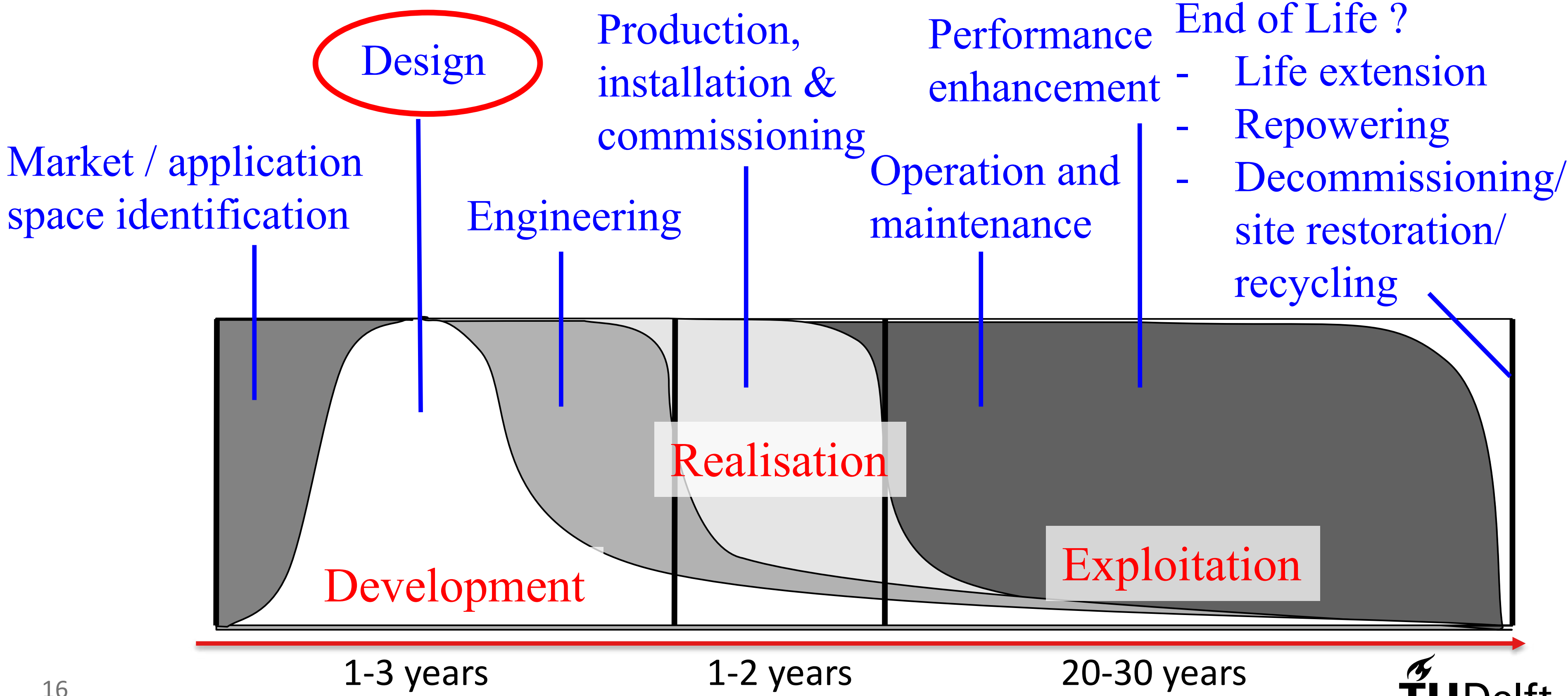
Design as part of the turbine life cycle



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Definition of wind turbine design

"Wind turbine design is the **process of defining** the **form and specifications** of a wind turbine for a given **application space** and **environment**.

Application space + **Environment** >> **Form (& specifications)**

Functions
Constraints
Objectives

\+

Physical
Institutional

\>>

Core concepts
Configuration
Dimensions

(Core concepts + Configuration: Working principles)

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Examples of objectives

$$\text{LCOE} \sim \frac{\sum OPEX + \sum CAPEX}{AEP}$$

- **Low levelized cost of energy (LCoE)**
  → beneficial for auctions in subsidy-bidding markets, markets with fixed price per kWh or grid-constrained markets
- **High energy yield** (annual energy production AEP)
  → beneficial in land-constrained markets with (high) feed-in tarifs
- **Low costs** (CAPEX, OPEX and/or life-cycle costs)
  → beneficial in markets with high financing costs or low available capital
- **High capacity factor** (Cf)
  → beneficial in baseload-driven markets

$$\text{Cf} = \frac{average\ power\ production}{peak\ power\ production}$$

- **High net present value** (NPV) or **high internal rate of return** (IRR)
  → beneficial in subsidy-free markets with variable pricing

Opinion poll

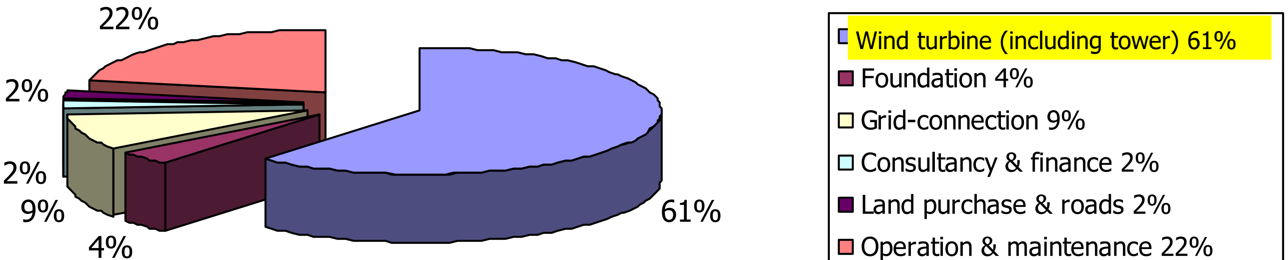
What is the **most expensive cost contributor** in a wind farm ?

- Foundation
- Wind turbine
- Grid connection
- Operating and maintenance (O&M) costs
- Decommissioning
- Finance
- Depends on onshore vs offshore wind farm

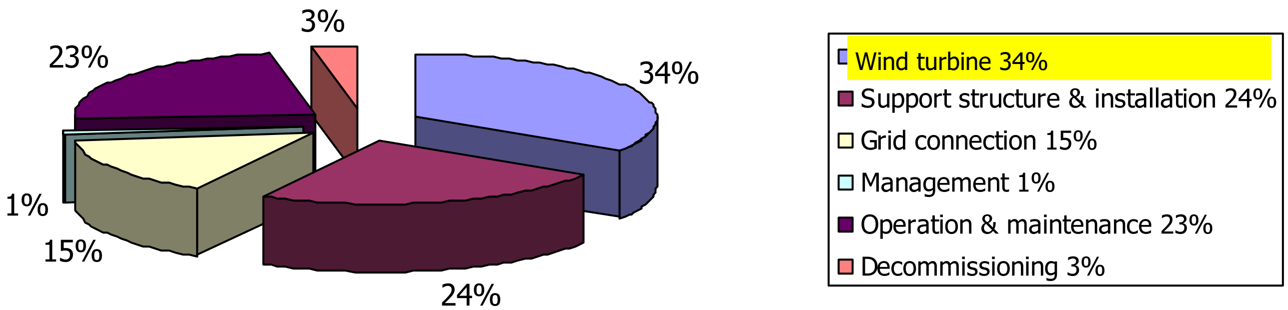
Examples of cost structure

- **Wind turbine** is typically the **largest cost contributor**
- **Offshore** (ca. 1/3) **less dominant** than for onshore (ca. 2/3)

→ Cost structure **impacts design trades and objectives**



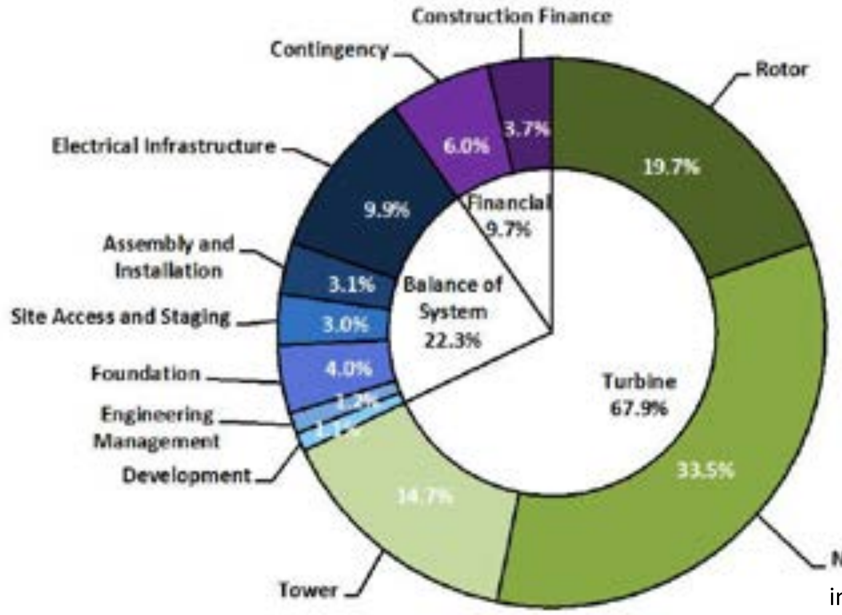
Onshore



Offshore

Example of onshore turbine cost breakdown

- Rotor / **blades**
  ca. 20%
- Nacelle with **drivetrain** (generator & gear box etc.) & yaw system
  ca. 30%
- **Tower**
  ca. 15%



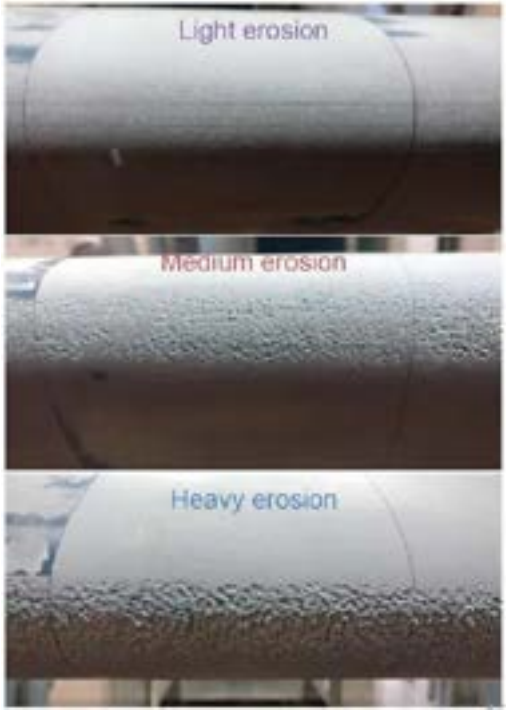
includes drivetrain

Source: The cost of wind energy 2017, NREL report

More severe onshore
More severe offshore

Example of constraints

- Noise restriction
- Visual impact restriction
- Space restriction
- Logistics
- Material deterioration
- Hydrodynamic loading
- Wind loading
- Ice loading
- Effects on nature (e.g. bird migration)



Erosion test at LM, AVATAR final report, Schepers et al. 2017

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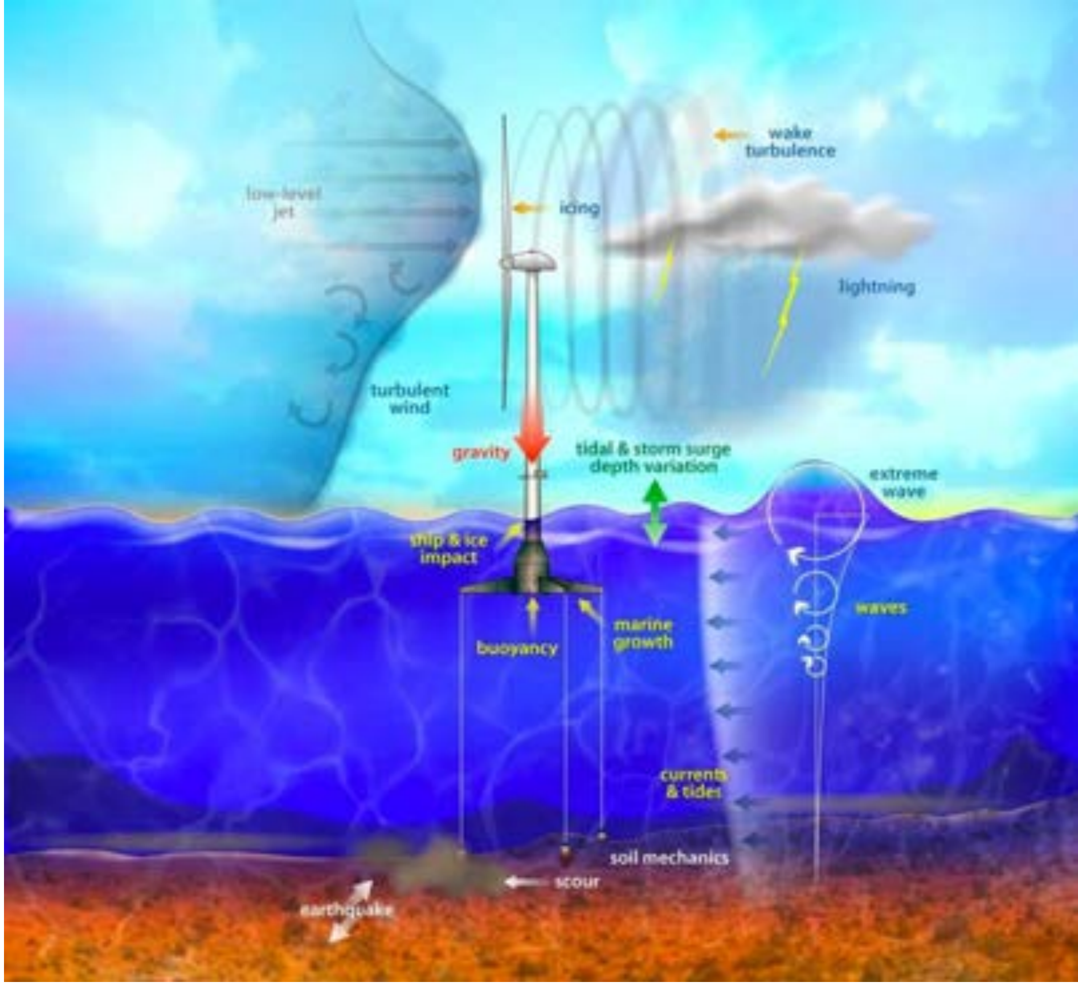
Example of environment



From Dykes & Meadows NREL/TP-5000-52616, 2011

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Example of environment: Wind classes

Wind Class/Turbulence	Annual average wind speed at hub-height	Extreme 50-year gust
Ia High wind - Higher Turbulence 18%	10 metres per second (36 km/h; 22 mph)	70 metres per second (250 km/h; 160 mph)
Ib High wind - Lower Turbulence 16%	10 metres per second (36 km/h; 22 mph)	70 metres per second (250 km/h; 160 mph)
IIa Medium wind - Higher Turbulence 18%	8.5 metres per second (31 km/h; 19 mph)	59.5 metres per second (214 km/h; 133 mph)
IIb Medium wind - Lower Turbulence 16%	8.5 metres per second (31 km/h; 19 mph)	59.5 metres per second (214 km/h; 133 mph)
IIIa Low wind - Higher Turbulence 18%	7.5 metres per second (27 km/h; 17 mph)	52.5 metres per second (189 km/h; 117 mph)
IIIb Low wind - Lower Turbulence 16%	7.5 metres per second (27 km/h; 17 mph)	52.5 metres per second (189 km/h; 117 mph)
IV	6.0 metres per second (22 km/h; 13 mph)	42 metres per second (150 km/h; 94 mph)

Based on design standard IEC 64100-1

Example wind turbine design

Parameter	Units	Value
Power rating	MW	15
Turbine class	-	IEC Class 1B
Specific rating	W/m²	332
Rotor orientation	-	Upwind
Number of blades	-	3
Control	-	Variable speed Collective pitch
Cut-in wind speed	m/s	3
Rated wind speed	m/s	10.59
Cut-out wind speed	m/s	25
Design tip-speed ratio	-	9.0
Minimum rotor speed	rpm	5.0
Maximum rotor speed	rpm	7.56
Maximum tip speed	m/s	95
Rotor diameter	m	240
Airfoil series	-	FFA-W3
Hub height	m	150
Hub diameter	m	7.94
Hub overhang	m	11.35
Rotor precone angle	deg	-4.0
Blade prebend	m	4
Blade mass	t	65

IEA 15MW offshore reference wind turbine

Parameter	Units	Value
Drivetrain	-	Direct drive
Shaft tilt angle	deg	6
Rotor nacelle assembly mass	t	1,017
Transition piece height	m	15
Monopile embedment depth	m	45
Monopile base diameter	m	10
Tower mass	t	860
Monopile mass	t	1,318

deg	degrees	rpm	revolutions per minute
m	meters	t	metric tons
m/s	meters per second	W/m²	watts per square meter

Description	Value	Units
Blade length	117	m
Root diameter	5.20	m
Root cylinder length	2.34	m
Max chord	5.77	m
Max chord spanwise position	27.2	m
Tip prebend	4.00	m
Precone	4.00	deg
Blade mass	65,250	kg
Blade center of mass	26.8	m
Design tip-speed ratio	9.00	-
First flapwise natural frequency	0.555	Hz
First edgewise natural frequency	0.642	Hz
Design C_P	0.489	-
Design C_T	0.799	-
Annual energy production	77.4	GWh

deg	degrees	kg	kilograms
GWh	gigawatt-hours	m	meters
Hz	Hertz		

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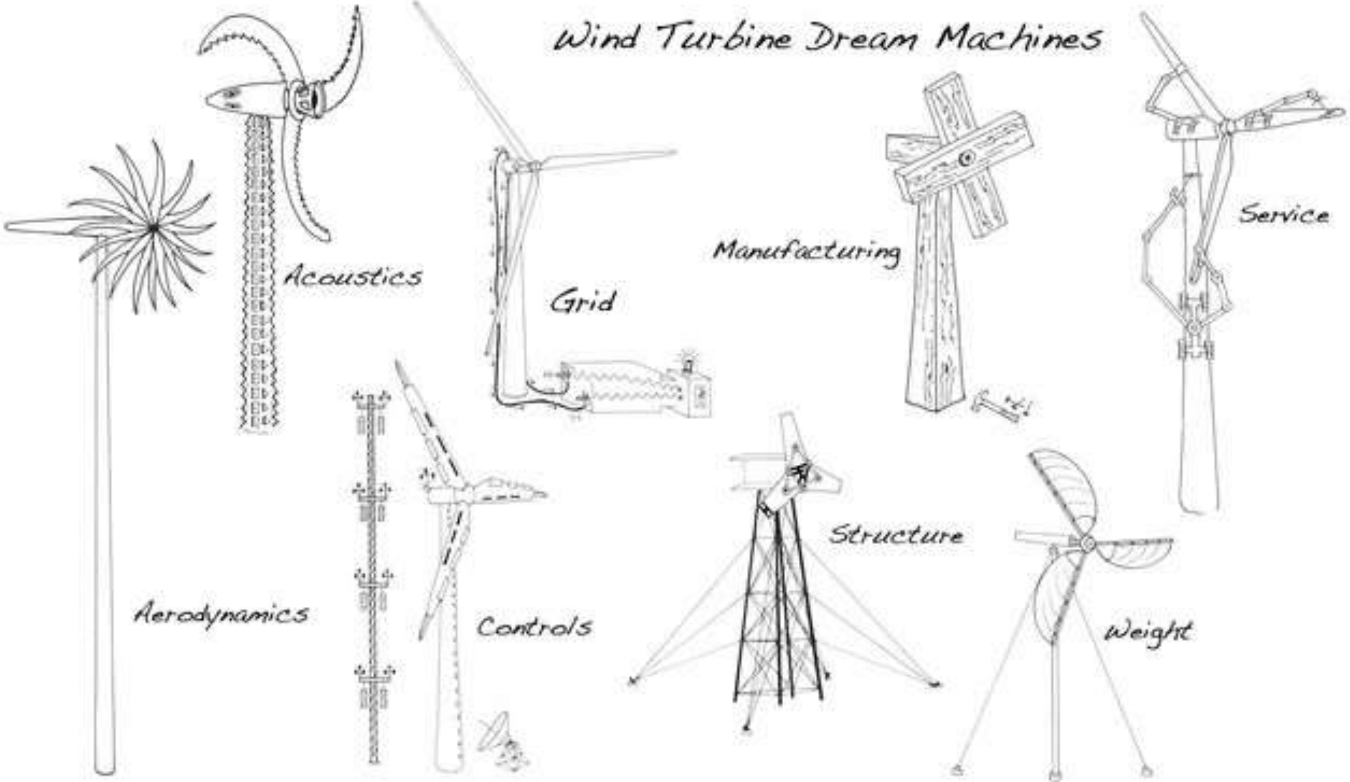
Part 3: Design process



From Dykes & Meadows NREL/TP-5000-52616, 2011

Balanced design

Overview of the design process

Design process commonly formalized with **design reviews at the end of each step**

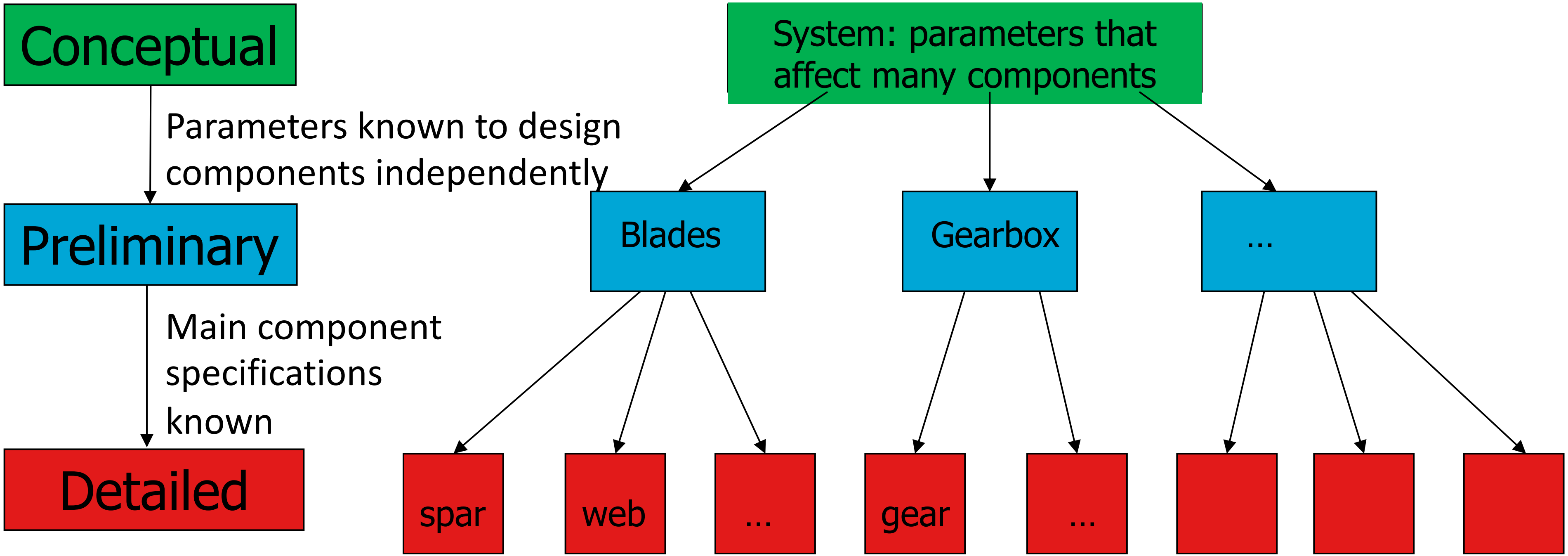
Conceptual Design Review (**CDR**) or System Requirement Review (**SRR**)

Preliminary Design Review (**PDR**)

Detailed Design Review (**DDR**)

Design steps

Targets for new turbine



All ready for manufacturing of prototype, certification and offering to customer

Conceptual design

- **Driven by market developments** (e.g. auctions, subsidy-free markets, etc.), new **application space** (e.g. deep water offshore, low wind speed sites, etc.), **existing experience and capabilities**
- **Applying simple engineering tools, scaling laws and surrogate models**
- **Typical outcome:**
  - **working principles with system architecture and configuration** (horizontal vs vertical axis, direct drive vs geared, upwind vs downwind, monopile vs floating foundation, etc.)
  - **key dimensions** (rotor size, rating, hub height etc.)

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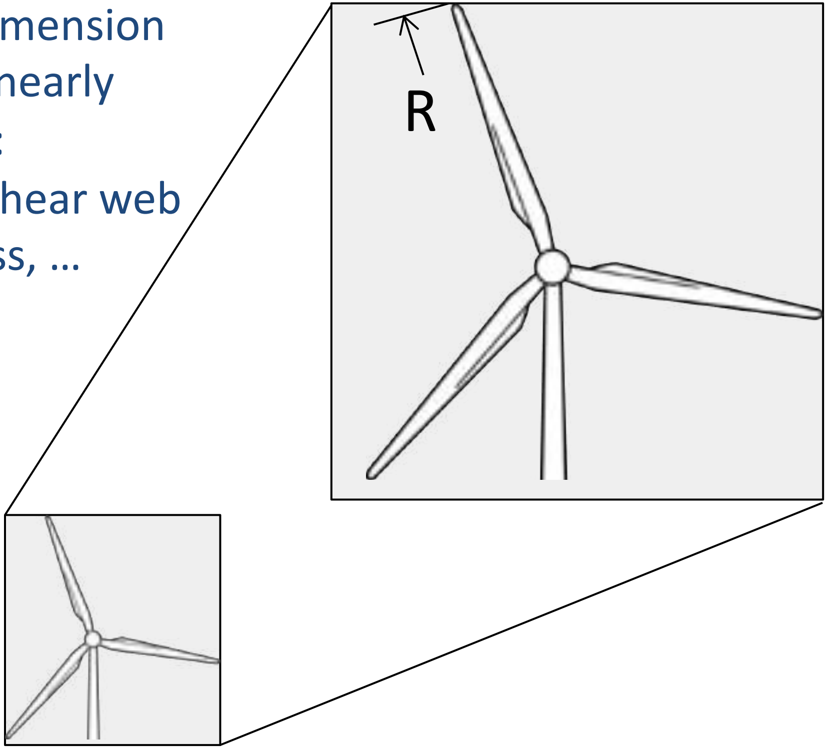
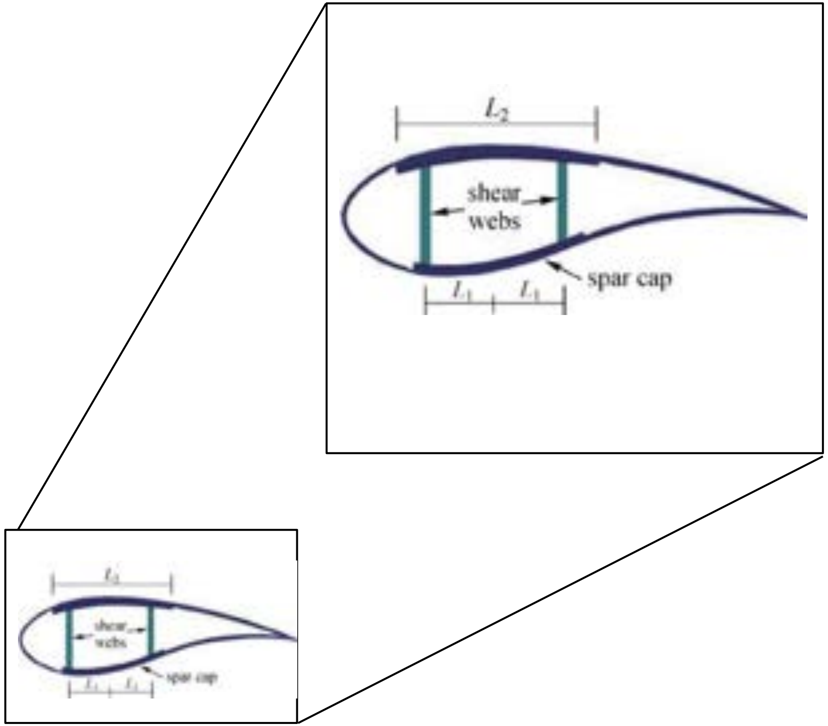
Geometric scaling based on rotor size

Every dimension scales linearly with ‘R’:
chord, shear web thickness, …





Scaling laws

Quantity	Symbol	Relation	Scale dependence
Power, forces, and moments			
Power	P	$P_1/P_2 = (R_1/R_2)^2$	$\sim R^2$
Torque	Q	$Q_1/Q_2 = (R_1/R_2)^3$	$\sim R^3$
Thrust	T	$T_1/T_2 = (R_1/R_2)^2$	$\sim R^2$
Rotational speed	Ω	$\Omega_1/\Omega_2 = (R_1/R_2)^1$	$\sim R^{-1}$
Weight	W	$W_1/W_2 = (R_1/R_2)^3$	$\sim R^3$
Aerodynamic moments	M_A	$M_{A,1}/M_{A,2} = (R_1/R_2)^3$	$\sim R^3$
Centrifugal forces	F_c	$F_{c,1}/F_{c,2} = (R_1/R_2)^2$	$\sim R^2$
Stresses			
Gravitational	σ_g	$\sigma_{g,1}/\sigma_{g,2} = (R_1/R_2)^1$	$\sim R^1$
Aerodynamic	σ_A	$\sigma_{A,1}/\sigma_{A,2} = (R_1/R_2)^0 = 1$	$\sim R^0$
Centrifugal	σ_c	$\sigma_{c,1}/\sigma_{c,2} = (R_1/R_2)^0 = 1$	$\sim R^0$
Resonances			
Natural frequency	ω	$\omega_{n,1}/\omega_{n,2} = (R_1/R_2)^1$	$\sim R^{-1}$
Excitation	Ω/ω	$(\Omega_1/\omega_{n,1})/(\Omega_2/\omega_{n,2}) = (R_1/R_2)^0 = 1$	$\sim R^0$
Note: R, radius			

Source: Manwell et al., 2009

The square-cube law

- If all dimensions scale proportional to rotor diameter
  Chord, nacelle dimensions, hub height, tower diameter, ...
- Then surfaces scale with R^2 (square)
  Rotor swept area → power → energy yield
- And volumes scale with R^3 (cube)
  Masses → costs

→ under the **linear geometric scaling** assumption,
costs increase faster than energy yield with size!
→ In reality this deviates due to new technologies and other factors that scale independently

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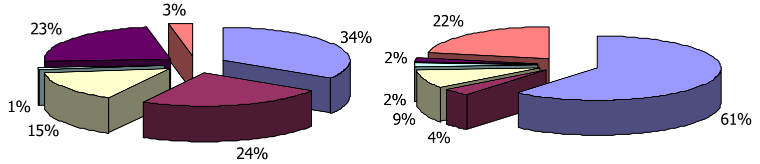
Think, pair & share: Size of turbines

1. **Sit in pairs**
   (pick your neighbor, move if alone)
2. **Introduce** each other
3. Use the **images** (right) and this lecture **as inspiration**
4. **Discuss with partner: Why are offshore wind turbines larger than onshore ?**
5. **Think of one reasoning**
6. **Share with everybody**



Onshore (left) vs offshore (right) cost structure: turbine cost share in blue

$$\text{cost of energy} \sim \frac{(sum\ of\ costs)}{Energy\ yield}$$

Similarity law – square-cube-law:
surfaces scale with R^2 (square)
Rotor swept area → power → energy yield
Volumes scale with R^3 (cube)
Masses → costs

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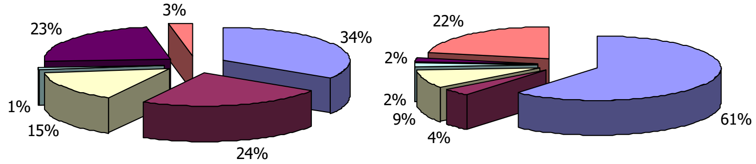
Why are offshore turbines larger than onshore ?

- Assume turbine cost increases with R^3 and energy yield with R^2
- Turbine costs are only part of the sum of costs, **not all costs scale with rotor size**
- For offshore, overall costs do not increase as fast as for onshore with rotor size

→ **Different optimum** (at larger size) possible



Onshore (left) vs offshore (right) cost structure: turbine cost share in blue

$$\text{cost of energy} \sim \frac{(sum\ of\ costs)}{Energy\ yield}$$

Similarity law – square-cube-law:

surfaces scale with R^2 (square)

Rotor swept area → power → energy yield

Volumes scale with R^3 (cube)

Masses → costs

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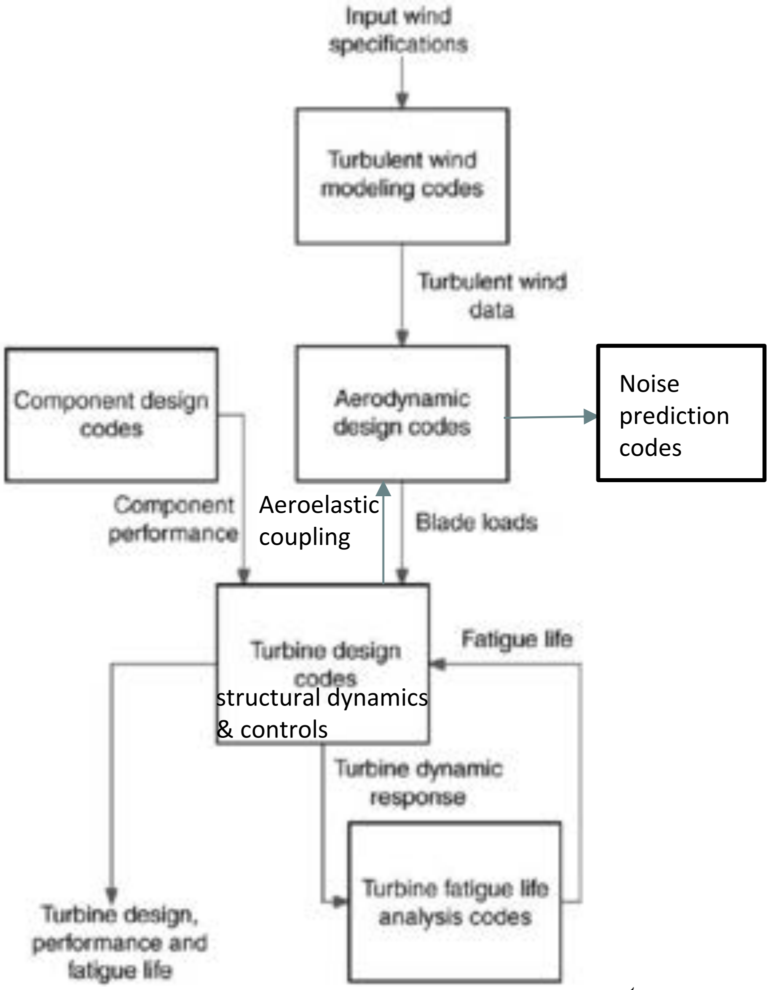
Preliminary design

Here the **research & engineering knowledge is used** to full extend. The following are typical objectives of a **preliminary design review (PDR)**:

- Ensure that all **system requirements** have been **validated**, are **complete**, and **adequate to verify system performance**
- Show that the **proposed design** is expected to **meet the functional and performance requirements**
- Show **sufficient maturity** in the proposed design approach **to proceed to detailed design**
- Show that the **design is verifiable** and a **risk analysis is performed**, **where all risks have been identified, characterized and mitigated** where appropriate.

Design tools

- Numerical **simulation tools** based on a mix of
  - physics-based scaling laws
  - physics-based engineering models
  - empirical engineering models
  - surrogate models
- **Validation** and **verification** critical
- Trade **speed vs accuracy** depending on where in the design process used



Adapted from Manwell et al., 2009

Design requirements: IEC 64100-1 standard

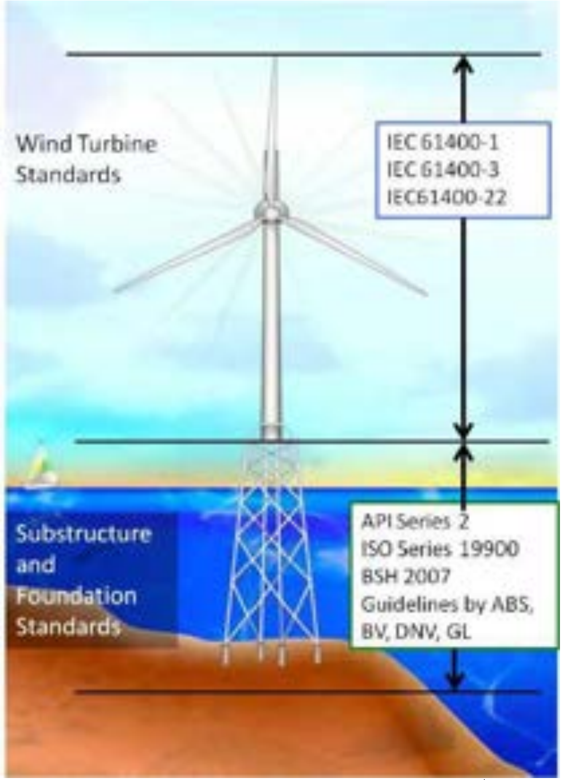
https://webstore.iec.ch/searchform&q=61400

Objectives of standard:

Specifies **design requirements** and methods to ensure integrity of the wind turbine design.

Provides appropriate level of **protection against damage** of all hazards of planned turbine lifetime

Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42,5	37,5	Values specified by the designer
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			

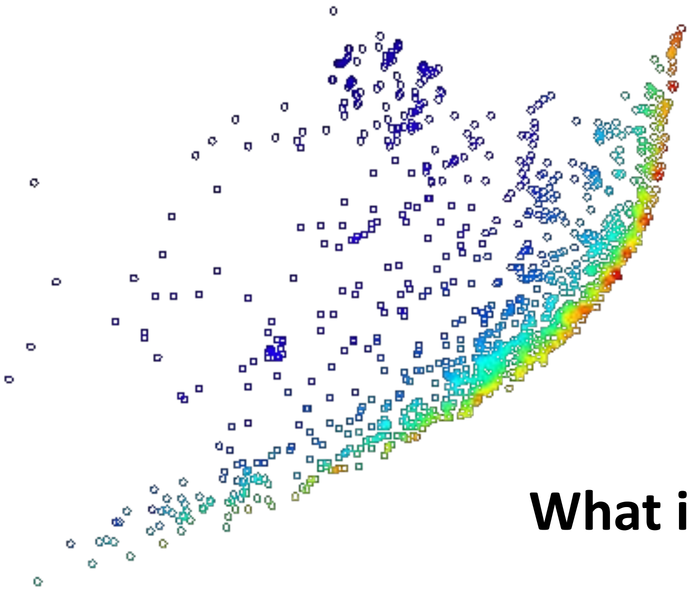


Detailed design

- Here **analysis tools and practical experience** are **used to full extend**
- **Details of components** and **full suite of design loads cases** (DLC of IEC standard 64100-1) need to be given
- **Typical tools:** Design for Manufacturing and Assembly (**DFMA**), Failure Mode Effects Analysis (**FMEA**) , **higher order simulation tools** (e.g. Finite Element for structural design, Computational Fluid Dynamics for aerodynamic design or risk mitigation, etc.)

DISCUSSION

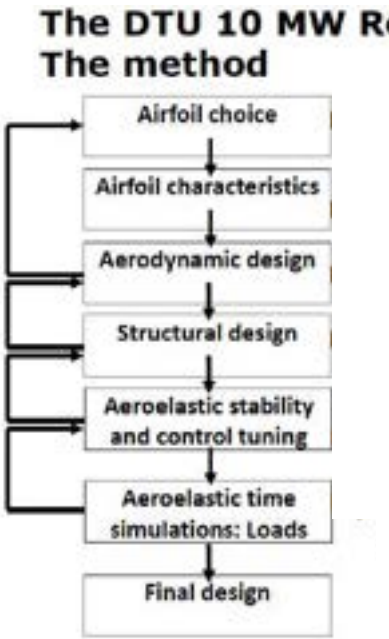
Part 4: Design optimization



What is this figure showing?

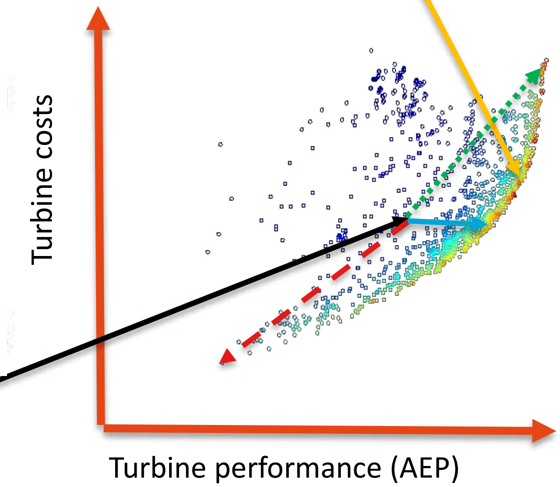
Rotor design optimization

From Bak et al., 2013, “The DTU 10-MW reference wind turbine”, DTU report



Process results in **<u>1 design</u>**,
need multiple designs to optimize!

Pareto front: can trade performance regarding different objectives but cannot improve on all (for same technology)



Lowest LCoE
Highest AEP
Lowest Cost

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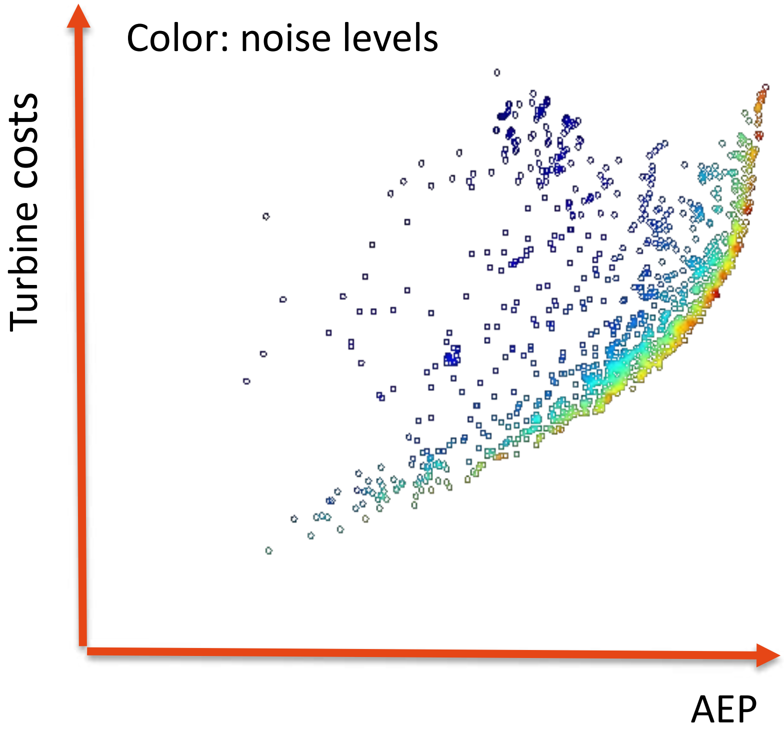
Design trades: Numerical optimization

- Each dot is a **preliminary blade design** → fast tools needed
- **Pareto front defines optimal design trades** (here: AEP vs costs with noise as a constraint)
- **Design objectives define design(s) to be chosen**



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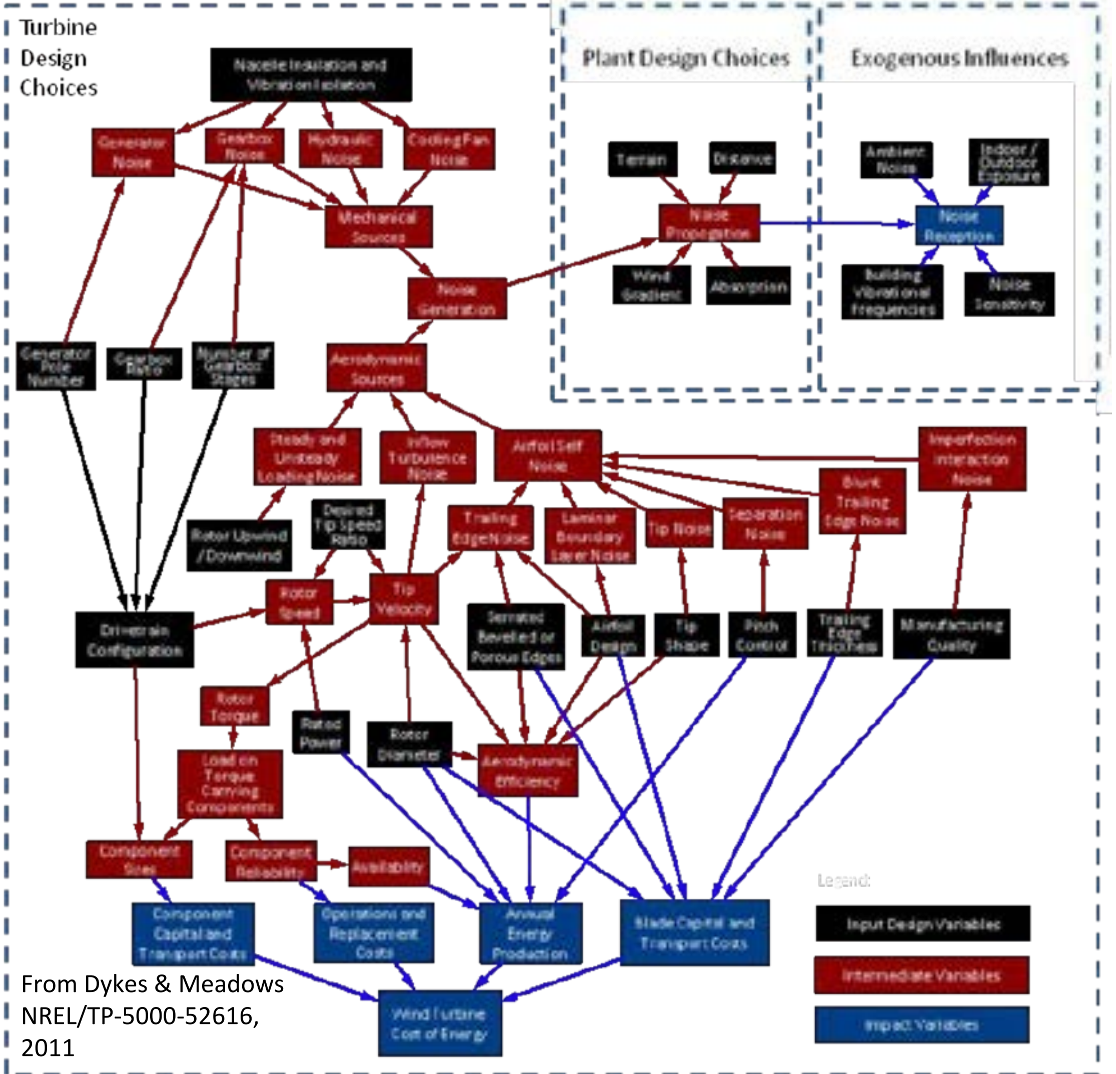
Design trades for conceptual design

Design solution / target	(Claimed) Positive effect	(Claimed) Negative effect
High C_p of rotor	High annual yield	High loads
High reliability	High availability / low O&M	High turbine costs
Number of blades: e.g. 2 instead of 3	Easy to install, less blade costs	Low performance / high loads / challenging controls
Number of blade pieces: e.g. 2 instead of 1	Easier logistics and O&M, larger yield possible	Additional costs of joint / lower reliability / lower blade loading
Rotor controls: e.g. stall instead of pitch	High reliability	Low performance / high loads
Architecture: e.g. vert. vs horiz. axis	Machinery at base for easy maintenance & less loads	Changes in supply chain & proven designs (less experience)

Example of design interactions: Noise

Highly complex interaction between **input design variable** and **impact variables**

→ **Numerical optimization** allows for **integrated design**



From Dykes & Meadows NREL/TP-5000-52616, 2011

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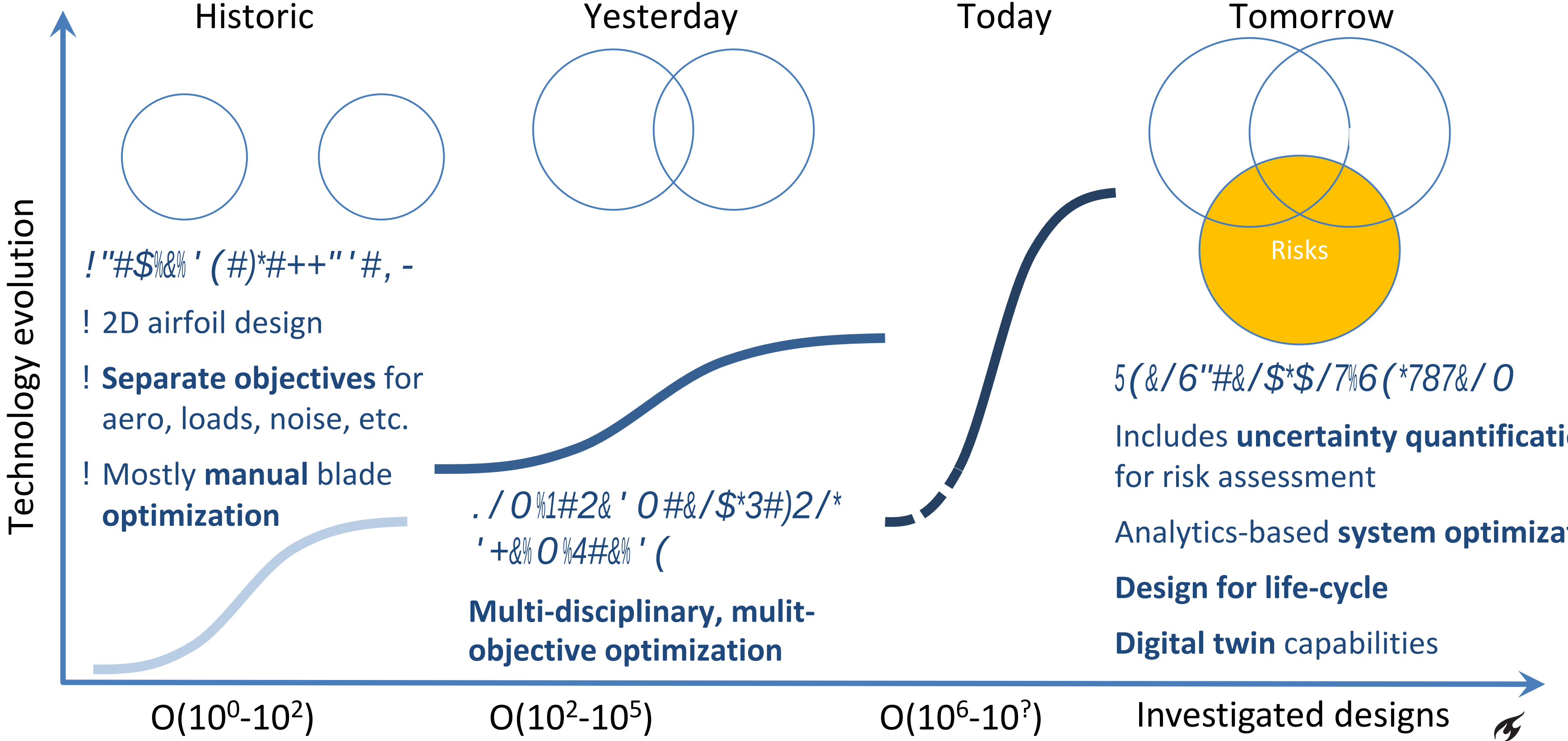
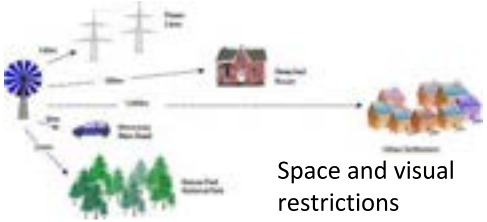
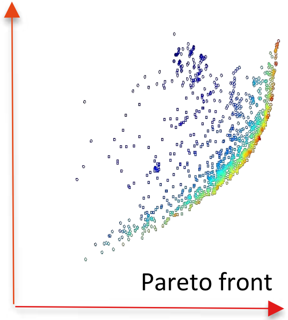
Multi-disciplinary rotor design optimization



Part 5: Constraints & limitations





Limitations as technical challenges due to design choices or set by external constraints

Physical limitations: inherent vs. external driven

Inherent **physical limitations due to** chosen **working principles**:

- **Square-cube-law**: upscaling of power vs loads (mass)
- **Betz limit**: maximum power extraction
- **Stall limit**: maximum angle of attack before lift breaks down
- **Speed of sound**: maximum local wind speed before shocks occur
- **Material limits**: maximum stress before failure, e.g. buckling, fatigue
- **Aeroelastic stability:** structural blade failure due to flow interactions
- **Tip deflection limit**: maximum bending of blade before it hits tower
- …

Other **physical limitations** are **imposed by external constraints**.

Example how constraints limit blade length

External constraints		Physical limitations
1. Available **space**	->	**Number of turbines and their size**
	->	Maximum **blade length**
2. Accessibility for **transport**	->	Maximum **component size**
	->	Maximum **blade length**
3. Acceptable **noise**	->	Maximum **tip speed**
	->	Maximum **blade length**
4. Minimum **operating life**	->	Minimum **fatigue & extreme loads**
	->	Minimum **blade life** (e.g. erosion sets maximum **tip speed**)
	->	Both set maximum **blade length**

Mechanical Load Assessment (MLA)

- **For design purposes**, the **life of a wind turbine** can be **represented by a set of design situations**, called **Design Load Cases (DLC)**, covering the most significant conditions that the wind turbine may experience.
- **MLA sets critical constraints** for the design to **avoid catastrophic turbine failures**

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Design Load Cases (DLC)

Load spectrum = all loads seen by the wind turbine in its life.

1. Production
2. Production + fault (grid outage, pitch, yaw error)
3. Start
4. Shutdown
5. Emergency shutdown
6. Parked / Idling
7. Parked / Idling + fault
8. Transport, erection, assembly

IEC 64100-1 requires MLA for all DLC with a suitable simulation tool or testing.

DLC from IEC 64100-11

Types of loads by **failure mechanism:**

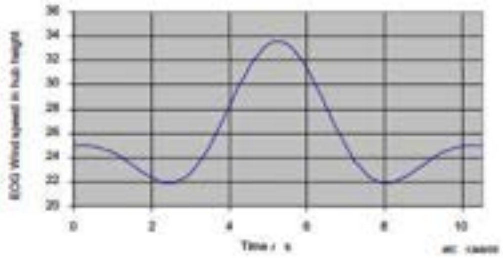
- **Fatigue** (F) and **ultimate** (U)
- **Normal** (N) and **abnormal** (A)
- Critical deflection (e.g. tip clearance)
- Partial **safety factors**:
    - γF : load factor
    - γM: material factor
    - γN: consequence-of-failure factor

Analysis usually requires **time series of representative wind fields** as input
-> **wind class sets constraints**

Types of loads by **physical mechanism:**

- **Gravitational & inertial loads** (mass)
- **Aerodynamic loads** (lift & drag)
- **Actuation load** (caused by control system)
- **Other loads** (e.g. icing, hydrodynamic, …)

Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42,5	37,5	Values specified by the designer
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			



Caracteristic extreme operating wind gust "Mexican hat" for DLC

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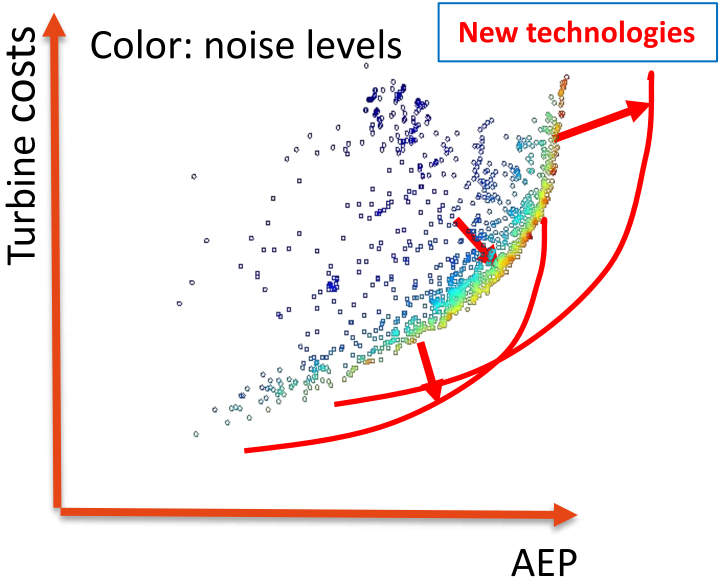
DLC from IEC 64100-11

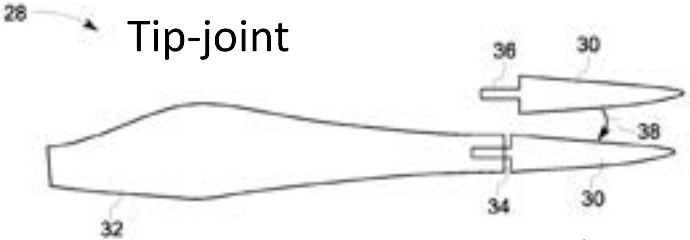
Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42,5	37,5	Values specified by the designer
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			

The following abbreviations are used in Table 2:	
DLC	Design load case
ECD	Extreme coherent gust with direction change (see 6.3.2.5)
EDC	Extreme direction change (see 6.3.2.4)
EOG	Extreme operating gust (see 6.3.2.2)
EWM	Extreme wind speed model (see 6.3.2.1)
EWS	Extreme wind shear (see 6.3.2.6)
NTM	Normal turbulence model (see 6.3.1.3)
ETM	Extreme turbulence model (see 6.3.2.3)
NWP	Normal wind profile model (see 6.3.1.2)
$V_r \pm 2$ m/s	Sensitivity to all wind speeds in the range shall be analysed
F	Fatigue (see 7.6.3)
U	Ultimate strength (see 7.6.2)
N	Normal
A	Abnormal
T	Transport and erection
*	Partial safety for fatigue (see 7.6.3)

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r - 2$ m/s, V_r, $V_r + 2$ m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0,7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T
	8.2	EWM	1-year recurrence period		U	A

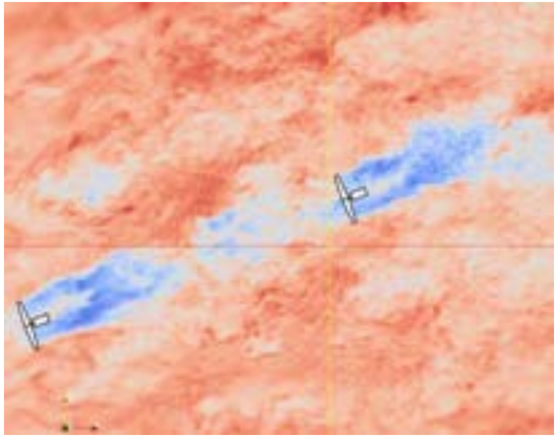
Part 5: The role of technology and markets





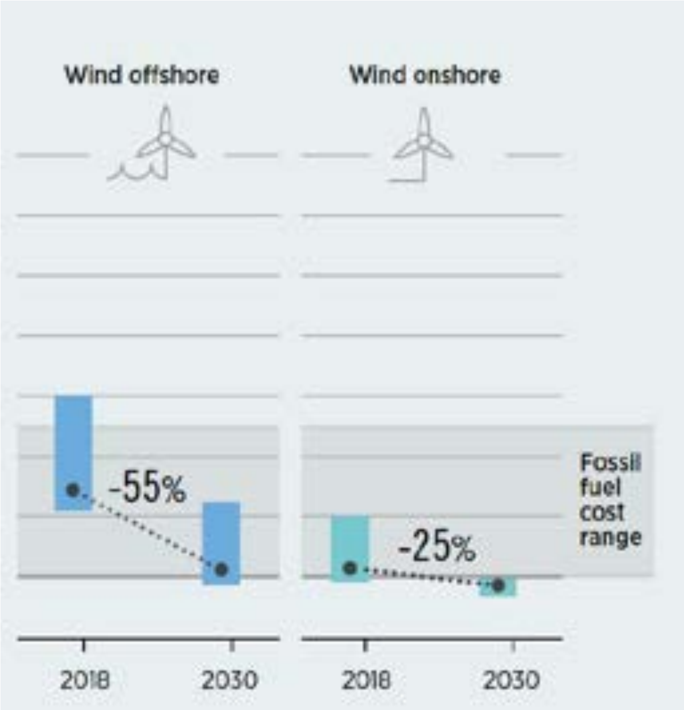
From patent application US 2015/0369211 A`1

Advanced simulation tools on supercomputers



AIAA paper 2017-1163

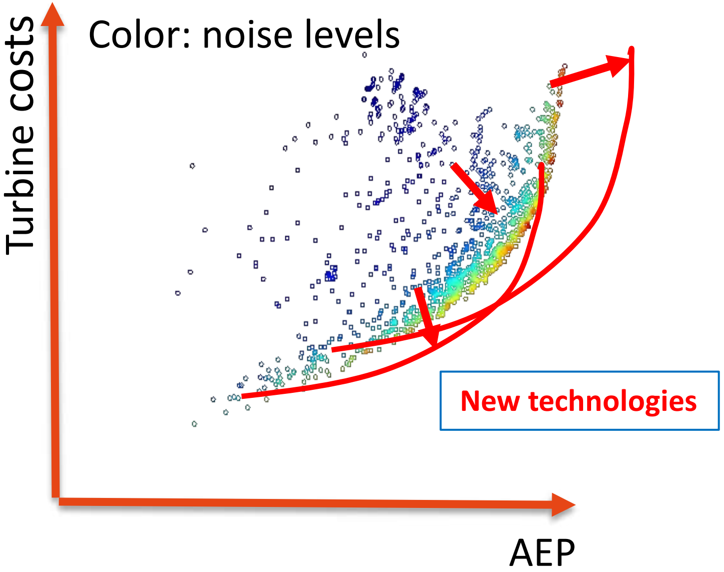
Forward-leaning designs



- Wind turbine **technology progresses fast**
- Auctions require future LCoE estimates
- Need to **include next level of technology to be competitive**
- OEM in discussion with developers and **commits to LCoE and other targets**
- OEM is **betting on engineering teams and technologies to deliver**

The role of technologies

Forward leaning design
Needed to be competitive



Technologies as technical opportunities to (re)move limits and constraints

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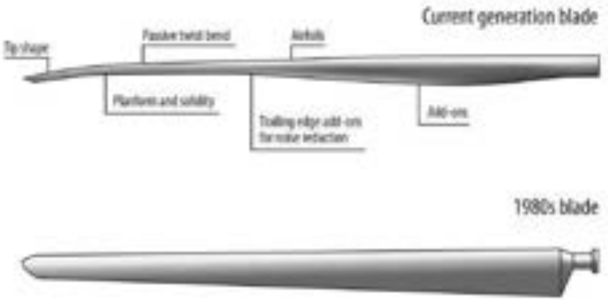
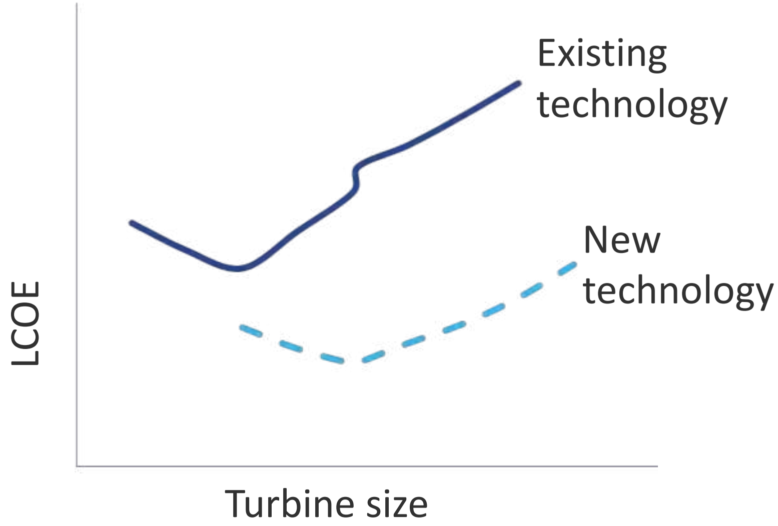
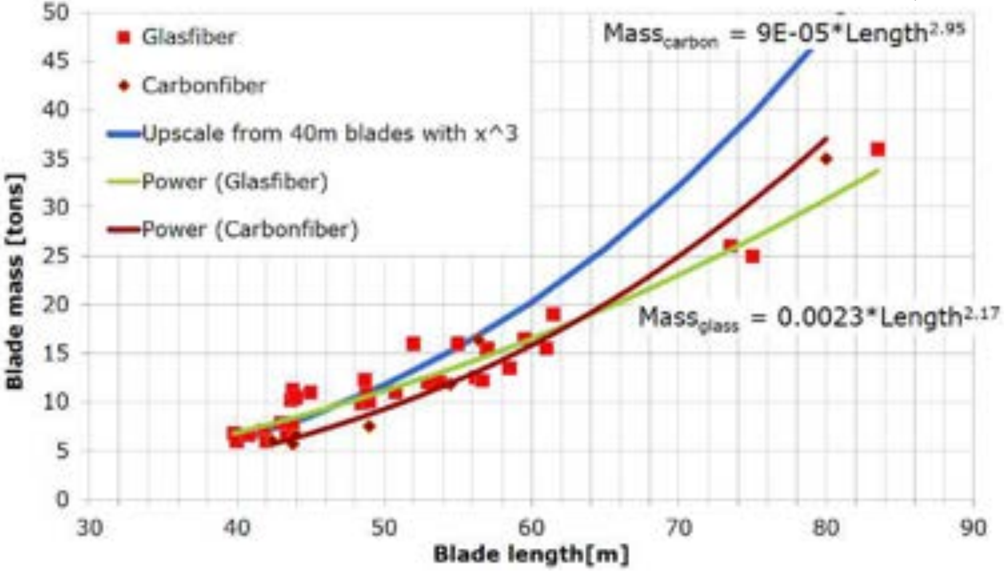
Shifting the Pareto front



From Veers et al., Science, 2019

Example: reducing LCOE





From Bak et al., 2013, “The DTU 10-MW reference wind turbine”, DTU report

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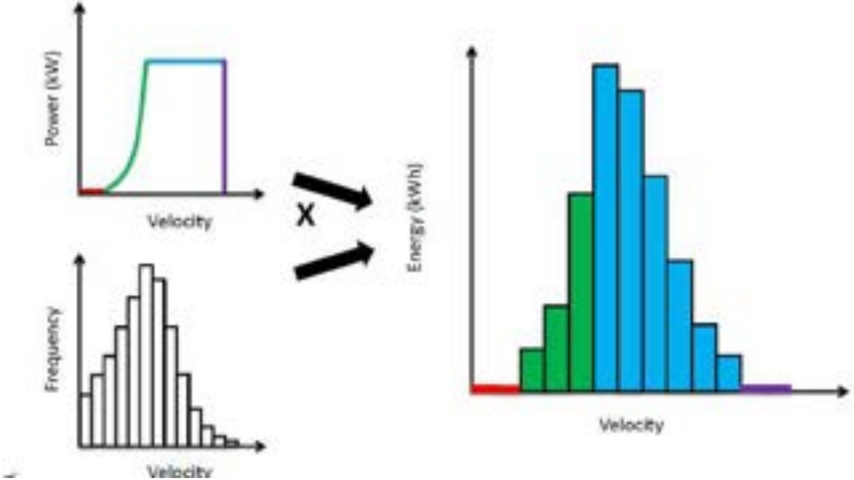
Blade technology examples

- **Passive techniques**
  - **Pre-bend design** (tip **deflection limit**)
  - **Aerodynamic add-ons** (e.g. for load reduction or **performance enhancement**)
  - **New materials** (e.g. for **higher load limits**)
  - **Aeroelastic tailoring** (e.g. bend-twist-coupling for **load reduction**)
  - **Protective layers** (e.g. for **erosion mitigation**)
- **Active techniques**
  - **Model based control** (e.g. individual pitch control for **load reduction**)
  - **Feed-forward control** (e.g. Lidar and pitch for **fatigue load reduction**)
  - **Active flow control** (e.g. flaps for **performance enhancement**)
  - **Storage integration** (e.g. for extreme **load case elimination**)

Annual energy production & revenue

$$Energy\ yield = \int_{U_a}^{U_b} p(U)\, P(U)\, dU$$



P(U): Power curve of **wind turbine**
p(U): Wind distribution at **local site**
U: Wind speed; a: cut-in; b: cut-out

- **AEP** (Annual Energy Production = energy yield of one year) **depends on** both **wind turbine design** and on local **site conditions**
- **Revenue** (=AEP x price) **depends in addition on market design**
- **New application space and/or market structure -> new wind turbine design !**

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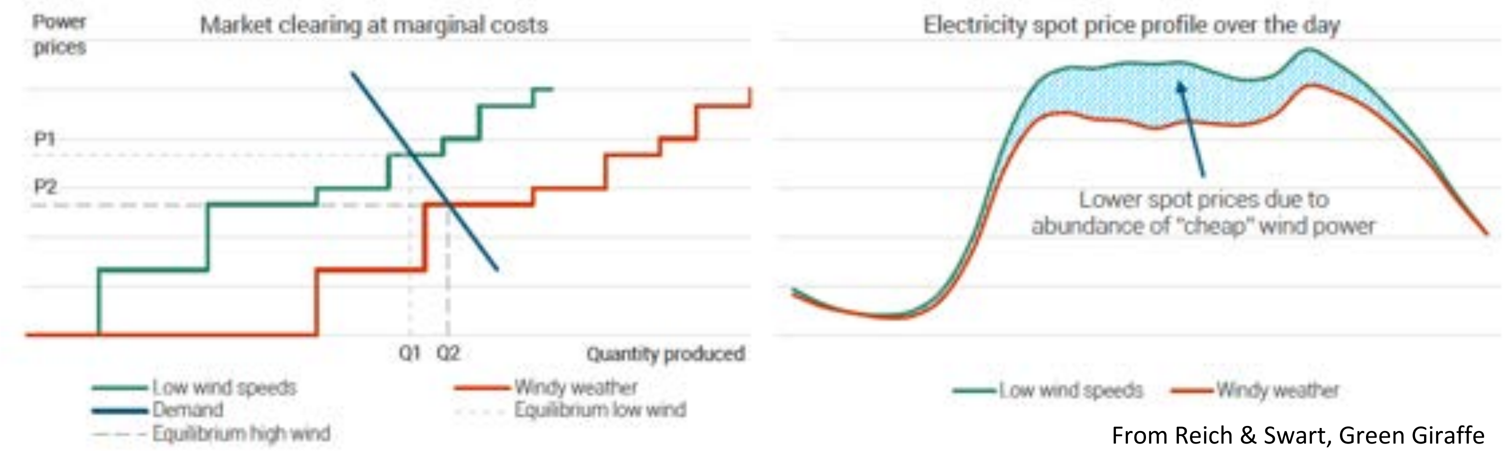
Self-cannibalization

Marginal cost: cost to incrementally increase production (ca. price of fuel)
Wind has zero marginal cost!



From Reich & Swart, Green Giraffe

- **More wind** energy **displaces other** (fuel burning) **production** from market
  -> electricity **spot prices drop** (good for consumers)
  -> **fossile generation drops** (desired cannibalization, good for climate)

- **Revenue of wind drops** as well with price
  -> **self-cannibalization** (reduces value story for new wind plants)

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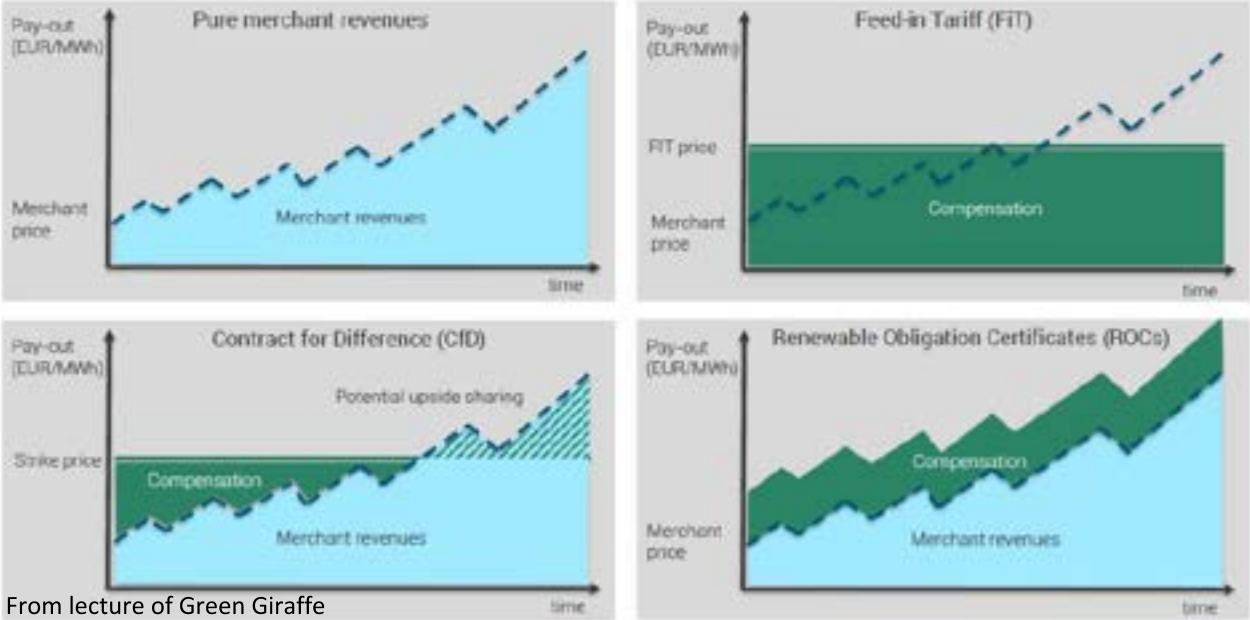
profit = revenue – costs
costs = LCoE x AEP x years

Impact of market design

Lower LCoE turbine not necessarily best for larger revenue & profit if wind production & price are strongly coupled (self-cannibalization)

Lower LCoE turbine
-> lower strike price
-> larger profit

Compensation reduces impact of self-cannibalization



From lecture of Green Giraffe

High FiT favors:
Larger AEP turbine
-> larger revenue

Low FiT favors:
Lower LCoE turbine
-> larger profit

No self-cannibalization

Lower LCoE turbine not necessarily best

Compensation reduces impact of self-cannibalization

Market design decides on who takes the **risk of price uncertainty**

Impact on **self-cannibalization** & **turbine design optimization**

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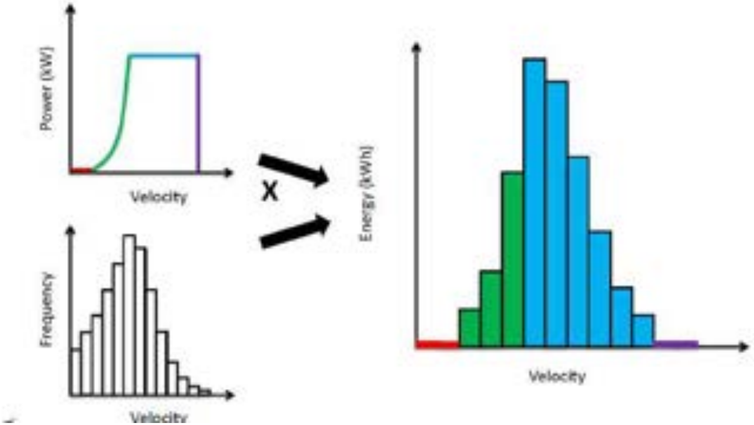
The role of the capacity factor C_f

$$C_f = \frac{actual\ energy\ production}{maximum\ energy\ production} = \frac{energy\ yield}{rated\ power\ x\ time} \leq 1$$



depends on

- **site conditions** (wind distribution)
- **turbine operation** (availability, e.g. downtimes, noise reduced operations etc.)
- **turbine design optimization** (rotor power coefficient & generator rating)

A **large(r) C_f** could be desirable as it indicates a
- **good match of turbine design to application space**
- **higher usage of assets** (C_f = 1 is baseload) & **lower production uncertainty**

but **C_f alone** can be **misleading!**

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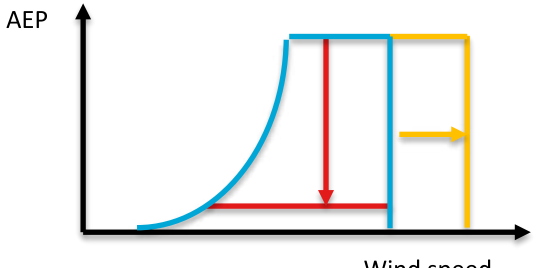
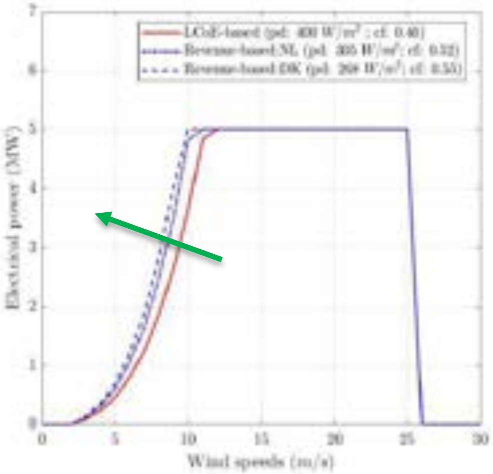
The role of the capacity factor C_f





- **Average C_f** in 2019
  38% offshore, 24% onshore
  Hywind floating ca. 55% (Siemens 6MW 154m rotor)
  Haliade-X predicted 63% (GE 13MW 220m rotor)

- **Decreasing generator rating** (from optimal design)
  Cf↑ but AEP (&revenue)↓, LCoE ↑ and profit↓

- **Increasing cut-out speed** (from optimal design)
  Cf↑ and AEP (&revenue)↑ but LCoE ↑ and profit↓

- **Improving rotor technology & design objectives**
  Cf↑, AEP(revenue)↑ and profit↑ but LCoE unclear

C_f needs to be assessed together with other parameters, e.g. AEP, LCoE and/or profit

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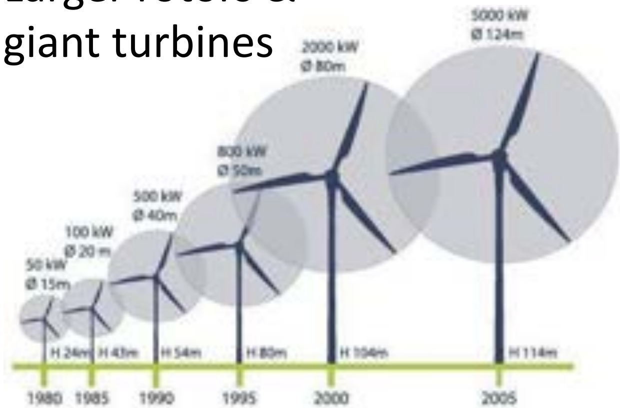
Part 6: Current trends

Standardization & modular design

Larger rotors & giant turbines



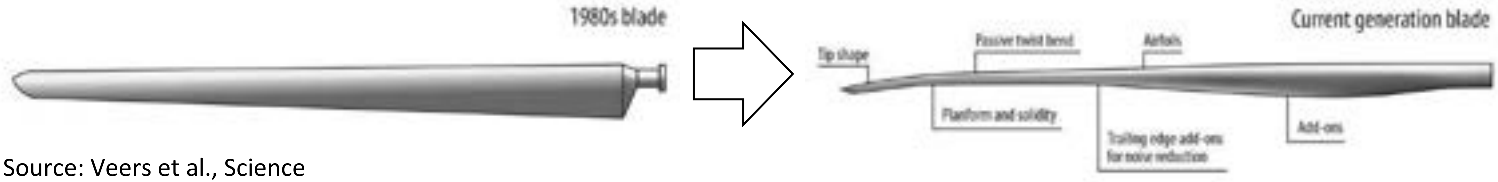
Source: Ananthan, A2e workshop, 2015

Decommissioning

Wikado playground Rotterdam 2008
Source: Superuse Studios

Digitalization

Repowering



Source: Veers et al., Science

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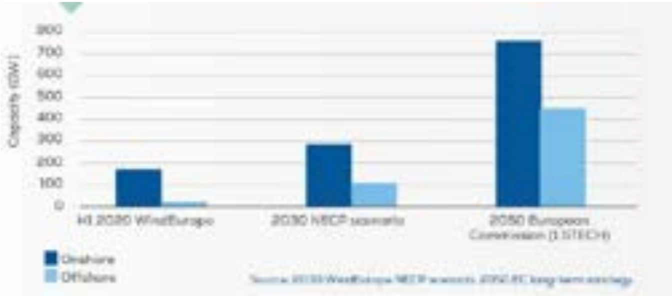
Power density [W/m²]
= rating / rotor area

Larger rotors: Low wind speed sites



Source: WindEurope 2020

- **Drastic increase of wind energy** onshore and offshore predicted
- Best (high-wind speed) sites onshore already in use
  -> **expand application space to low wind speed sites**
- Optimizing turbine design for the new application space results in **lower power density and taller towers**
- **New technologies and better physical understanding remove external limitations** to **enable larger rotors** (e.g. jointed blades, low noise technologies, etc.) and **taller towers** (e.g. advanced controls)

For low wind speeds, overall drive to large rotors and tall towers

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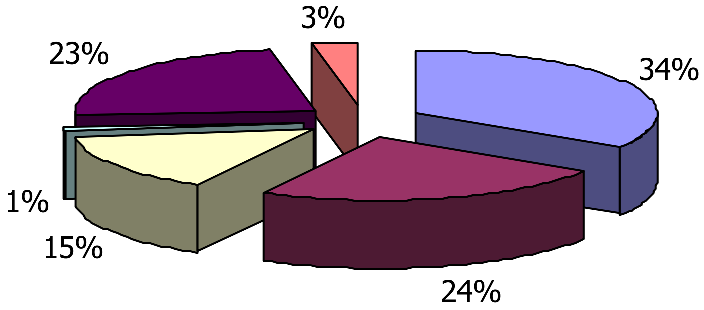
Larger rotors: Offshore wind

Turbine cost share: offshore ca. 1/3, onhore ca. 2/3

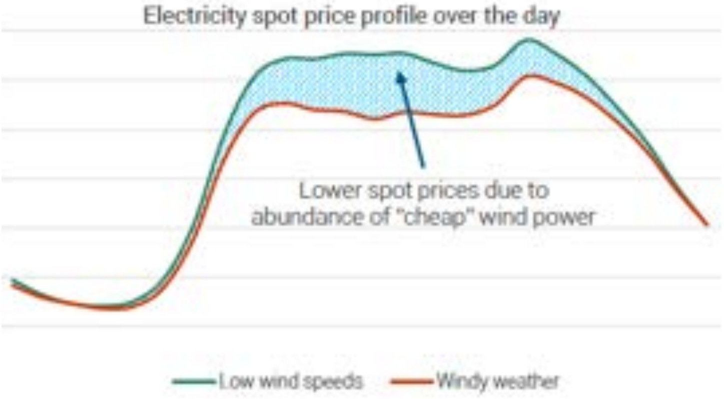


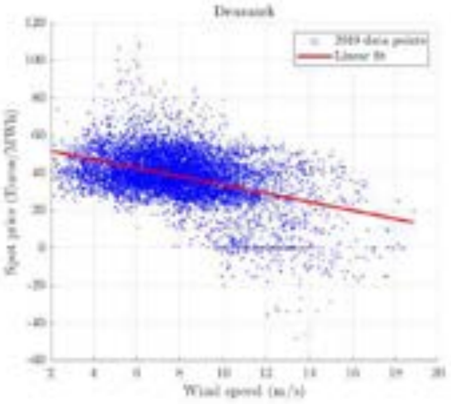
Economics and society drive trend to **more and larger offshore wind farms.** These **favor giant wind turbines** because

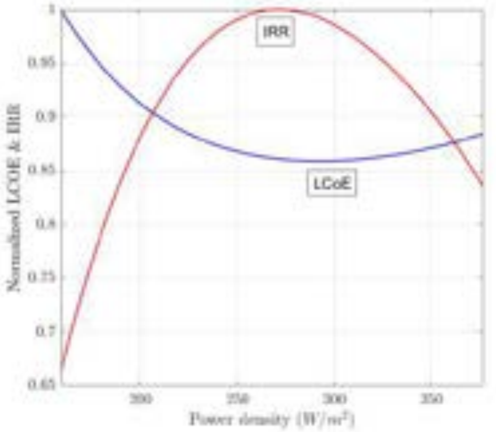
1. **Turbine cost share** offshore considerably smaller than onshore -> **larger rotor size & rating** as AEP benefit outweighs cost increase
2. **New technologies and better physical understanding** shift design **to larger blades**
3. **Additional optimization objectives**, e.g. capacity factor, profit (IRR), etc. **tend to favor larger rotors** (see next slide)

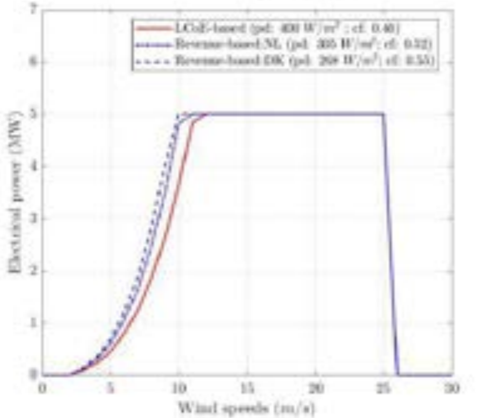
For offshore wind, main trends reinforce each other towards giant turbines

Large rotors: Revenue-driven design









- In some markets, **more wind results in lower price**
- **LCoE not necessarily best optimization objective**
- **Alternative strategies:**
  - Low wind speed optimized designs
  - Higher C_f (for similar LCoE)
  - Revenue or profit optimization (IRR or NPV)

  -> all show **trends to larger rotors**

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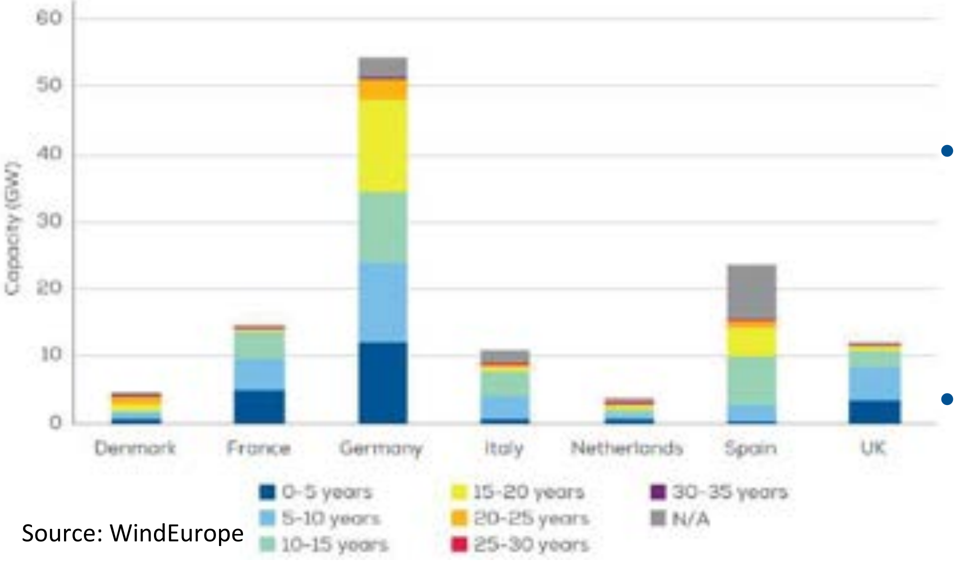
Options at “end-of-life”

Age of wind turbine fleet in Europe:

- 50% of Danish fleet >15 years
- >16GW (30%) of German fleet >15 years



Source: WindEurope

- **End-of-life:** assets reaches 20 years of life
- **Life extension:**
  continued maintenance and possibly modernization of existing turbines, e.g. uprating, blade add-ons or replacement, bearing replacements, new control software and actuators, etc.
- **Repowering:**
  dismantlimg the original turbines (including foundations) at an existing site and replacing them with new ones
- **Decommissioning:**
  dismantling of turbines, reusing, recycling or disposing of components, and restoring the site to another use

Opinion poll: End-of-life options

In Europe, between 2019 and 2023, **22 GW reach "end of life"**, i.e. the assets reach 20 years of age.

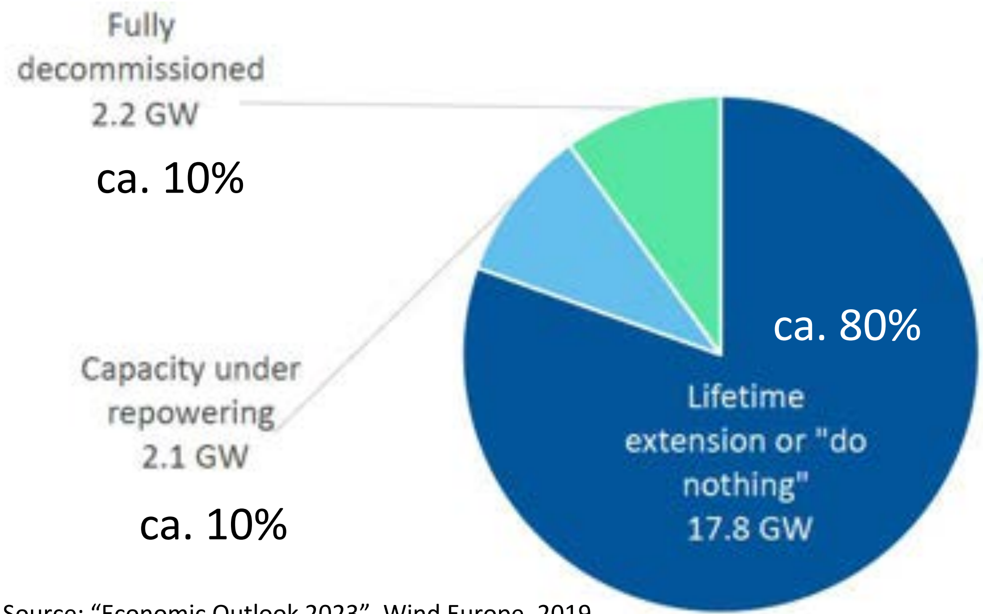
What **percentage** of the turbines will be fully **decommissioned**?

- ❑ <20%
- ❑ 20-40%
- ❑ 40-60%
- ❑ 60-80%
- ❑ >80%

What **percentage** of the turbines will be **repowered**?

- ❑ <20%
- ❑ 20-40%
- ❑ 40-60%
- ❑ 60-80%
- ❑ >80%

End-of-life options



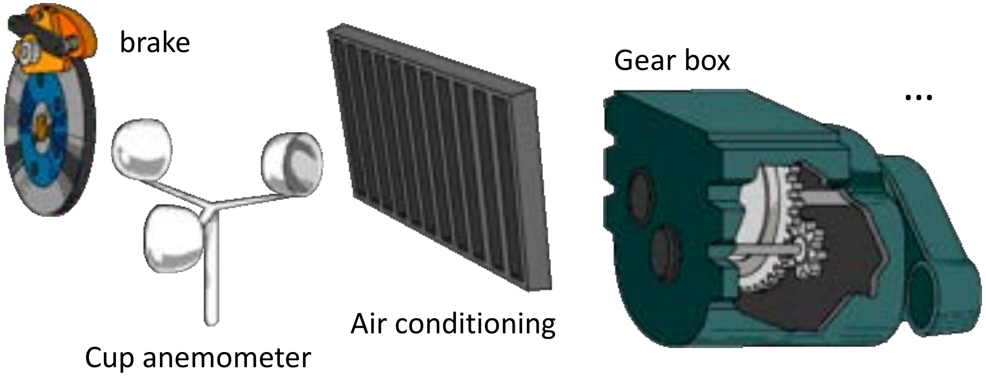
Source: “Economic Outlook 2023”, Wind Europe, 2019

In Europe, between 2019 and 2023, 22 GW reach end of life, i.e. the assets reach 20 years of age

Life extension:

- The standard **lifetime** of an onshore wind turbine is **25 years**
- Some turbines now **reaching up to 35 years**

Standardization & modularization



Inspiration:
Automotive sector, with integrated supply chain, but OEM holding core expertise in

- System integration & dynamics
- Combustion engine
- Customer relationship

Objective:

- Cost reduction via **economy of scale**

Philosophy:

- **Plattform design concept**

Means:

- **Standardization** of components allows for larger market with multiple suppliers and OEMs
- **Modular design** of components allows to use (or scale) components for different application spaces

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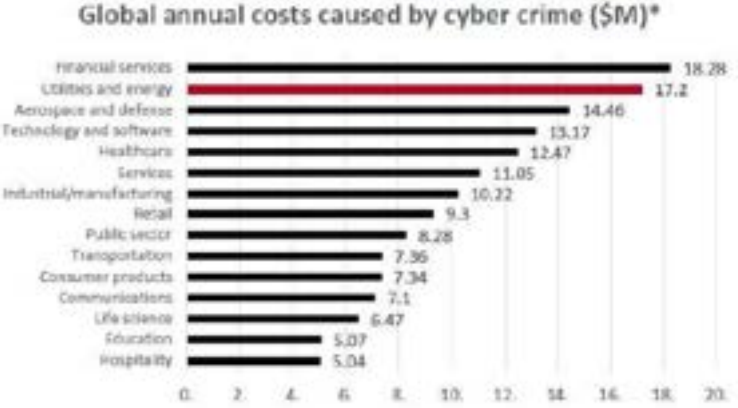
Digitalization: Key words

- On-board analytics (smart turbines)
- Novel & virtual sensors
- Internet of Things (IoT)
- Big data analytics
- Advanced controls
- Cyber security
- Integrated design
- Digital twin
- Digital thread
- High performance computing

Source: GE – Illustration of IoT & digital wind farm



Global annual costs, per targeted organization, caused by cybercrime. Source: Accenture & Ponemon Institute 2017

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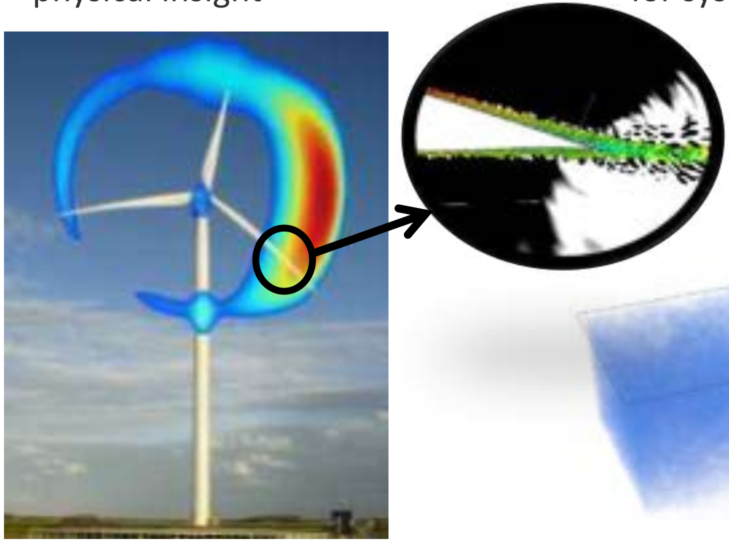
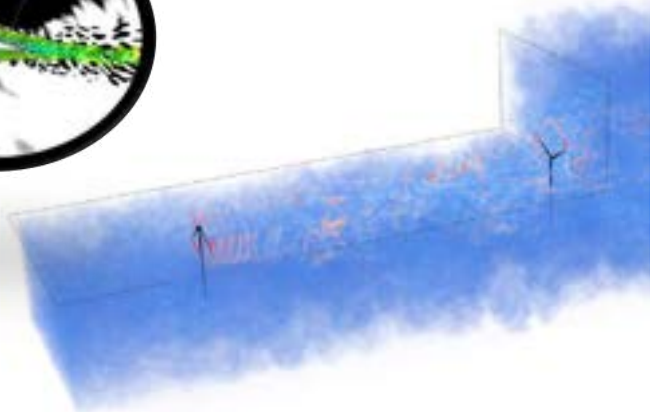
Digitalization: High-performance computing

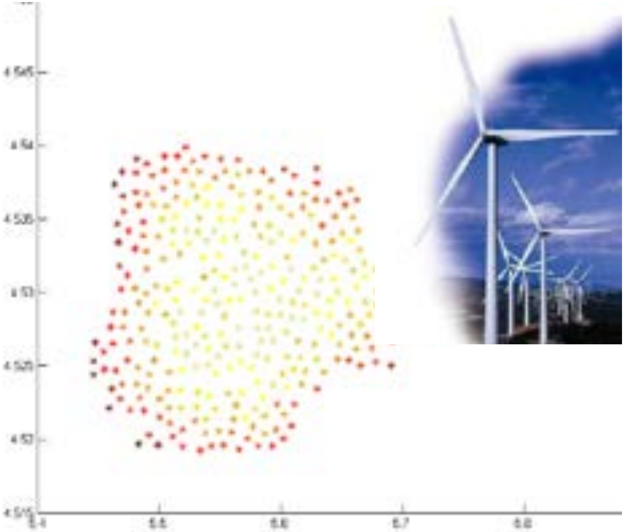
Microscope…
developing greater physical insight

Macroscope…
component interaction for system performance

Optimization…
Compare many design or site layout solutions







“Magnification”
Details limited by computational horse power

“System or sub-system”
Domain size limited by computational horse power

“Alternative designs”
Number limited by computational horse power

From D. von Terzi, „Windturbinen und Windparks im Zeitalter des industriellen Internets“, ERCOFTAC Tech-Tag, 2014

Digitalization: Digital thread

Source: www.compositesworld.com

- Communication framework to connected data flow and integrated view of assets throughout lifecycle
- Breaking "silos"
- Delivering "the right information to the right place at the right time
- Example: design system and digital models for manufacturing can be incompatible

Digitalization: Digital twin

Source: www.compositesworld.com

- Calibrated digital model of a particular asset
- Includes design specifications and engineering models describing its geometry, materials, components and real-life behavior
- Includes the as-built and operational data unique to the specific physical asset
- Requires data assimilation techniques, Internet of Things, Digital Thread
- For "real time co-simulation", requires surrogate models and/or high-performance computing

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Summary

- We revisited **key components of a wind turbine.**
- We learned about **objectives** of wind turbine design and how they are driven by the **application space**.
- We identified the steps of the **design process**, their purpose and typical **design tools** to be used.
- We explored the principles and benefits of **multi-disciplinary design optimization** and of **design trades**.
- We looked at the **role of technology and markets** in turbine design
- We explored **current trends** to **giant wind turbines** with **large rotors**, **standardization & modular design**, **end-of-life** options and **digitalization.**

DISCUSSION