Wind power technology trends

PHYS-E6572 Advanced Wind Power Technology

Hannele Holttinen

2.12.2022

VTT

Modern wind turbine

- Increase rotor size has improved turbine efficiency
- Increase in tower height has improved yield
- New materials and new manufacturing processes
- Square-cube –law:
  - Power output ~ r^2
  - Weight / materials ~ r^3
- ➔there is a limit where increase in size will no longer be worth it

Manufacturing a blade for Vestas V236 wind turbine prototype
Blade length 115.5m.

https://www.vestas.com/en/products/offshore/V236-15MW/prototype

Future

- Blades have reached 100m
- Generator capacity 15 MW
- Offshore
- Increased interest in floating offshore

Hywind Tampen – Assembly of the world's largest floating wind farm - YouTube

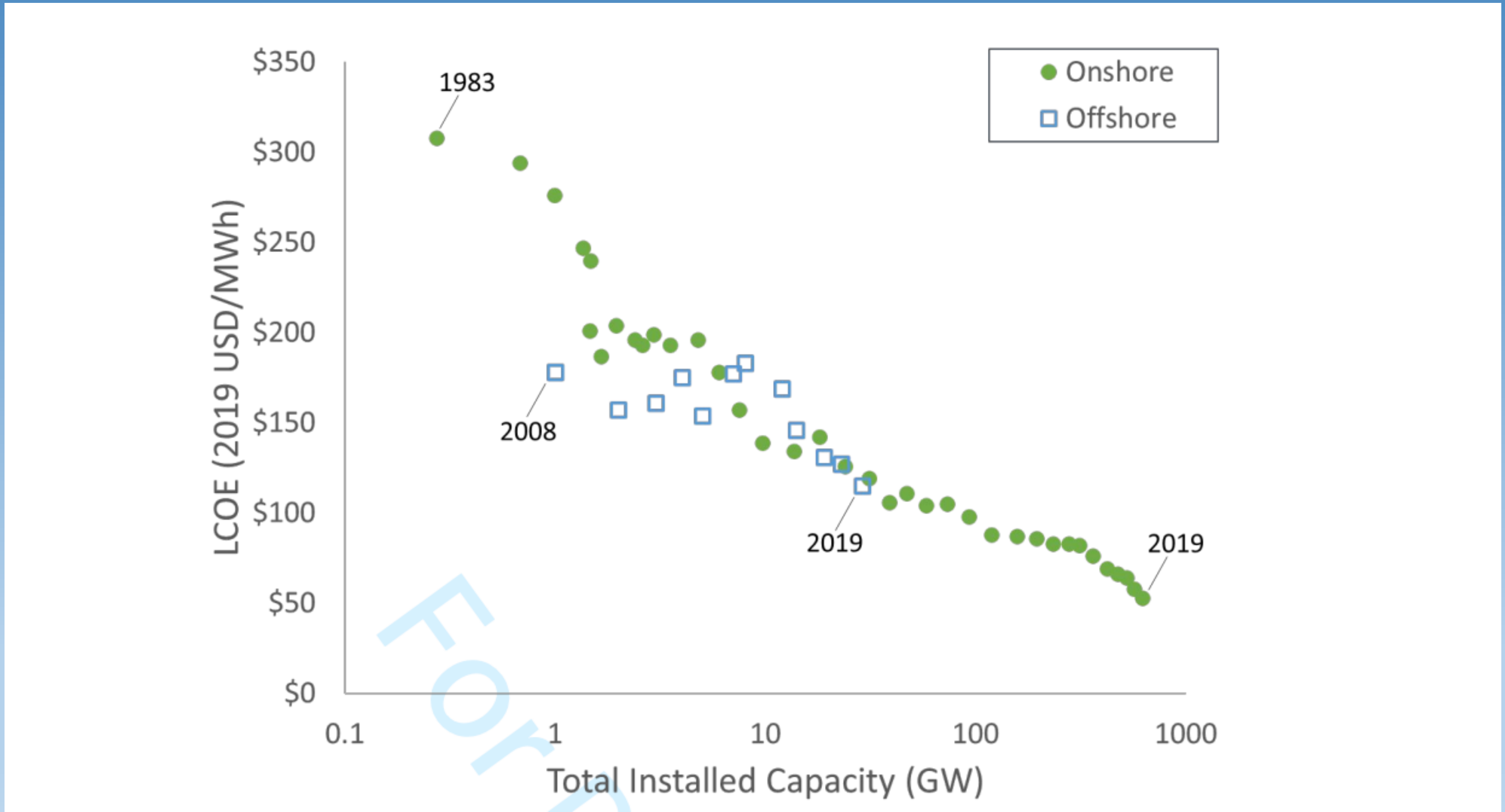
Haliade-X offshore wind turbine - installation time lapse - YouTube

Photo courtesy of Cobra Group.
Source:
https://www.principlepower.com/news/kowl-worlds-largest-floating-windfarm-fully-operational

Contents

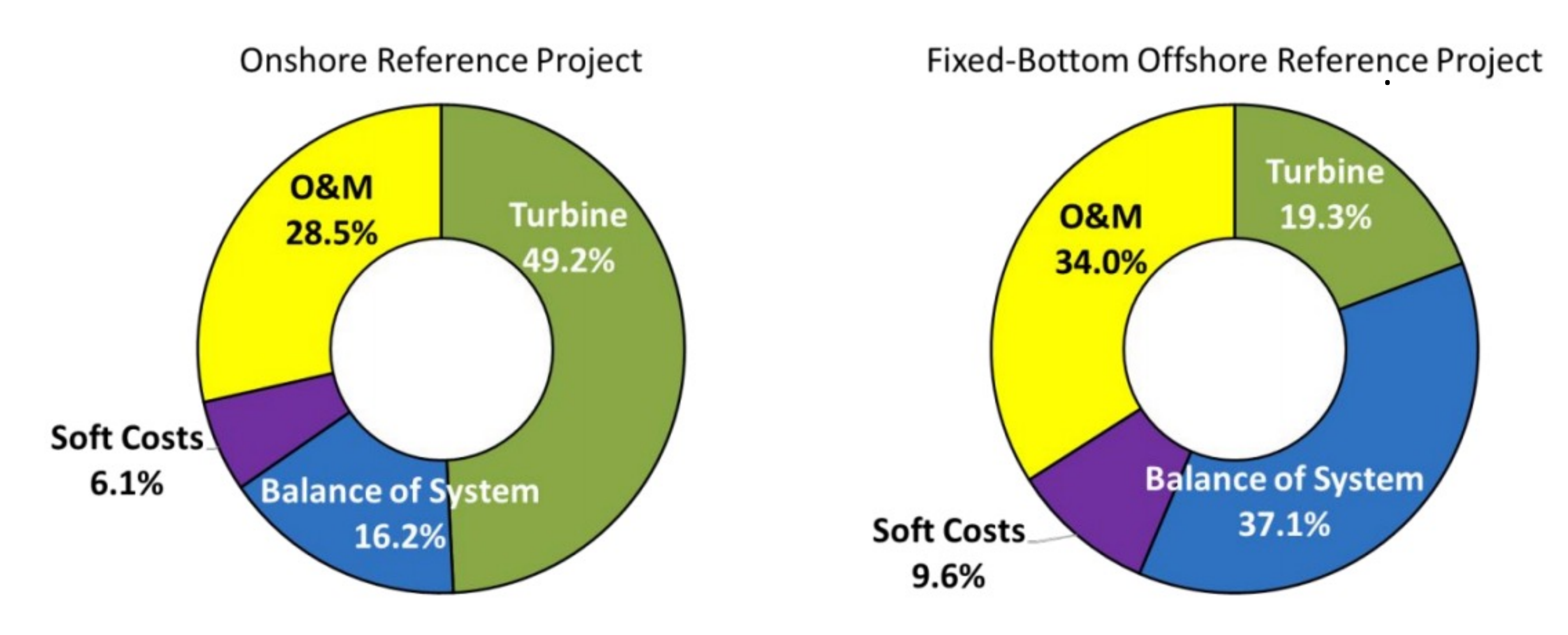
- Costs trend
- Industry consolidation
- New concepts?
- Technology
  - Larger turbines – upscaling challenge
  - Lower specific ratings – larger rotors for same generator
  - Advanced controls – for energy yield, loads and electricity markets
  - Operation and maintenance, and extending life time
  - Materials, recycling and end-of-life
  - Grid support
- R&D challenges
  - Beyond LCOE, Social acceptance
  - step up from 850 GW today to 6000 GW in future

Cost reduction trend



Source: Breiter, P, et al, Wind power costs driven by innovation and experience with further reductions on the horizon. https://doi.org/10.1002/wene.398

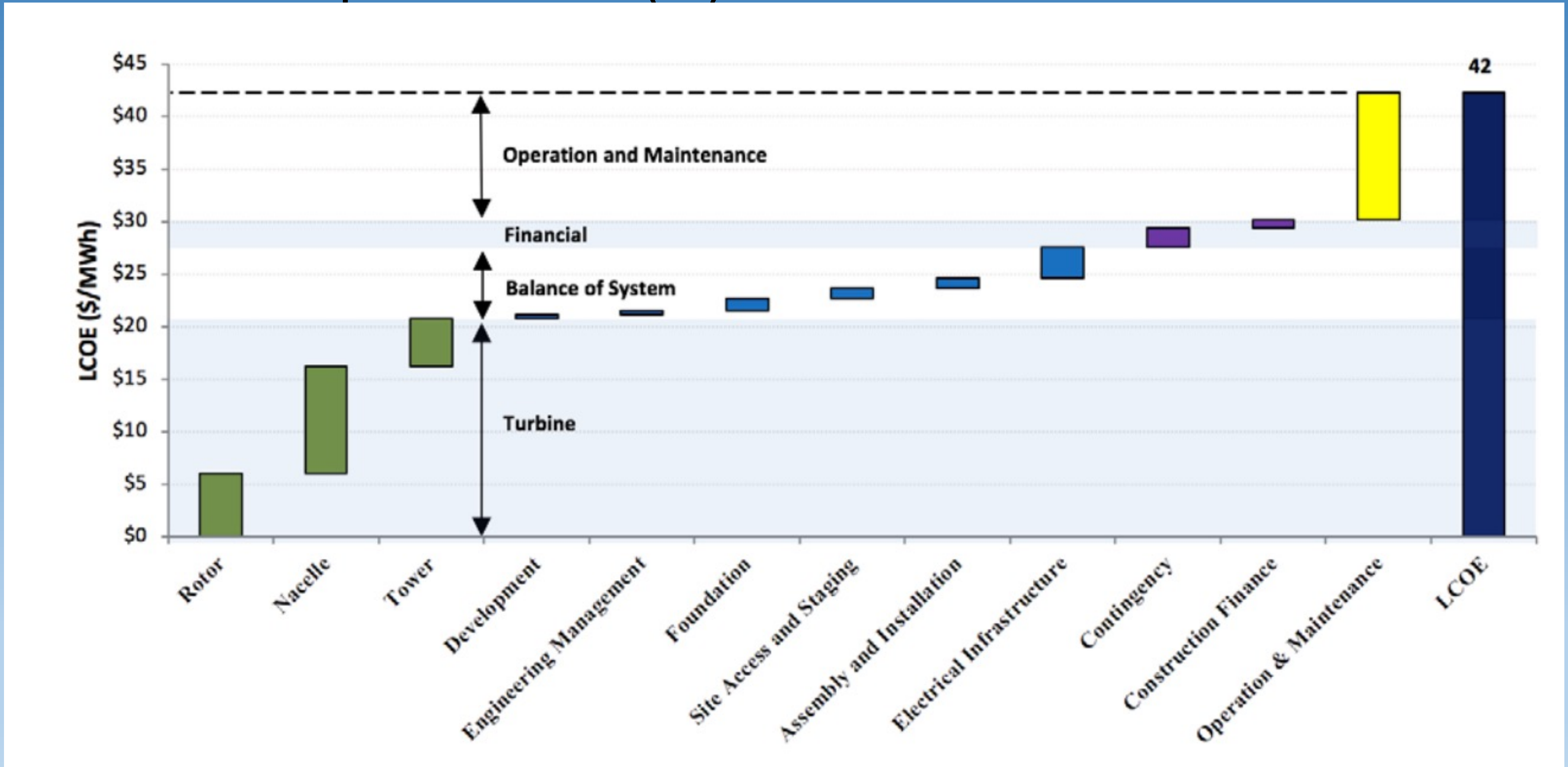
Where to reduce costs? Cost components



- Balance-of-system costs include all parts of the wind plant except the turbines including foundations, electrical infrastructure, access roads, etc.
- Soft costs include construction financing and contingency funds

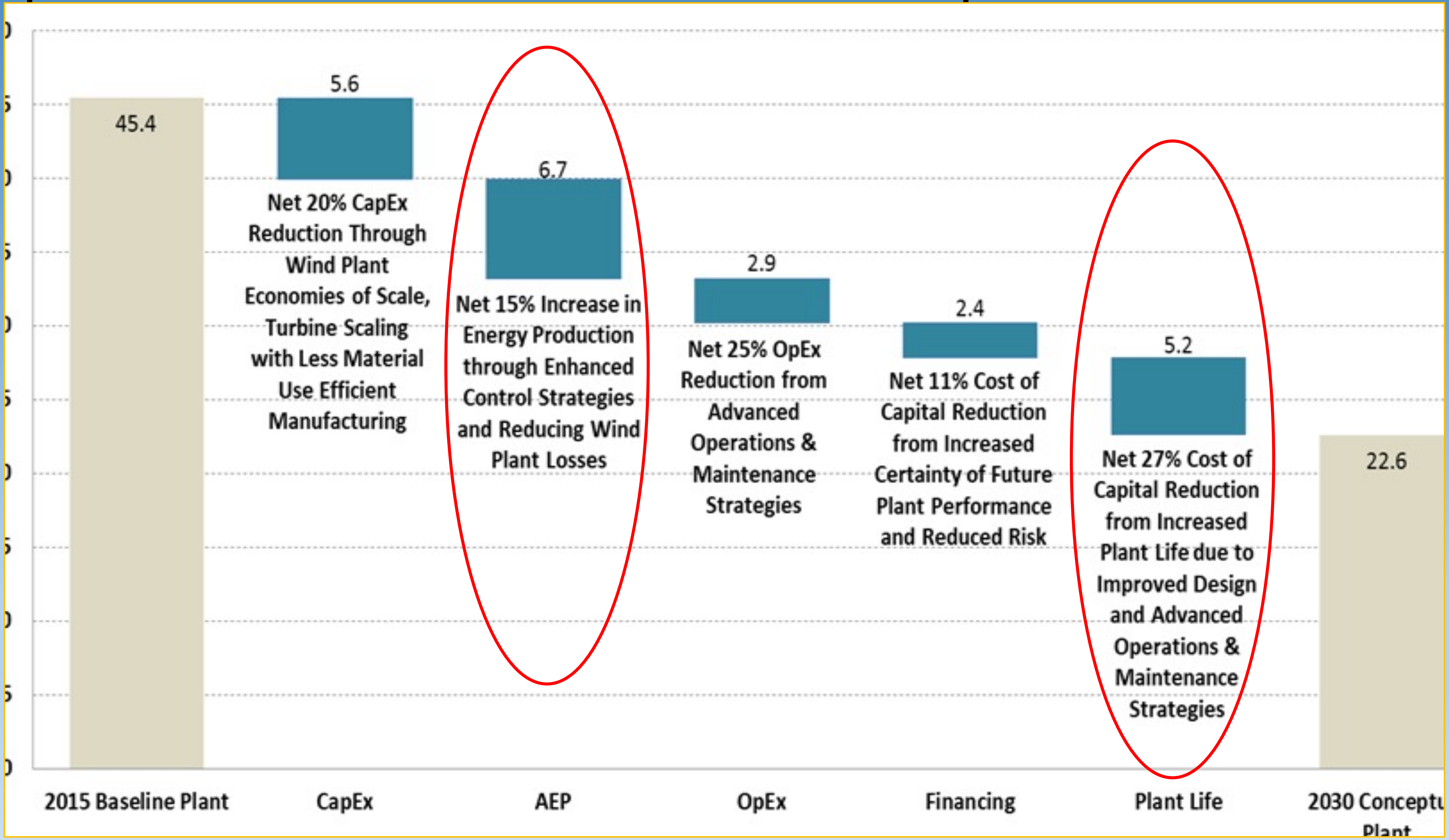
Source: Breiter, P, et al, Wind power costs driven by innovation and experience with further reductions on the horizon. https://doi.org/10.1002/wene.398

Cost components (2)



Source: NREL (2019) 2018 Cost of Wind Energy Review
https://www.nrel.gov/docs/fy20osti/74598.pdf

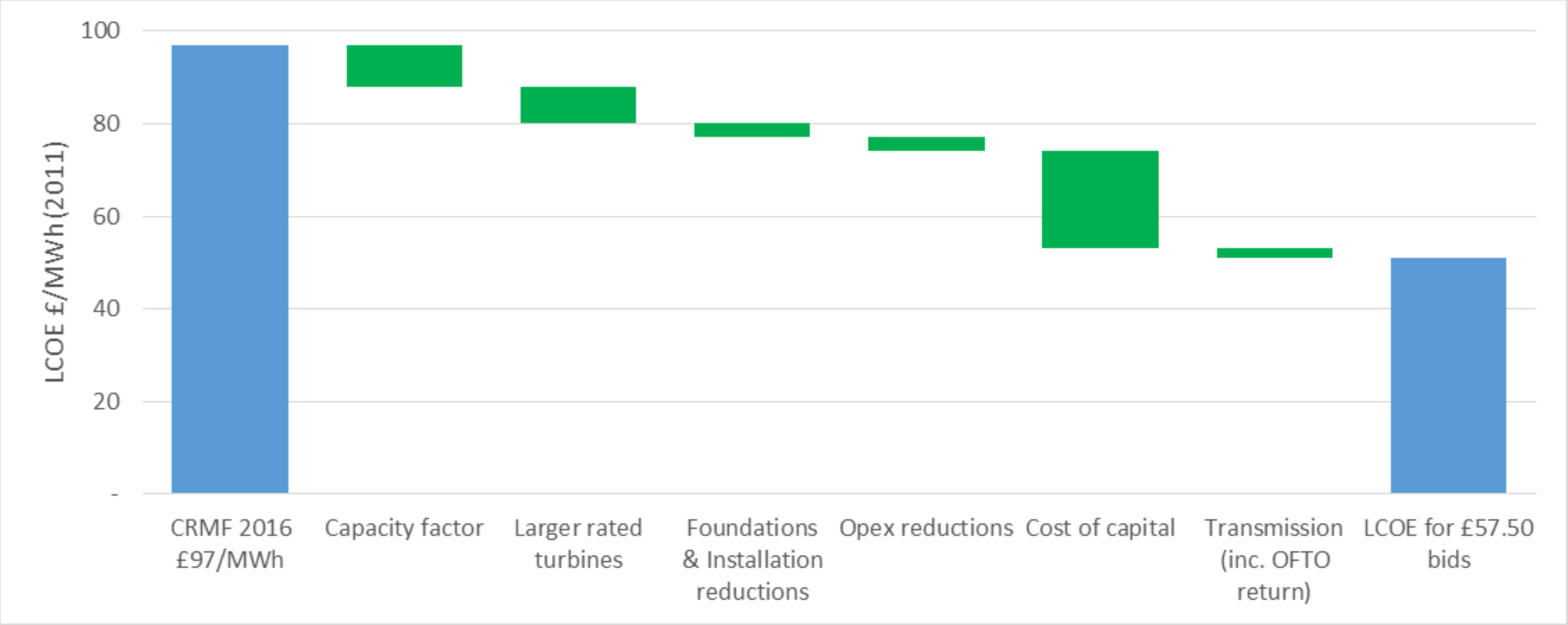
Cost reduction potential – also from energy production and increased plant life



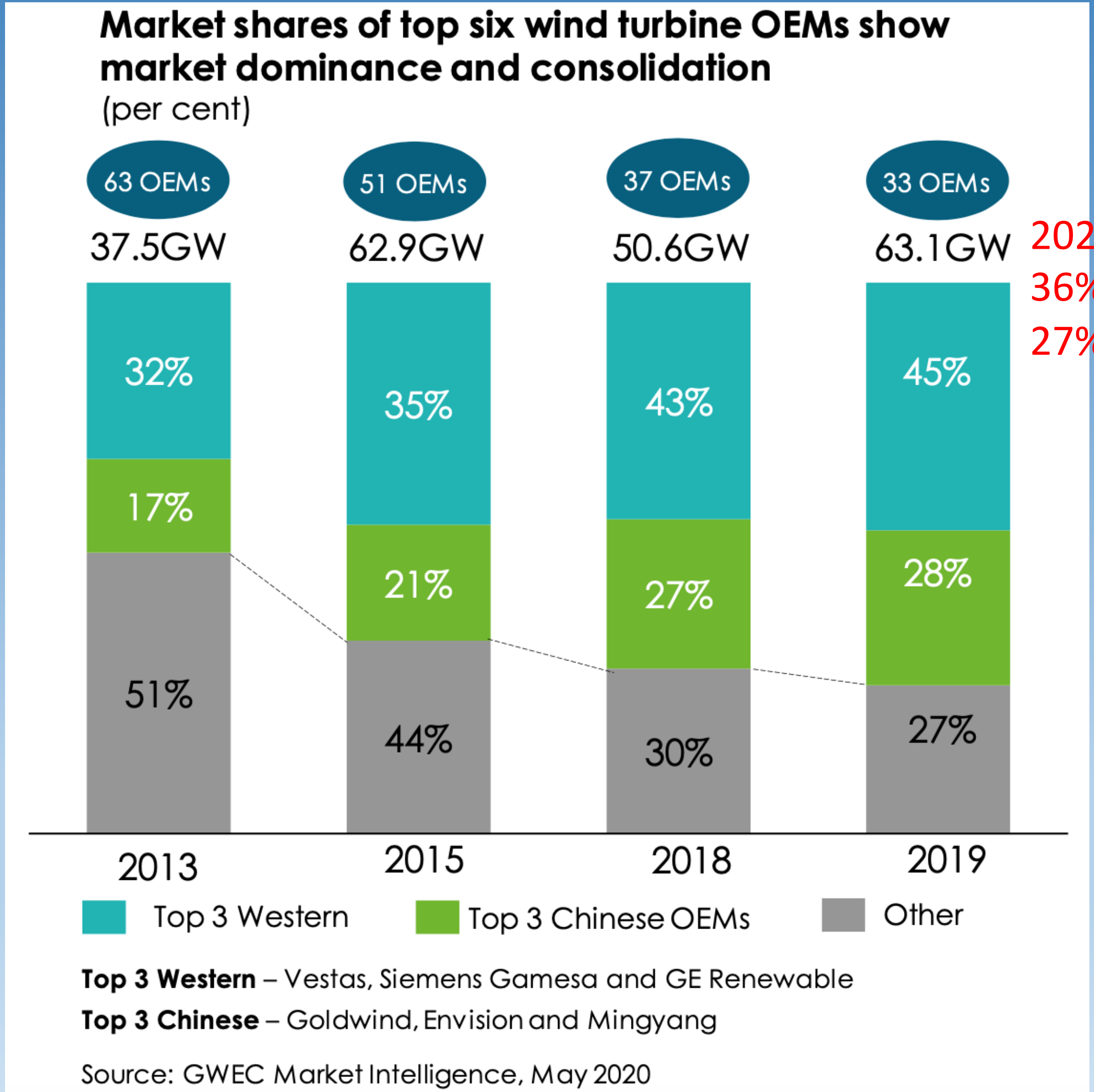
Innovations enabled through advancements in atmospheric physics, wind plant optimization, and plant-level control could reduce land-based wind costs an additional 50% by 2030

Cost of capital has been a major factor in cost reduction for recent UK offshore projects

- Capacity factor increase in region of 10%
- Expect turbines in range 9.5 - 10MW (plans for 13MW-15MW)
- Opex reductions from improved logistics and (site-dependent) shared facilities
- **Critical reductions in cost of capital – low interest rates, investor comfort with risks and strategic play to develop in UK offshore wind market; Now seen as good infrastructure assets to have.**
- Transmission cost reductions partly offset by distance from shore but also benefit from competition in OFTO market



Industry consolidation



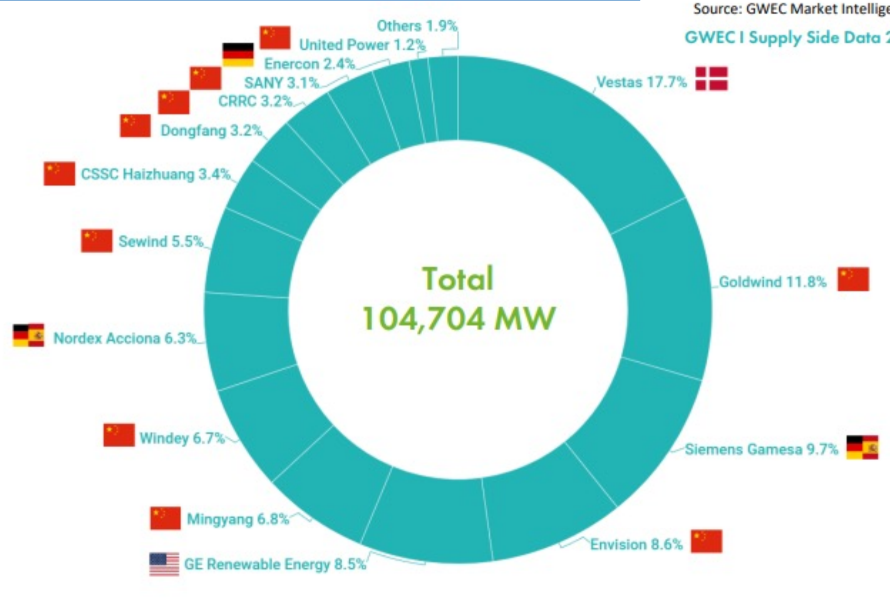
2021 (104 MW)
36% Top Western
27% Top Chinese

Top 15 suppliers cumulative MWs end 2021

Rank	Supplier	Cumulative MW to end 2021	Total share end of 2021
1	Vestas	152,502	17.5%
2	SGRE	119,176	13.7%
3	GE Renewable	98,111	11.3%
4	Goldwind	84,881	9.7%
5	Enercon	57,003	6.5%
6	Nordex Acciona	42,117	4.8%
7	Envision	40,092	4.6%
8	Mingyang	33,461	3.8%
9	United Power	23,469	2.7%
10	Sewind	22,842	2.6%
11	Dongfang	20,950	2.4%
12	Senvion	19,461	2.2%
13	Windey	18,803	2.2%
14	Suzlon	18,128	2.1%
15	Sinovel	17,090	2.0%
	Others	103,407	11.9%
	Global totals	871,493	100%

Source: GWEC Market Intelligence, May 2022

GWEC I Supply Side Data 2021 I 10

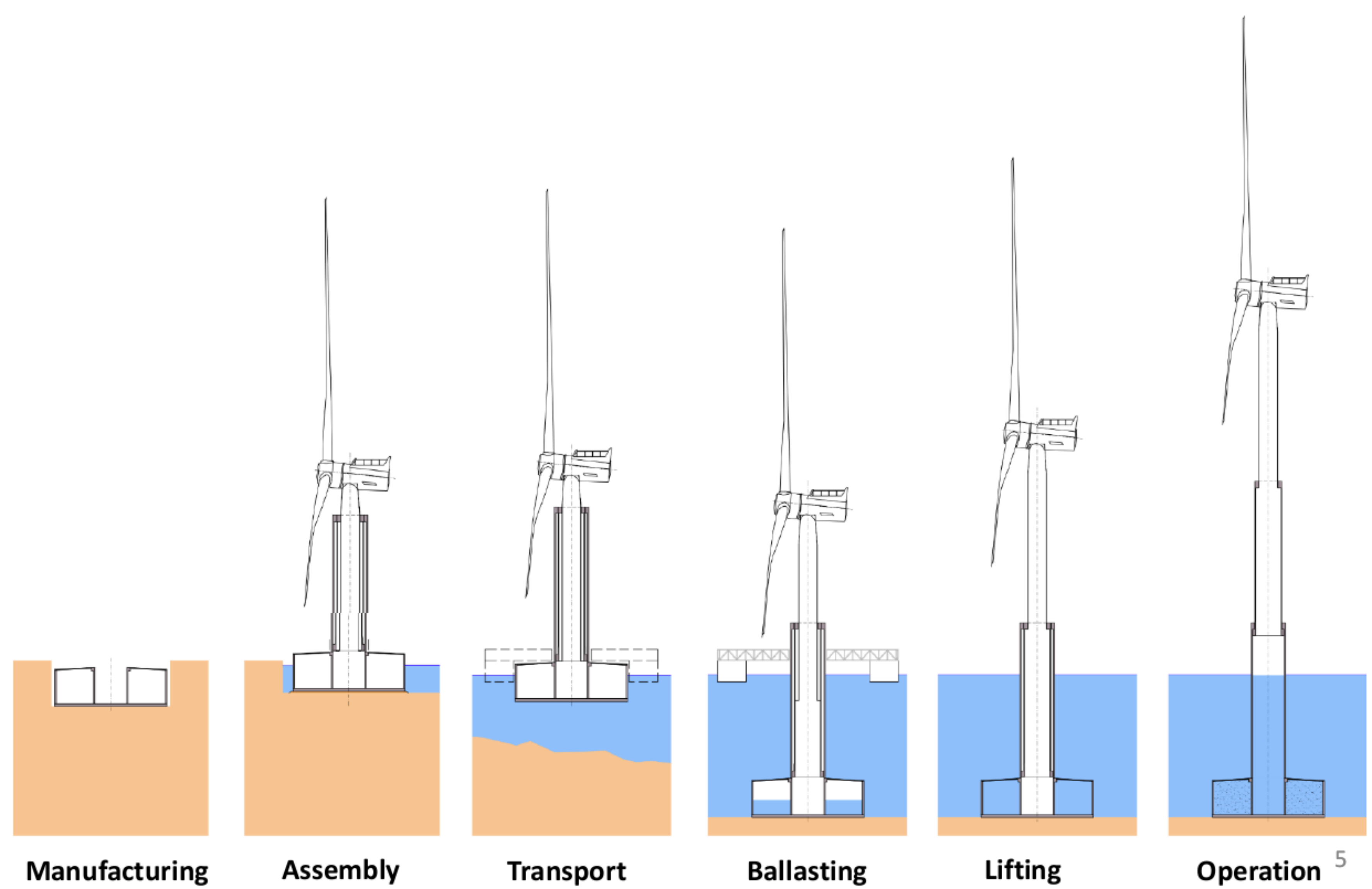


Source: GWEC Market Intelligence, May 2022

GWEC I Supply Side Data 2021 I 8

Top 15 suppliers annual market share 2021

New ways for installing offshore, example EU project ELICAN:



Offshore grids – and energy islands

- Meshed grid offshore instead of radial connections today
- Acting as interconnectors btw countries
- Possibility to electrify oil and gas platforms

- Denmark pioneering with North Sea and Bornholm energy islands
  - a hub for 200 wind turbines

Many research questions:

- Stability
- Fault management
- Optimal grid topology
- Multi-vendor HVDC
- Grid forming converters
- Market design
- Optimal Power-to-X integration
- ...

d turbines, 260m (850ft) in height

a dedicated EU strategy on offshore renewable energy (COM(2020)741) Nov 2020 proposes sets targets for an installed capacity of at least 60 GW of offshore wind by 2030, and 300 GW by 2050

Floating offshore – also promising cost reductions

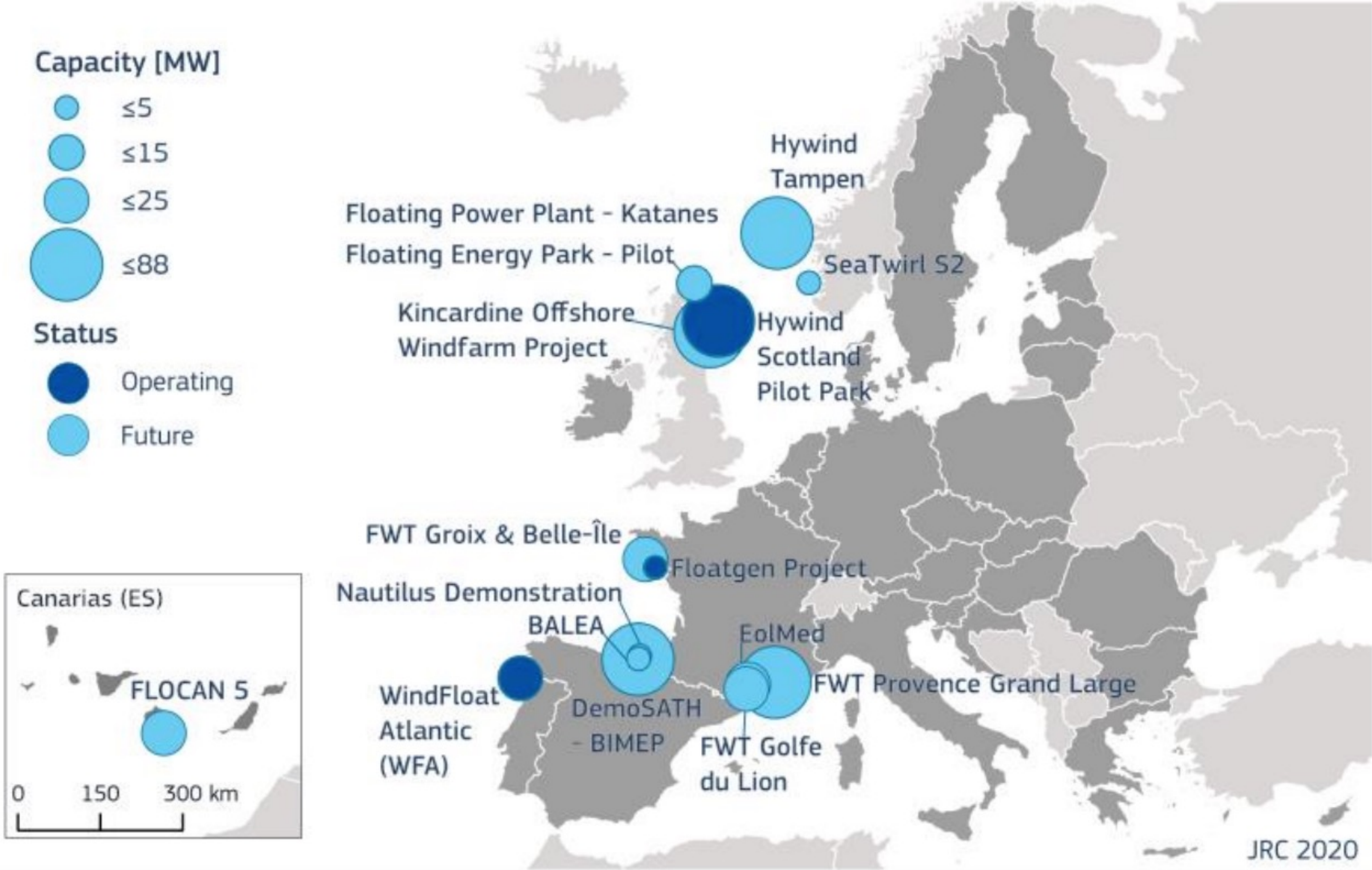
2020: 25 MW, 3 x 8.4MW Vestas off Portugal coast

The Hywind Scotland floating wind farm. (Photo: Øyvind Gravås / Woldcam - Statoil ASA)

2017: The 30MW wind farm, operated by Statoil in partnership with Masdar, is located 25 kilometers offshore Peterhead in Aberdeenshire, Scotland. Hywind can be used for water depths up to 800 meters, thus opening up areas that so far have been inaccessible for offshore wind.

50 MW, 5 x 9.4MW Vestas being installed off the coast of Aberdeen in 2020

Floating offshore wind – Operating and upcoming



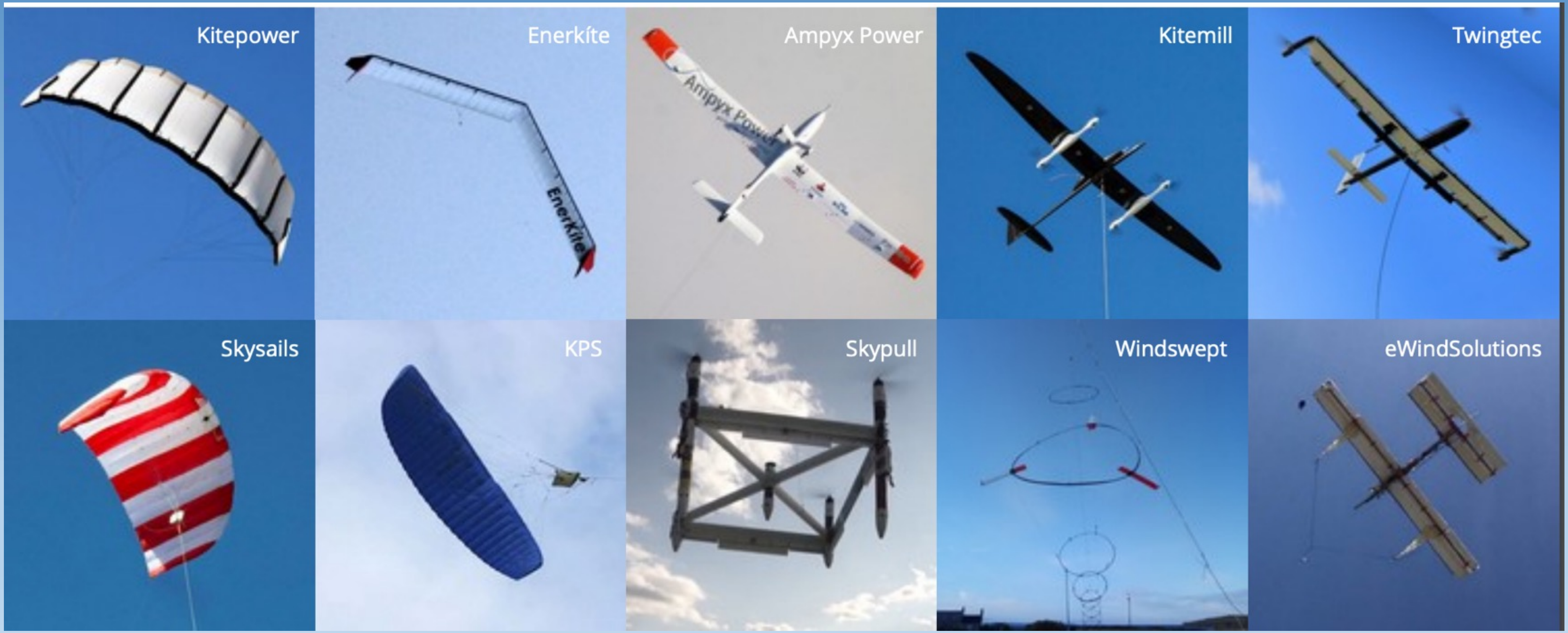
- Multiple floating designs (substructure)
  - Spar-buoy
  - Semi-Submersible
  - Tension-leg platform
  - Barge
- No concept prevailed over the others
  - Pre-commercial: Equinor's spar-buoy concept (Hywind Scotland)
- TRL 4-9

Source: JRC 2020: Technology Development Report Wind Energy, Forthcoming

New concepts for wind energy?

- Floating offshore wind power
  - could use different concepts – however, most currently using state-of-the-art turbines
- Multi-rotor concept?
  - First proposals in 1990's too heavy/costly
  - DTU demonstration with Vestas in 2017 (was dismantled)
    - could use mass production for smaller turbines, easier to transport to site
- Airborne wind
  - Less material, access to high altitude more steady wind
  - But: more complex, requires reliable & robust control, depends on high-performance materials and need to revise current regulatory framework

Airborne wind power – So far demonstrations only of short time periods



Main floating offshore concepts

Stiesdal

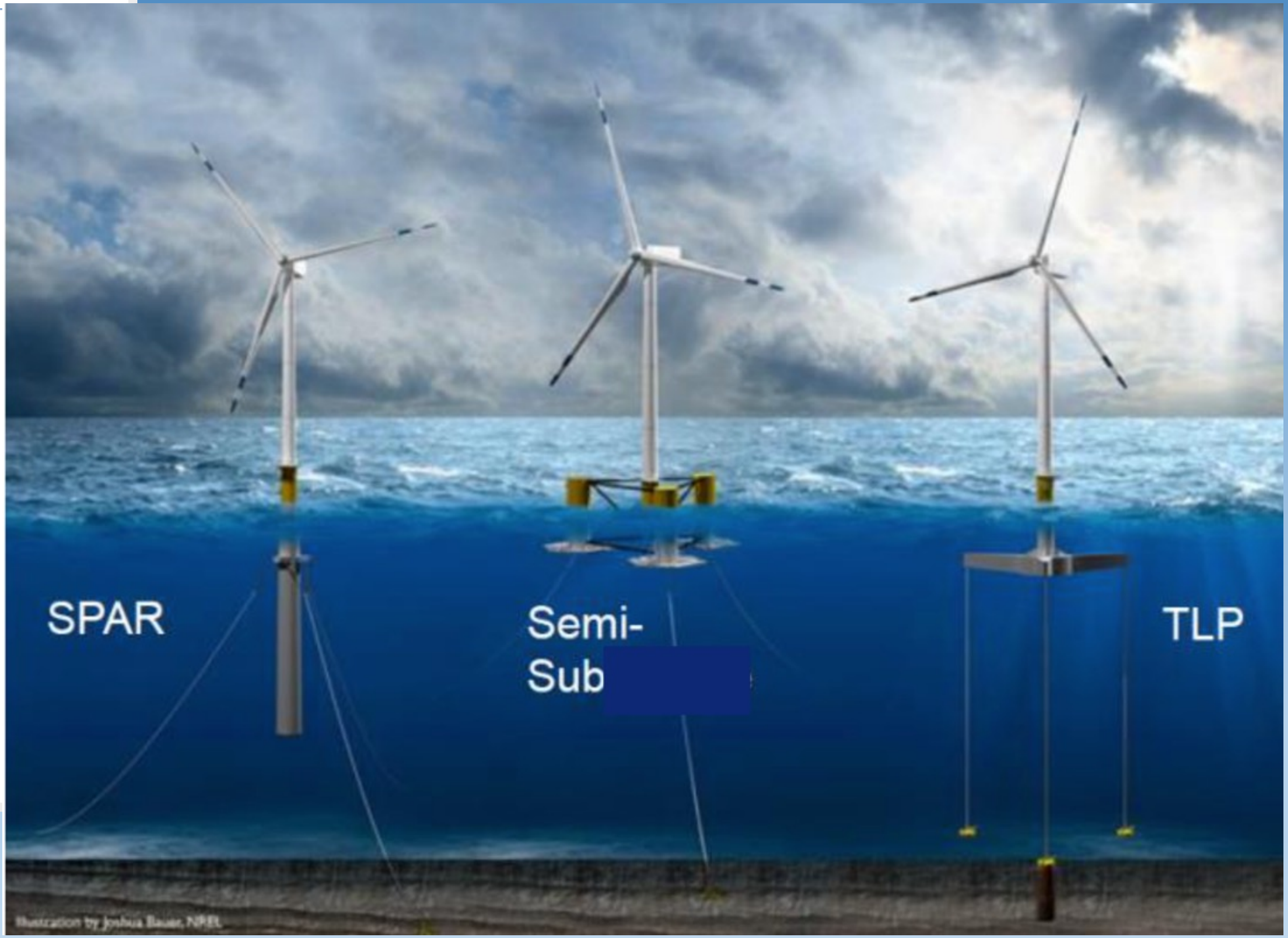
Characteristics of existing and proposed solutions

Shared characteristics
- Very heavy – 2000–6000 tons for 6 MW class turbines
- Construction methods from offshore oil and gas sector
- Fabrication typically at port of floater launch
- Build times typically measured in months

Particulars for steel structures
- Hydrostatic pressure managed with internal braces/stringers
- Tens of thousands of manual welding hours

Particulars for concrete structures
- High weight requires specialized launch arrangements
- High mobilization effort

© Stiesdal 2016, All Rights Reserved



TLP: Tension-leg platform

Aiming for mass production reducing costs

Stiesdal

Introducing a world champion …

The humble wind turbine tower

- Probably the world's lowest cost per kg of any large steel structure
- High quality welds and surface protection
- More than 20,000 towers manufactured annually in highly industrialized processes

How did we get there?

- Separation of fabrication and installation
- Modularization and standardization
- No IP of any significance – costs kept low through open competition

Picture credit: Danish Wind Turbine Manufacturers' Association

© Stiesdal 2016, All Rights Reserved 27

Stiesdal

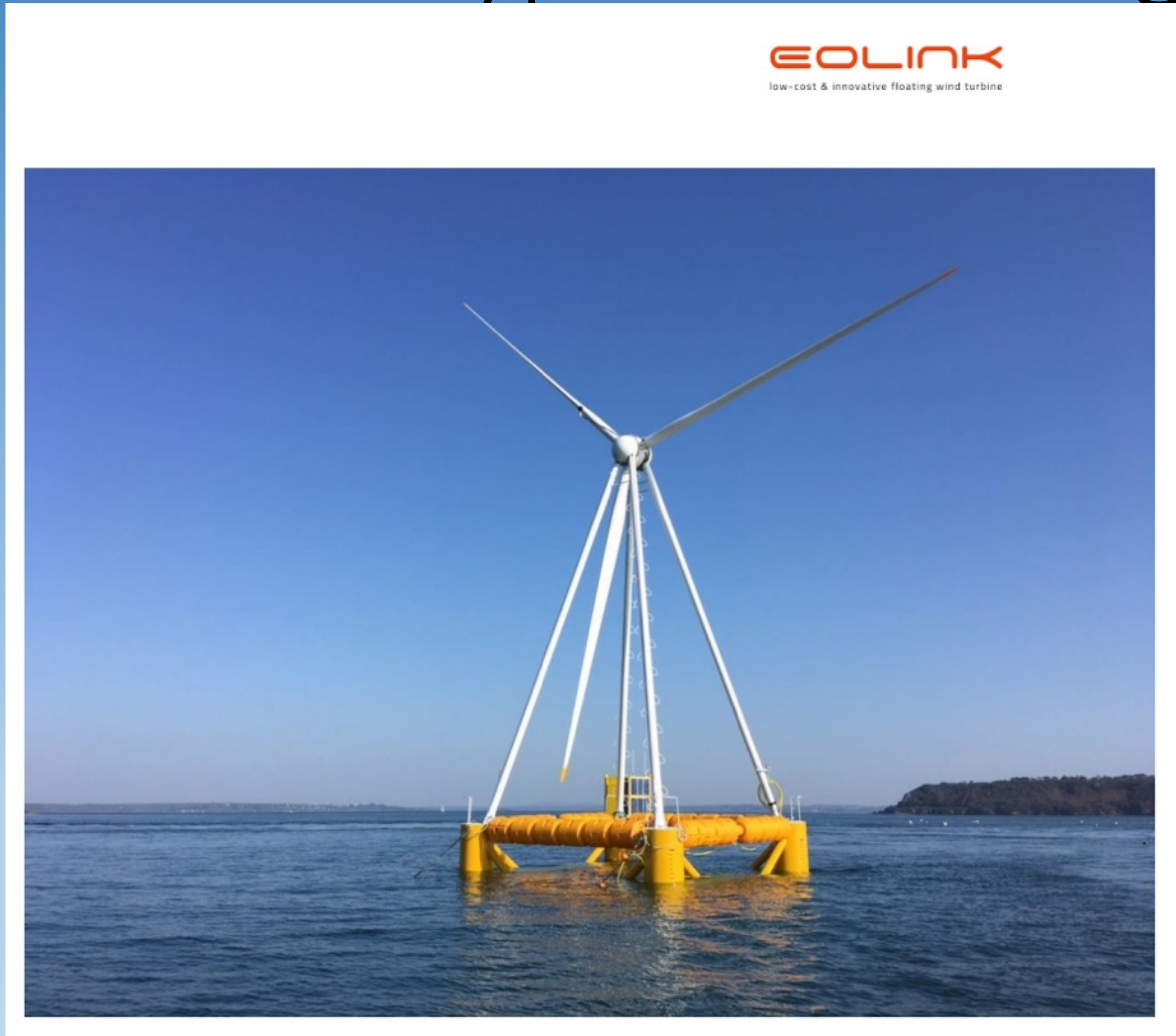
In-Float Concept

Guiding Principles

- Keep it simple!
- Tetrahedral structure with minimal bending moments
- Modular – all components manufactured in factories, no fabrication in harbor
- Components with dimensions and weights known from wind turbines, transported by road
- Components assembled with bolts
- Buoyancy with pressurized tanks – lightweight structures with no need for dimensioning to hydrostatic pressure

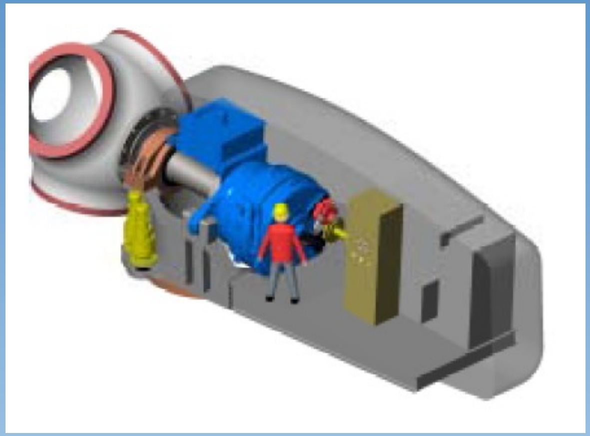
© Stiesdal 2016, All Rights Reserved 28

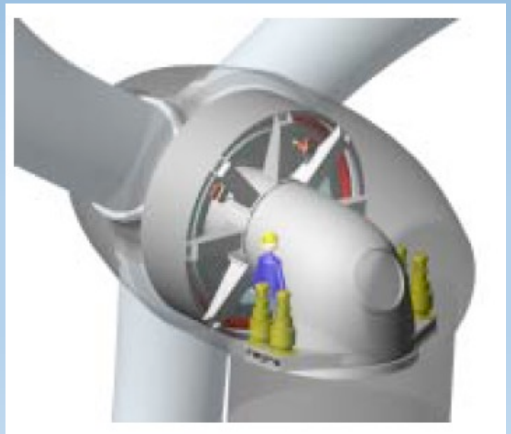
New types of floating offshore - France



Lot of innovation to be seen in components of the current 3 bladed industry concept

- Blades: new/smart materials, aerodynamic/aeroelastic improvements, modular or integrated solutions
- Drive train concepts: gearless generators, one-stage gearbox with slowly rotating gearbox, several generators. Using frequency converter. Integrated designs
- Towers: managing loads, smart structures, more slender structures, offshore: managing wave/wind/ice loads
- Foundation: new designs for deeper sea (<50m),



More and more controls

also controlling the inverters for grid support -together with flow control

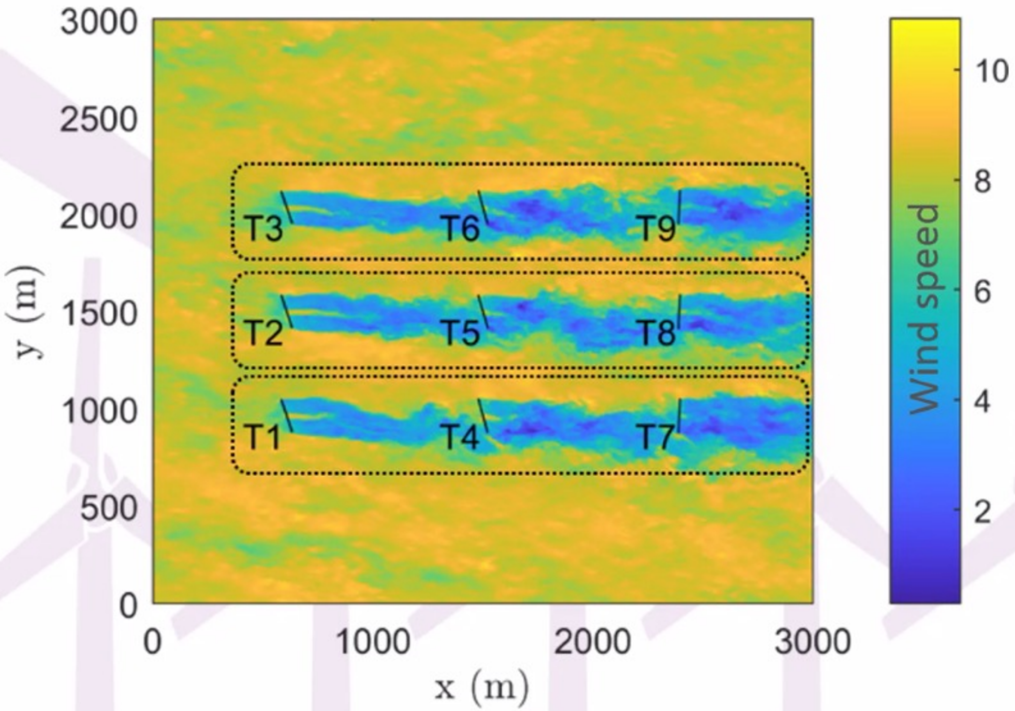
Wind farm flow control

Coordination of the actions of individual turbines in a farm

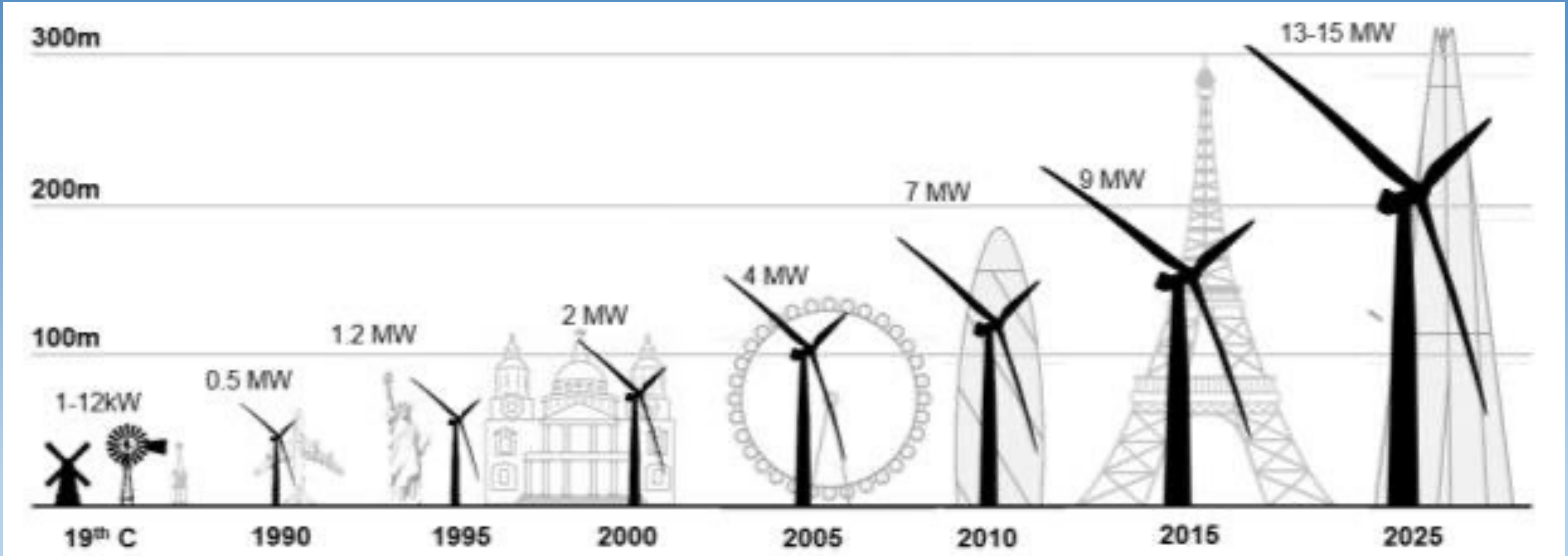
for the purpose of **improving inter-turbine aerodynamic interaction**

to better the overall farm power production

and/or reduce or distribute the structural loading among wind turbines



Turbine size increase trend



Source: Bloomberg New Energy Finance BNEF

.

Offshore: Siemens 14 MW pilot with a 222-m rotor diameter SG 14-222 DD Nov-21 at Österild test centre, Denmark. Vestas V236-15MW launched, installation in Nov-22 at Österild test centre

Drivers for wind turbine upscaling

The following rationale has proven true in the past:

- Higher power per turbine results in **fewer individual turbines** per MW, reducing costs in:
  - Balance of system
  - Operation & Maintenance
- Higher turbines reach **higher winds**, increasing yield

Source: Raul Prieto, VTT

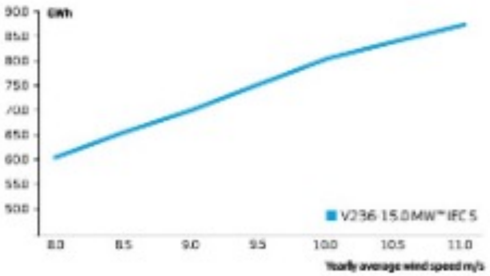
V236-15.0 MW™

Facts & figures

Source : Vestas

POWER REGULATION	Pitch regulated with variable speed
OPERATING DATA	
Rated power	15,000 kW
Cut-in wind speed	3 m/s
Cut-out wind speed	30 m/s
Wind class	IEC S or S,T
Standard operating temperature range	from -10°C to +25°C* with a de-rating interval from +25°C to +45°C
	*high ambient temperature variant available
SOUND POWER	
Maximum	118dB(A)
ROTOR	
Rotor diameter	236 m
Swept area	43,742 m²
Aerodynamic brake	three blades full feathering
ELECTRICAL	
Frequency	50/60Hz
Converter	full scale
GEARBOX	
Type	three planetary stages

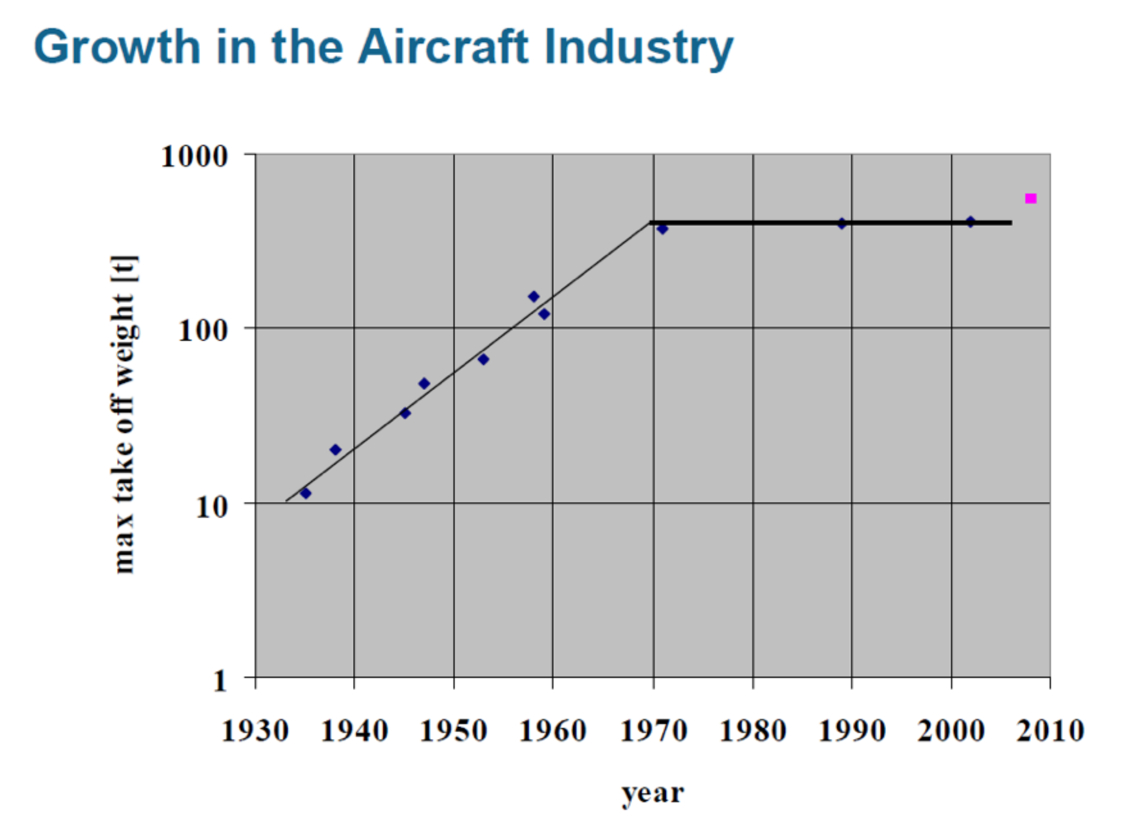
ANNUAL ENERGY PRODUCTION



Siemens Gamesa's SG 14-222 DD prototype offshore wind turbine installed at the test centre in Østerild, Denmark
Source : offshorewind.biz Dec 10, 2021

Challenges in wind turbine upscaling

- According to the **Square-Cube** law, by doubling the size of a wind turbine
  - the rotor area changes x 2^2 (and power), but the mass changes x 2^3
  - the overall design efficiency in terms of annual-energy / top-head-mass **divides by 2**
- **This unfavourable increase of weight per energy is the square cube law**
- In practice the Square-Cube law has not fully applied in wind until now because:
  - By increasing the size of the wind turbine we are also reaching **higher heights**, with better winds
  - **So far technological progress** has continuously reduced the mass of components in succesive wind turbine design generations



Source: DNVGL – P. Jamieson "Evolution of wind technology" Supergen Wind Training Seminar

Source: Raul Prieto, VTT

Challenges in upscaling

Offshore Project cost MEUR/MW

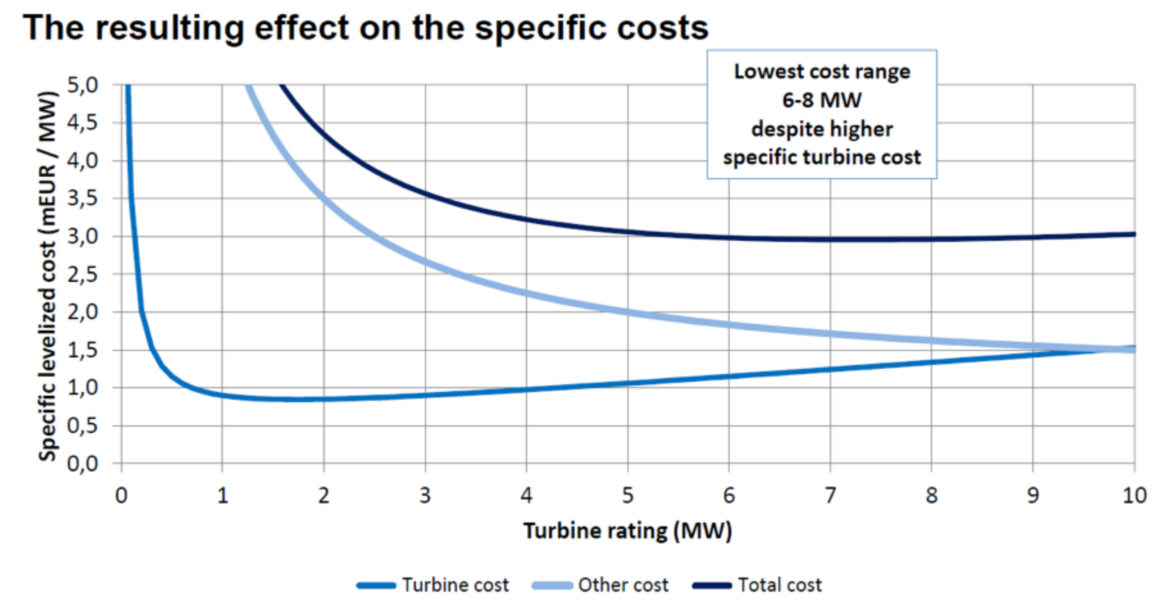
- Lowest cost range at 6-8 MW or 3-5MW depending on assumptions of future cost of balance of plant:
  - If we assume a signifficant reduction of cost of balance of plant, then the optimal band would move to 3-5MW
  - .. which by the way would also allow other players into the offshore wind market, with second round effects (lower turbine costs due to higher competition)

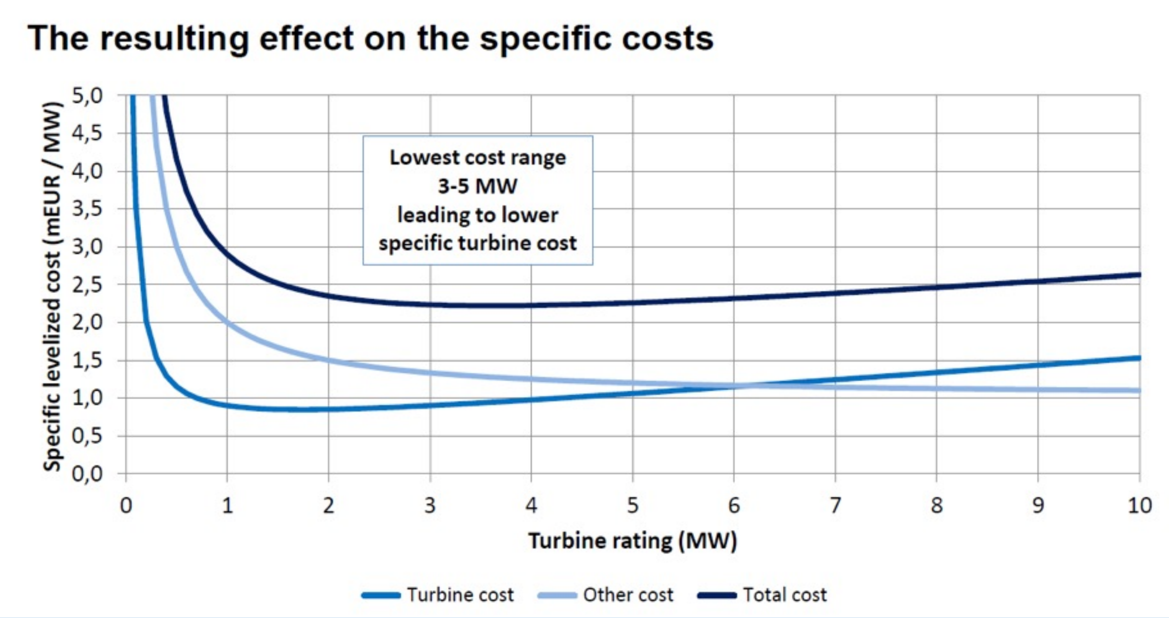
Still to be proven that next generation ~12MW is more cost effective.

- Market dynamics also important

The square-cube law will limit the size at some point

Source: Raul Prieto, VTT

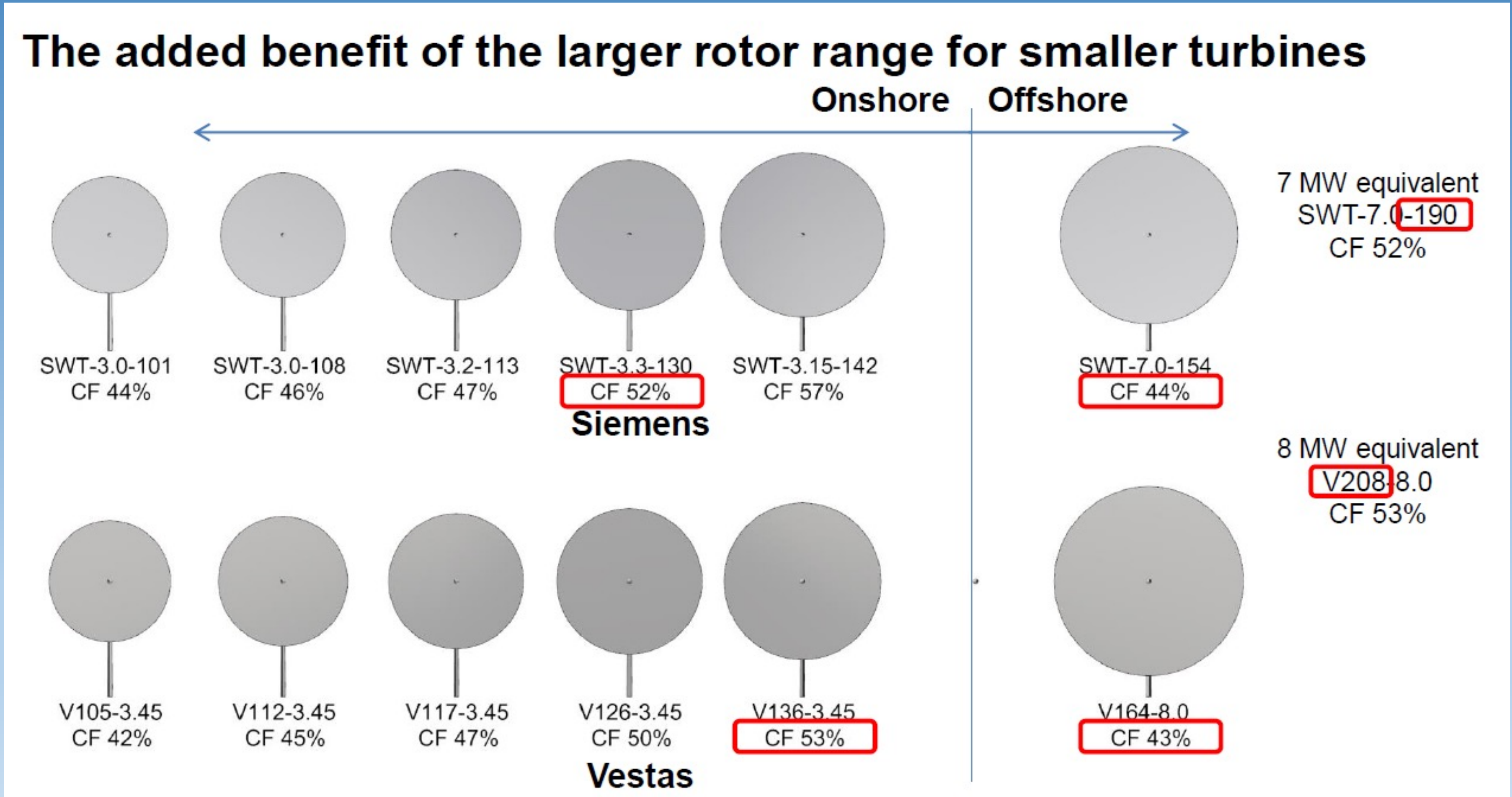




Source: Henrik Stiesdal (Stiesdal A/S. 2016)

Challenges in upscaling

Capacity factors in onshore and offshore turbines

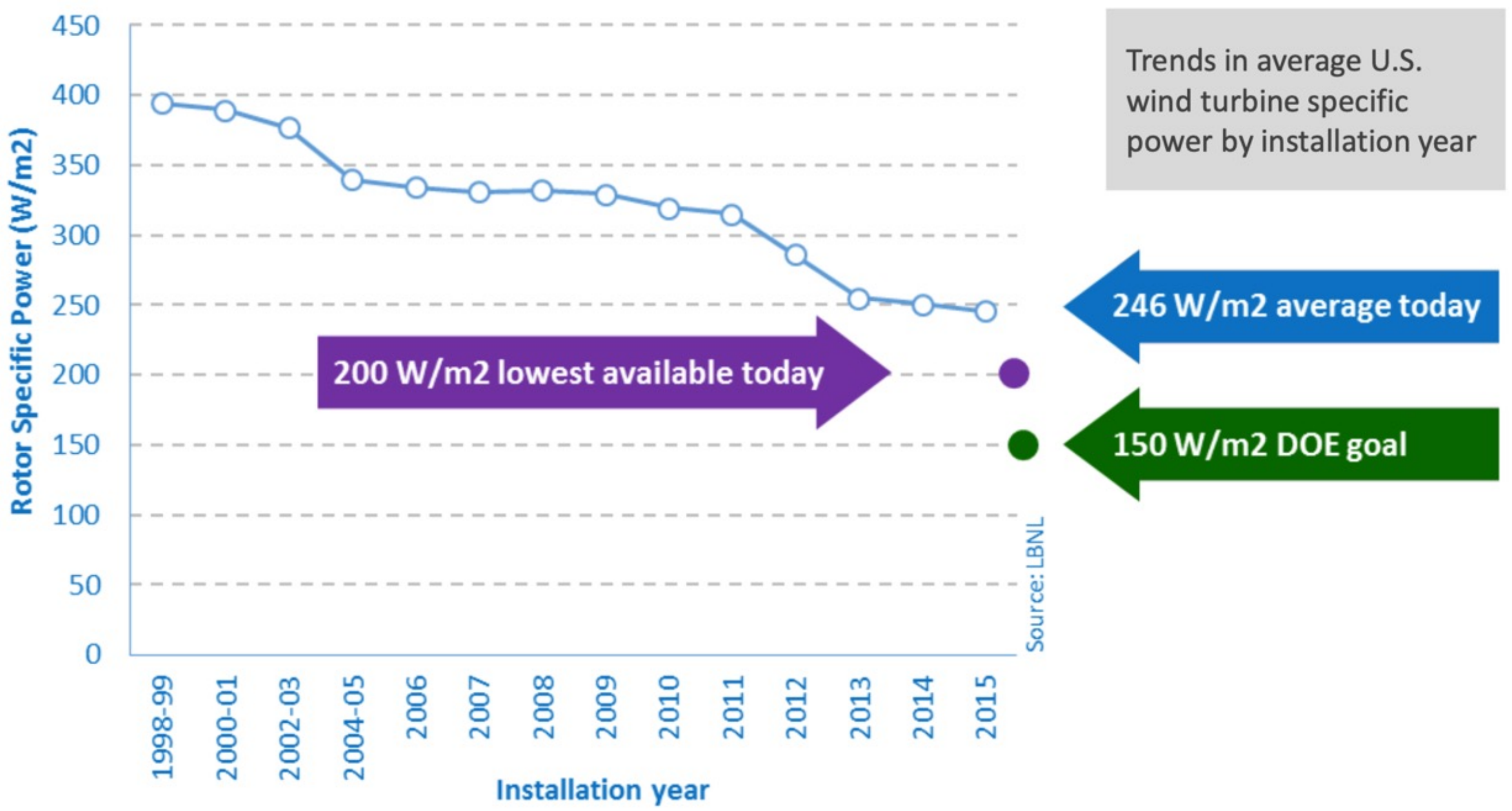


Source: Raul Prieto, VTT

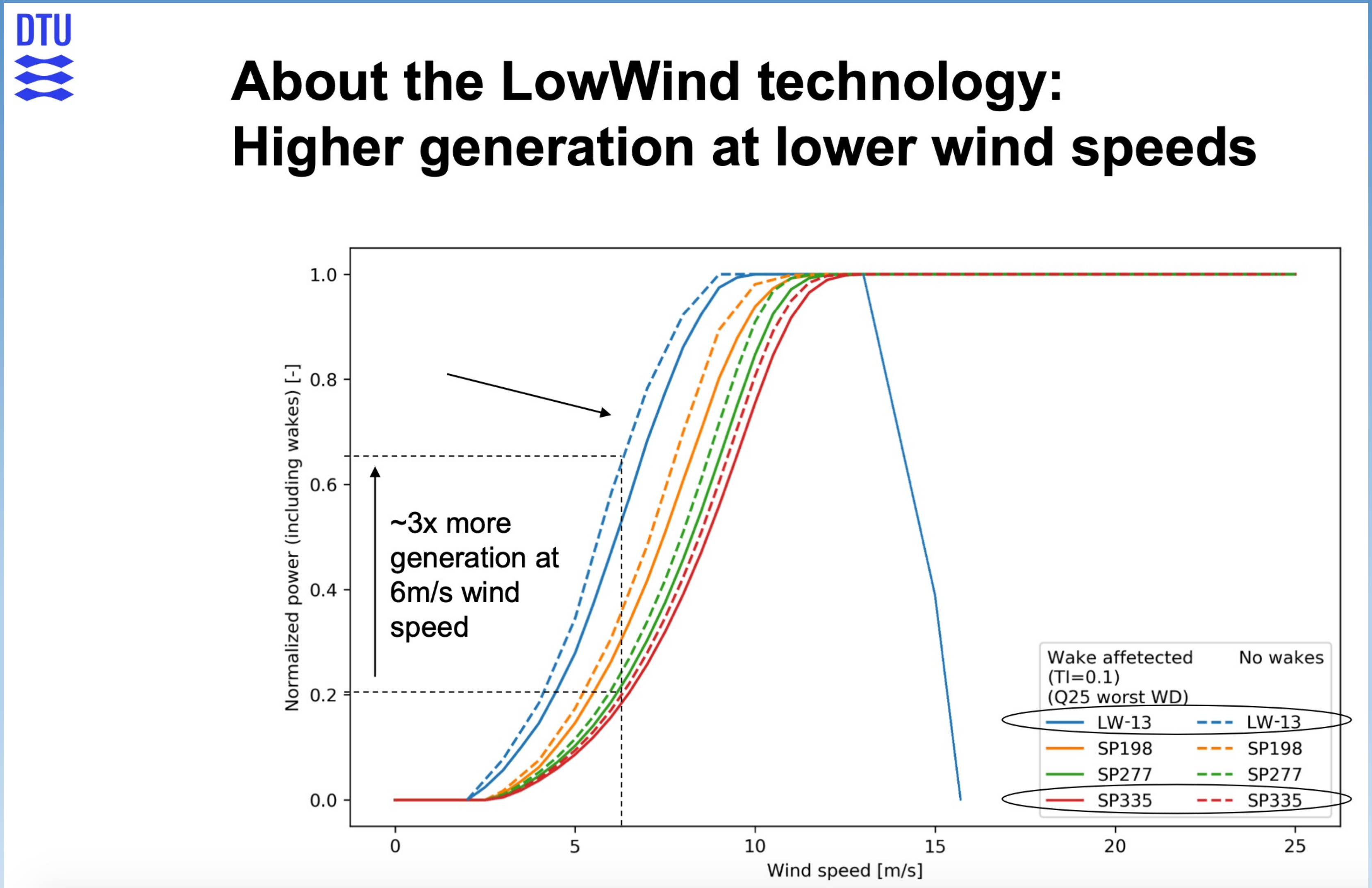
Source: Henrik Stiesdal (Stiesdal A/S. 2016)

Towards lower specific ratings – larger rotors

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



Turbines that produce mostly at low winds –when other turbines not producing much

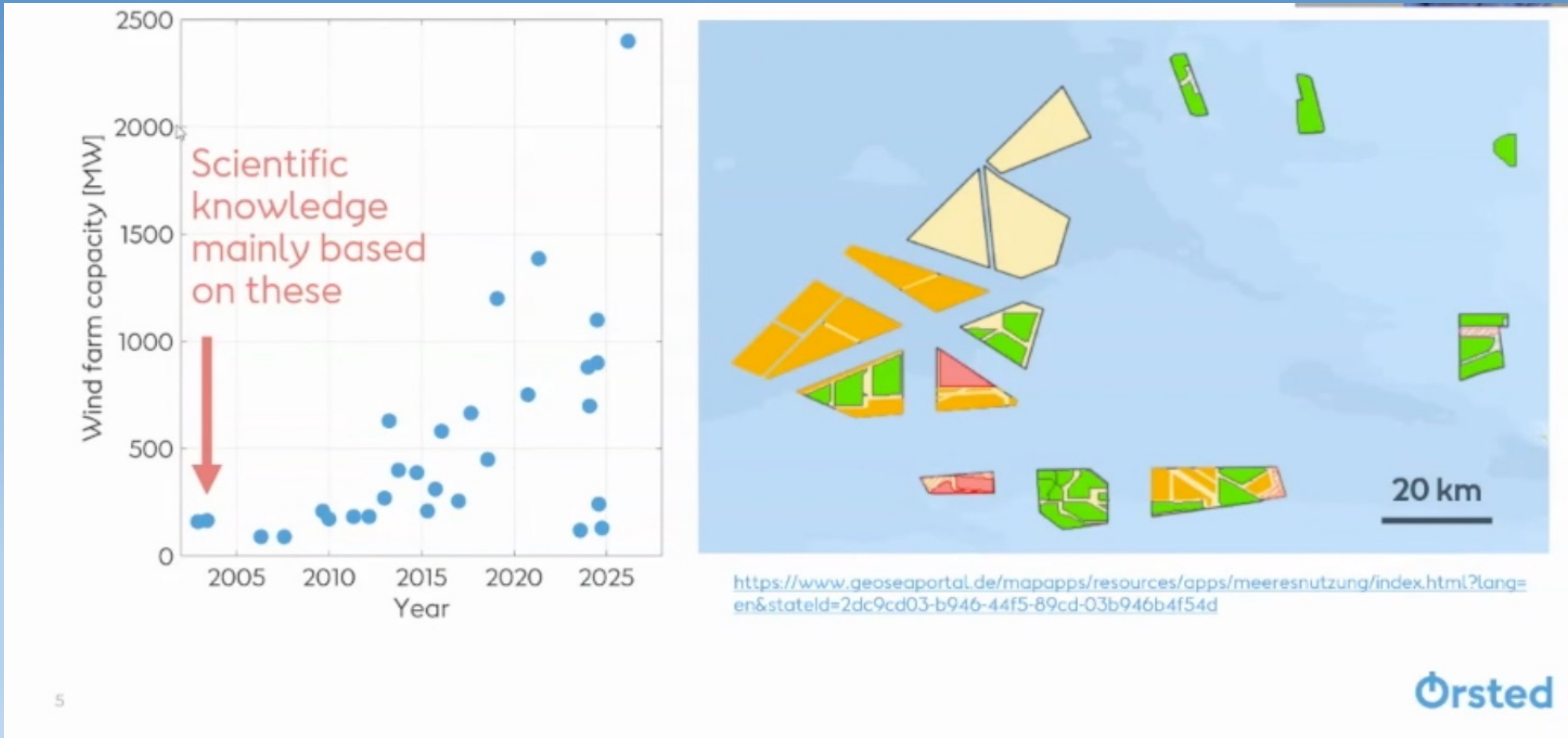


Addressing future systems where market value of wind will be close to 0 during windy days – diversifying the capacity
(same idea for solar PV: part of the panels facing North /East /West, not South

Source: DTU LowWind project

Wind power plant size challenge especially offshore

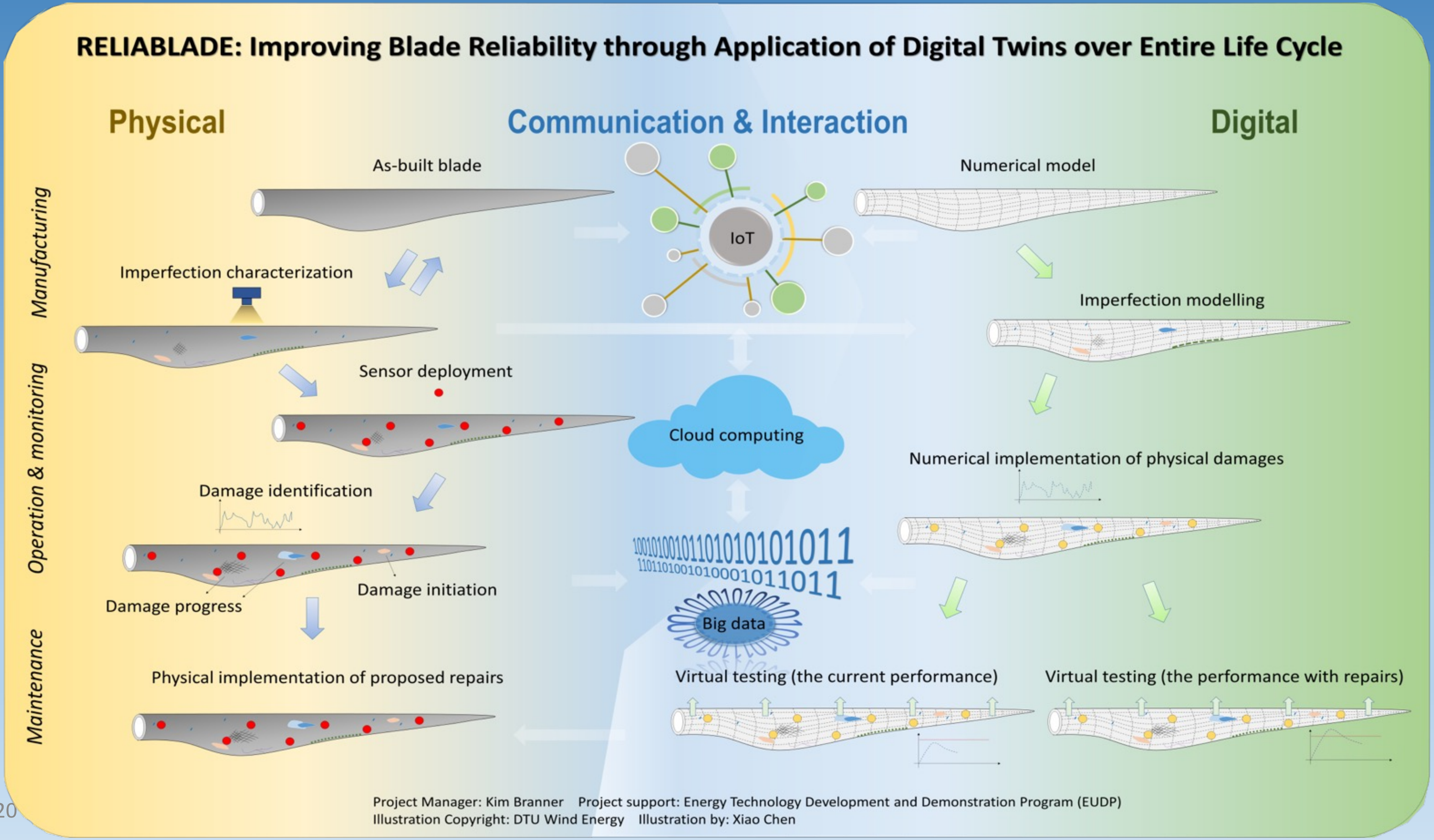
- wind speed measuremens – streching ability to extrapolate, quantifying uncertainty
- wakes, also btw countries



O&M, End of Life / Life extension

- O&M trends towards using predictive maintenance, condition monitoring, and digital twins
- These needed for component replacements, but also to determine when to take down the turbines and replace
- Siemens announced 35 year life time in 2021

Digitalisation – digital twins



Types of Data Useful for Life Prediction

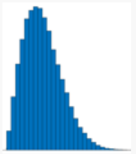
A detailed procedure for remaining lifetime estimation may require:

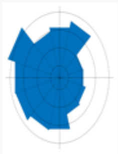
Wind turbine specification
- rotor size
- hub height
- rated power, rpm

IEC design class
- Reference conditions used for design

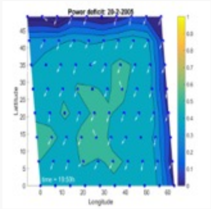
Farm layout
- Turbine positions
- Bathymetry

Site-specific climate conditions
– wind speed, direction, turbulence

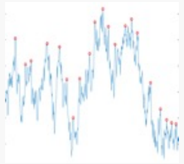




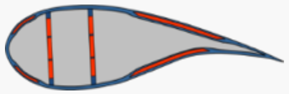
Farm model
- Wakes



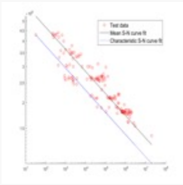
Dynamic model
- aerodynamics
- component weights and stiffness
- controller



Detailed component models
- geometry
- component stresses

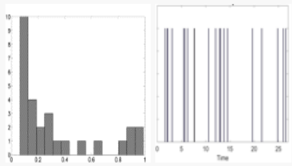


Material degradation model
- fatigue rule (S-N)
- influence of defects



Maintenance history
- component repairs

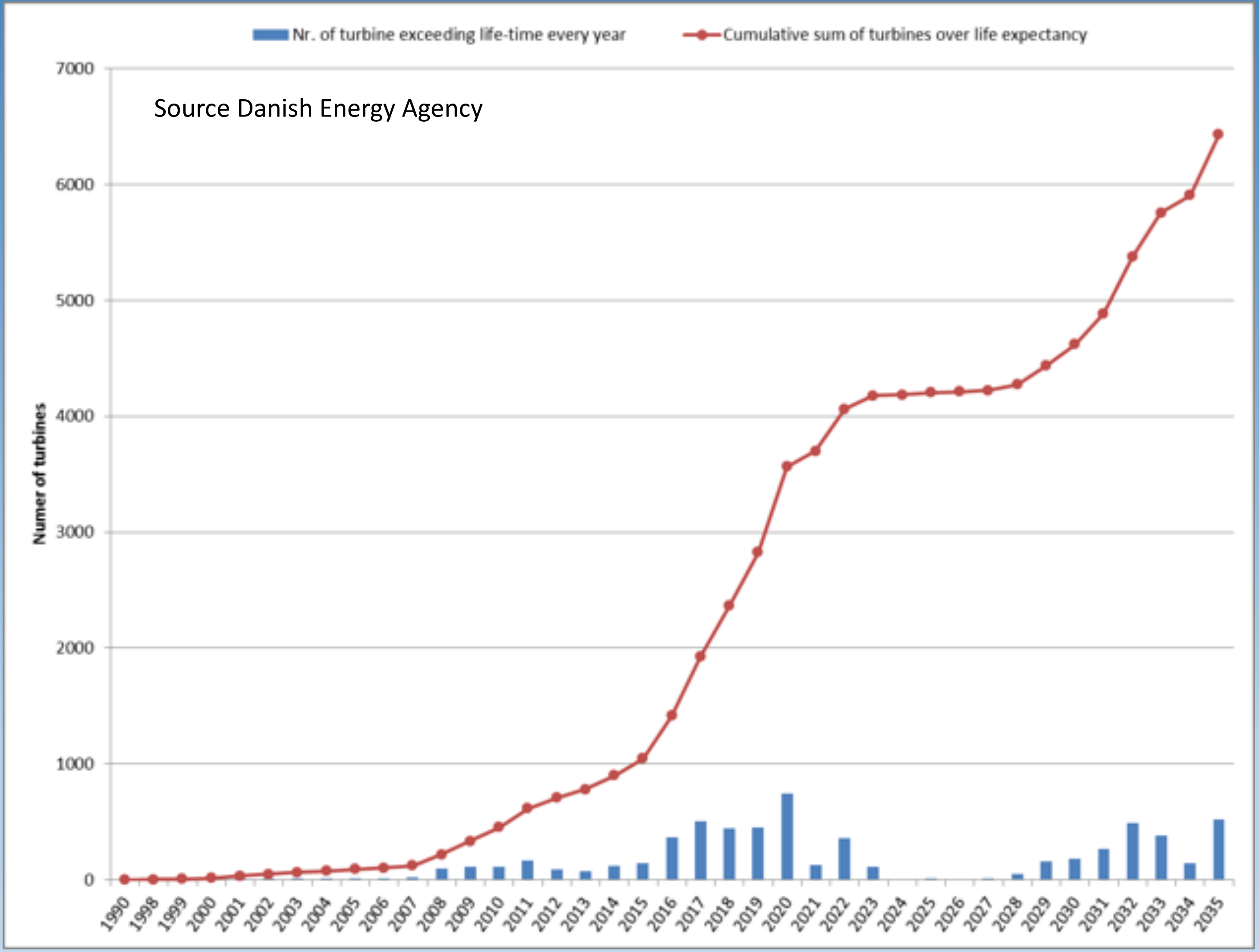
Operating history
- grid connection
- curtailment
- shutdowns



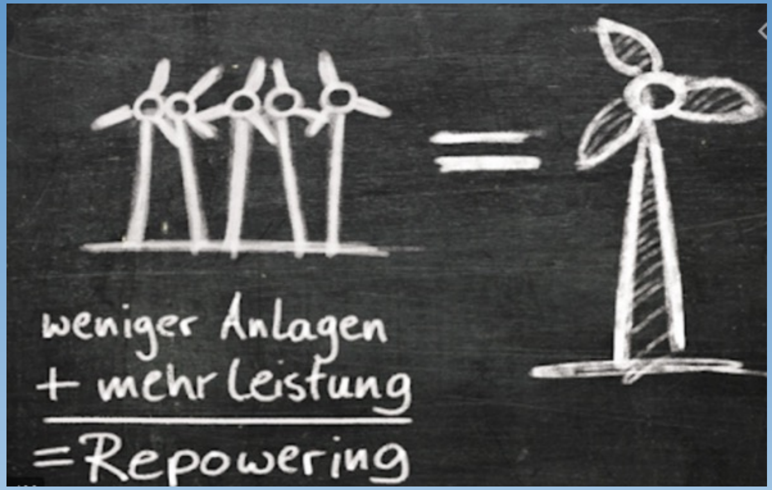
https://iea-wind.org/

Source: IEA Wind Task 42 – Wind Turbine Lifetime Extension

Repowering

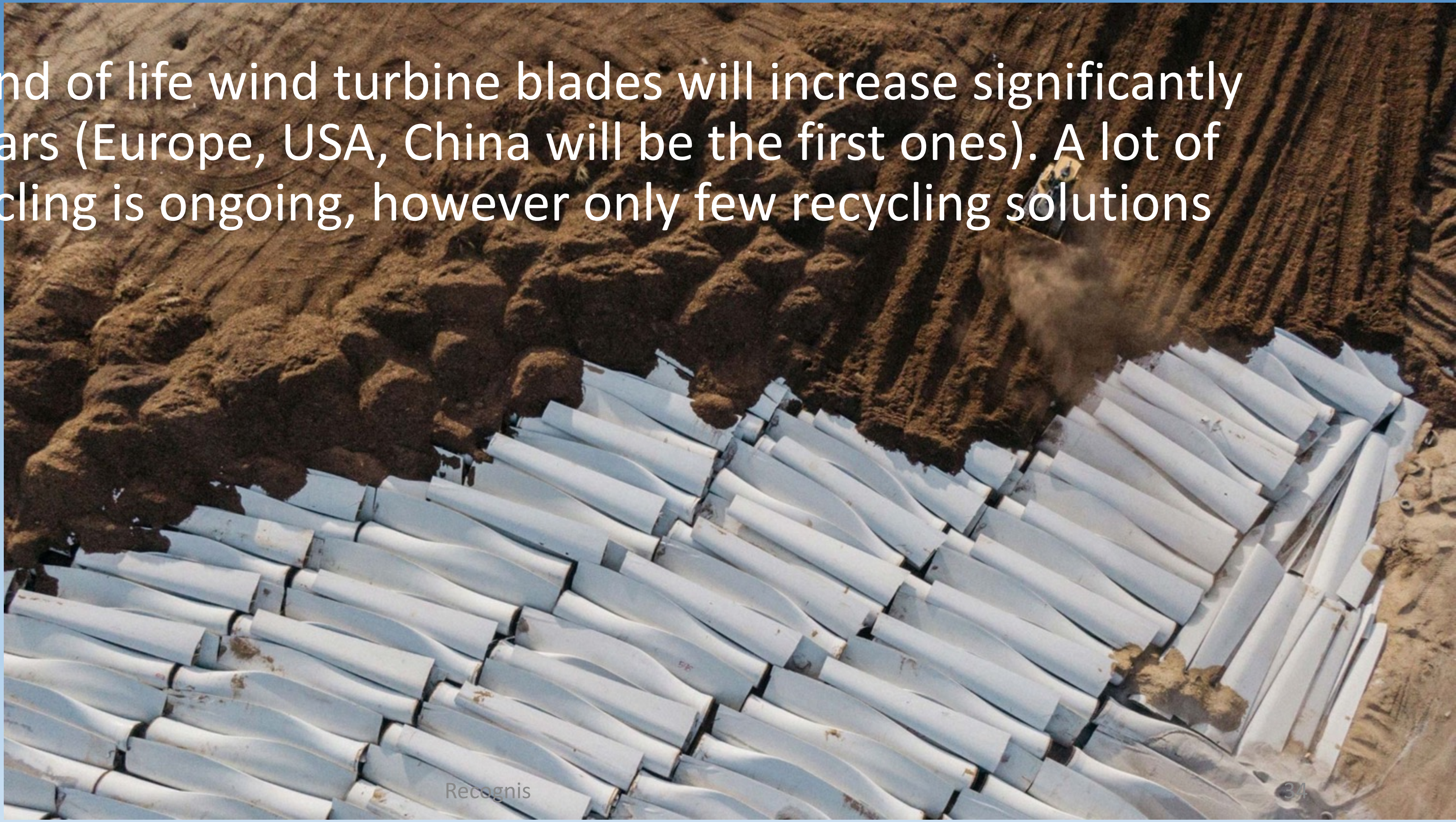


Turbines exceeding 20 years in Denmark



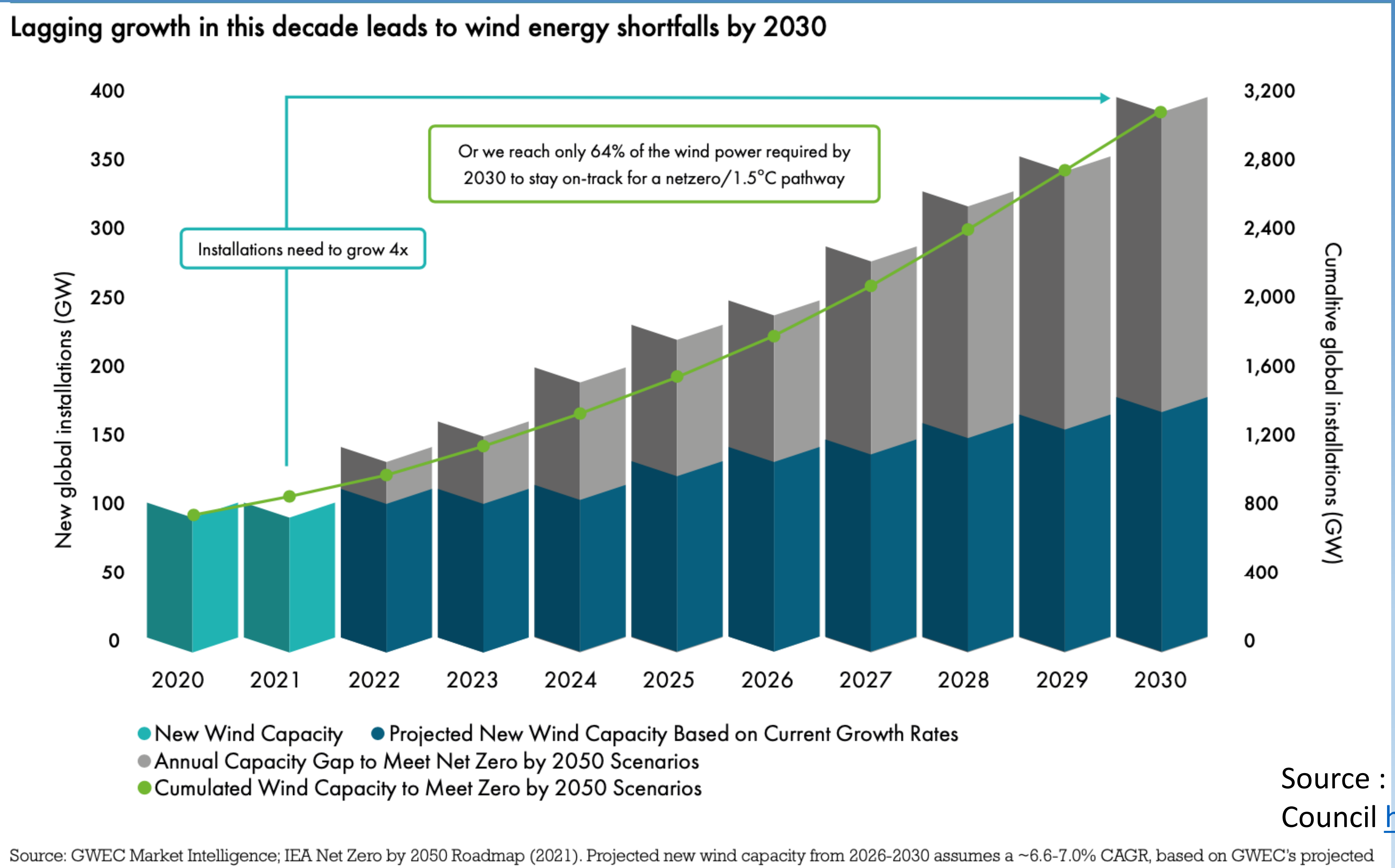
Materials - Recycling

The amount of end of life wind turbine blades will increase significantly in the coming years (Europe, USA, China will be the first ones). A lot of research on recycling is ongoing, however only few recycling solutions are available



- Technical aspect of recycling,
- Analysis and value chain
- Legislations, standards and certifications

Stepping up deployment to meet targets



Energy crisis and war adding urgency and ambition to targets, set for mitigating climate change.

2022: EU REPowerEU Action plan, strategic plan for reducing Russia's fossil fuel imports and accelerating the growth of renewables: Europe's wind energy to grow from 190GW to 480GW by 2030

Source : Global Wind Energy Council http://gwec.net/

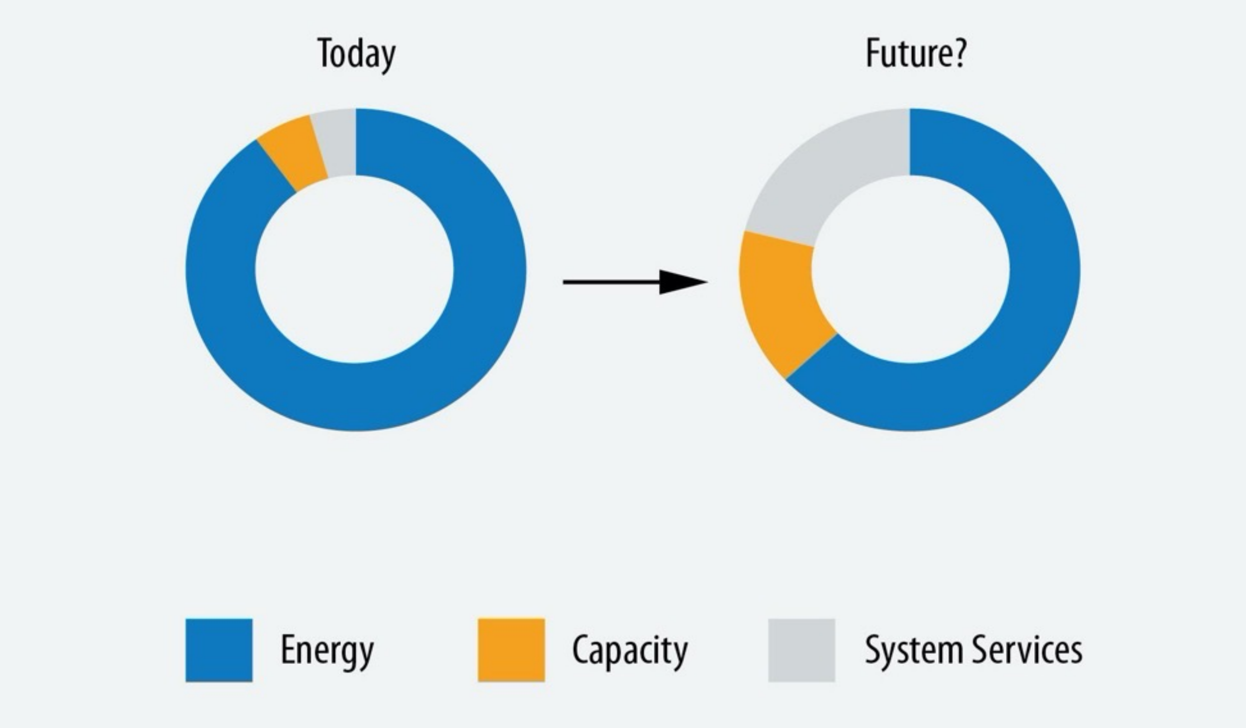
A Grand Vision for Wind Energy

IEA Wind Grand Vision for Wind Energy explores a future scenario of 80% of the world electricity supply coming from renewables – a paradigm shift in system architecture, technologies and markets

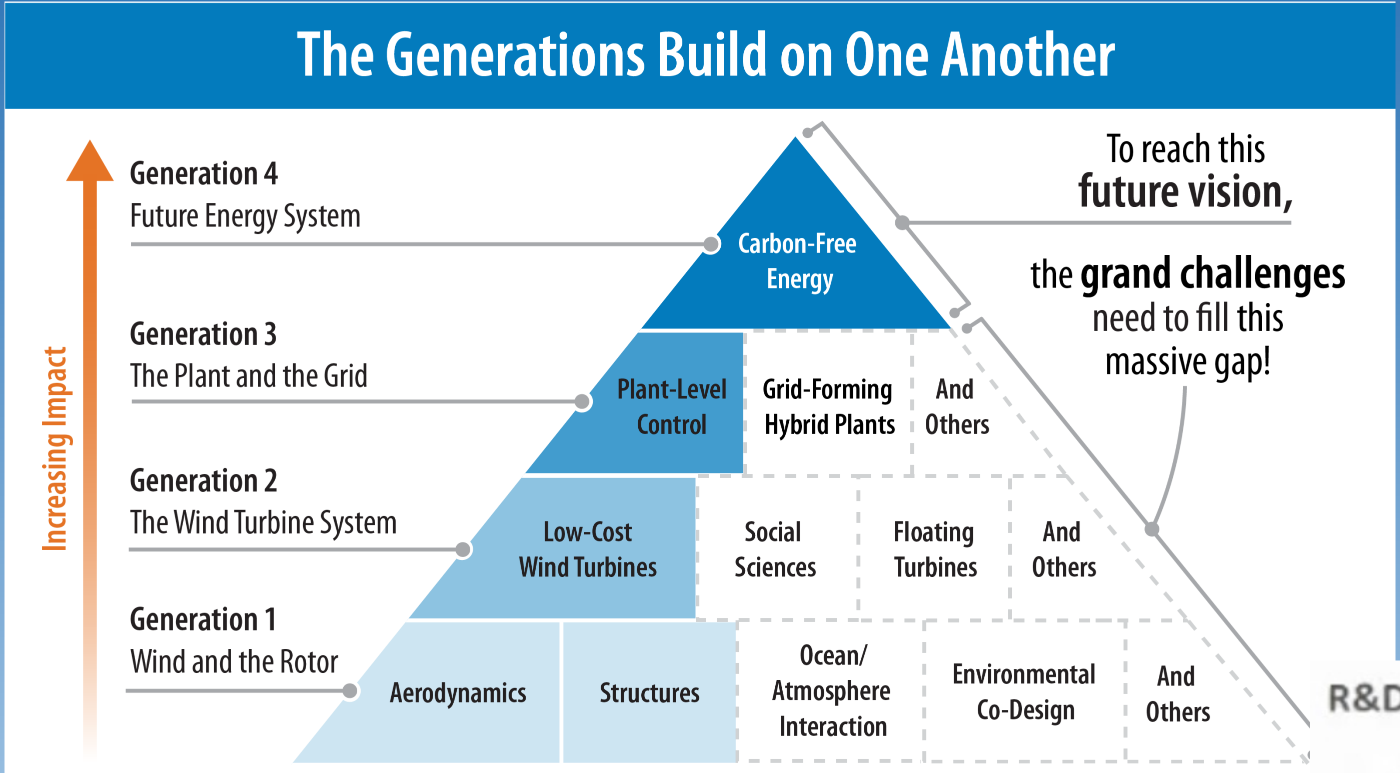
Success of wind energy in the future:

If storage, power-to-x ubiquitous, highly elastic demand, then do nothing, focus on cheap electrons (**LCOE**)

If dispatchability, capacity value dominate revenue, then rethink options and increase value of wind energy (**Beyond LCOE**)



Future electricity system market structure (Source: Dykes et al 2019 based on Ahlstrom et al 2015)



Graphic by the National Renewable Energy Laboratory

Grand Challenges for Wind Energy Science, 2019, Available at IEA TCP WIND publications site, now https://iea-wind.org

Veers, P, et al (2022) Grand Challenges: Wind energy research needs for a global energy transition. Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2022-66 Preprint in https://wes.copernicus.org/preprints/wes-2022-66/wes-2022-66.pdf

R&D Challenges

- Atmospheric Science
- Wind Plant Aerodynamics
- Technology Development
- High-penetration Grid Integration
- Siting and Environmental Impacts

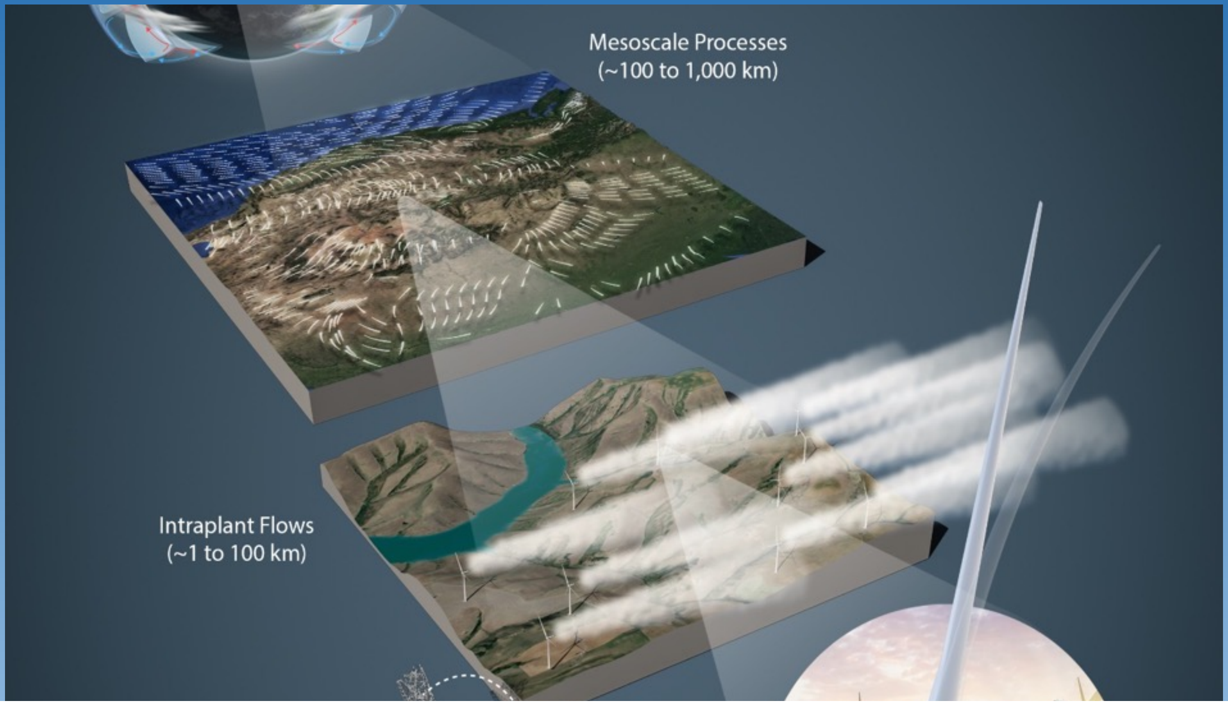
R&D Challenges

- High Fidelity Modeling
- Design Tools
- Further scaling
- Floating Offshore coupled turbines/foundations
- Controls
- Design for End of Life

R&D Challenges

- Bird and Bat Collisions
- Construction Noise
- Habitat Changes
- Radar Interference

Grand Challenge #1: Mastering the physics of resource from the atmosphere to the intra-plant flows

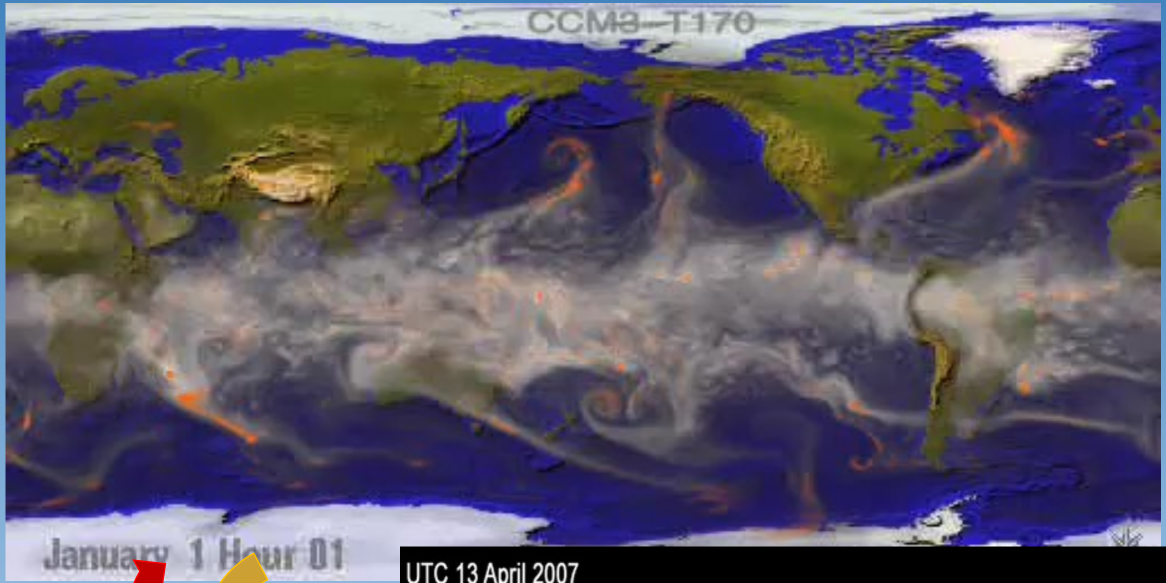


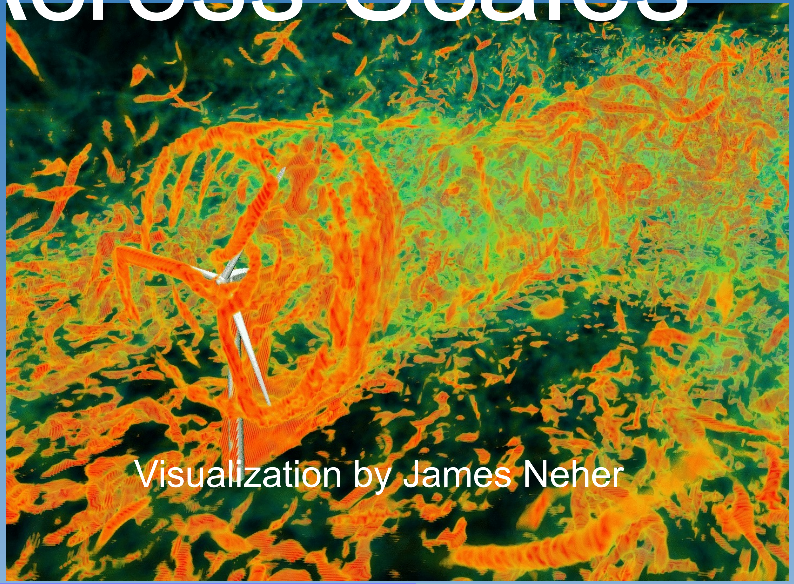
Source: NREL

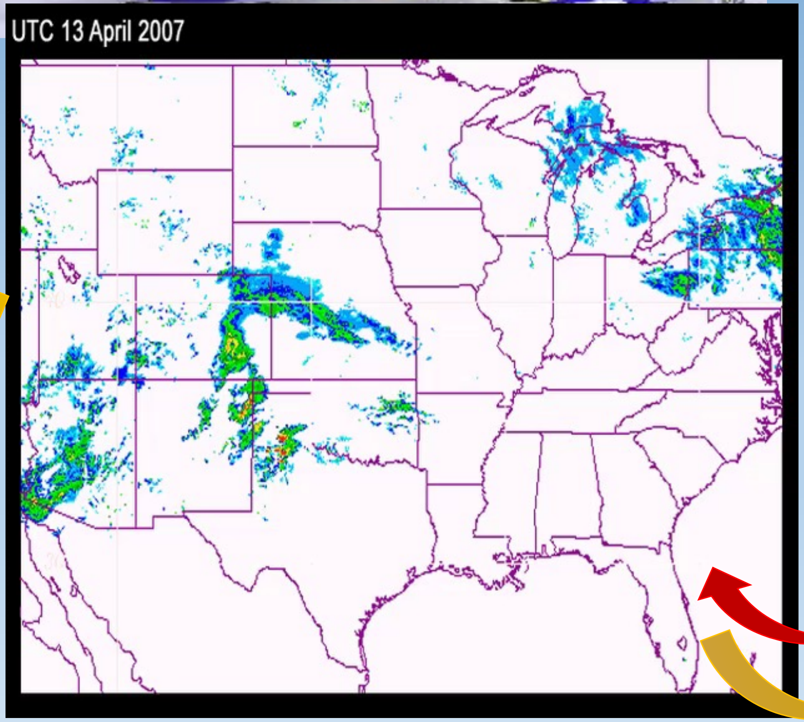
Key Issues

- The **size of modern wind turbines places them in a scientific "grey zone"**; this grey zone persists in part due to lack of measurements
- **Computer models** for the micro and meso scales around this zone **are of completely different character**
- Turbulence, shear, veer, and other **effects are uncharacterized, yet they weigh heavily productivity, reliability**, and ultimately cost of energy
- **Wind plant wakes become increasingly important** as deployment continues and capacity accumulates in a given location

Forcing and Transfer of Energy Across Scales



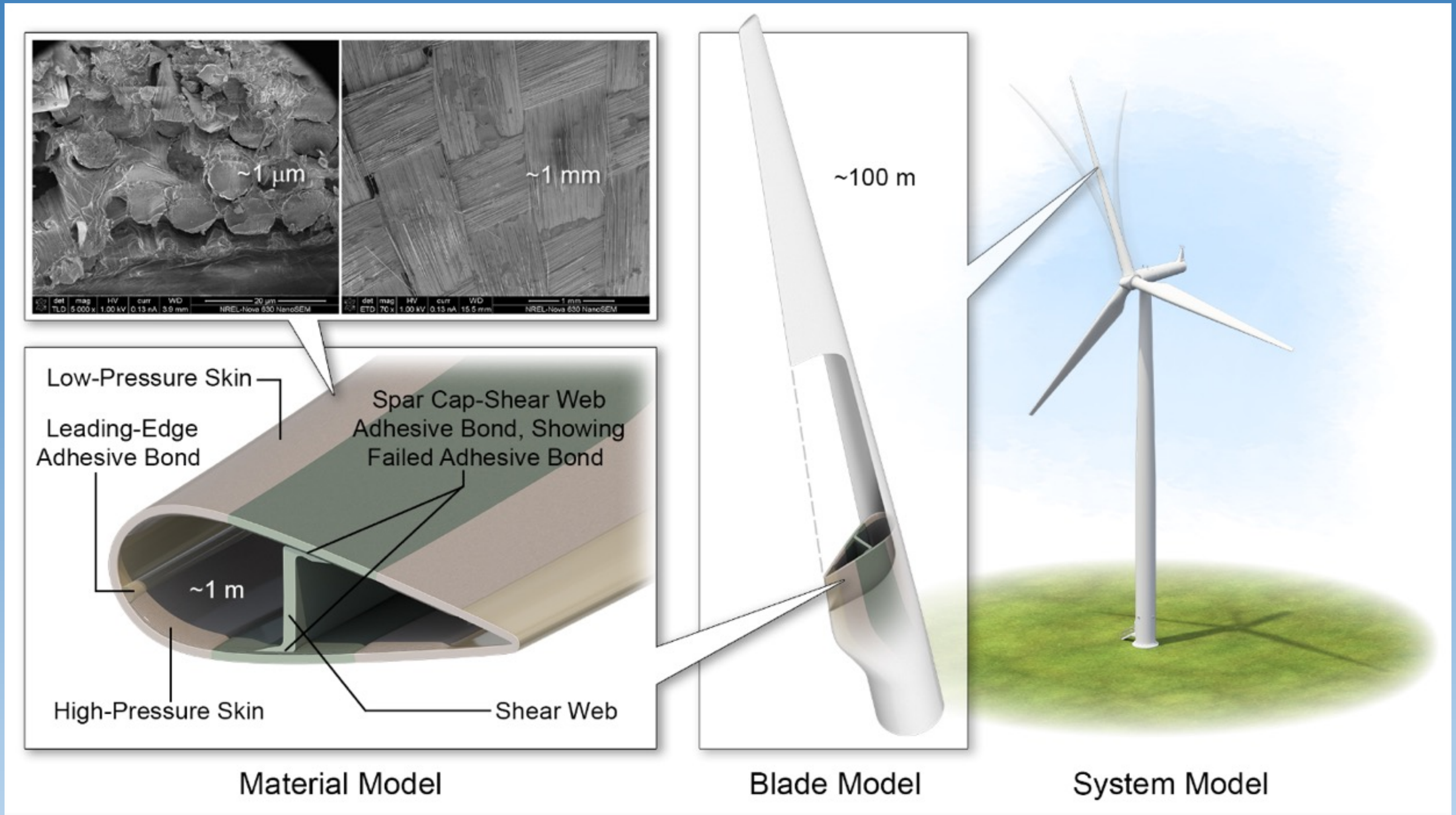




Courtesy Sue Haupt of NCAR and colleagues

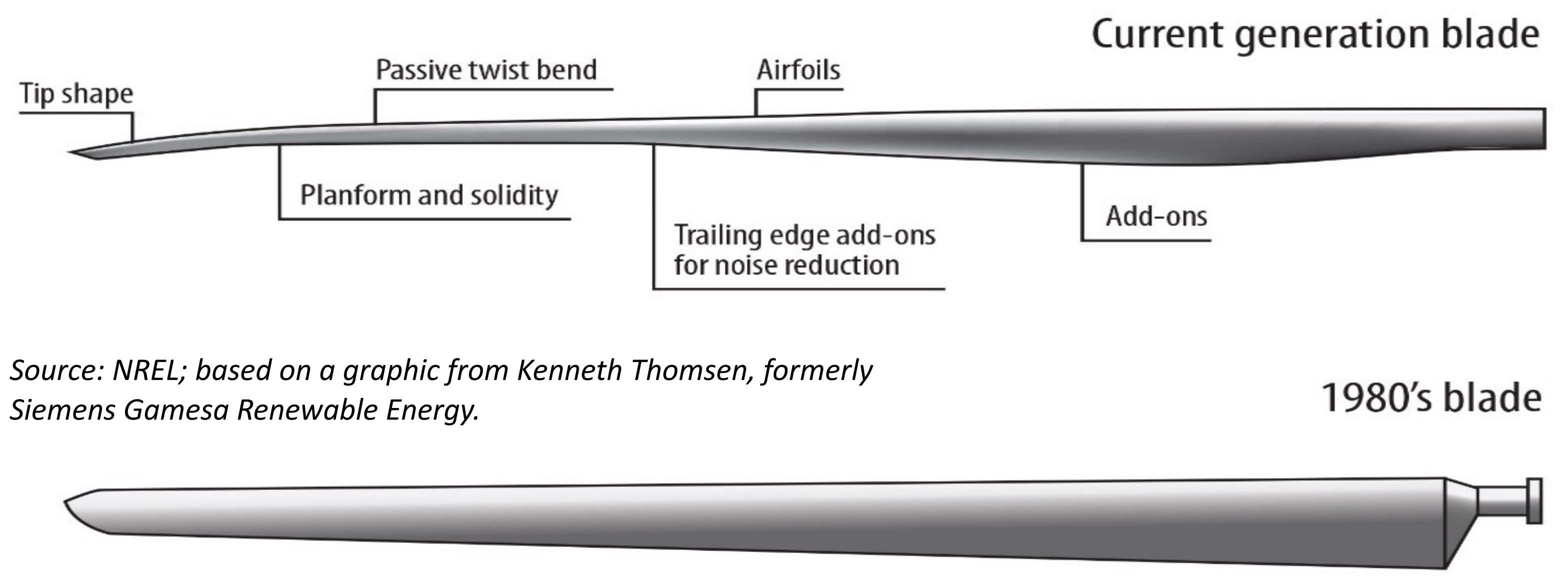
Courtesy Jeff Mirocha, LLNL

Grand Challenge #2: Characterizing the structural, aero and hydrodynamics of some of the largest standing structures ever built coupled with access to the most advanced material properties at commodity prices



Source: NREL

Grand Challenge #2

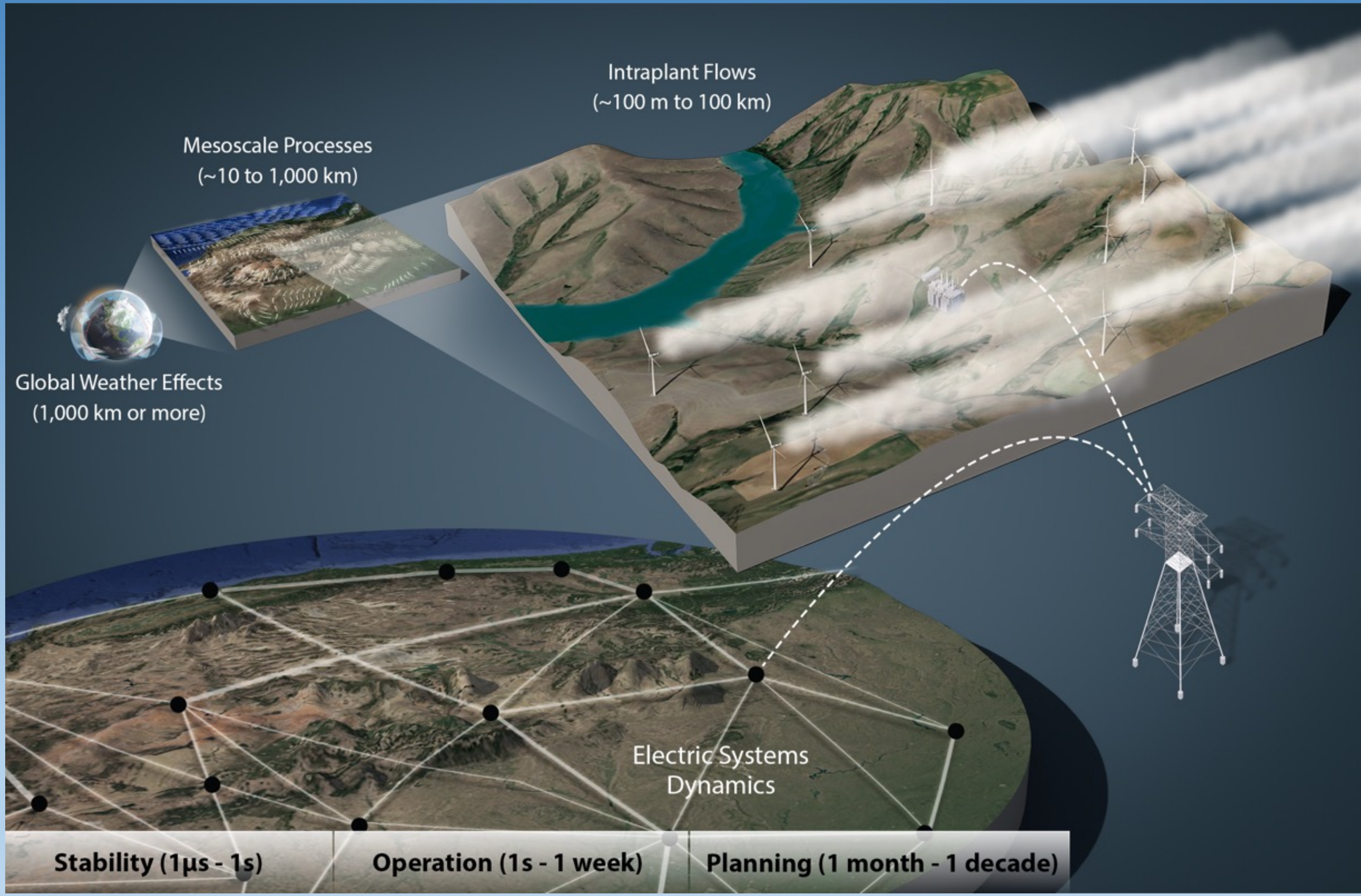


Source: NREL; based on a graphic from Kenneth Thomsen, formerly Siemens Gamesa Renewable Energy.

Key Issues

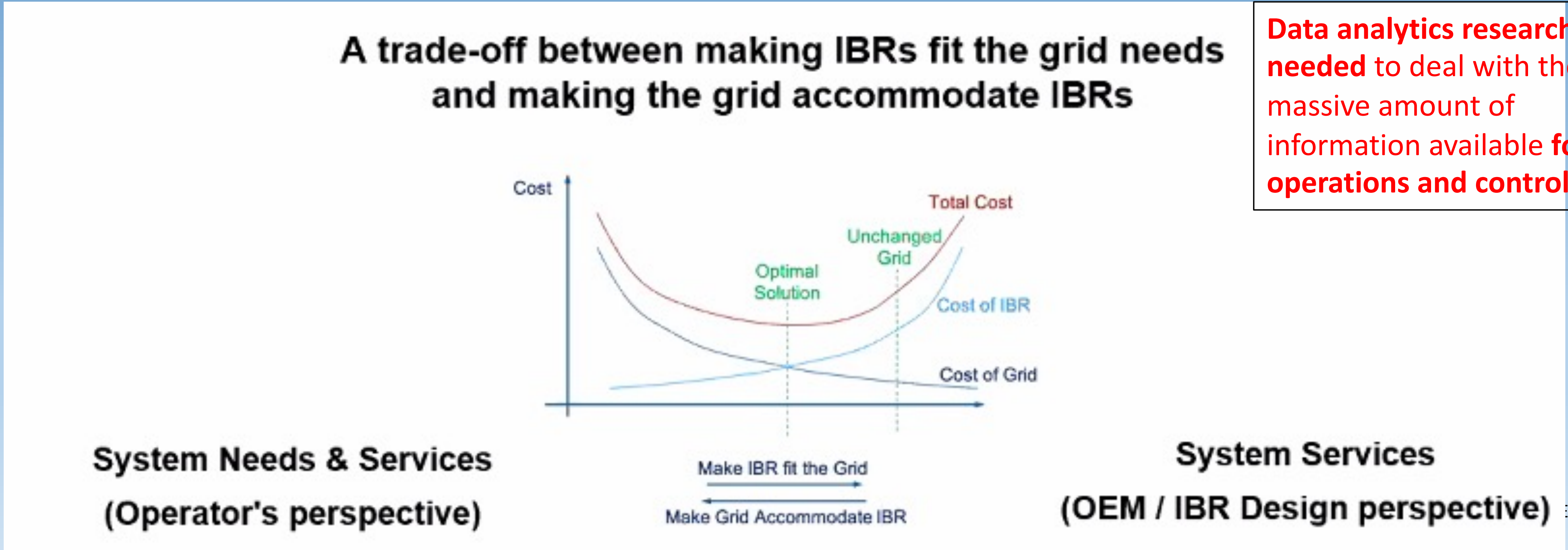
- Turbines **scaling continues to support LCOE** reduction
- Turbine designers are **moving closer to stability boundaries** not of concern at smaller sizes
- Experiments at DTU show that the **aerodynamics at these scales begin to change**
- **Existing design criteria may not represent atmospheric conditions** at these larger scales
- **Constraints on transportation and manufacturing** require a rethinking of material and process choices
- Continuing to drive cost down will also depend on **innovation in materials and manufacturing**

Grand Challenge #3: Systems science and control of wind power plants to orchestrate wind turbine, plant, and grid forming operations to provide low cost energy, stability, resiliency, reliability and affordability in the future power system



Grand Challenge #3 Key Issues:

- Opportunities to **add value** through increased output and provision of grid support **depends on advanced plant control**
- Moving to high shares of **wind and solar will require "formation" of the grid** through inverters (grid forming inverters)
  - **Wind provides real rotational inertia but this can only be accessed through control**

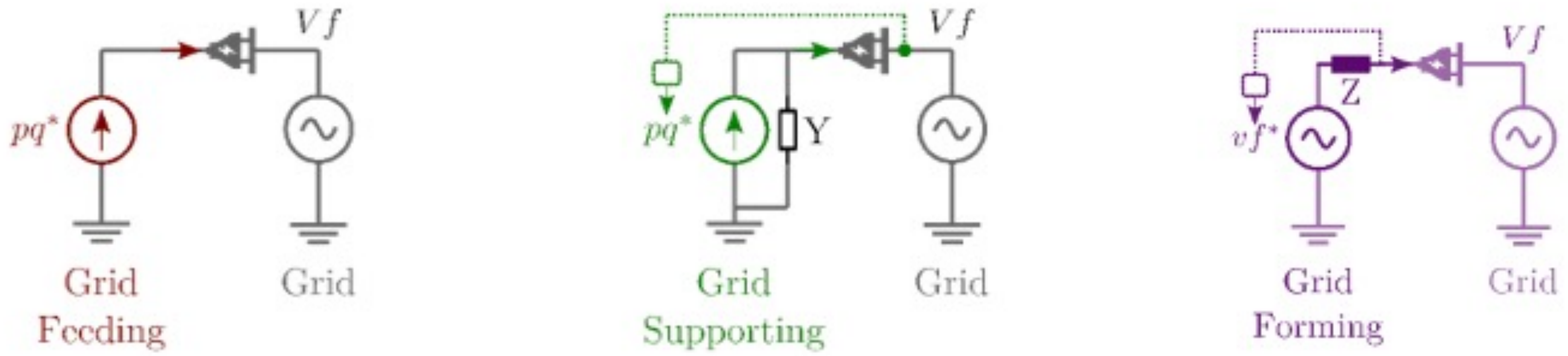


Data analytics research is needed to deal with the massive amount of information available **for plant operations and control**

Grid forming and grid following inverters

Wind turbines/plants control

First generation | Second generation | Next generation



First generation

- Focus on MPPT
- Ability of controlling P & Q
- Needs energized and strong grid
- Minor contribution to system stability

Second generation

- (still) Focus on MPPT
- Ability of controlling P & Q
- Support F & V
- Needs energized and (strong) grid
- Increased contribution to system stability

Next generation

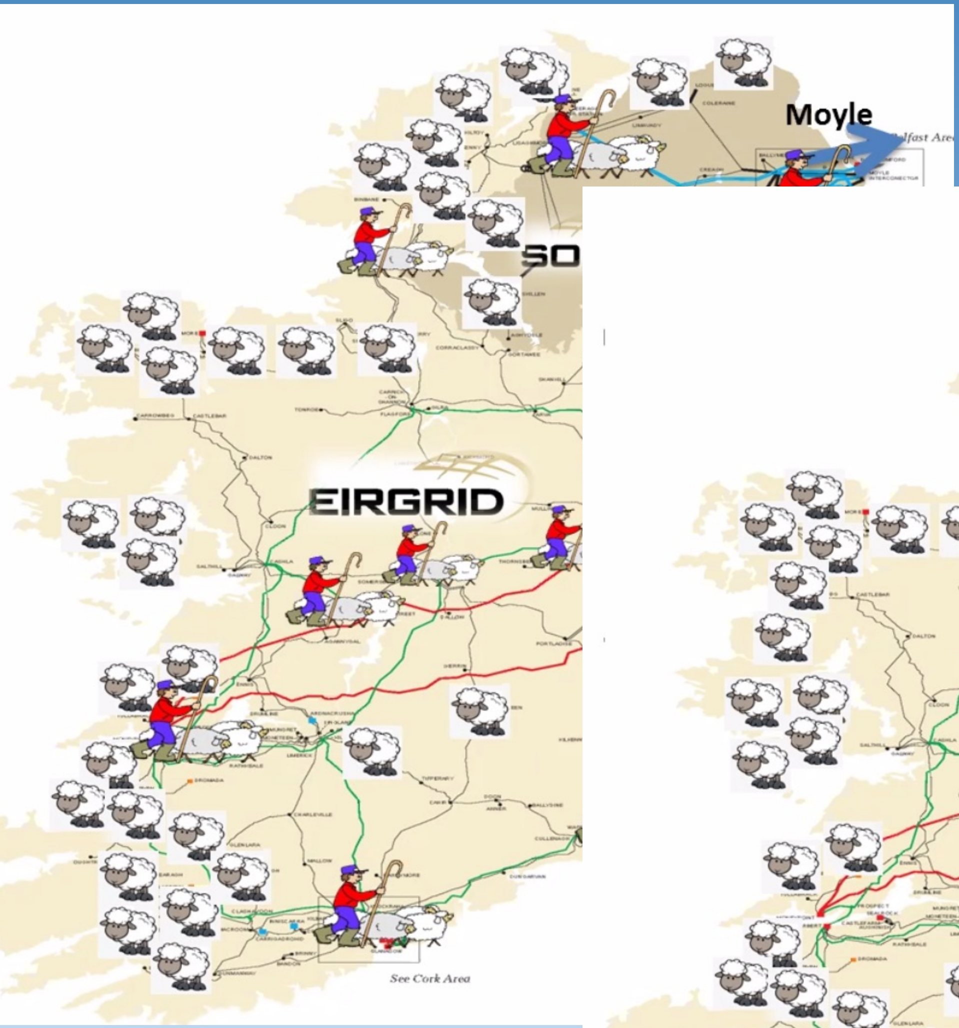
- (maybe) MPPT, more "on demand"
- Ability of controlling P & Q
- Create F & V
- ~~Needs energized and strong grid~~
- Major contribution to system stability

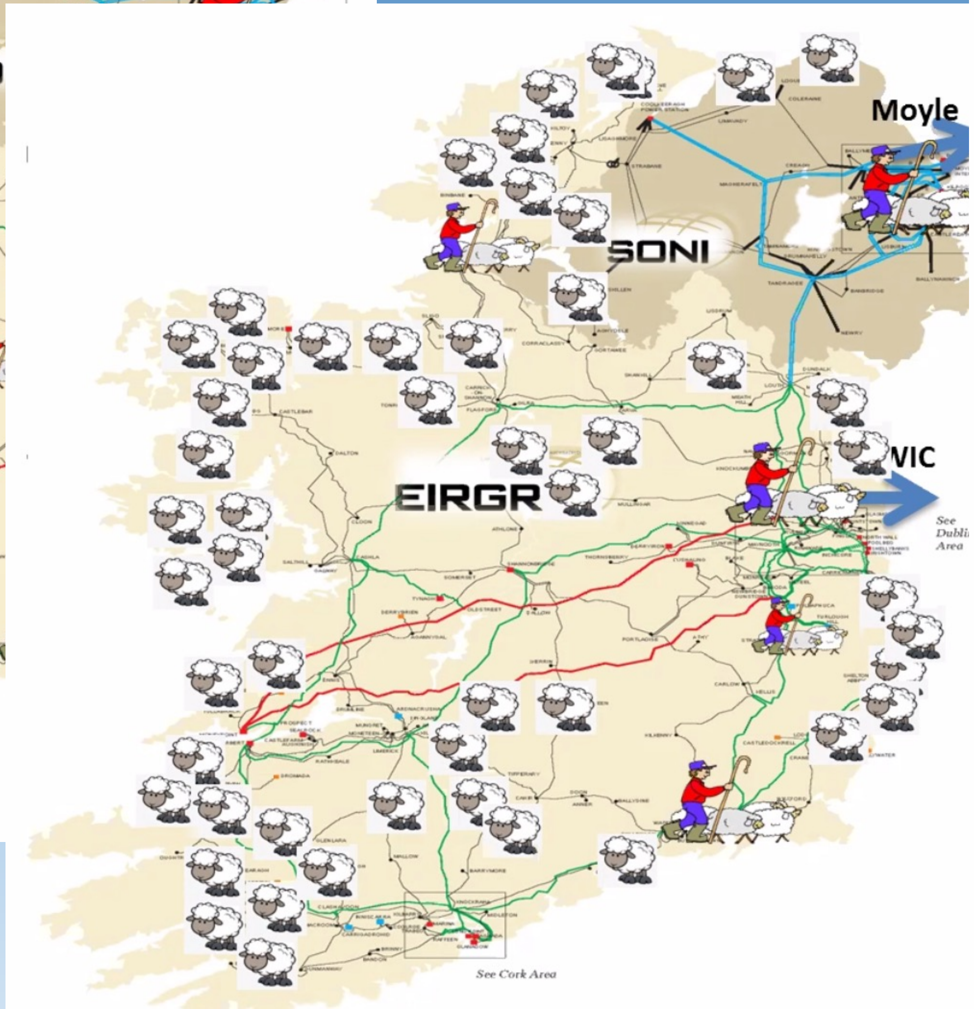
These services also available from

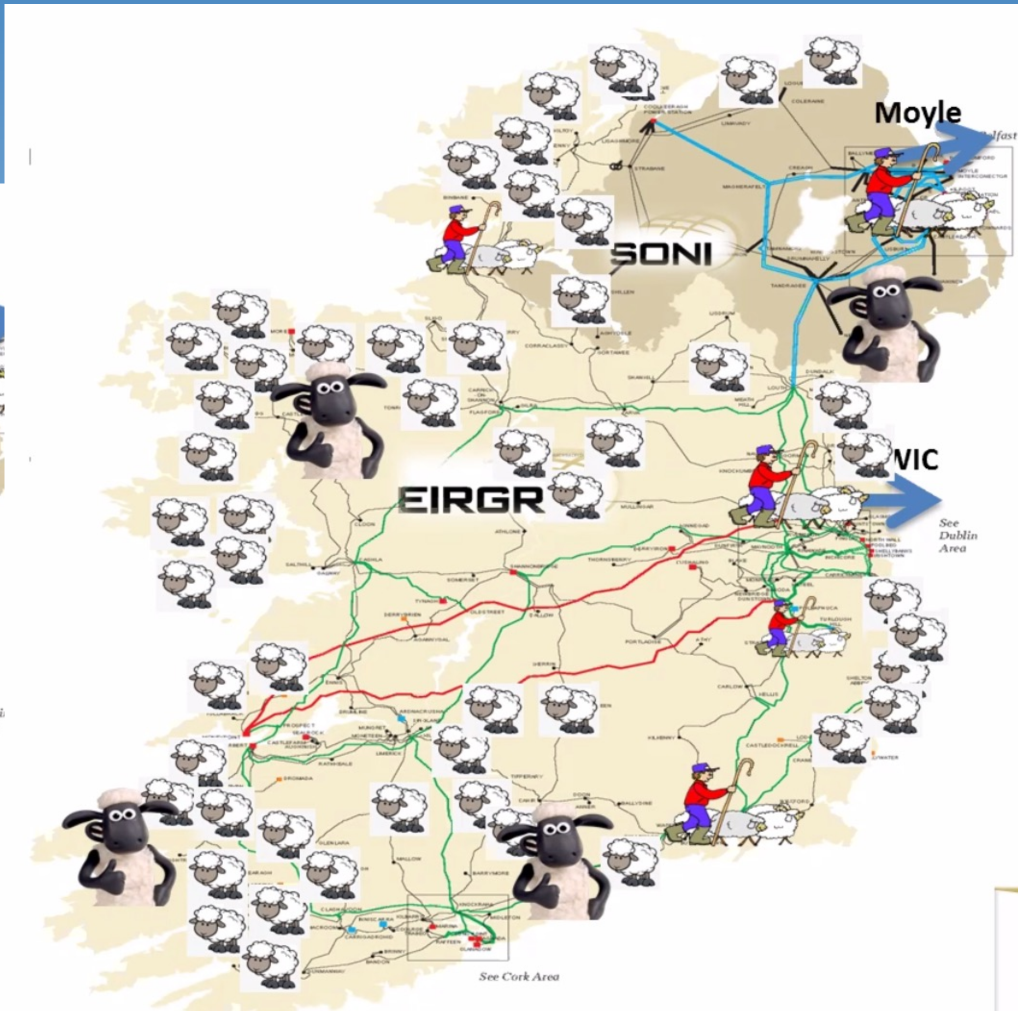
- Battery Energy Storage Ssystems (BESS);
- Synchronous condensers;
- HVDC converters

MPPT maximal power point tracking, F frequency, V voltage

System operation at 100% non synchronous ~30% grid forming inverters needed







Source: Eirgrid, Ireland

Challenges for wind from 0.8TW to 6 TW

- Manufacturing capacity to 100 GW/year by 2030
  - global markets, scale, volume and learning
- Grid connection, transmission and flexibility
  - Power and energy system integration
  - From WPP point of view: electrical performance, grid stability, as well as energy production estimates in all time scales
- Looking beyond LCOE for system value
  - system services
  - integrated energy solutions, energy system integration, power2X products
- Streamlined permitting processes – public acceptance
  - sustainability and life-cycle environmental impacts

Sources: Torque2020 conference RnD Industry session; GWEC

Summary of today – main trends

- cost reduction
  - onshore, offshore, floating
  - controls: more energy, less loading, grid support services
  - materials, design, manufacturing
  - O&M, digitalisation, digital twins
  - Beyond LCOE taking into account the value of wind
- upscaling challenge, larger rotors (lower specific rating)
- life extension, end of life and repowering, recycling
- Grand challenges:
  - 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
- Also other than technical challenges like public acceptance

References

As written material for this lecture:

- Veers, P, et al (2022) Grand Challenges: Wind energy research needs for a global energy transition. Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2022-66 Preprint in https://wes.copernicus.org/preprints/wes-2022-66/wes-2022-66.pdf

Others:

- NREL (2019) 2018 Cost of Wind Energy Review https://www.nrel.gov/docs/fy20osti/74598.pdf
- Breiter, P, et al. (2020) Wind power costs driven by innovation and experience with further reductions on the horizon. https://doi.org/10.1002/wene.398
- Clifton, A, et al (2022) Grand Challenges in the Digitalisation of Wind Energy. Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2022-29
- Veers, P, et al (2022) Grand Challenges in the Design, Manufacture, and Operation of Future Wind Turbine Systems. Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2022-32
- Veers P., Dykes K., Lantz E., Barth S., Bottasso C.L., Carlson O., Clifton A., Green J., Green P., Holttinen H. et al. (2019). Grand challenges in the science of wind energy. Science Vol. 366, Issue 6464, https://doi.org/10.1126/science.aau2027
- IEA Wind TCP publications https://iea-wind.org/
- Global Wind Energy Council GWEC publications https://gwec.net/

Thank you for your attention

www.recognis.fi

hannele.holttinen@recognis.fi