Wind Energy Grand Challenges

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Presented at the Workshop on “Grand Challenges in Wind Renewable Energy: from technology and sustainability to social acceptance and economics”

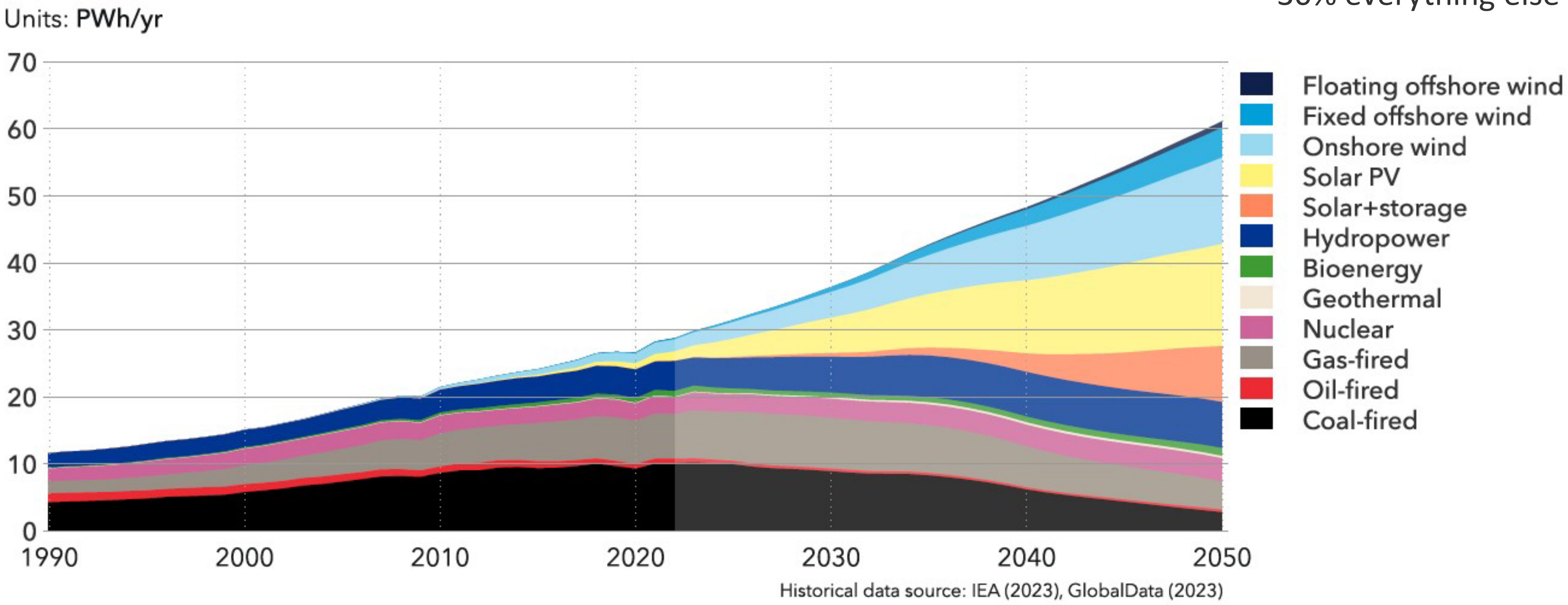
Photo by Dennis Schroeder, NREL 40481

Electricity demand predicted to more than double by 2050

FIGURE 2.4

World grid-connected electricity generation by power station type

- 30% wind
- 40% solar/storage
- 30% everything else



DNV ENERGY TRANSITION OUTLOOK 2023: A global and regional forecast to 2050

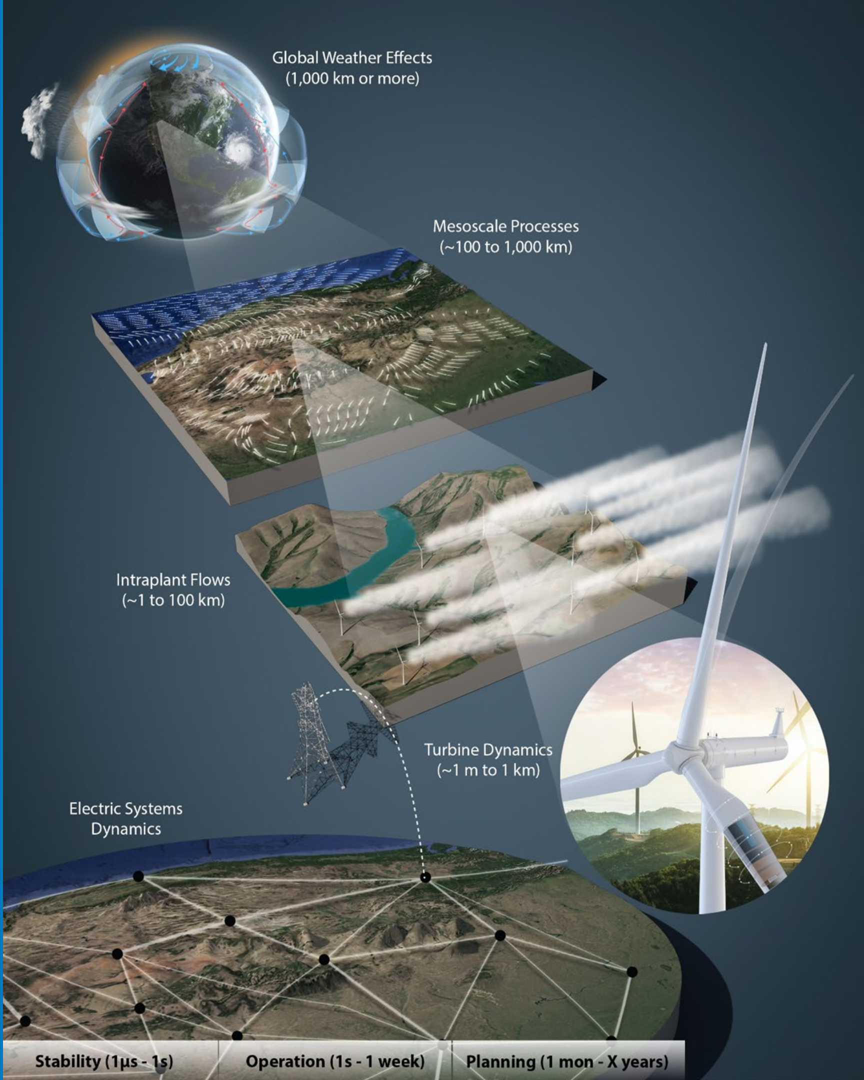
What issues need to be resolved for wind to supply 50% or more of global electricity?

The Grand Challenges extend from the global weather system to the minutiae of materials science to sub-second power system stability

- Multi-scale
- Multi-disciplinary
- Complex (“Wicked”)

Review article, “Grand Challenges in the Science of Wind Energy,” published in *Science* in October 2019.

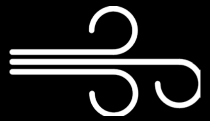
https://www.science.org/doi/10.1126/science.aau2027



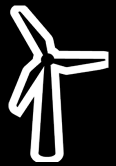
Source: NREL

Realizing a Carbon-free Energy System Requires Fundamental Research and Integration of Ideas across Several Domains

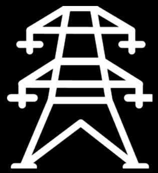
The Grand Challenges of Wind Energy Science include:



The **physics of atmospheric flow,** especially in the critical zone of wind power plant operation



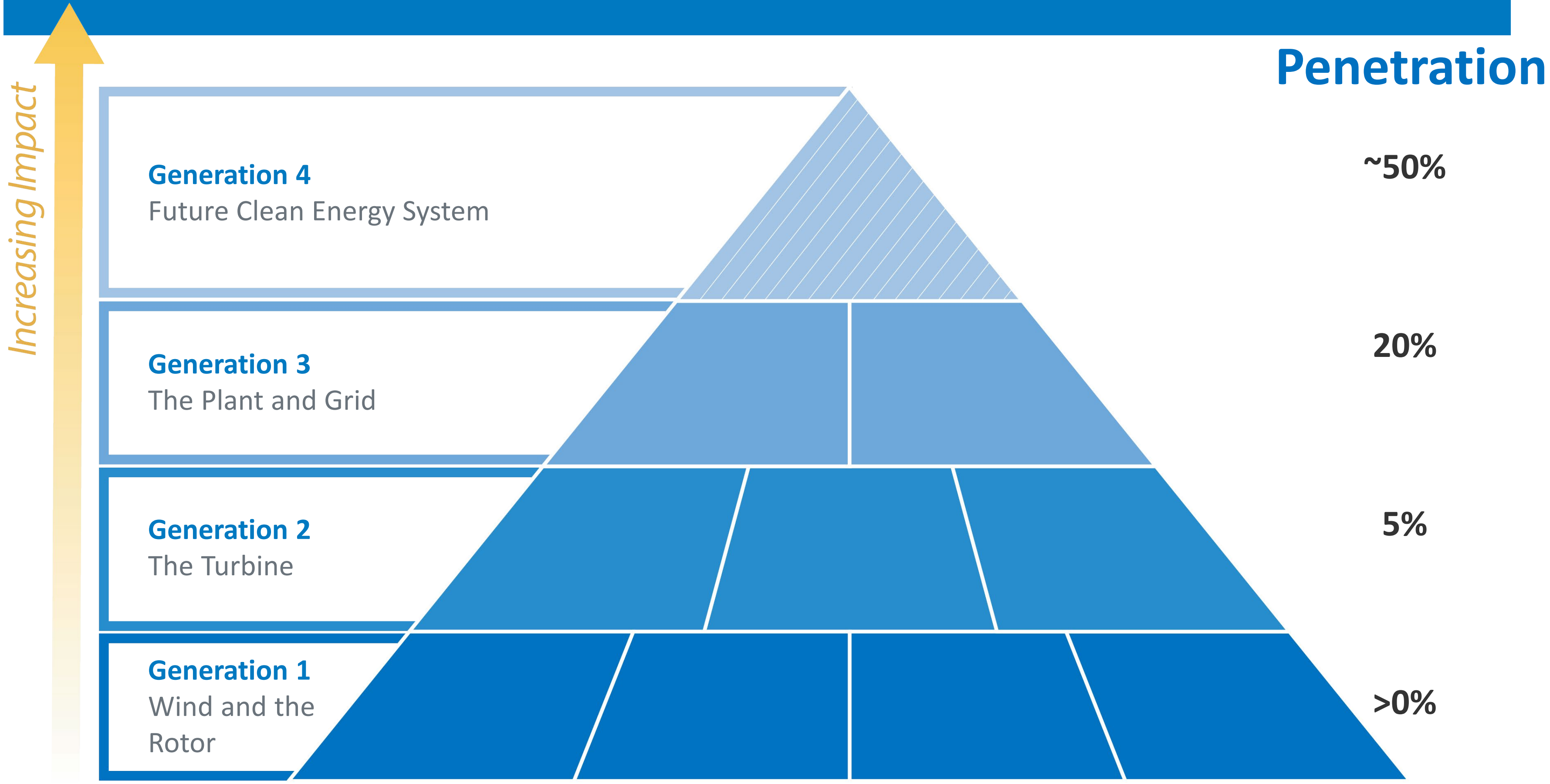
The **system dynamics and materials** of the largest, most flexible machines that have yet to be built



Optimization and control of fleets of wind plants made up of hundreds of individual generators working **to support the electric grid**

Emerging issues: Social Science and Environmental Co-design

There are Generations of Progress in Wind Energy



Generation 1: Wind and The Rotor

- Configuration Chaos
- The aerodynamics of rotating blades is considered the foundational problem
- Early research issues
  - Steady wind models of the atmosphere define the resource well and the loads poorly
  - Structural requirements take second place to aerodynamic efficiency
  - Era marked by many structural failures
  - Turbulence models inform fatigue loading
- Design Standards are developed to identify critical survival criteria

CART-3 & CART-2

Westinghouse 600kW turbines first installed in the 1980's in Hawaii, then moved and reconfigured at NREL's National Wind Technology Center (NWTC)

Photos courtesy NREL

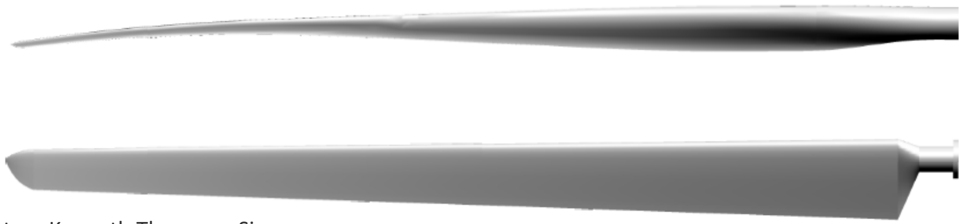
Blade structural testing at NWTC.

From Generation 1 to 2

If a blade from the 1980's is scaled up to the length of a blade from the 2010's it would weigh 10 times a much.

=> Blade weight has been effectively reduced by 90%.

2010's blade



1980's blade

Courtesy Kenneth Thomsen, Siemens (now DTU)

Generation 3 blades/rotors are so large and flexible that they are outside the 1990's design basis.

Generation 3 on Land

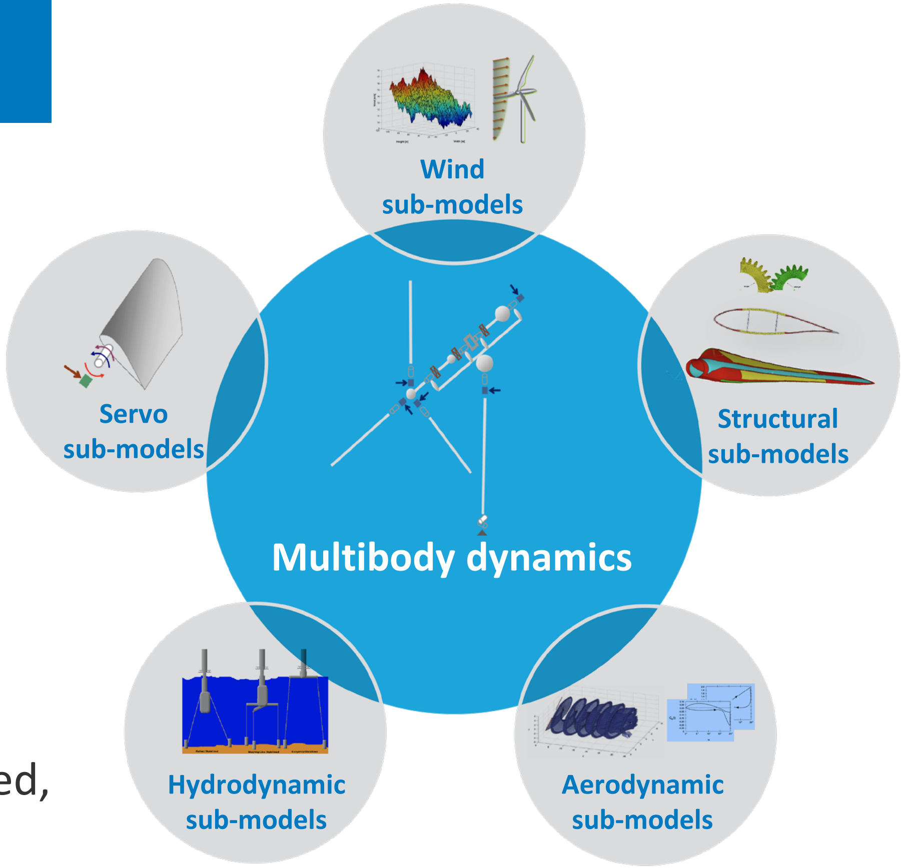
An 84.3-metre blade for Vestas' V172-7.2MW turbine being transported to the Østerild test centre in Denmark. (Ref: WindPower Monthly)

https://www.windpowermonthly.com/article/1879876/vestas-installs-72mw-onshore-wind-turbine?bulletin=windpower-daily&utm_medium=EMAIL&utm_campaign=eNews%20Bulletin&utm_source=20240709&utm_content=Windpower%20Daily%20(37)::www_windpowermonthly_com__5&email_hash=

Generation 2: The Turbine

- Full-turbine aeroelastic modeling is the basis for innovation
- Control provides safety, increases net productivity
- Light-weighting across the board pushes each component to its limits
- Optimization begins to cross disciplinary boundaries
- Offshore turbines add hydrodynamic complexity

Configurations converge on upwind, 3-bladed, pitch controlled, variable speed



Graphic by Carlo Bottasso, TUM

Example simulation: Two NREL 5-MW turbines in turbulent atmospheric flow

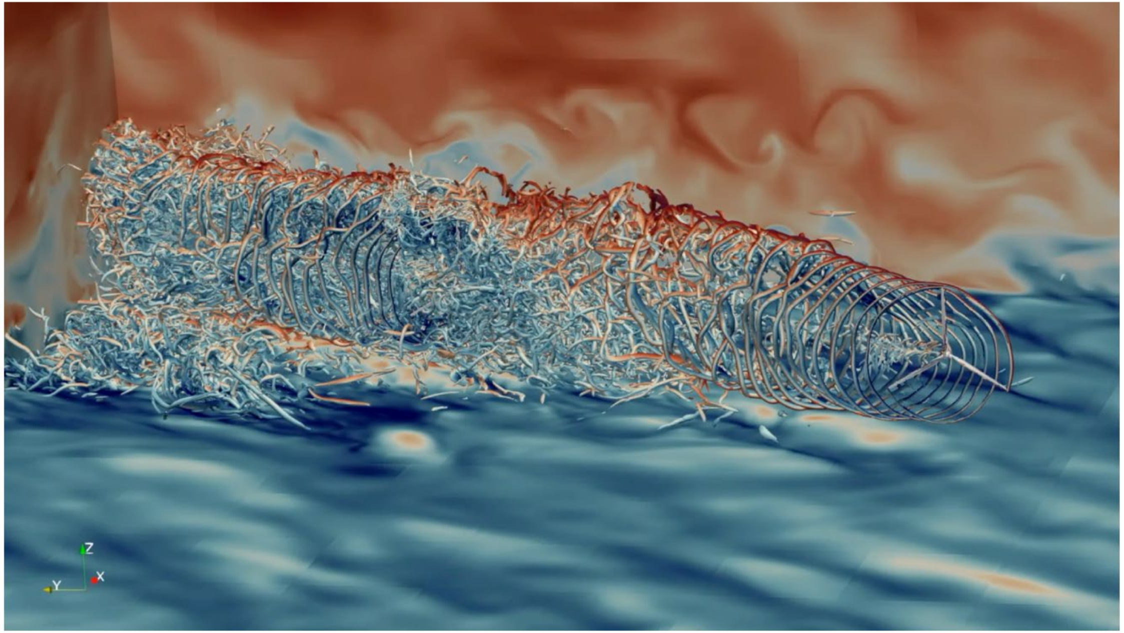
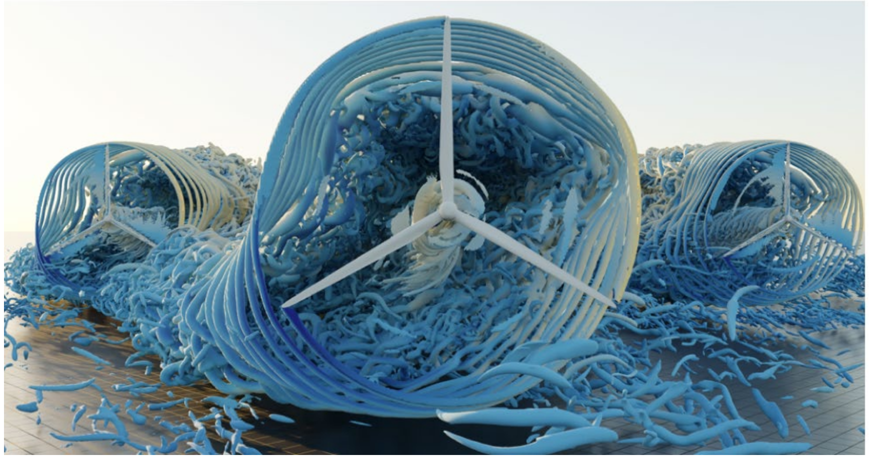


Image credit: Brazell, Brunhart-Lupo, Henry de Frahan, Rood, Sharma, Vijayakumar, et al.

ExaWind simulation of two NREL 5-MW turbines in turbulent atmospheric flow.

Wind turbine interactions in atmospheric flows

Videos courtesy of Nicholas Brunhart-Lupo, NREL



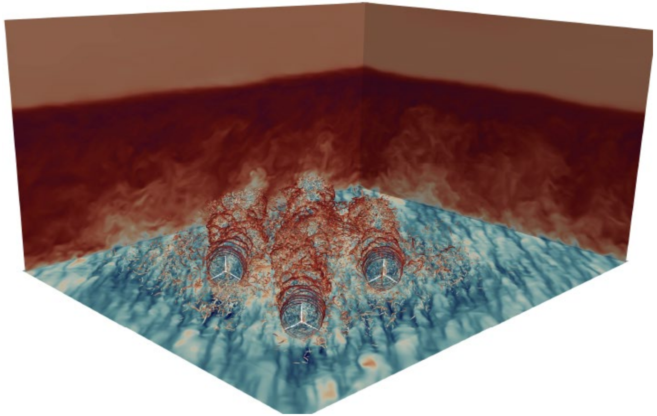
Stable (stratified) Atmosphere

Unstable (mixed) Atmosphere

ExaWind provides a multi-fidelity modeling capability

Highest fidelity (turbine resolved):

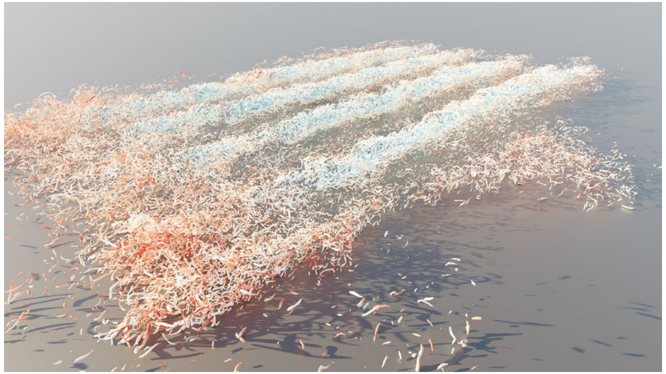
- Blade geometry resolved



Wind farm simulation where 4 turbine rotors are fully resolved (600 million gridpoints shown; run up to 20 billion gridpoints)

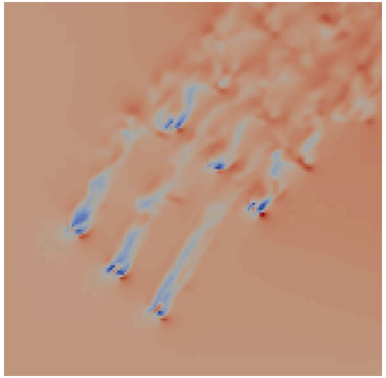
Middle fidelity (turbines modeled):

- Actuator lines



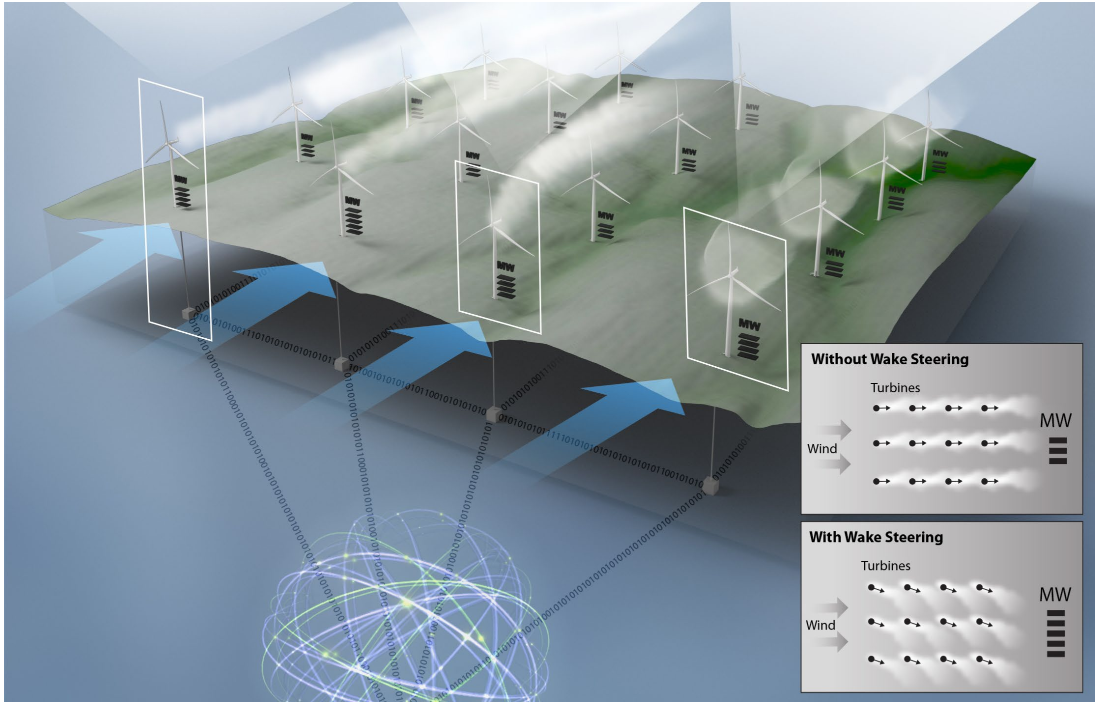
Wind farm simulation where 20 turbines are modeled as “actuator lines” with fluid-structure interaction (1.4 billion gridpoints)

- Actuator disks



Wind farm simulation where 8 turbines are modeled as “actuator disks” (1.2 million gridpoints)

Generation 3: The Plant



Graphic by Josh Bauer, NREL

- The power plant rather than the turbine becomes the focus
- Energy losses due to plant scale effects are identified
- Wakes and flow fields are recognized as both a constraint and an opportunity for control at a higher level
- Wind plants need to provide many ancillary (essential) grid services
- Inverter-based Resources (IRBs) begin to “form” the grid

Needs for 3rd generation wind sector

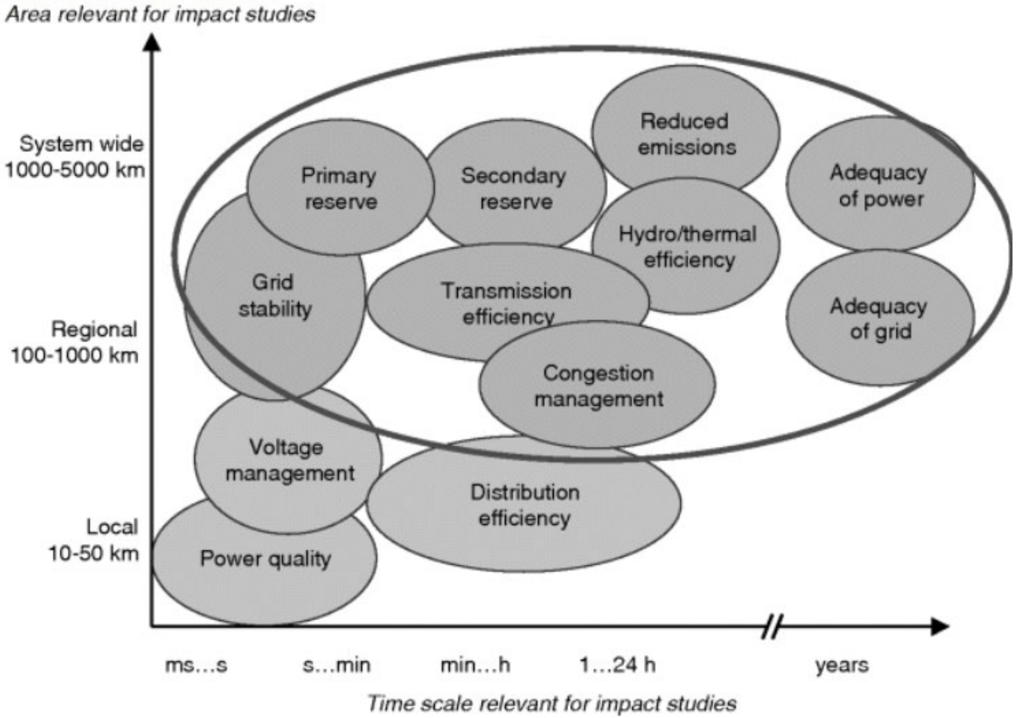
Courtesy Lena Kitzing, DTU

Decarbonisation

System operation

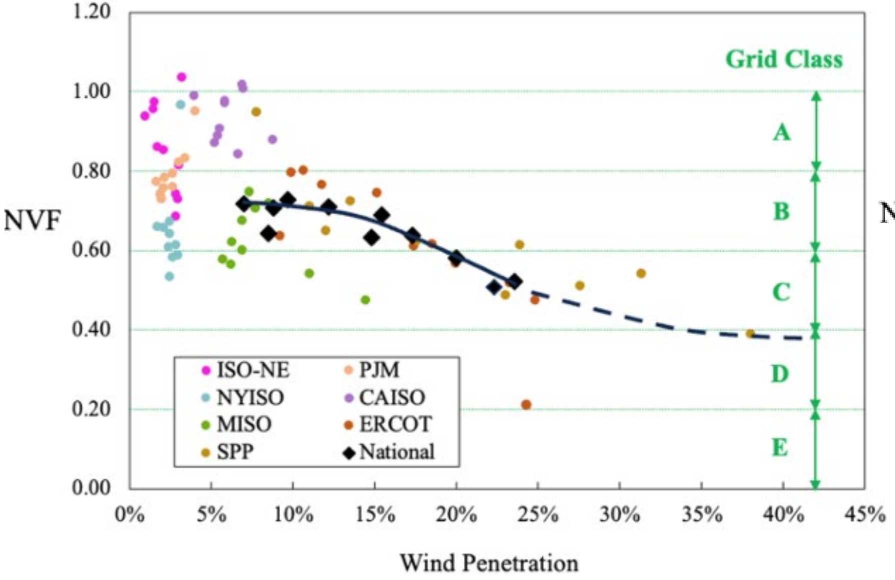
- Ensure security of supply
- Stability
- Ancillary services

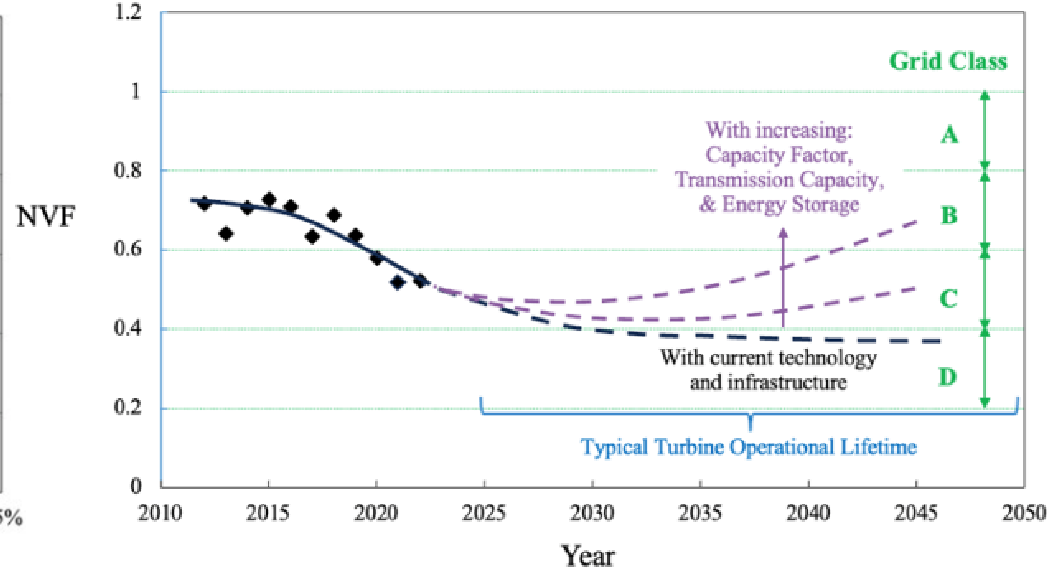
Figure 6.11 Power system impacts of wind power, causing integration costs. Some of the impacts can be beneficial to the system, and wind power can provide value, not only generate cost. Reproduced with permission from H. Holttinen *et al.* (2009)



Wind Power in Power Systems, T. Ackermann, 2012

Market Values: Net Value Factor of Wind is Decreasing





Before we can think of increasing values – we need to first mitigate the impeding decline of market values

Courtesy Lena Kitzing, DTU

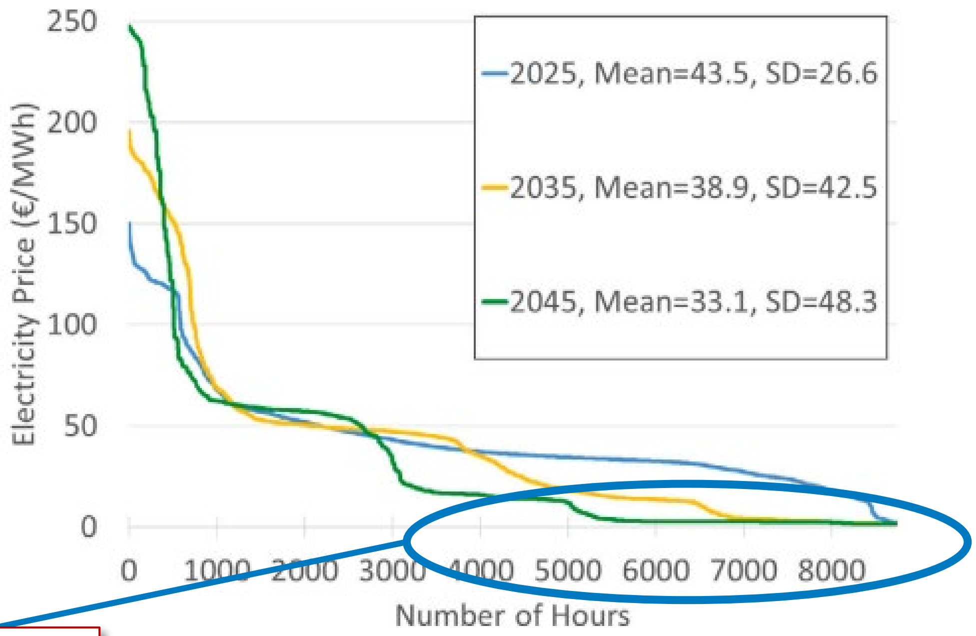
Loth, E., Wind energy value and deep decarbonization design, what's next?, 2023, doi-org.proxy.findit.cvt.dk/10.1016/j.nxener.2023.100059

Why is this important for Generation 4?

Courtesy Lena Kitzing, DTU

Some solutions can be found in:

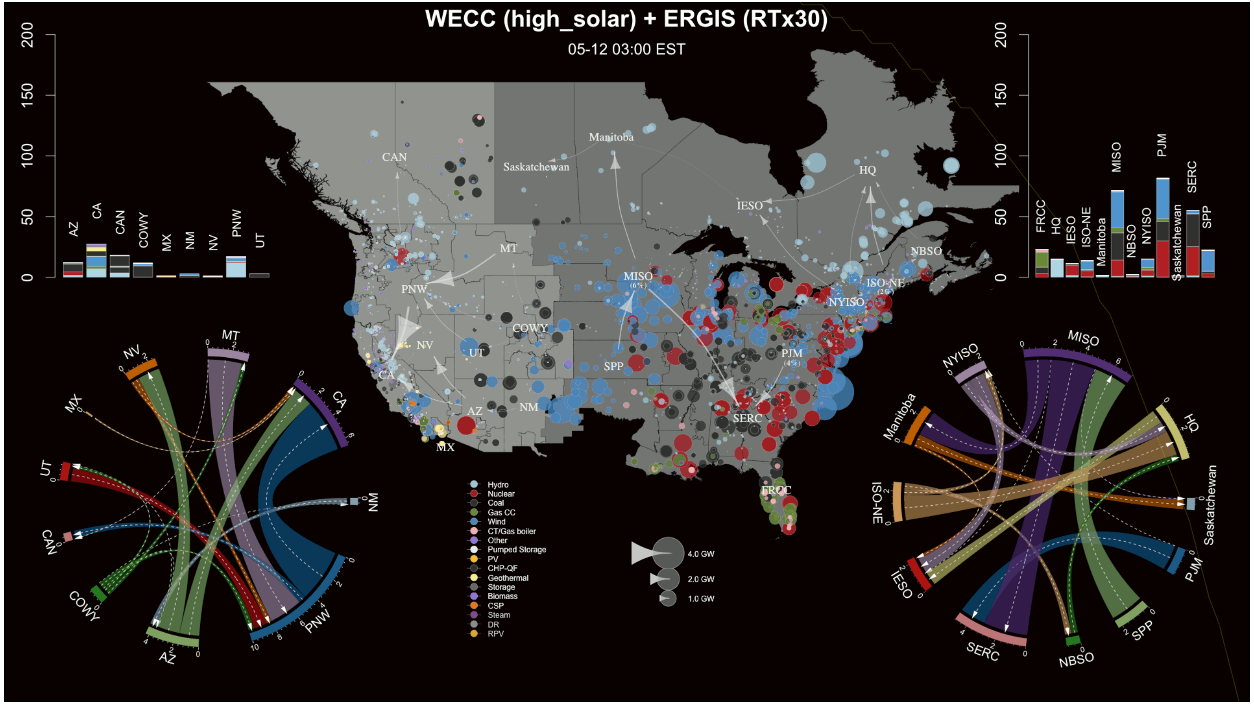
- Increasing Plant Capacity Factor
- Enhanced Transmission
- Energy Storage and Energy-to-X



Risk of many zero-price hours in future energy systems
= Effort needed to avoid and ensure value is keeping up

Swisher et al (2022), Competitiveness of a low specific power, low cut-out wind speed wind turbine in North and Central Europe towards 2050, DOI

Generation 4: The Energy System



- Wind Energy is the foundation for a low-carbon energy system
  - **30-50%** of a carbon-free electricity sector
  - Supplying the energy for fuels and seasonal storage
  - Integrated into optimized hybrid plants
- Turbines are operating in locations and modes that have never been done before
- Economic drivers of turbine and plant design change to integrate social and environmental demands

Courtesy Beth Clark, NREL
https://www.youtube.com/watch?v=YcgvGe2sN8Y&list=PLmIn8Hncs7bEl4P8z6-KCliwbYrwANv4p&index=26

Generation 4: The Energy System

Veers et al., "GRAND CHALLENGES REVISITED: IEA Wind TCP Task 11 Technical Report Wind Energy Research Needs for a Global Energy Transition," IEA Wind TCP Task 11 Technical Report, Dec. 2023.

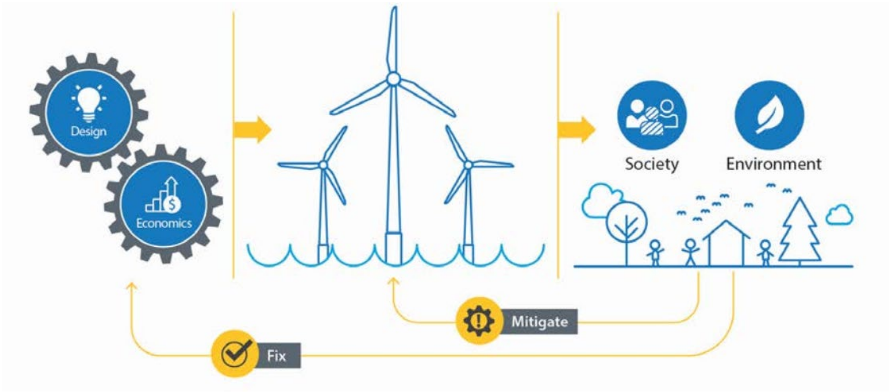


Figure 12. Today's cost-centric design. ***Illustration by Taylor Henry, NREL, based on an illustration from Carlo Bottasso, Technical University of Munich***

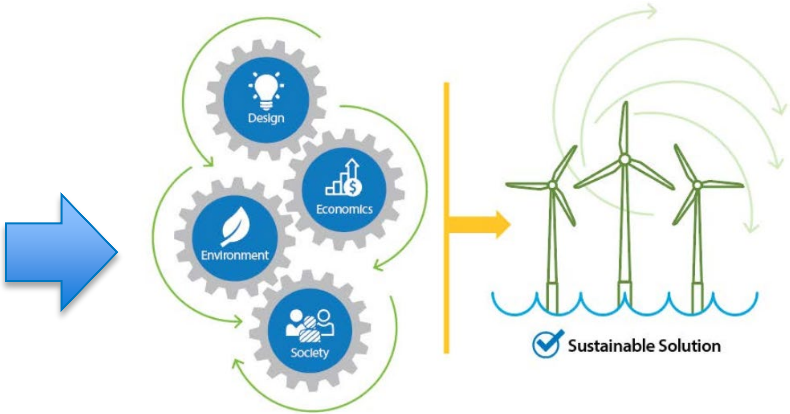
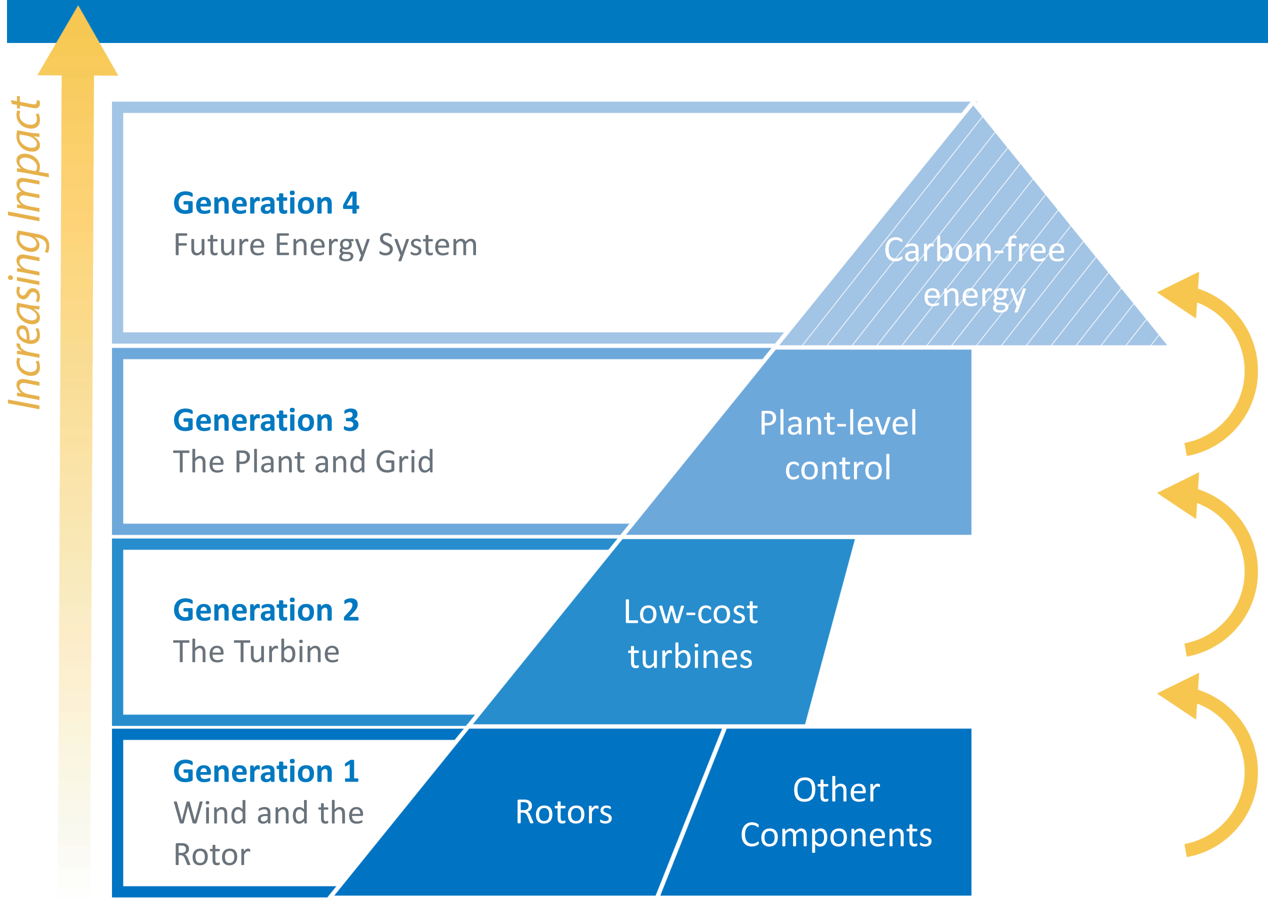


Figure 13. Tomorrow's environmental and social co-design. ***Illustration by Taylor Henry, NREL, based on an illustration from Carlo Bottasso, Technical University of Munich***

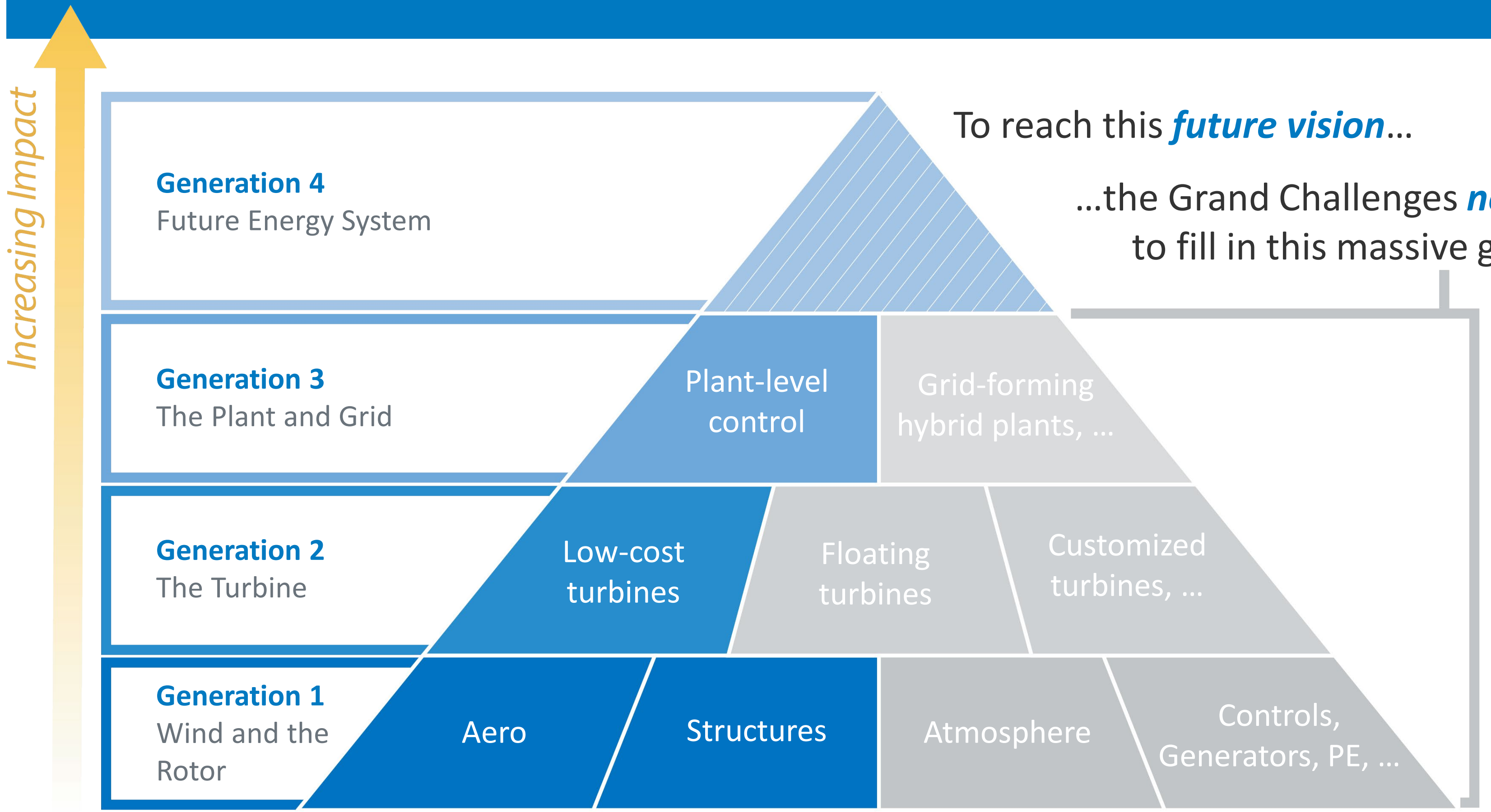
Wind plants extend into areas where social and environmental effects must be elements of the design optimization.

Each Generations Requires a Shift in Focus



While scope has grown, resources have been stretched, and the fundamental science has not kept up with the demands

The Generations Build on Each Other



Wind Energy is not Done

- Automobiles were not “done” in 1924 when the Ford Model-T was beginning to fill the roadways. They were:
  - Functional
  - Cost-effective
  - Reliable
- Wind Energy Systems are not “done” now that they are beginning to supply a significant portion of our electricity. They are now:
  - Functional
  - Cost-effective
  - Reliable
- The Grand Challenges of wind are still Grand.

1924 Ford Model-T

2024 Tesla

2024 Wind Turbine

Wind energy in the future

?

Thanks! - Questions?

www.nrel.gov

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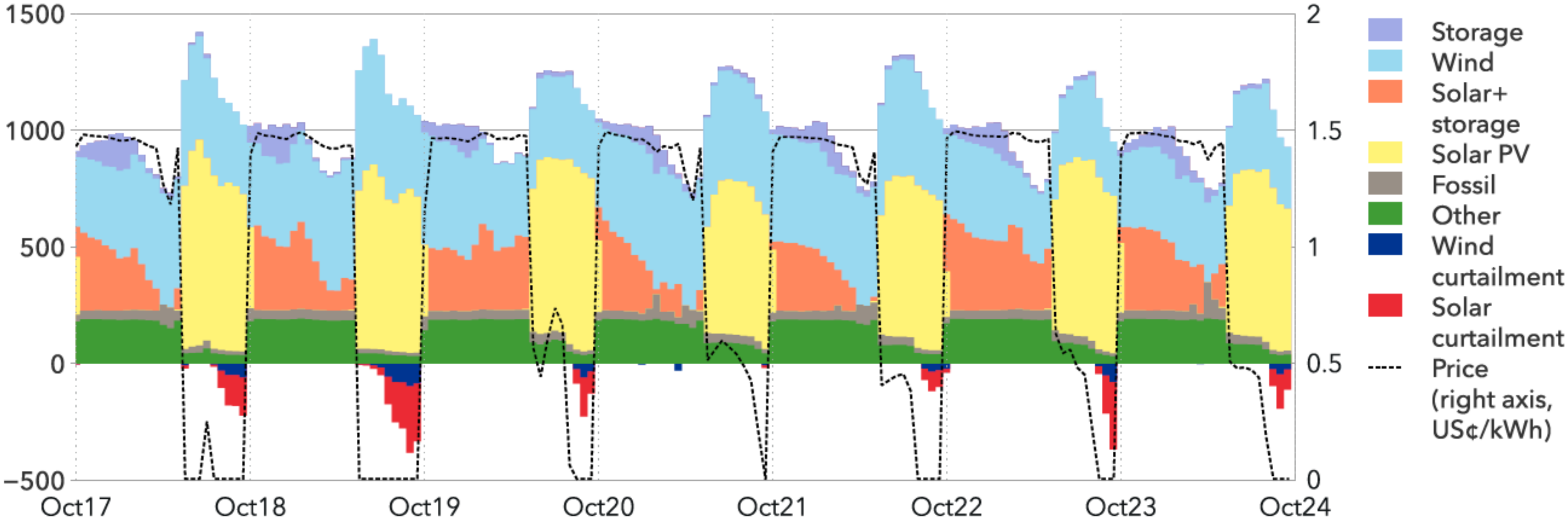
NREL Transforming ENERGY

Typical Week at 70% Renewable Electricity

FIGURE 3.3

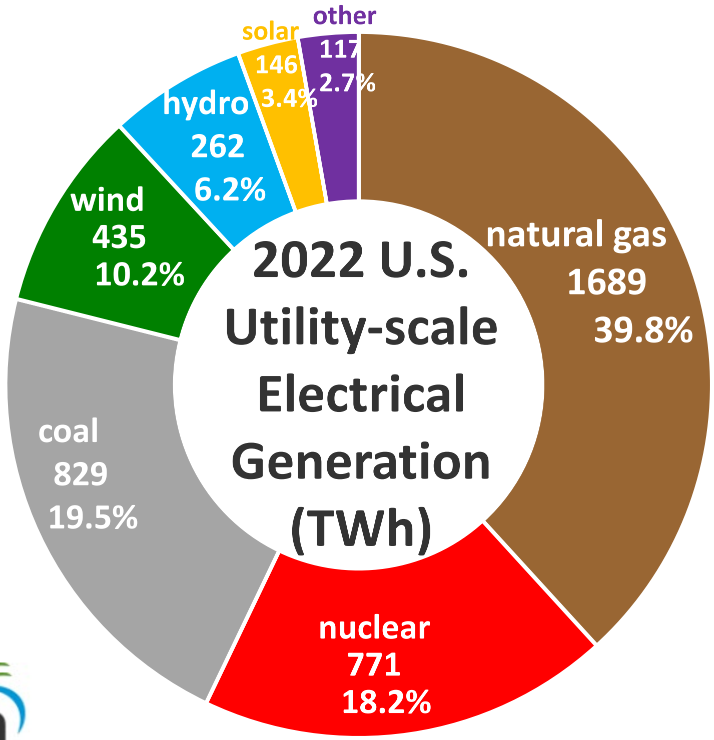
Hourly electricity supply in a typical 2050 week in North America

Units: GWh/hr



Source: DNV Energy Transition Outlook 2023 (EXECUTIVE SUMMARY) A global and regional forecast to 2050

Current and carbon-neutral future U.S. electricity



Electric Power Monthly
February 2023

- Renewable Energy will need to provide ~80% of electricity (nuclear to provide ~20%) to be carbon-neutral
- Wind will have to supply about 40%:
  - Day and night delivery
  - Often a good capacity match for solar

Courtesy Sue Haupt, NCAR

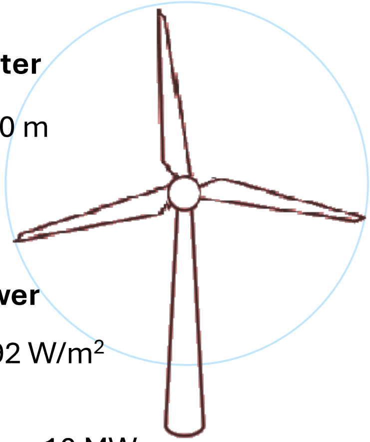
Wind is always blowing somewhere

Outperforming LCOE

Rotor diameter 180 m

Specific Power 392 W/m²

Capacity 10 MW



CAPEX

1.3 M€/MW 1.9 M€/MW

Capacity Factor

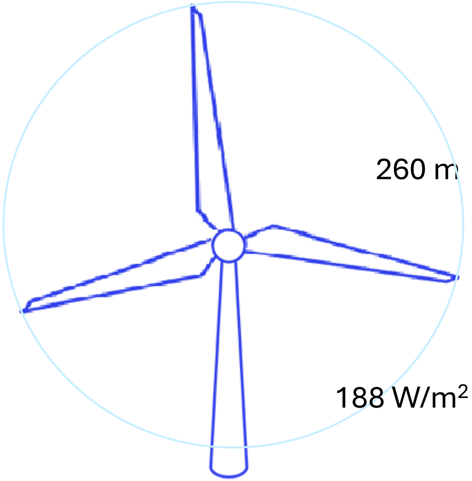
45% 55%

LCOE

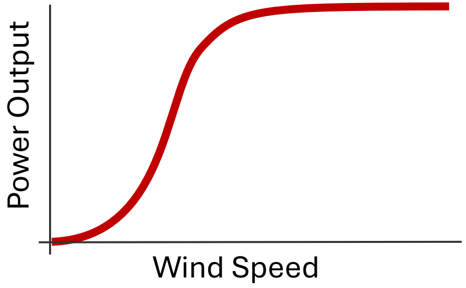
Lower 48 €/MWh 50 €/MWh

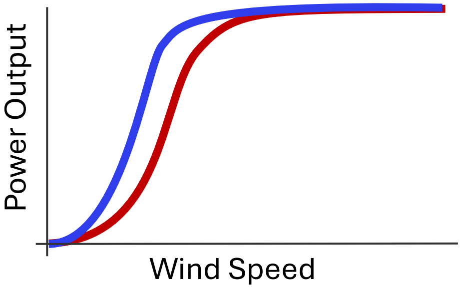
Average achieved price = Market Value

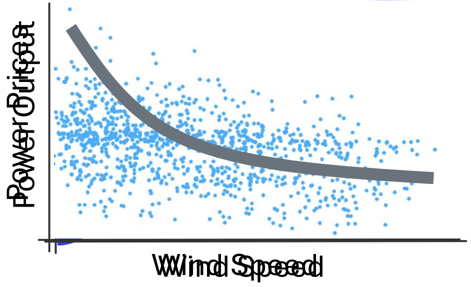
50 €/MWh 55 €/MWh **Higher**



10 MW







Courtesy Lena Kitzing, DTU