

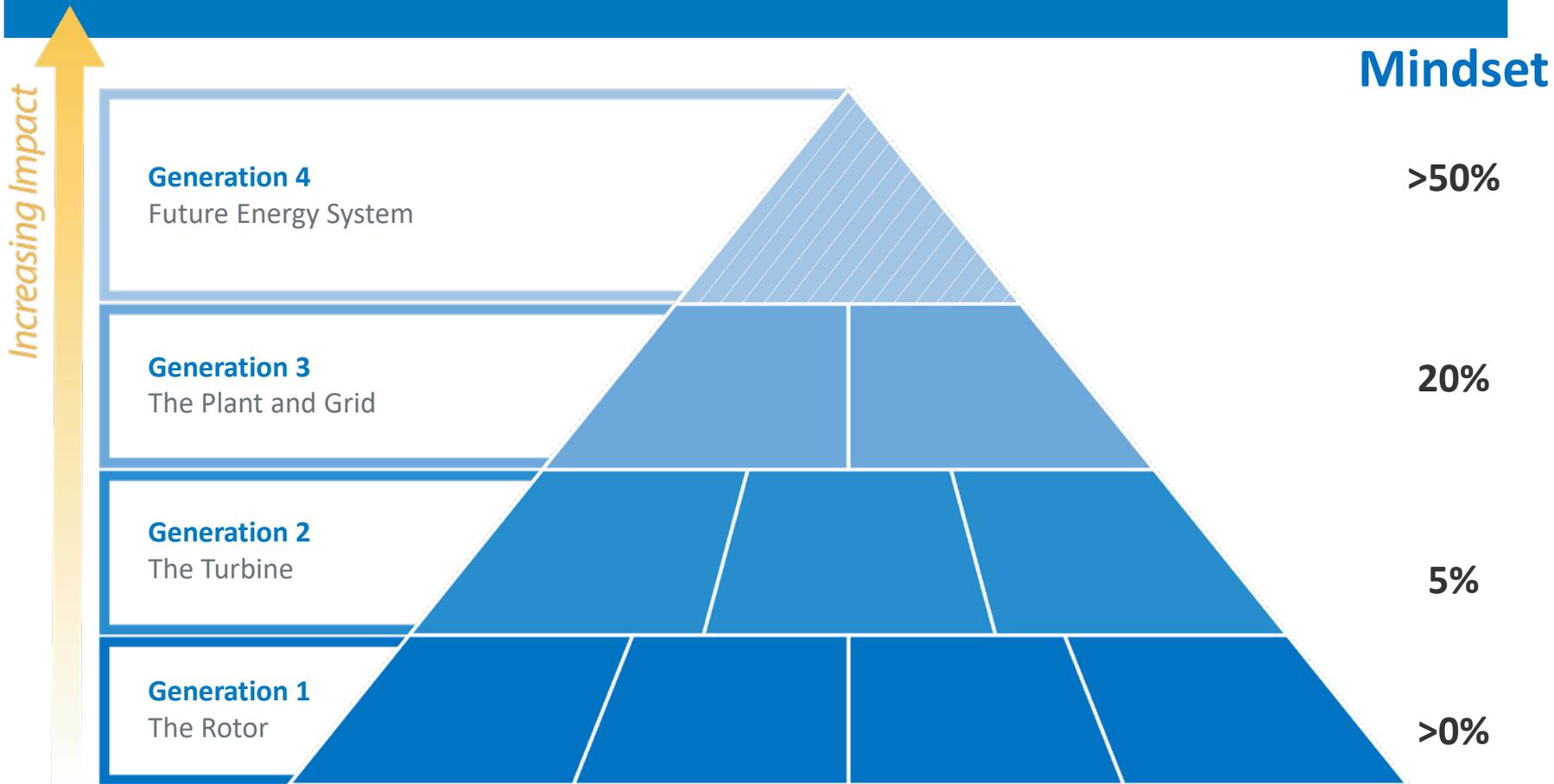
Grand Challenges in the Science of Making Torque from Wind: Then and Now

Paul Veers
NREL Senior Research Fellow
Torque, TU Delft, June 2022

The Science of Making Torque from Wind

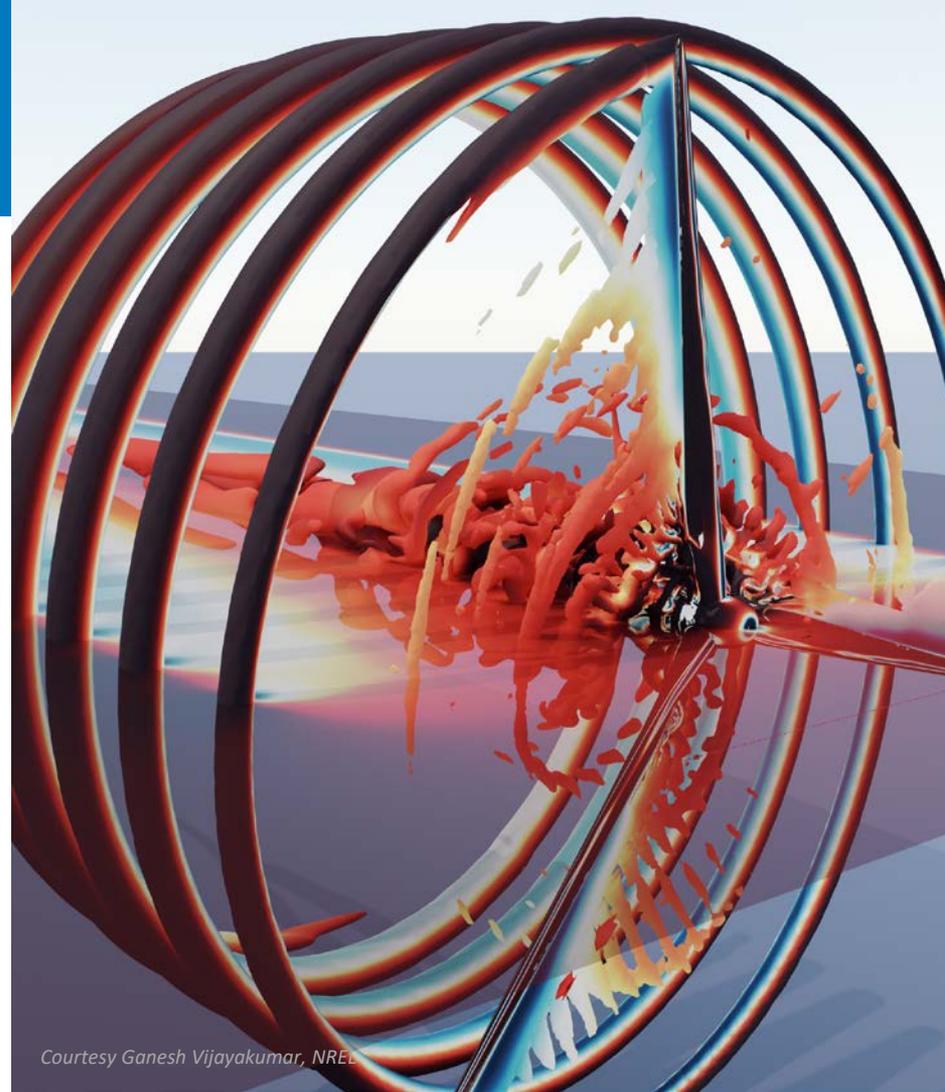
How did we get from that conference title
to the diverse and multidisciplinary
conference we are attending today?

There are Generations of Progress in Wind Energy



Generation 1: The Rotor

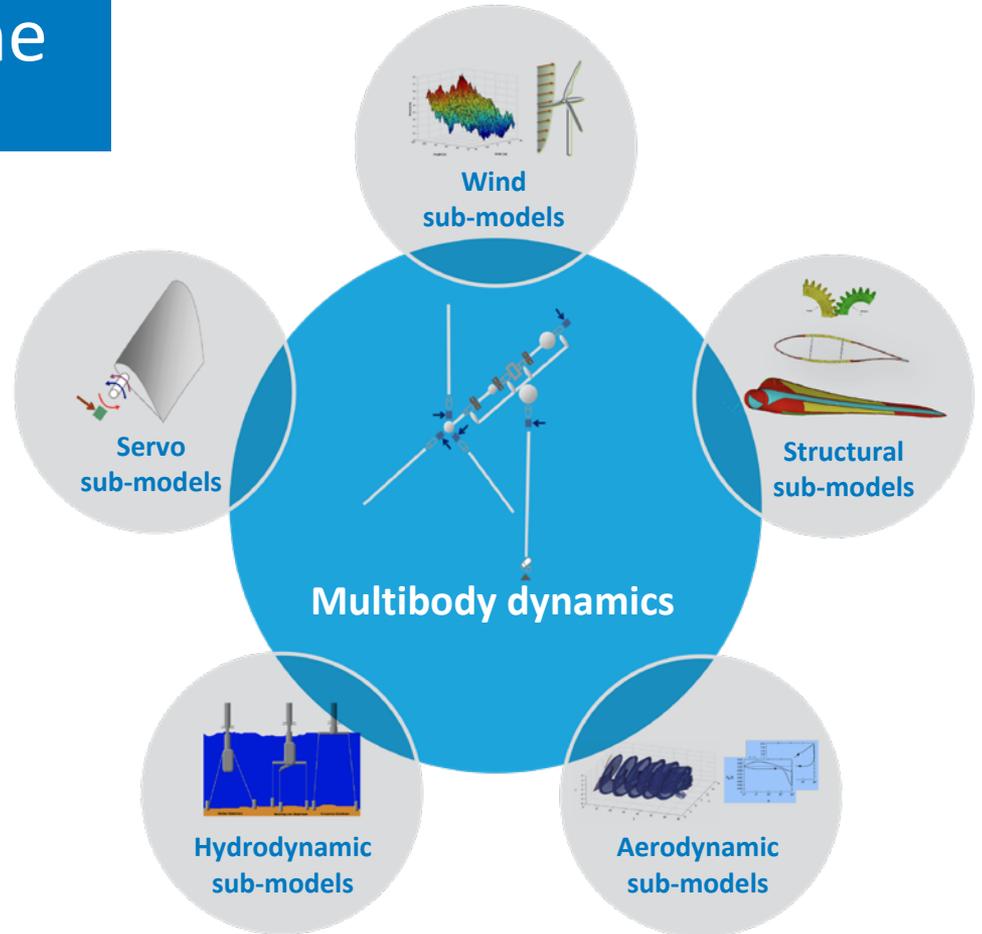
- The aerodynamics of rotating blades is a foundational problem
- Early bridges with aerodynamics research
 - Atmospheric flows define the resource and the loads
 - Structural requirements vs. aerodynamic efficiency
 - Many materials and manufacturing methods are explored
- Standards are developed to identify critical design criteria



Courtesy Ganesh Vijayakumar, NREL

Generation 2: The Turbine

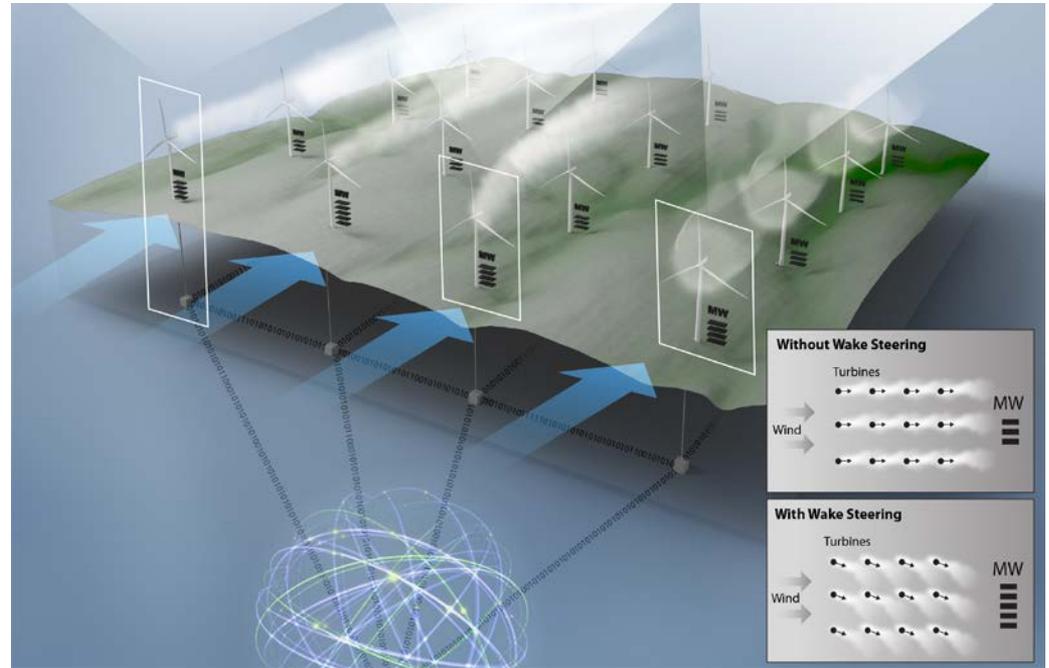
- Full-turbine aeroelastic modeling is the basis for innovation
- The explosion of generator types and drivetrain configurations
- Control provides safety, increases net productivity
- Light-weighting across the board pushes each component to its limits
- Optimization begins to cross disciplinary boundaries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



Graphic by Carlo Bottasso, TUM

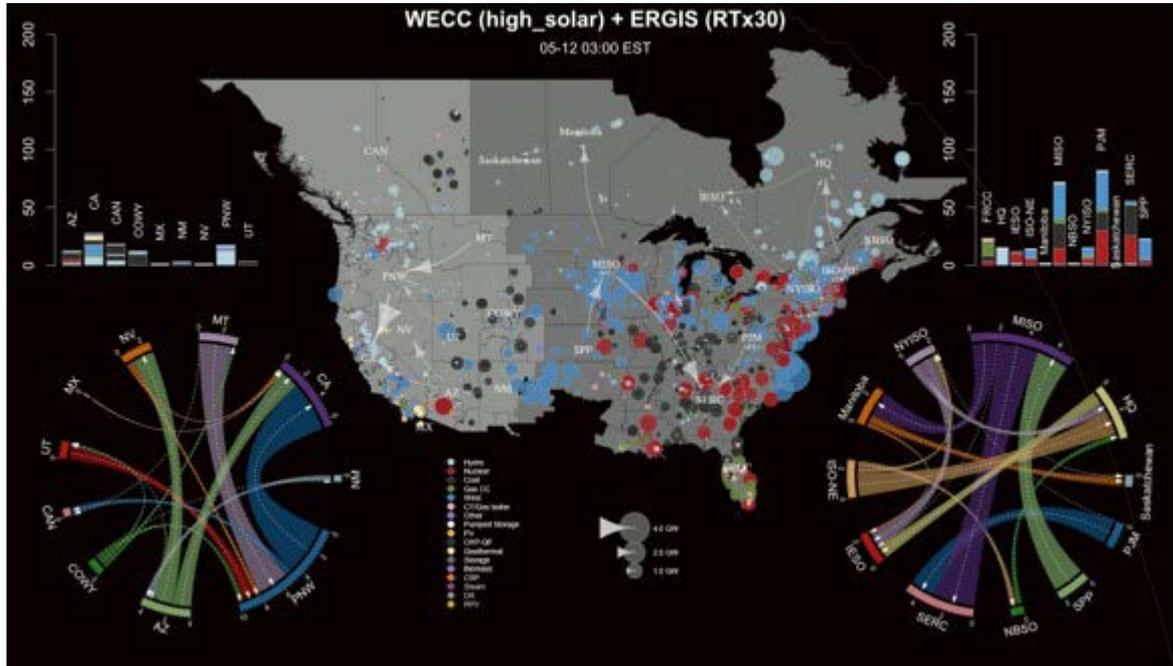
Generation 3: The Plant

- The Power Plane 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 are shown to provide many ancillary services (essential grid services), but more are needed



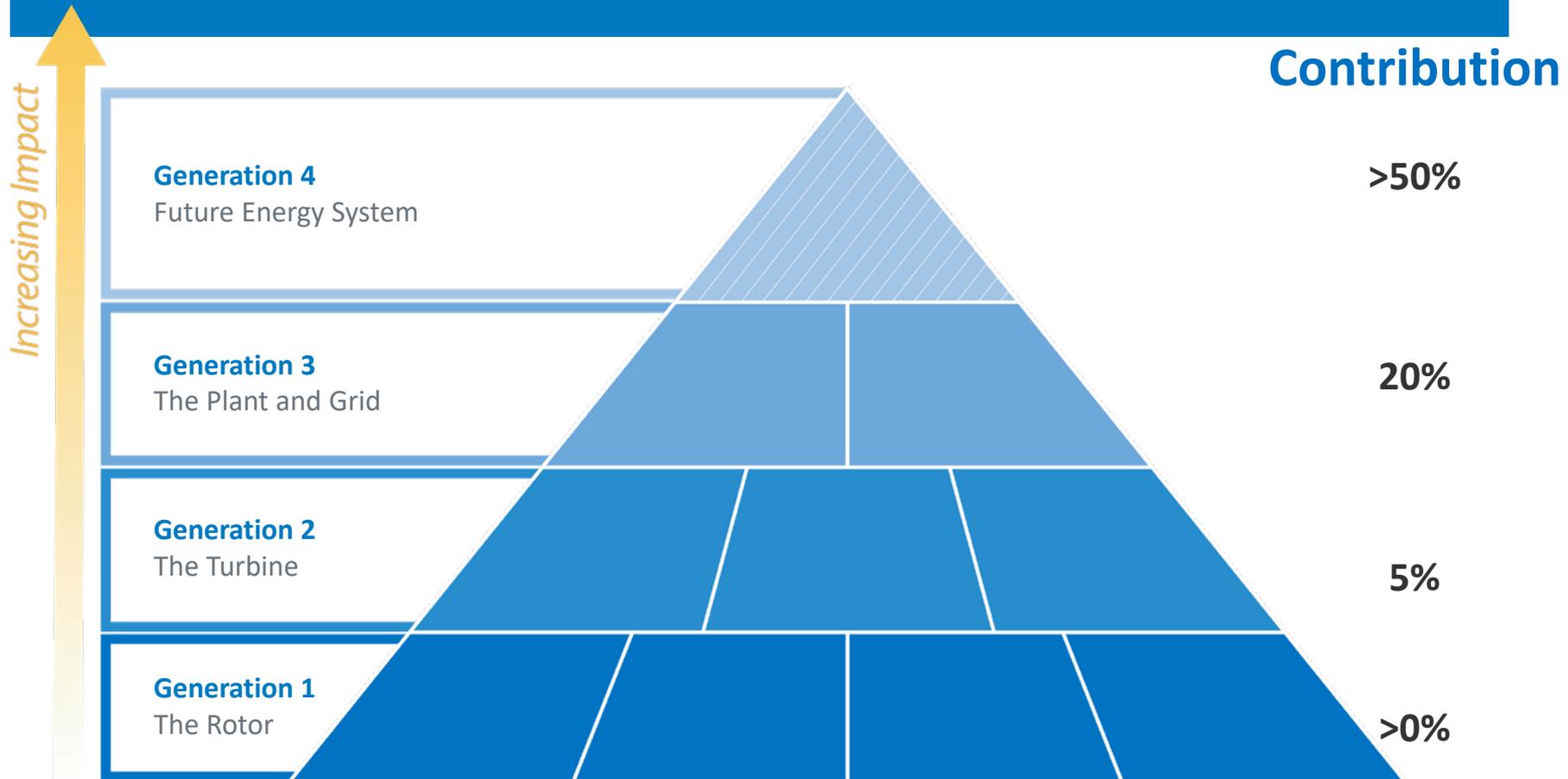
Graphic by Josh Bauer, NREL

Generation 4: The Energy System



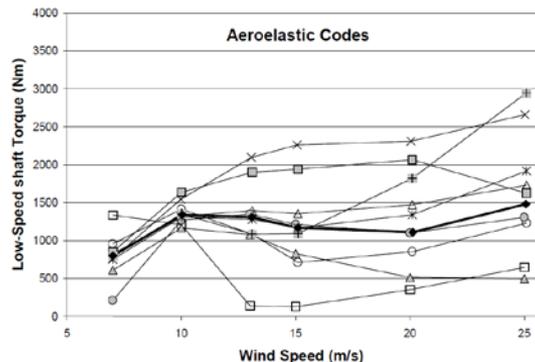
- Wind Energy is the foundation for a low-carbon energy system
 - **30-50%** of a carbon-free electricity sector
 - Supplying the energy for fuels and seasonal storage
 - Integrated into optimized hybrid plants
- Grid control and stability define how plants need to operate
- Turbines are operating in locations and modes that have never been done before
- Economic drivers of turbine and plant design change to optimize systems

The Generations Build on Each Other



Reality Check in the Year 2000

NASA Ames 80x120 Wind Tunnel Experiment



Rotor Torque operating in Steady Wind with Zero Yaw: Predicted and Measured

Generation 2

The Turbine

Low-cost turbines

Generation 1

The Rotor

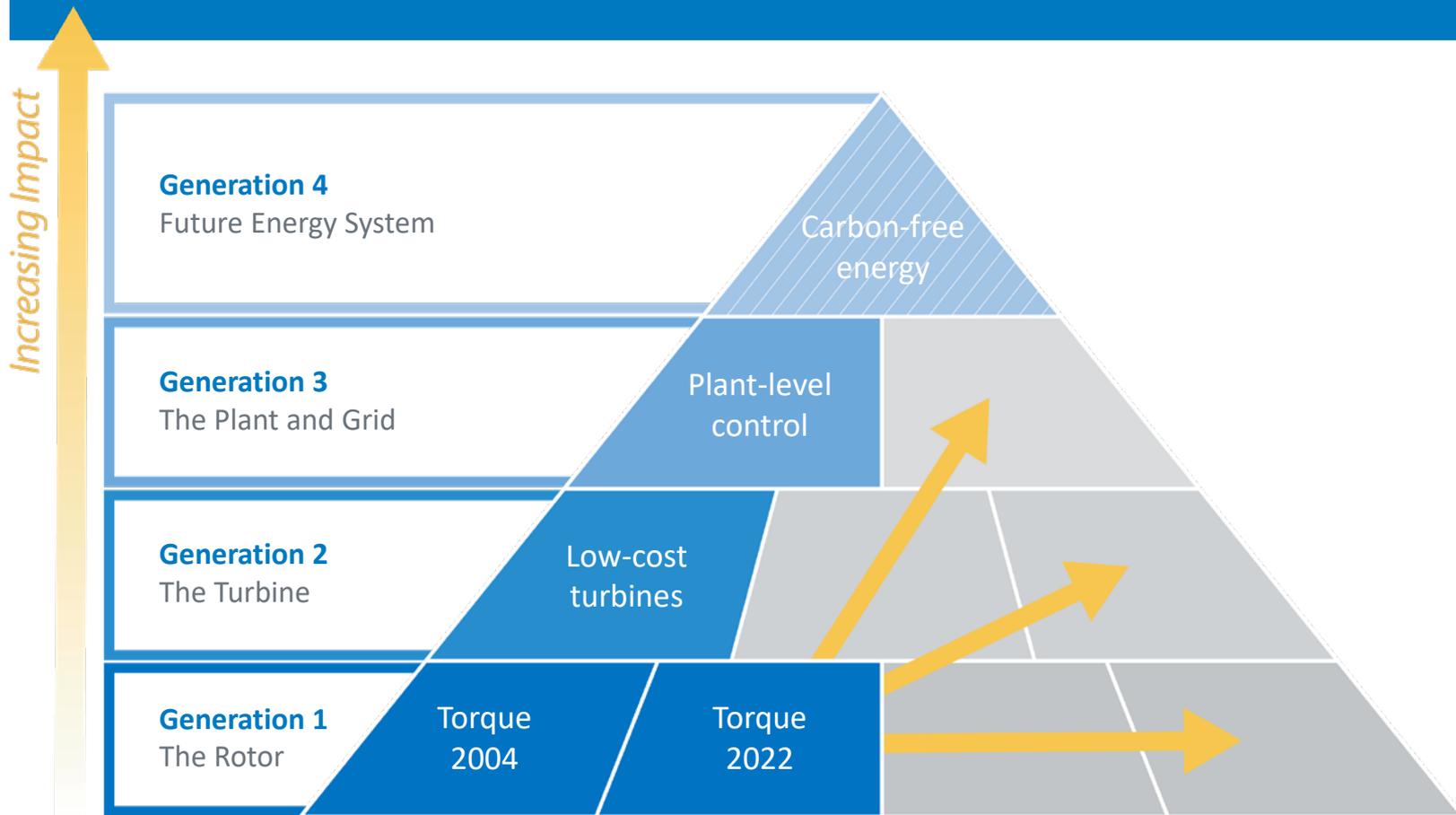
Aero, Structures, Controls, ...

Torque 2004

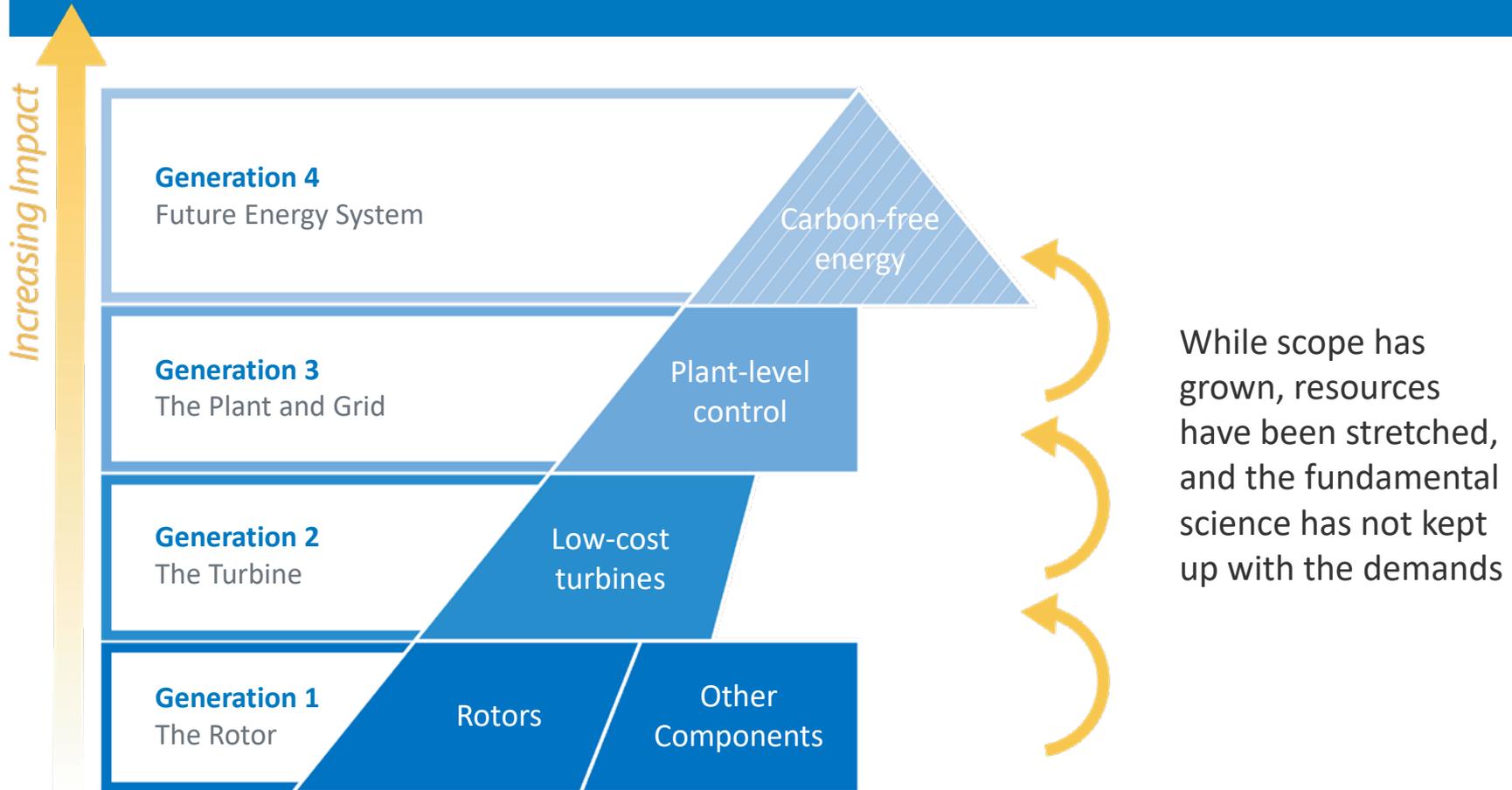


Photos by Lee Jay Fingersh, NREL

The Torque Conference Has Expanded into the Gap

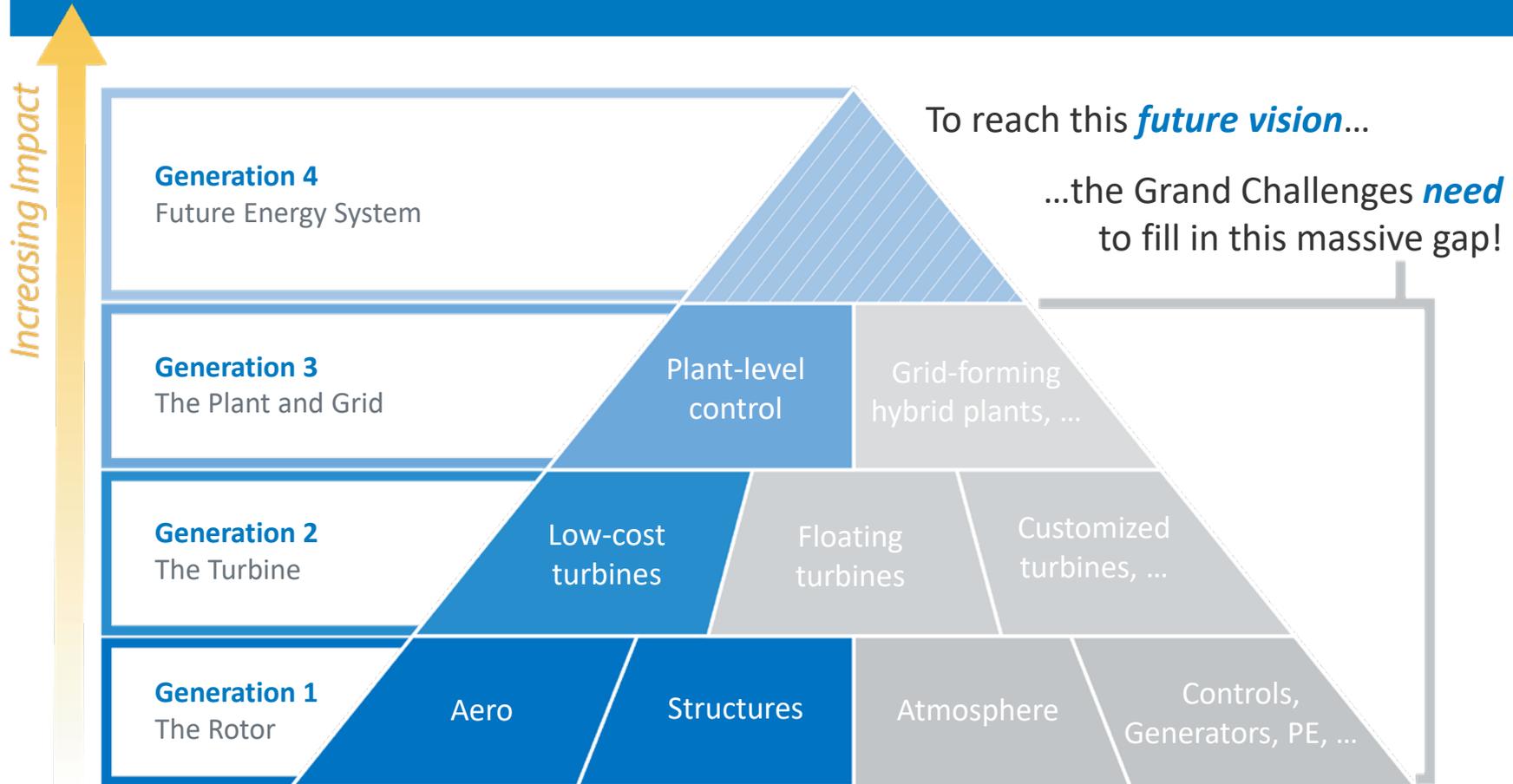


Each Generations Requires a Shift in Focus



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



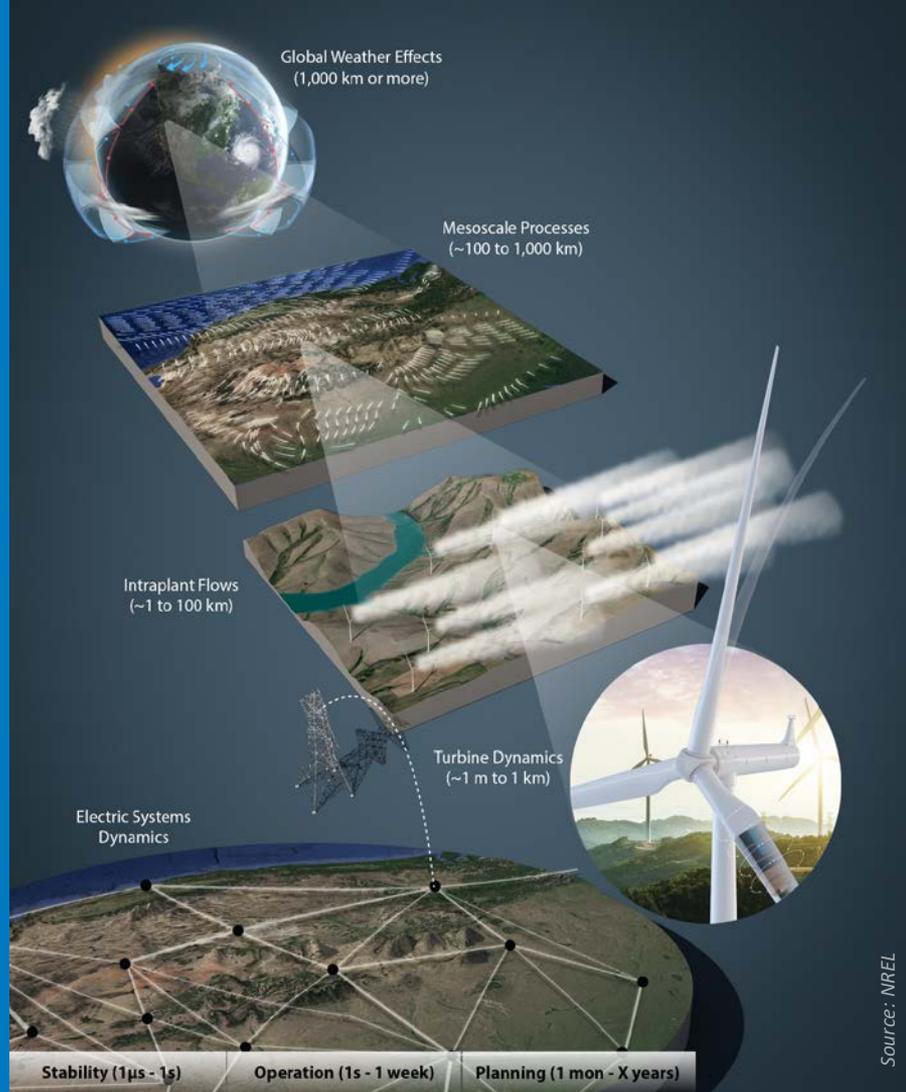
What issues need to be resolved for wind to supply 50% or more of global electricity?



IEA Wind TCP Topical Experts Meeting #89: A Grand Vision for Wind Energy

- **Purpose:** Explore the question of how to enable a future in which wind energy achieves its full potential as global energy resource
- **Participants:** Over 70 experts representing 15 different countries
- **Outcomes:** IEA report, “...Grand Vision for Wind Technology” and *Science* article: “Grand Challenges in the Science of Wind Energy”

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



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**

Cross-cutting issues were **Digitalization, Education, Systems Perspective**

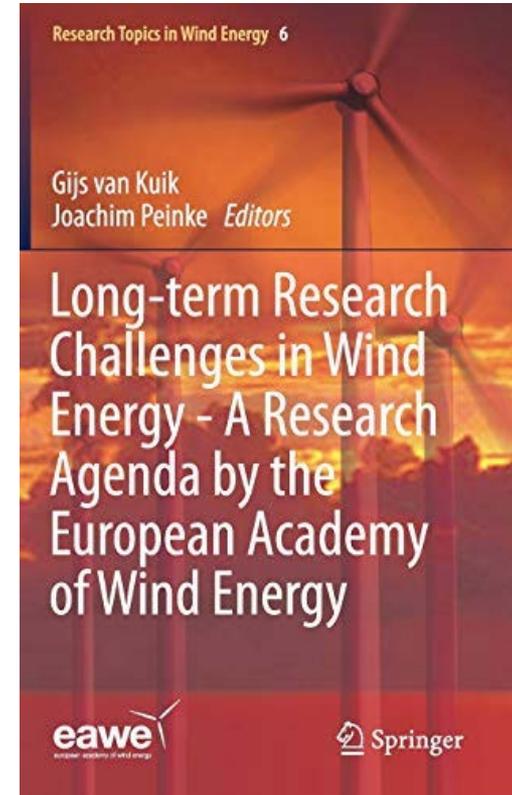
Expansion to Environmental, Social, and Small Wind Issues



- The *Science* article attracted two critical letters noting that the “Grand Challenges” stopped short of critical issues
 - **Social Science**: Letter from Jeremy Firestone, University of Delaware
 - **Environmental issues**: Letter led by Jay Diffendorfer at USGS
- Expansion to **Small Wind** challenges from the EAWE Small Wind Turbine Technical Committee

Challenges are explained in a suite of papers in WES

- Inspired by the “Long-term Research Challenges...”, van Kuik and Peinke (eds.), 2016.
- WES Editors eager to support articles for discussion
- Each is a Review PLUS Recommendations
- WES offers open review and discussion
- Official Sponsors
 - Katherine Dykes (co-lead)
 - NREL Leadership
 - IEA Wind
 - EAWE Publications Committee



Research Issues Expanded and Explained in 10 Articles



Turbulence

(Kosovic, NCAR and Basu, TU Delft)



Mesoscale Interactions

(Lundquist, CU/NREL)



Offshore Atmospheric Science

(Shaw, PNNL) – *Submitted Dec 2021*



The Turbine

(Veers, NREL) – *Submitted April 2022*



Wind Plant Control

(Meyers, KU Leuven) – *Submitted April 2022*



Grid and Hybrid Systems

(Holttinen, Recognis Oy)



Digitalization (Clifton, Enviconnect) –

Submitted March 2022



Environmental Co-Design

(Straw, USGS)



Social Science

(Kitzing, DTU)



Small Wind

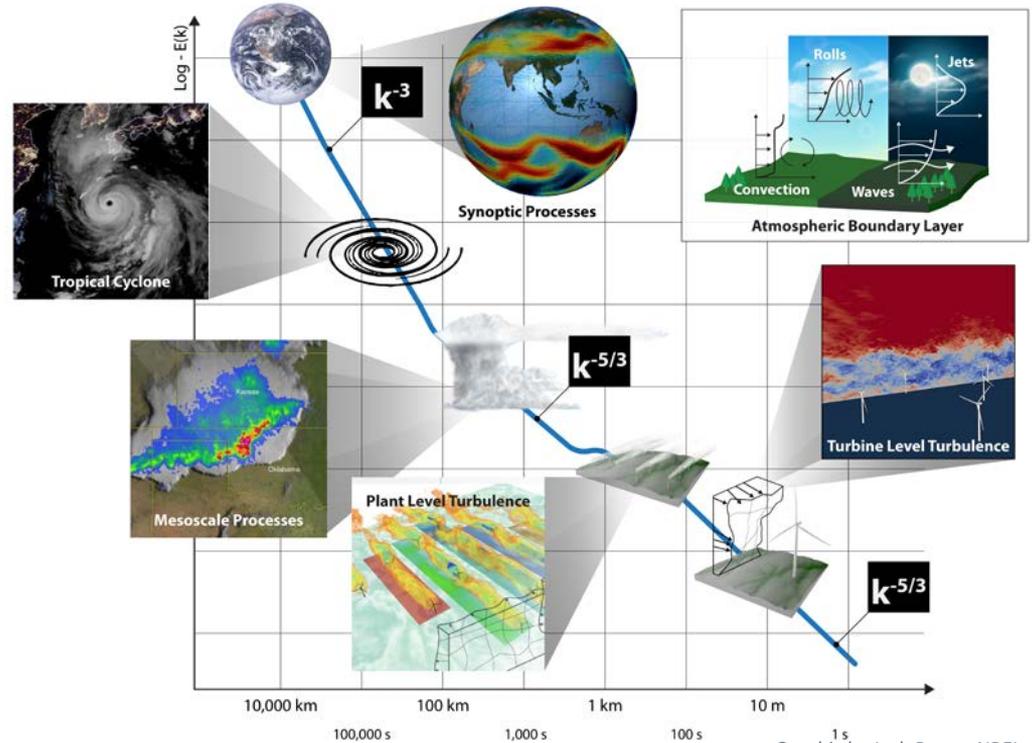
(Bianchini, University of Florence)

Total of >100 authors, 10 papers, to be submitted within CY 2022



Atmosphere: Multi-scale Turbulence

- Impacts of shear, veer, and turbulence on large turbines
- Spectra and coherence functions for a variety of conditions and locations
- Extreme conditions from tropical cyclones, thunderstorms, etc.
- Multi-scale, high-fidelity modeling to characterize atmospheric conditions for wind plant/turbine operation

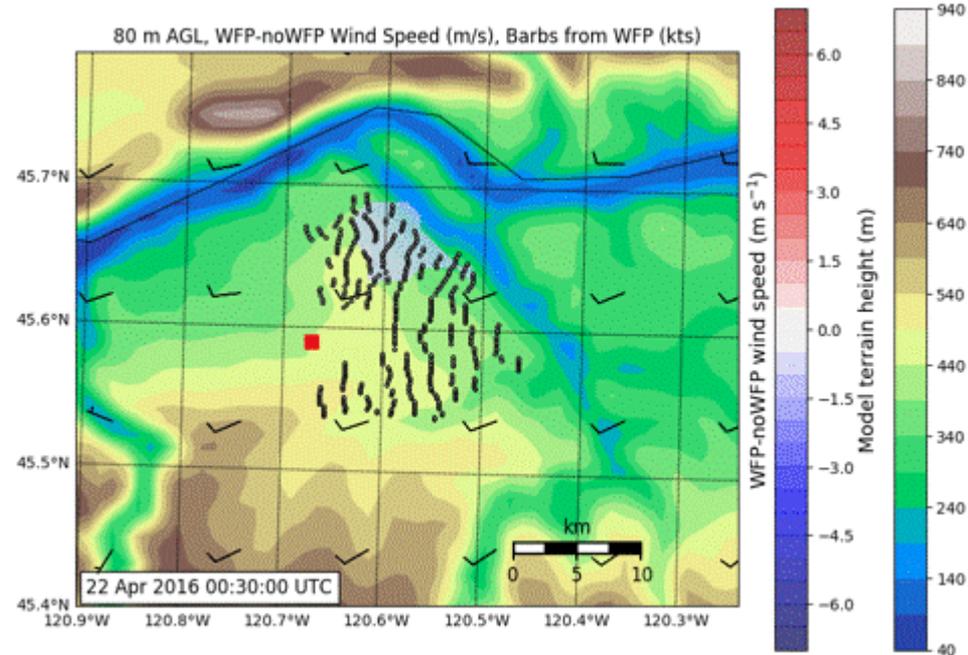


Graphic by Josh Bauer, NREL



Atmosphere: Mesoscale Wakes

- Wakes induce downwind changes in
 - Surface winds & temperatures
 - Hub-height impacts on power production and loads
- Stably stratified conditions induce strongest wakes
- Few datasets are available to validate mesoscale wake models
- Active areas of research:
 - aggregate wake effects on wind resource
 - simulating sub-grid scale wake interactions
 - interactions of wakes with terrain, changes in surface roughness, and weather features.



Courtesy Julie Lundquist and Rochelle Worsnop

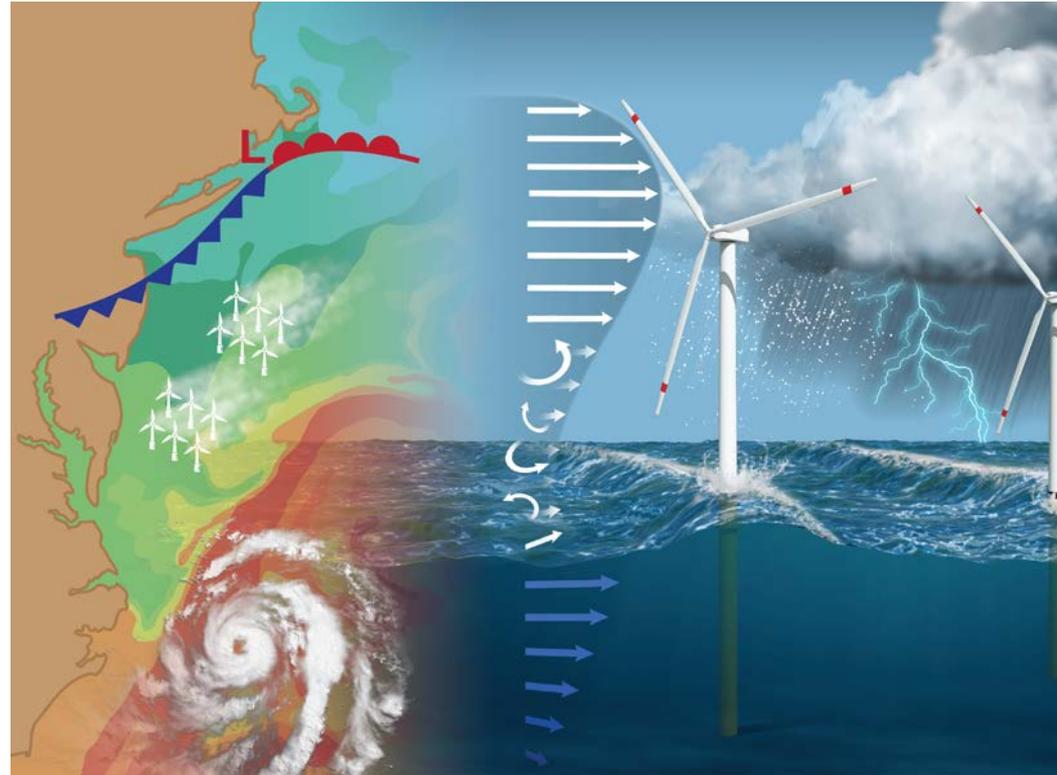


Atmosphere: Offshore

- Physical processes different than on land due to ocean circulations and air-sea processes
- Marine environment is hostile to measurement systems, resulting in sparse observations
- Phenomena: extreme events; low-level jets; precipitation; anomalous wind shear due to stratification

First Steps

- Additional observations offshore from both in situ and remote sensing systems
- Improved and validated simulations of wind-wave-wake coupling across all scales
- Improvement in subgrid-scale parameterizations incorporating AI/ML

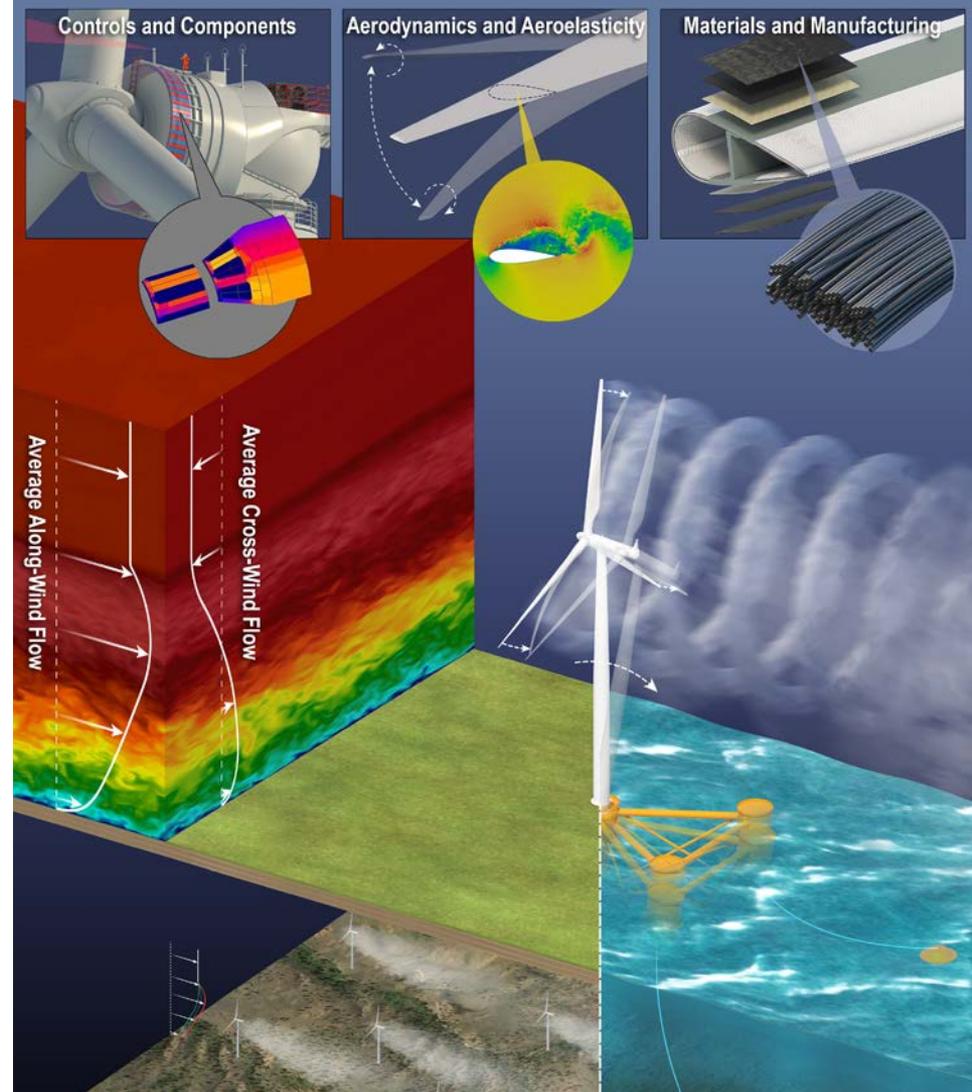


Source: PNNL



The Turbine

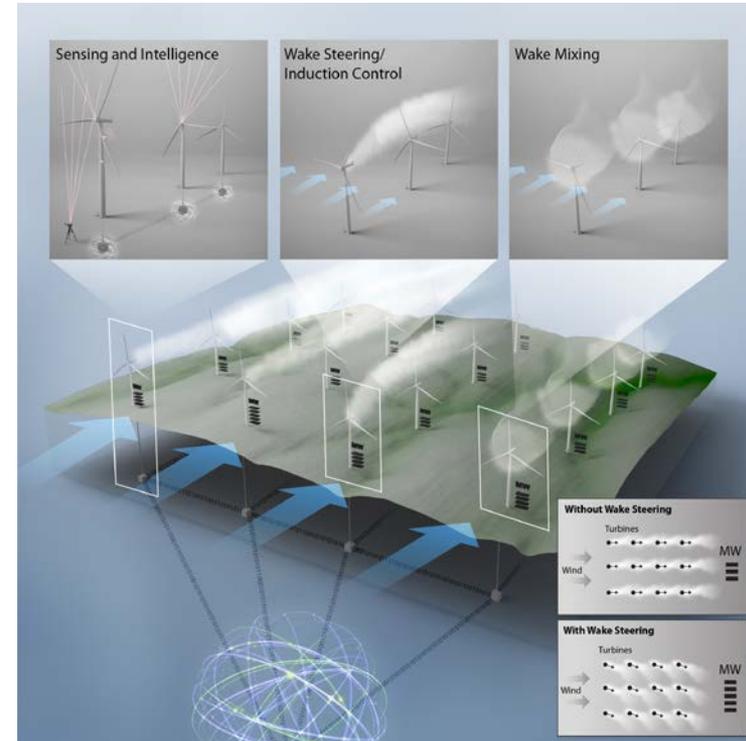
- Turbine size lies outside the inflow design basis
- Design tools are unvalidated for modern architectures (flexible and floating)
- Control co-design to expand and meet grid demands
- Manufacturing and materials innovation at scale
- Capturing the Exa-scale computational revolution





Wind Plant Flow Control

- Flow physics: improve understanding
 - Average wake response under various atmospheric conditions
 - Dynamic control of wakes and turbulence
- Algorithms:
 - Evolve from open to closed loop control
 - Reduce uncertainty and models errors
 - Incorporate machine learning and AI
- Validation and testing: improve and standardize
 - Large-eddy simulations
 - Wind tunnel testing
 - Small field campaigns
- Co-design:
 - Incorporate wind-farm control into the design process
 - Possibly leading to denser farms that better exploit varying market conditions



Graphic by Josh Bauer, NREL



The Grid

Services needed for system operation in addition to energy and capacity: frequency and voltage control, damping, angle stability, protection and black start

- Turbine control/sensing, power electronics, integrated storage
- Plants optimized to provide services with less loss of energy
- Hybrids (multiple generation sources and storage) add to service capabilities and avoid transmission congestion
- The energy system integrates wind power with other energy and grid technologies – no need to provide all services from wind power at all times

Graphic by Josh Bauer, NREL



Digitalization

- Huge amounts of data enable scientific progress, offer business insights, and enable innovation
- Data can be hard to find, difficult to share, and not suited for reuse: *Not Actionable*
- Organisational cultures that support and encourage digital innovation

Working together to develop ways to enable data flows, while still maintaining their own competitive advantage.



Data

Creating reusable data frameworks



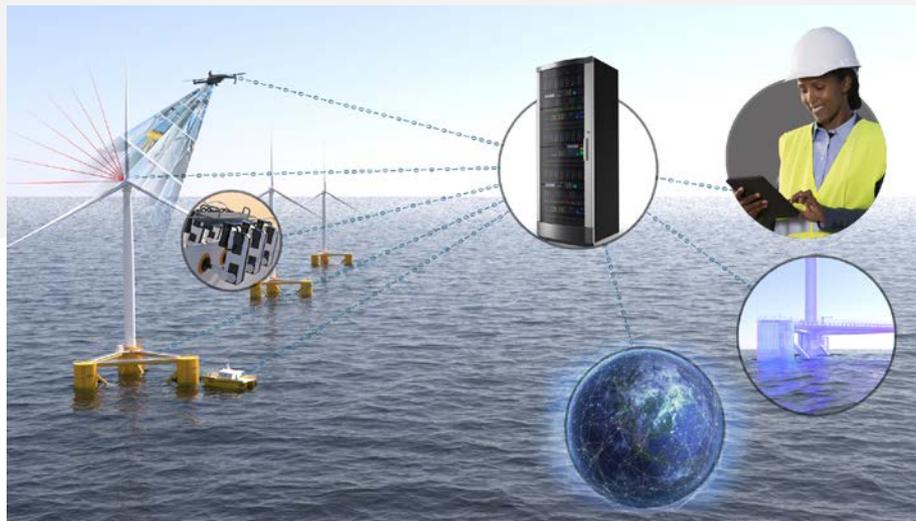
Culture

Connecting people and data to foster innovation



Coopetition

Enabling collaboration and competition



Graphic by Josh Bauer, NREL

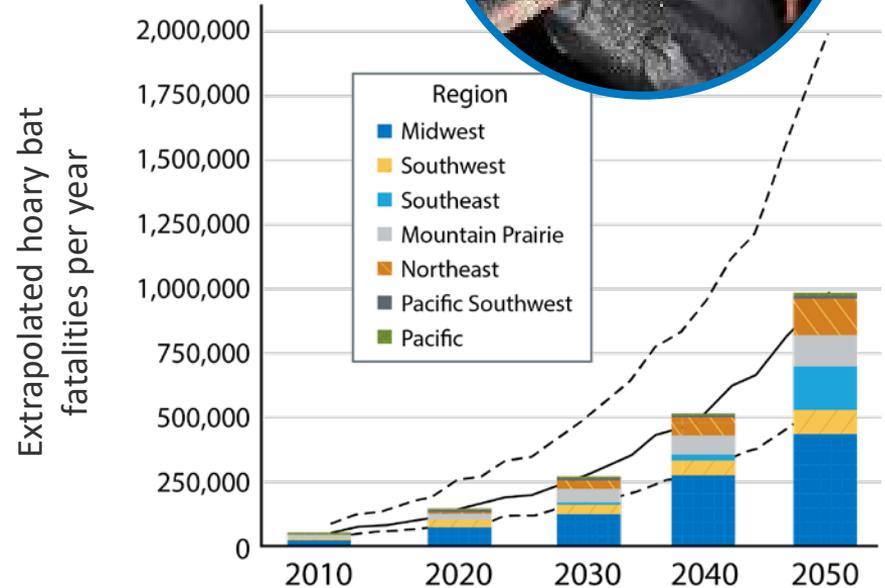


Environmental Co-design

- Environmental impacts are now avoided through constraining current technology
- Mitigation often takes on the form of curtailment (shutting down the plant)
- Co-design would optimize the technology
 - Combining physical, economic and environmental requirements
 - Produce new and customized technology



Photos courtesy of Chris Hein, NREL





Social Science: Human Interaction

- Co-design for turbine, plant, and social considerations throughout the life-cycle
- Spatial planning and land use management to foster informed tradeoffs between competing human uses
- Community participation and benefits
 - What's appropriate and equitable
 - What's compelling vs viewed as a buyout
- Public engagement in
 - Projects
 - Spatial planning
 - Energy planning and tradeoffs

Setback types include:

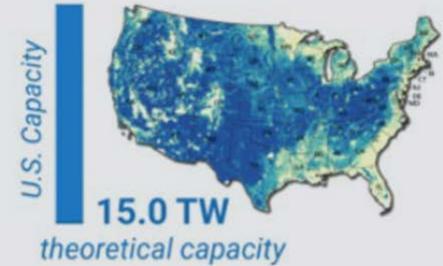
- Infrastructure (buildings, property lines, roads, etc.)
- Height
- Sound
- Shadow Flicker

Other restrictive ordinances

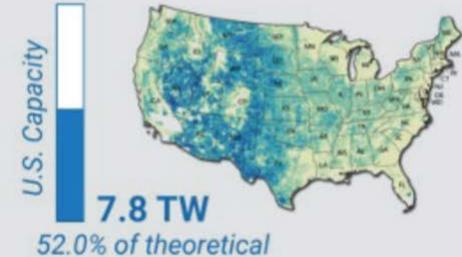
- Outright ban (moratorium)
- Maximum installation size
- Tower density
- Lot size

Restrictive Siting Reduces Developable Potential at Substantive Levels

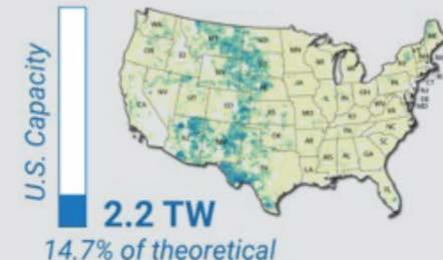
Open Access Scenario



Reference Access Scenario



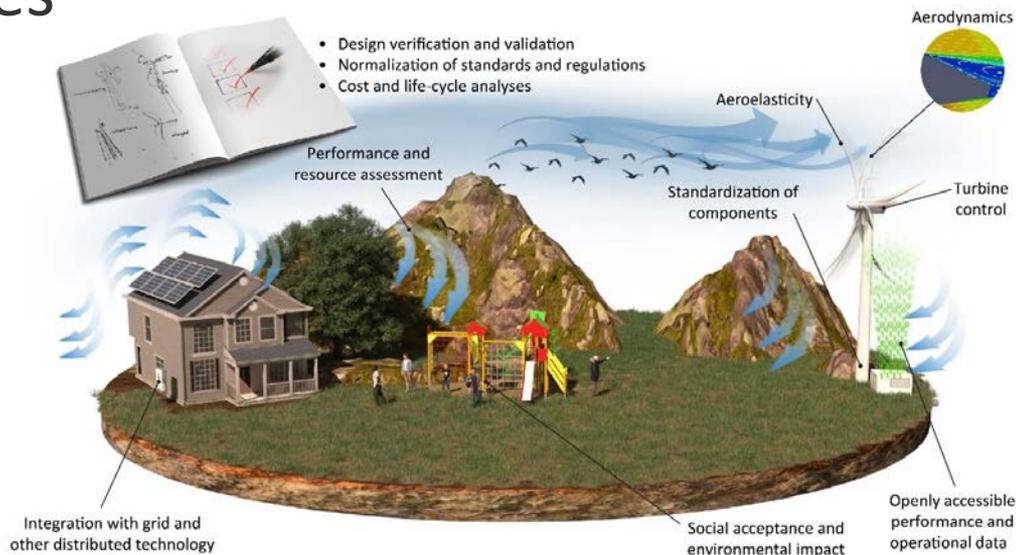
Limited Access Scenario





Small Wind Turbines

- Improve energy conversion through design and control, especially in case of turbulent wind
- Better predict long-term turbine performance with limited resource measurements and prove reliability
- Facilitate electrical system integration
- Improve economic viability
- Foster engagement, social acceptance, and deployment for global distributed wind markets



Source: Bianchini, et al., "Current status and grand challenges for small wind turbine technology," WES, (to be submitted, 2022)

Far from the largest rotating machines on earth, the **physics**, **design**, and **applications** of small wind turbines have been often neglected.

Actions to Address the Challenges Multi-faceted, Multi-scale, and Long-term

At Scale

- Turbine aeroelastic validation experiments (land and offshore)
- Wind plant control and interaction experiments
- Instrumented sites for research and prototyping of floating offshore systems

At ALL Scales

- Validation of grid stability based on wind and hybrid plants
- Turbulence and bulk flow dynamics for extreme events

Expanding Our Scope

- Social engagement that drives value to impacted communities
- Environmental/Social/Economic Co-design to design bespoke turbines and plants

A Decade Long Effort

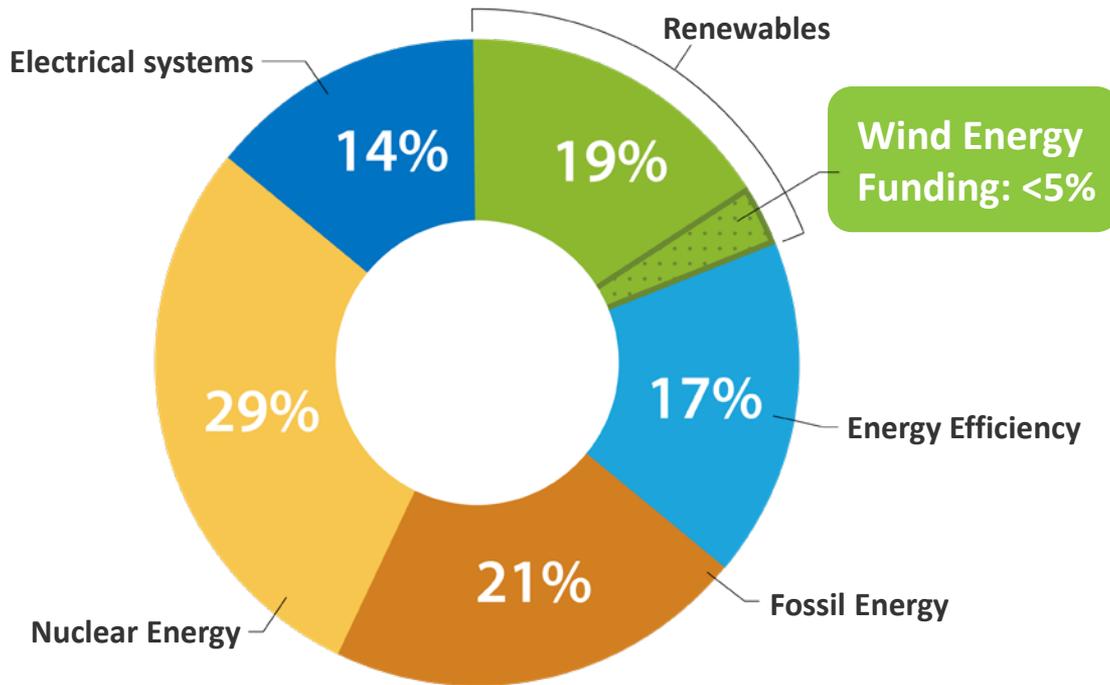
- Rewrite the design standard to navigate the multi-dimensional space

And many, many others...

Each of these required actions would stretch the resources now devoted to wind energy, and we need to do them all, and more!

Do we have a funding problem? U.S. Example

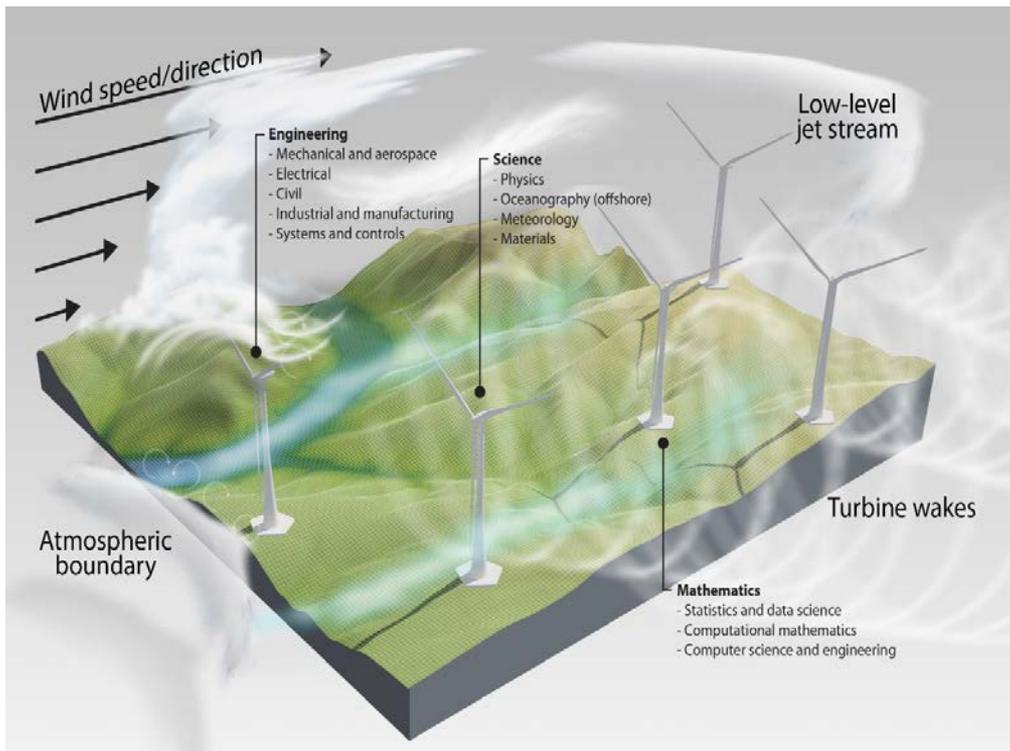
DOE Energy Technology Share of Funding, FY 2009-FY2018



Past Success and Future Expectations

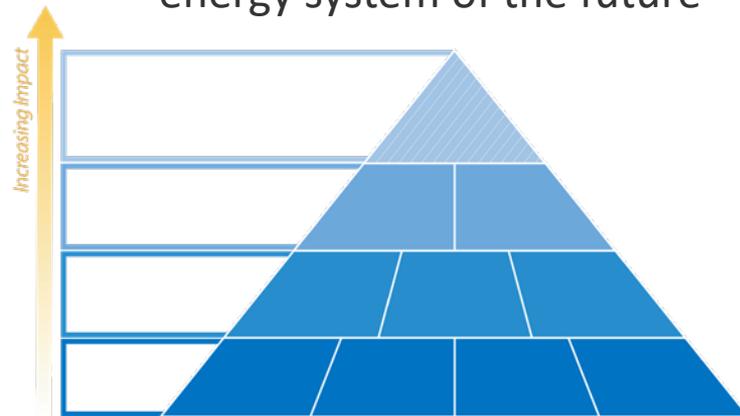
- **Wind** must grow to supply 40% of electricity by 2035
 - Currently \$114M/year
- **Solar** must do the same
 - Currently \$290M/year
- **Nuclear** in the U.S. grew to 20% in 20 years
 - Currently \$1,600M/year and was much higher

Expertise to Achieve Success – System Perspective



+ Wildlife Biologists and Social Scientists

Wind as foundation of the energy system of the future



Thank You

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Panel Members

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- Sarah Barber (Eastern Switzerland University)
- Sukanta Basu (TU Delft)
- Nicolaos Cutululis (DTU)
- Johan Meyers (KU Leuven)
- Paul Veers (NREL)
- Simon Watson (TU Delft), Conference Chair, Wrap-up