NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Wind Plant Modeling and Simulation: The amazing interrelationships of physics and engineering in wind plant design

Paul Veers, NWTC Chief Engineer, NREL

AIAA Science and Technology Forum and Exposition
January 7, 2019
San Francisco, California

NREL/PR-5000-73088

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under **Contract No. DE-AC36-08GO28308**. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

New Book: Modeling and Simulation in Wind Plant Design and Analysis (to be published by IET in 2019)

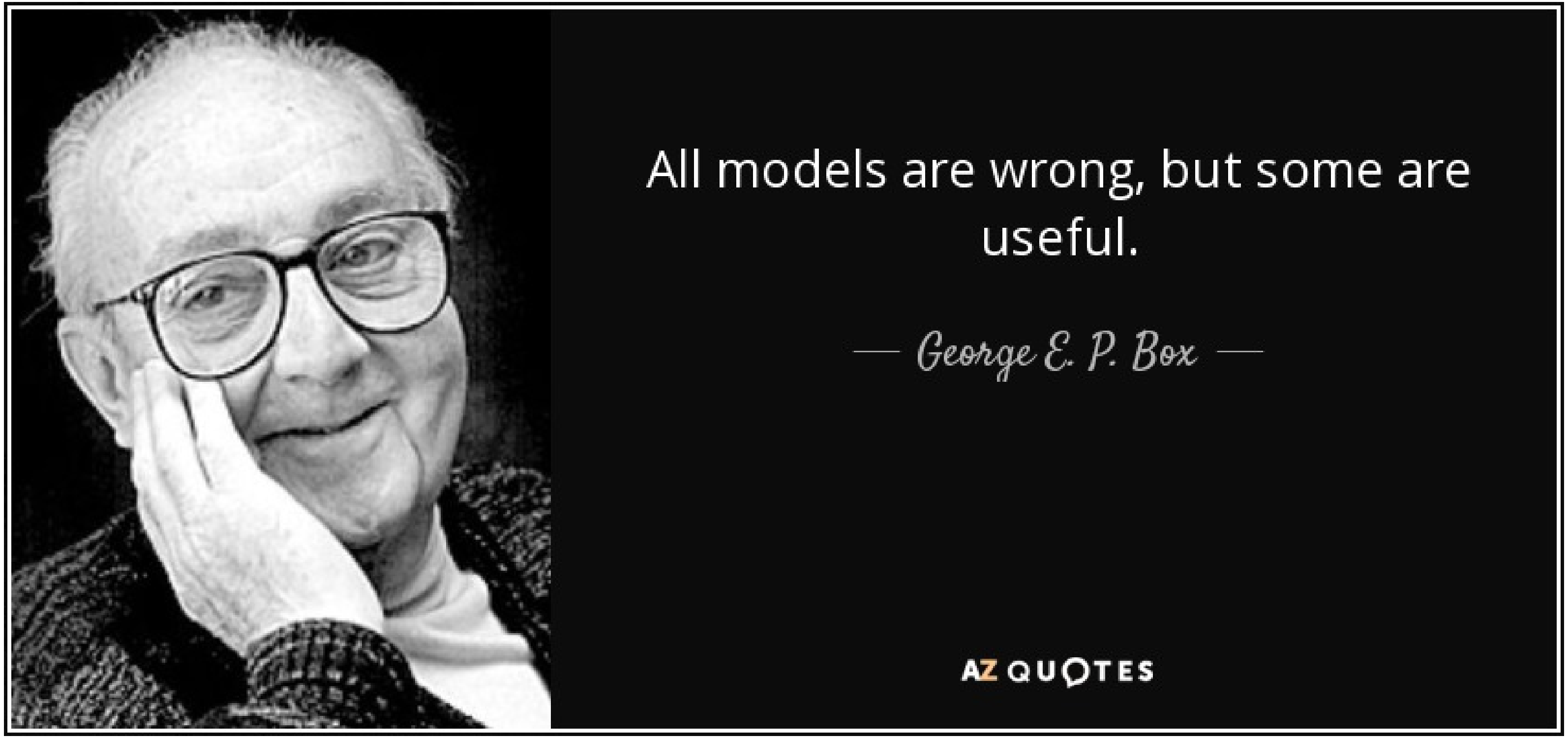
- Volume 1: Atmosphere and Plant

1. The Exascale Computational Challenge (Sprague and Robinson, NREL)
2. Bladed-resolved modeling with fluid-structure interaction (Vijayakumar and Brasseur, NREL and CU)
3. Meso-scale modeling of the atmosphere (Haupt et al., NCAR)
4. Mesoscale to Microscale Coupling for High-Fidelity Wind Plant Simulation (Mirocha, LLNL)
5. Atmospheric turbulence modeling and simulation (Berg and Kelley, DTU)
6. Modeling the flow through full wind plants: Wakes and Wake Interactions (Churchfield and Moriarty, NREL)
7. Control of Wind Plants and Power Output (van Wingerden et al., TU Delft and NREL)
8. Forecasting for Wind Power Production and Grid Operations(Zack, UL)
9. Cost of Energy and Financial Structures Modeling (Hand, et al., CCEC and NREL)

- Volume 2: Turbine and System

1. Aerodynamics of wind turbines (MOL Hansen, DTU)
2. Structural Dynamics: the turbine as an aeroelastic system (Morten Hansen, LM/GE)
3. Blade/Rotor design and analysis and optimization (Bottasso and Bortolotti, TU Munich and NREL)
4. Drive Train Analysis for Reliable Design (Zhang, et al., Romax and NREL)
5. Offshore turbines with bottom-mounted or floating support systems (Matha, et al., Ramboll and NTNU)
6. Turbine Controller design (Wright, et al., NREL, CU, CSM, TU Delft)
7. System Engineering and optimization of wind turbines and plants (Ning and Dykes, BYU and NREL)
8. Wind Plant Electrical System: Electrical Generation, Machines, Power Electronics and Collector Systems (Muljadi and Gevorgian, Auburn and NREL)
9. Grid Modeling with Wind Plants (Miller and Stenclik, GE)

The truth about modeling and simulation



https://www.azquotes.com/author/22390-George_E_P_Box

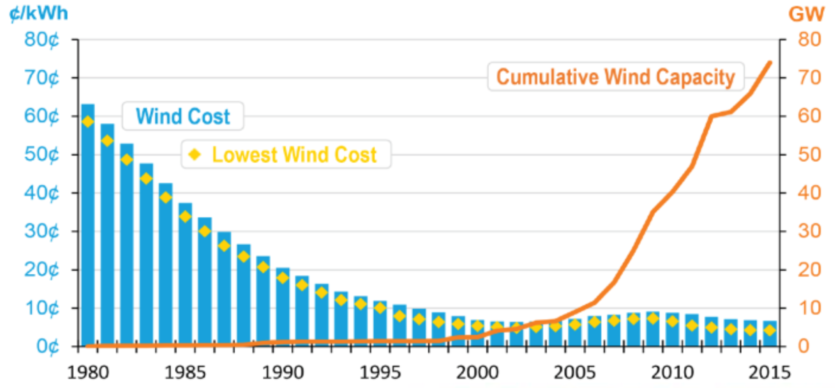
Outline

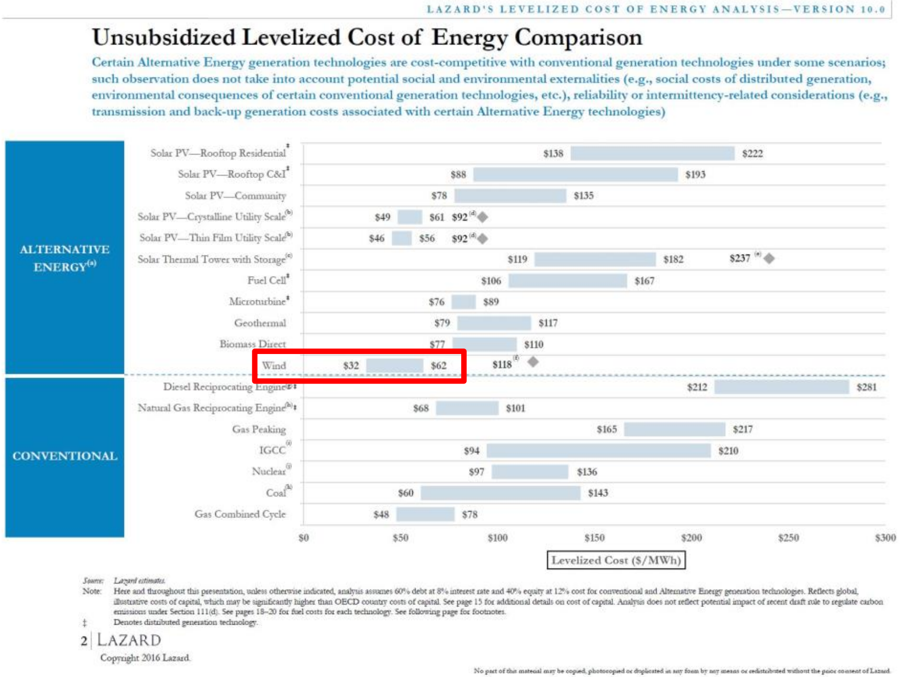
- Technology deployment status
- Drivers of success – past turbine focus, future system perspective
- The revolution in computational capabilities
- Upstream of the turbine
- Downstream of the turbine
- Controlling the power plant
- Grid connection and integration

Wind Energy: Past and Present (end of 2017)

Decreased Costs in Wind Energy have led to Exponentially Increasing Deployment

- Lowest cost electricity available in 2016 (Lazard)
- Current costs: 3-7 cents/kWh
- Wind provided over 6% of U.S. electricity in 2017
- US Wind capacity (89GW) now exceeds hydropower (80GW)




LAZARD'S LEVELIZED COST OF ENERGY ANALYSIS—VERSION 10.0

Unsubsidized Levelized Cost of Energy Comparison

Certain Alternative Energy generation technologies are cost-competitive with conventional generation technologies under some scenarios; such observation does not take into account potential social and environmental externalities (e.g., social costs of distributed generation, environmental consequences of certain conventional generation technologies, etc.), reliability or intermittency-related considerations (e.g., transmission and back-up generation costs associated with certain Alternative Energy technologies)

	Technology	Low	High	Other
ALTERNATIVE ENERGY(a)	Solar PV—Rooftop Residential‡	$138	$222	
	Solar PV—Rooftop C&I‡	$88	$193	
	Solar PV—Community	$78	$135	
	Solar PV—Crystalline Utility Scale(b)	$49	$61	$92(d)
	Solar PV—Thin Film Utility Scale(b)	$46	$56	$92(d)
	Solar Thermal Tower with Storage(c)	$119	$182	$237(e)
	Fuel Cell‡	$106	$167	
	Microturbine‡	$76	$89	
	Geothermal	$79	$117	
	Biomass Direct	$77	$110	
	Wind	$32	$62	$118(f)
CONVENTIONAL	Diesel Reciprocating Engine(g)‡	$212	$281	
	Natural Gas Reciprocating Engine(h)‡	$68	$101	
	Gas Peaking	$165	$217	
	IGCC(i)	$94	$210	
	Nuclear(j)	$97	$136	
	Coal(k)	$60	$143	
	Gas Combined Cycle	$48	$78	

$0 $50 $100 $150 $200 $250 $300

Levelized Cost ($/MWh)

Source: Lazard estimates.
Note: Here and throughout this presentation, unless otherwise indicated, analysis assumes 60% debt at 8% interest rate and 40% equity at 12% cost for conventional and Alternative Energy generation technologies. Reflects global, illustrative costs of capital, which may be significantly higher than OECD country costs of capital. See page 15 for additional details on cost of capital. Analysis does not reflect potential impact of recent draft rule to regulate carbon emissions under Section 111(d). See pages 18–20 for fuel costs for each technology. See following page for footnotes.
‡ Denotes distributed generation technology.

2 | LAZARD

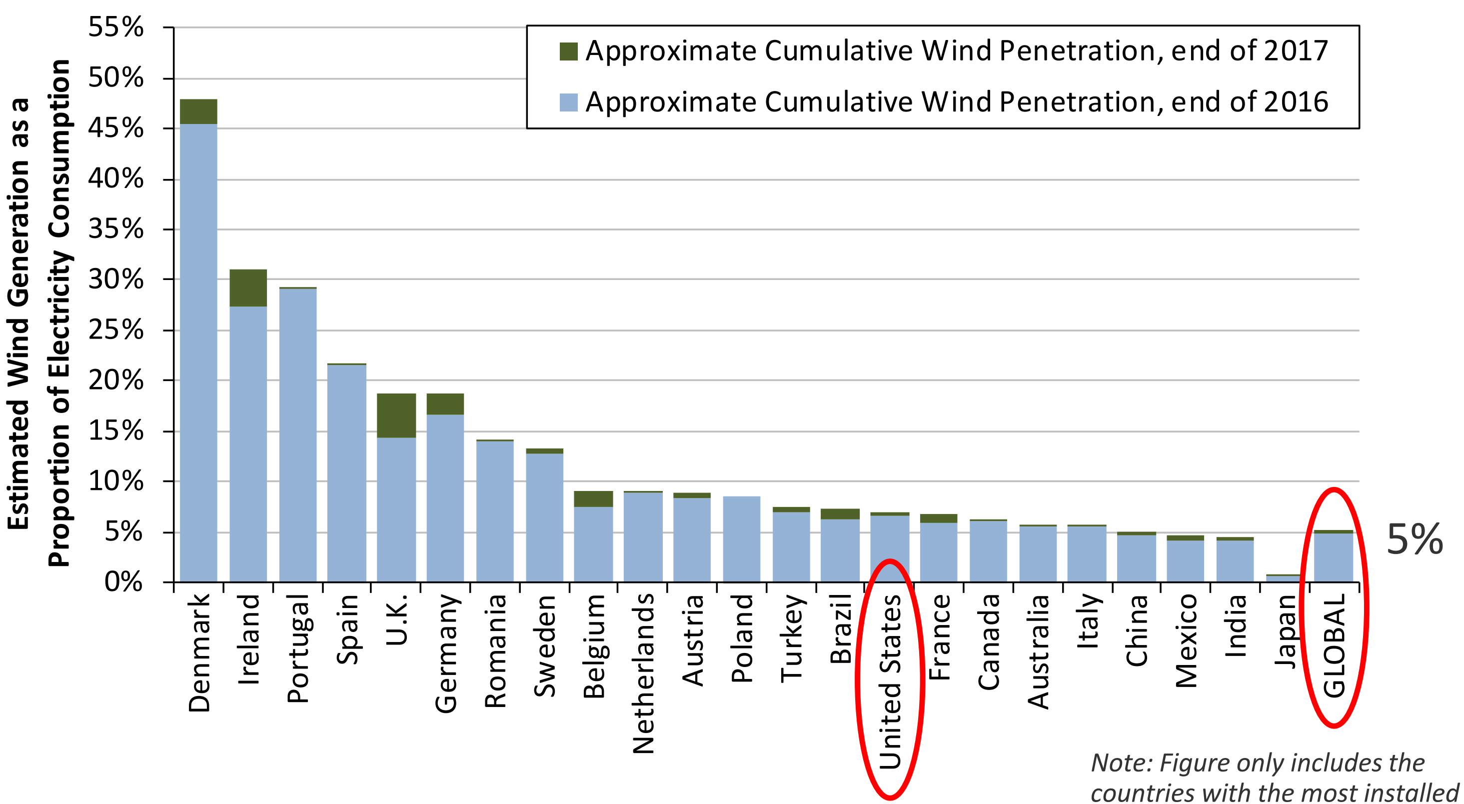
Globally, the U.S. Placed 2nd in Annual Wind Power Capacity Additions in 2017, and in Cumulative Wind Power Capacity

Annual Capacity (2017, MW)		Cumulative Capacity (end of 2017, MW)	
China	19,660	China	188,392
United States	**7,017**	**United States**	**88,973**
Germany	6,581	Germany	56,132
United Kingdom	4,270	India	32,848
India	4,148	Spain	23,170
Brazil	2,022	United Kingdom	18,872
France	1,694	France	13,759
Turkey	766	Brazil	12,763
South Africa	618	Canada	12,239
Finland	535	Italy	9,479
Rest of World	5,182	*Rest of World*	82,391
TOTAL	**52,492**	**TOTAL**	**539,019**

- U.S. also remains a distant second to China in cumulative capacity
- Global wind additions in 2017 were below the 54,600 MW added in 2016 and the record level of 63,000 MW added in 2015

Courtesy Ryan Wiser and Mark Bolinger of LBNL for data from the 2017 Market Report.
https://emp.lbl.gov/publications/2017-wind-technologies-market-report

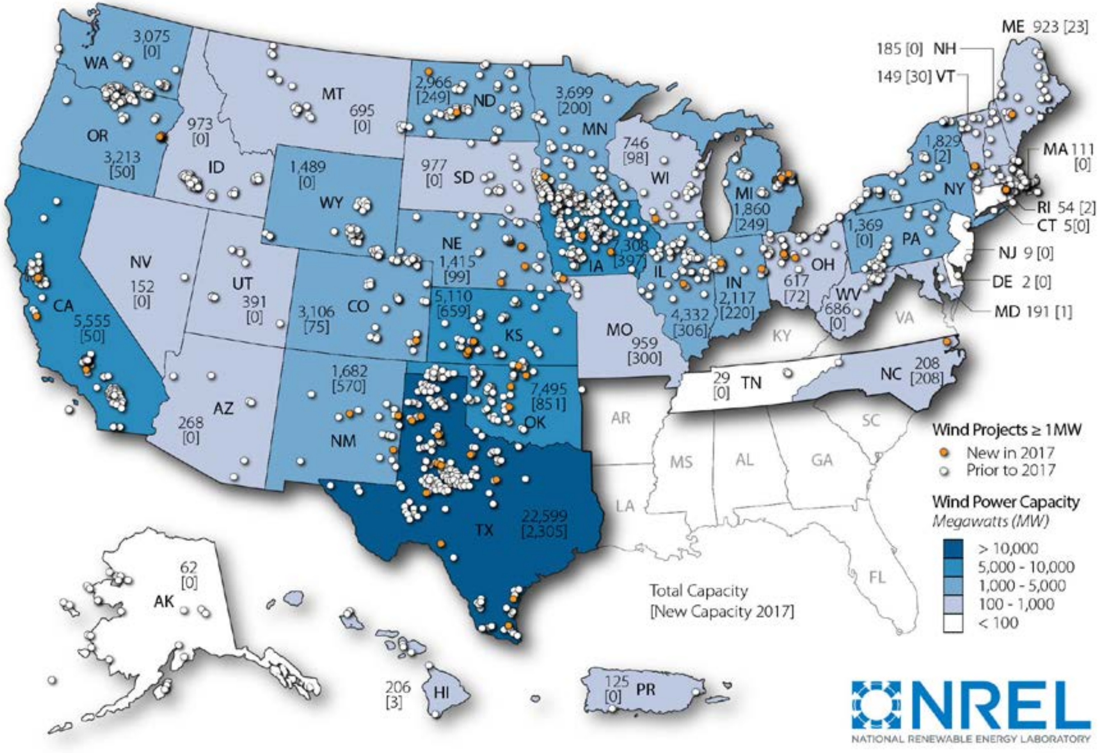
The United States is Lagging Other Countries in Wind as a Percentage of Electricity Consumption



Note: Figure only includes the countries with the most installed wind power capacity at the end of 2017

Courtesy Ryan Wiser and Mark Bolinger of LBNL for data from the 2017 Market Report.
https://emp.lbl.gov/publications/2017-wind-technologies-market-report

The Geographic Spread of Wind Power Projects Across the United States Is Broad, with the Exception of the Southeast



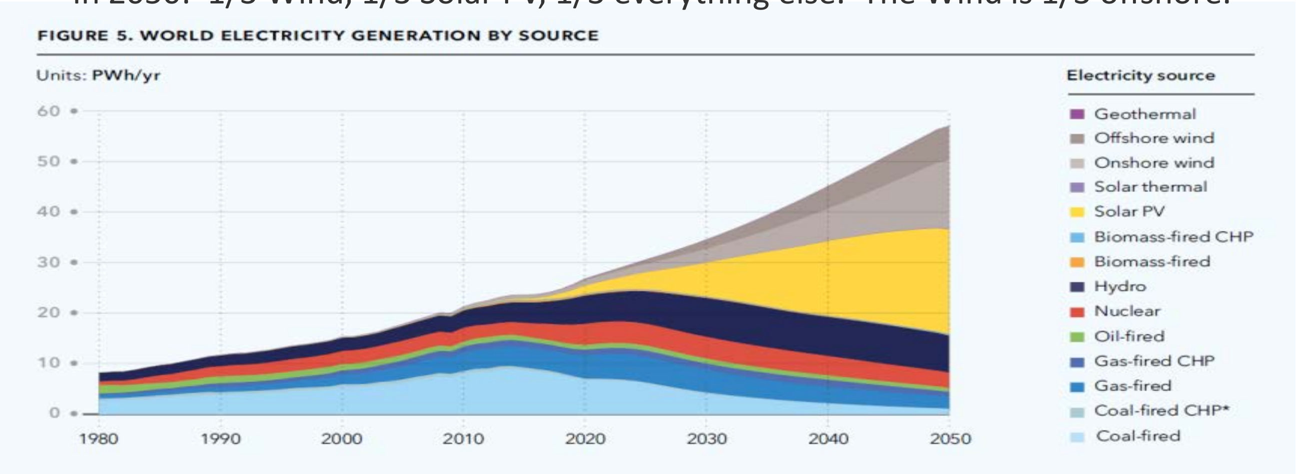
Note: Numbers within states represent cumulative installed wind capacity and, in brackets, annual additions in 2017

Courtesy Ryan Wiser and Mark Bolinger of LBNL for data from the 2017 Market Report.
https://emp.lbl.gov/publications/2017-wind-technologies-market-report

DNV GL Energy Transition Outlook 2017 - Electricity

"… a base or 'central' case, … is the aim of this present exercise, which is a forecast, not a scenario." *Remi Eriksen, Group President & CEO DNV GL*

In 2050: 1/3 Wind, 1/3 Solar PV, 1/3 everything else. The Wind is 1/3 offshore.



Source: DNV GL Energy Transition Outlook 2017
https://eto.dnvgl.com/2017/main-report

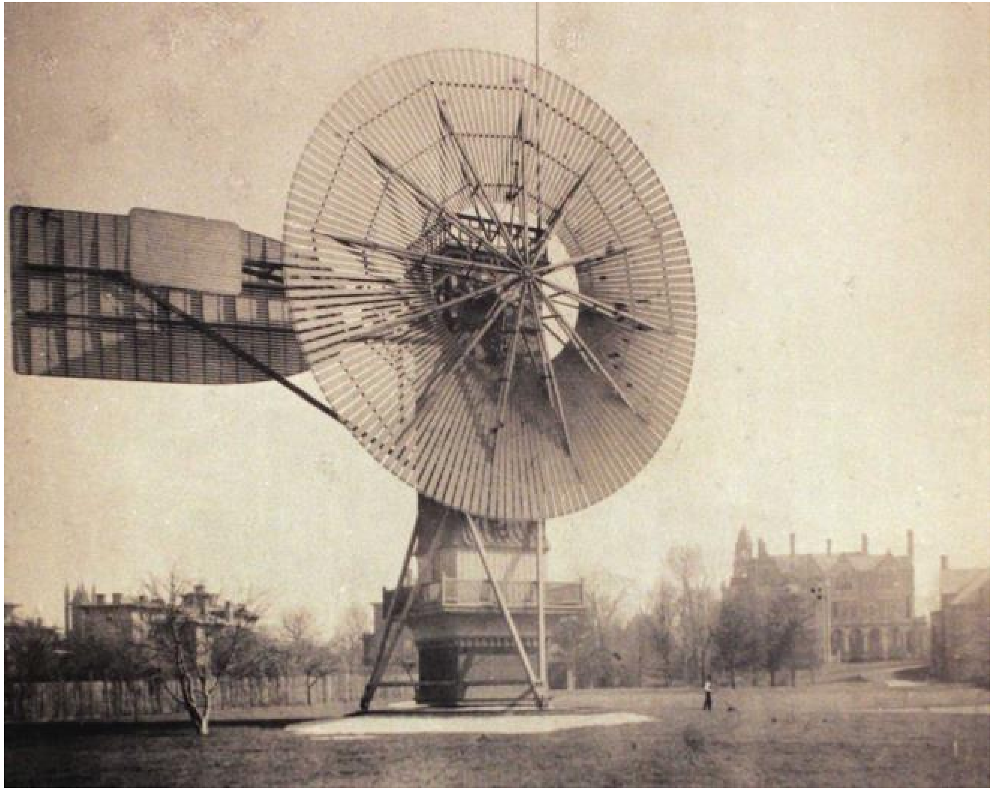
Historical Look

Historically, the secret to wind energy has been *SURVIVAL*

Nansen and Johansen arctic expedition, 14 March 1895. (Public Domain)

US: wind energy for everyone

Charles Brush windmill, Cleveland, Ohio, USA, 1888

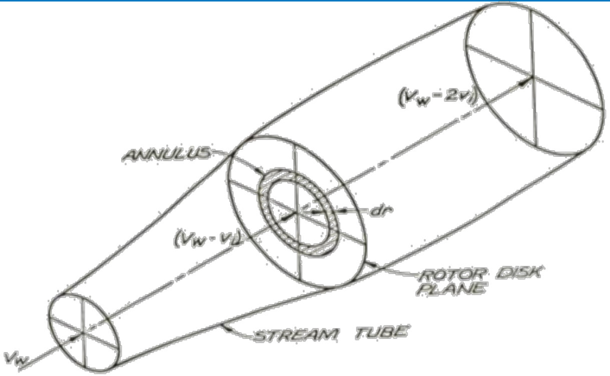


(Public Domain)

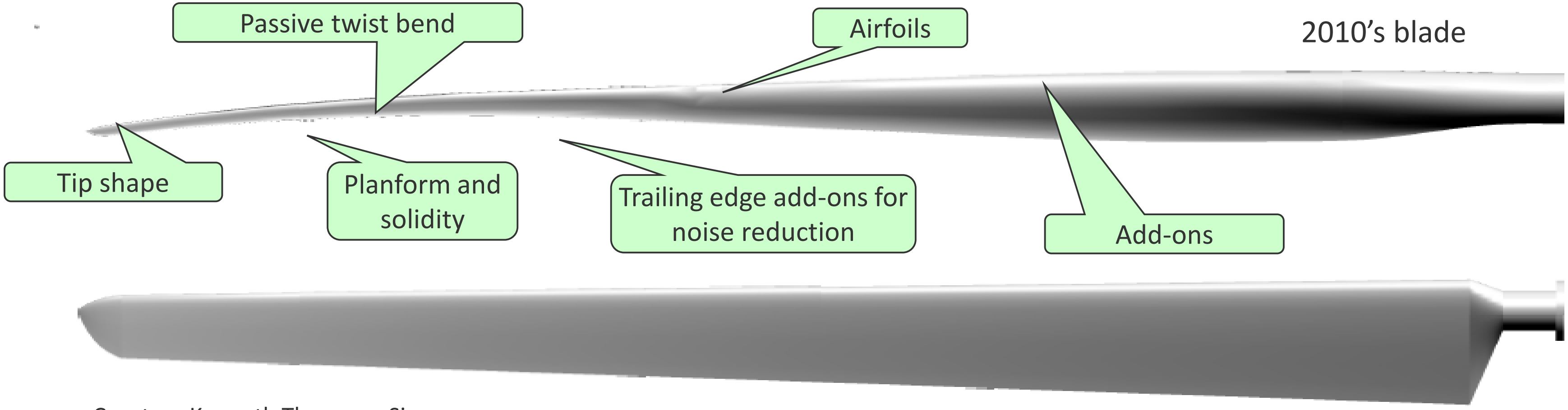
https://www.pinterest.com/pin/114701740307223354/

Basics

- Earth's atmosphere has wind
- Wind is moving air
- Air is a fluid
- A fluid is a continuum



Early View of Wake and Energy Extraction



Courtesy Kenneth Thomsen, Siemens

Extrapolation of turbine markets in 2030

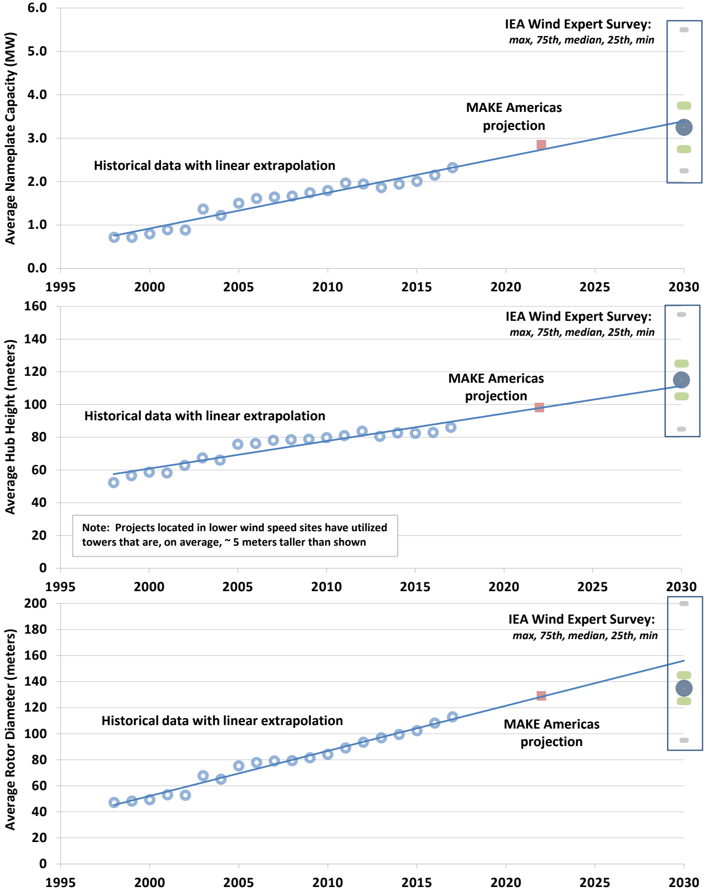
- Everything is getting bigger

- Rotor diameter has more than doubled over the last 20 years

Capacity – 3.3MW

Hub Height – 111m

Rotor Diameter – 156m

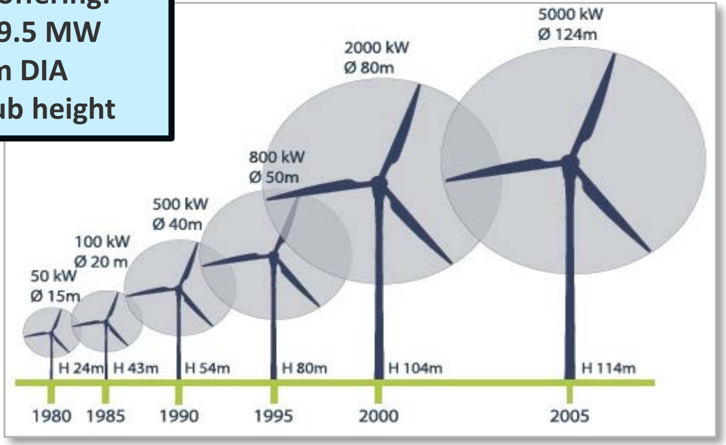


Courtesy Ryan Wiser and Mark Bolinger of LBNL for data from the 2017 Market Report. https://emp.lbl.gov/publications/2017-wind-technologies-market-report

R&D Focus Transition: Turbine → Plant

Largest offering:
Vestas 9.5 MW
164m DIA
140m hub height

Yesterday
(Individual Turbines)



2020 (and beyond)
(SMART Wind Plants)

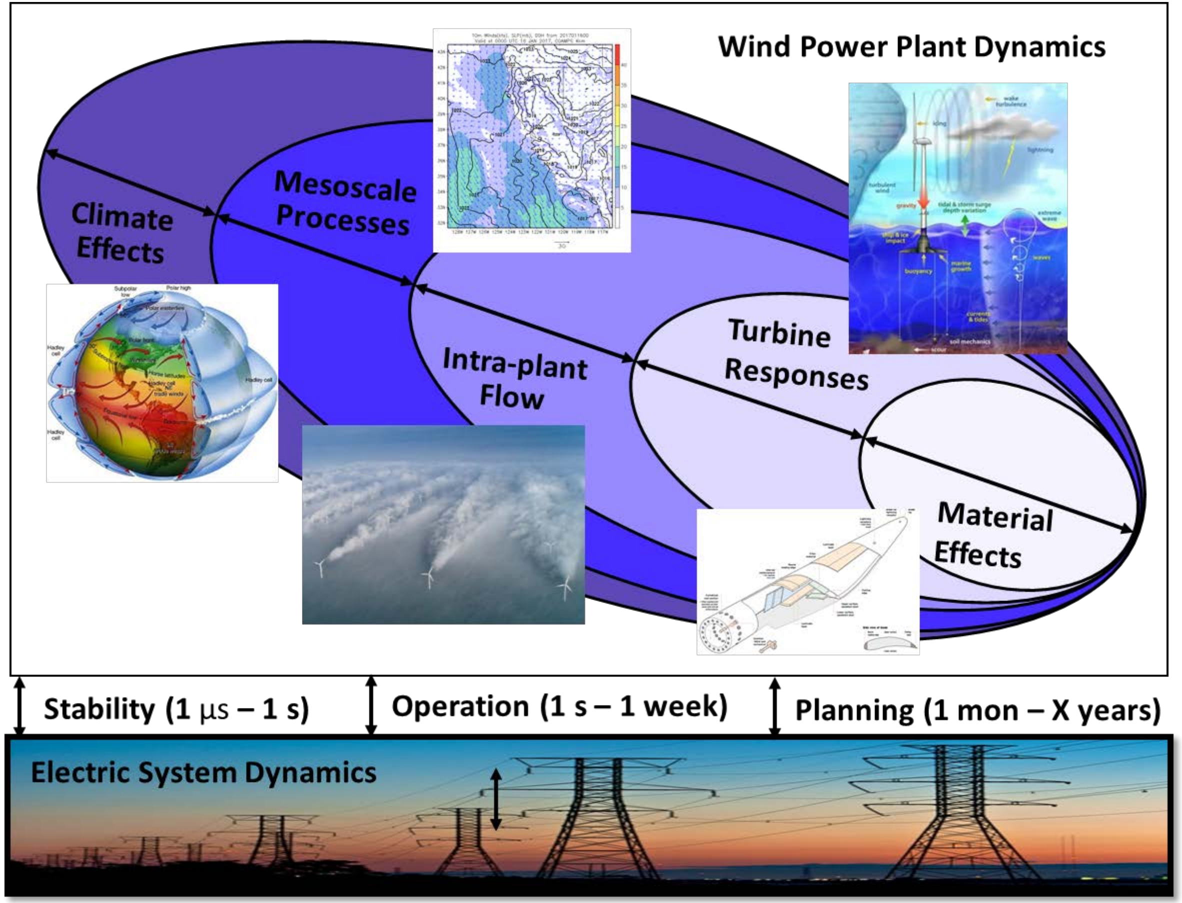
Individual wind turbine R&D

- >90 GW Deployed (~6% of U.S. Electricity)
- Land-based wind: 3-6 ₵/kWh (beating coal)
- Multi-Billion dollar industry with involvement dominated by multi-national corporations
- Advances in fundamental science driving major innovation: validation of internal tools and engineering processes

Wind plant optimization R&D

- Develop new technologies that exploit interactions among turbines, resource, & operating environment
- Design for operation at optimal project profitability and Internal Rate of Return (IRR)
- Wind plant physics & science challenges require new core competencies

Wind Plant design spans several orders of magnitude



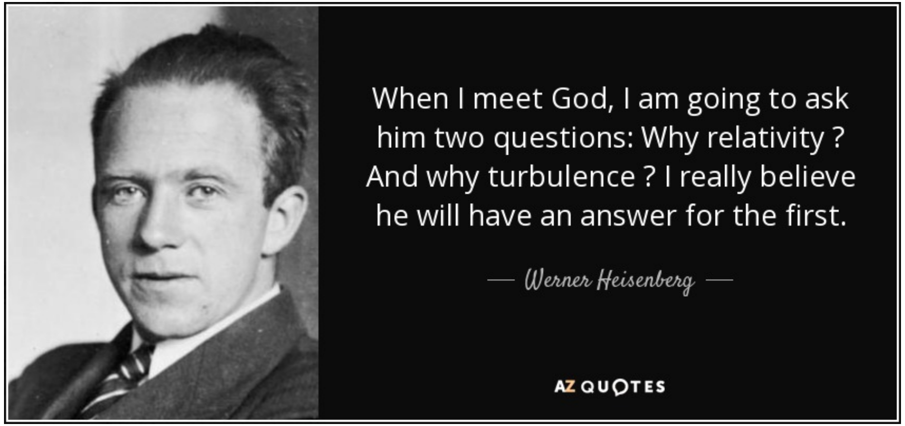
Courtesy Katherine Dykes, NREL

The design of the wind plant is a multi-scale, multi-physics problem

Wind plants are connected to the largest machine on the planet – the grid

Computational Revolution
(Especially in Fluid Dynamics)

Can we solve Navier-Stokes equations?



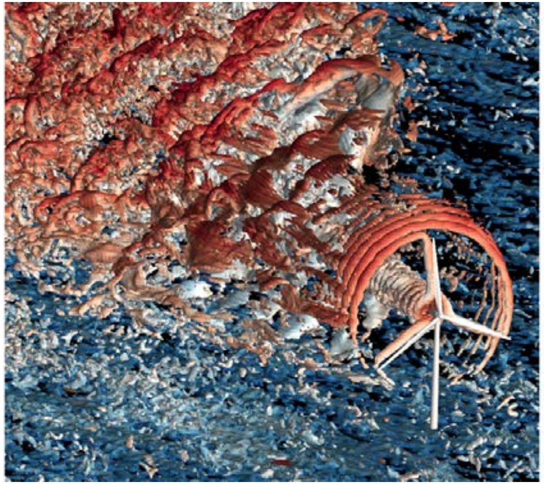
https://www.azquotes.com/quote/590633

Atmospheric Turbulence Scales:

- Largest ~1 km, Smallest ~1 mm
- Resolving the smallest scale in a domain that contains the largest scale requites a billion-billion computational cells (10^18)
- The answer is Not DNS!

- Analytical solutions only exist for the **most simple laminar** problems **without turbulence**
- **Turbulence** brings in orders more complexity

  "Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity." -- Lewis Richardson

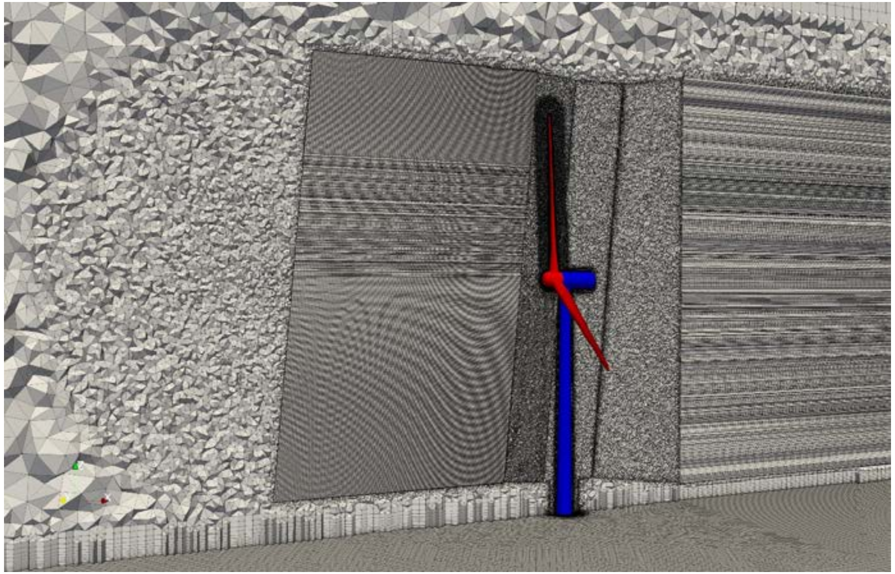


Courtesy Matt Churchfield, NREL

5-MW turbine example: Discretization of the fluid domain

NREL 5-MW reference turbine*

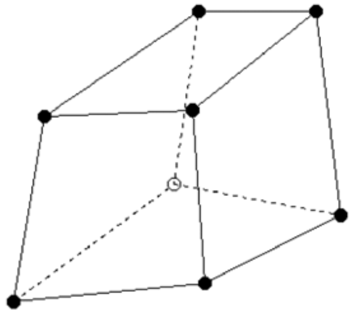
- Rotor diameter: 126 m
- Rated tip speed: 80 m/s
- Hub height: 90 m



Mesh created by M. Lawson

Fluid domain is broken up into a mesh composed of “cells” or “elements” defined by **“nodes”**

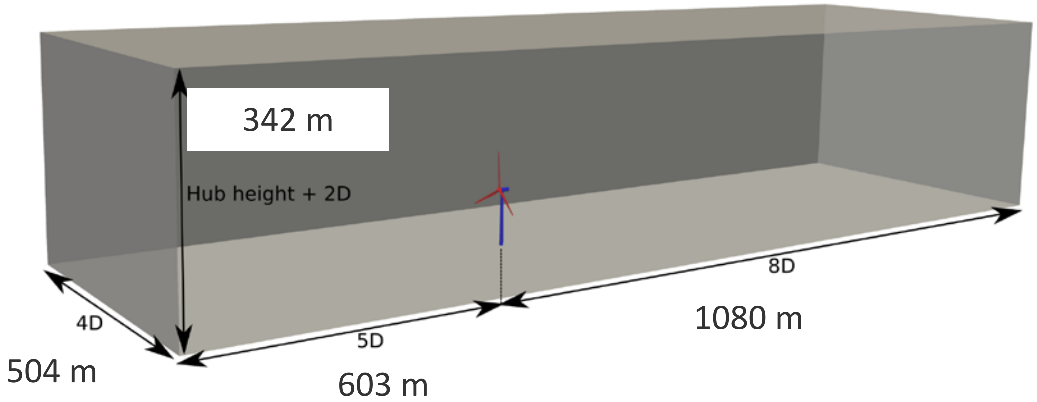
Example 8-node hex element

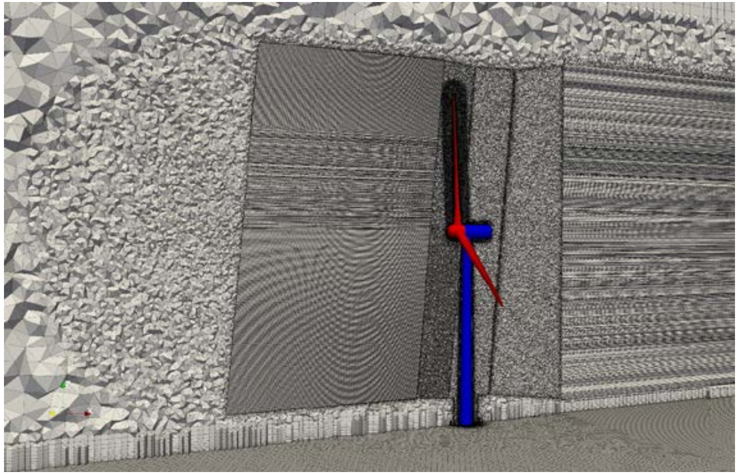


*Jonkman et al., 2009, “Definition of a 5-MW Reference Wind Turbine for Offshore System Development
https://www.nrel.gov/docs/fy09osti/38060.pdf

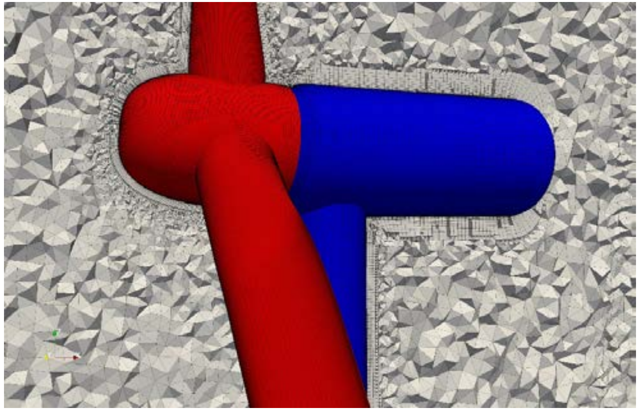
5-MW turbine example: Extreme scale separation in the mesh

- The overall domain size is large but not large enough to capture all the scales of turbulence
- There are 761,112,204 nodes in this mesh





In order to capture boundary layers near blades, near-blade elements have length of only 10^(-6) m



Mesh created by Mike Lawson via Pointwise

5-MW turbine example: A HUGE system of equations

761,112,204 equations and 761,112,204 unknowns; need to be solved every time step

$$31.3\,p_{0} - 5.68E\text{-}16\,p_{54289} - 1.25E\text{-}2\,p_{54290} - 1.42E\text{-}12\,p_{54288} - 1.25E\text{-}2\,p_{54293} - 31.3\,p_{54292} - 3.55E\text{-}13\,p_{54286} = -2.52E\text{-}4$$

$$3.98\,p_{1} - 1.48\,p_{348838} - 2.41E\text{-}16\,p_{45689} - 1.25\,p_{45620} + 2.31E\text{-}4\,p_{45617} - 6.24E\text{-}1\,p_{309759} - 6.26E\text{-}1\,p_{45557} - 2.47E\text{-}4\,p_{45556} = -1.09E\text{-}2$$

$\vdots$

761,112,202 more equations

$\vdots$

$$14.9\,p_{761112203} - 2.45\,p_{760949391} + 1.89E\text{-}2\,p_{761005822} - 2.54\,p_{760912181} - 2.42\,p_{760949223} - 2.54\,p_{760912134} + 3.24E\text{-}2\,p_{760949228} - 2.44\,p_{761040744} = -3.52E\text{-}4$$

$$9.93\,p_{761112204} - 1.25\,p_{761091736} - 1.15\,p_{760894555} - 1.25\,p_{761091735} - 1.25\,p_{760941077} - 9.33E\text{-}2\,p_{761091799} + 9.35E\text{-}2\,p_{761094150} - 9.36E\text{-}2\,p_{761111725}$$
$$-1.15\,p_{760918135} - 1.08\,p_{761096490} - 4.85E\text{-}2\,p_{761091758} - 1.06\,p_{761091757} - 3.33E\text{-}1\,p_{761092138} - 1.36\,p_{761100648} + 5.86E\text{-}3\,p_{761091738} = -1.01E\text{-}3$$

If you wrote out these equations with 10-pt font, your paper could stretch between Washington, D.C. and San Francisco

We are now moving from PetaFLOPS to ExaFLOPS

A **BIG** computer!

Courtesy: Lawrence Berkeley Labs

NERSC Cori: 14 PetaFLOPS system

- **Speed characterized in floating-point operations per second *(FLOPS)***
- ***PetaFLOPS:* one thousand million million (10^15) FLOPS**

Courtesy: NREL

NREL Eagle: 8 PetaFLOPS

Courtesy: Oak Ridge National Laboratory

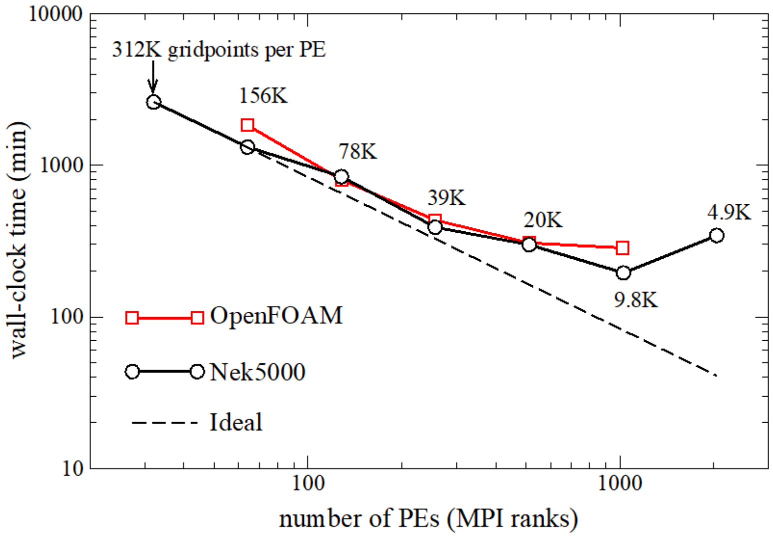
OLCF Summit: 200 PetaFLOPS

Strong-scaling limit: An example

Strong scaling: For a fixed problem size, use more of the machine

- i.e., reduce the number of equations for each processor

Ideal strong scaling: Using twice as many processors cuts simulation time in half



Example shows how CFD codes typically exhibit good strong scaling down to about 40,000 equations per processor

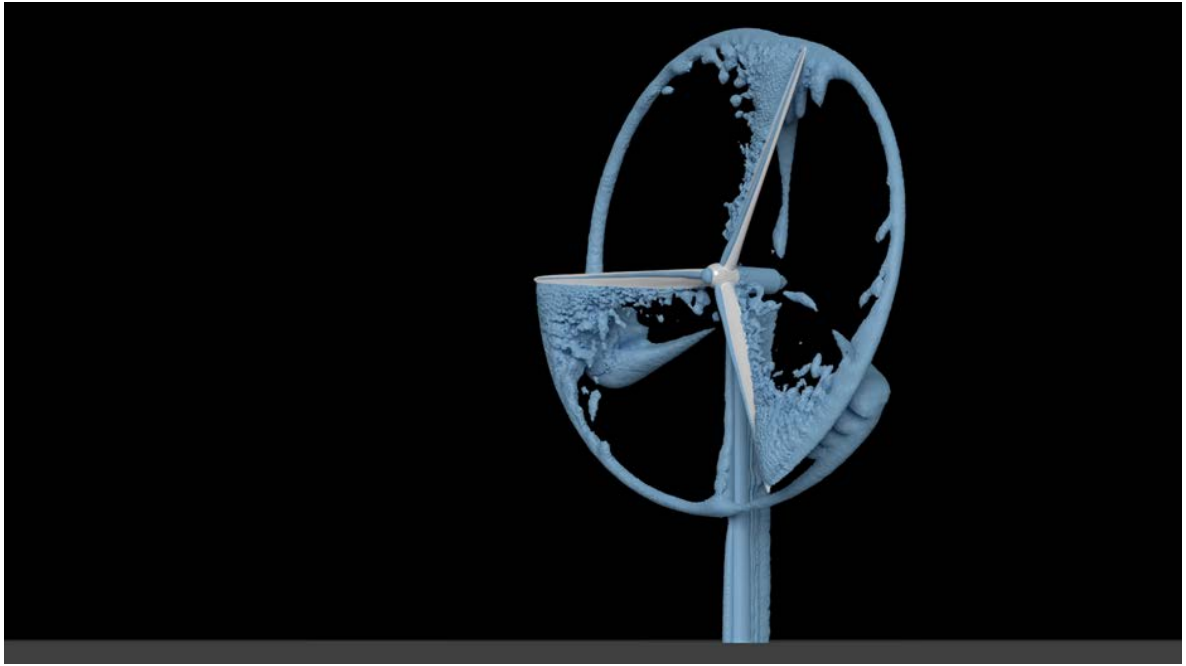
Data transfer between processors becomes the bottleneck

For a given problems size, we can only use so much of a supercomputer

Blade-resolved simulation of the NREL 5-MW turbine using Nalu-Wind

ExaWind Project
(Office of Science)

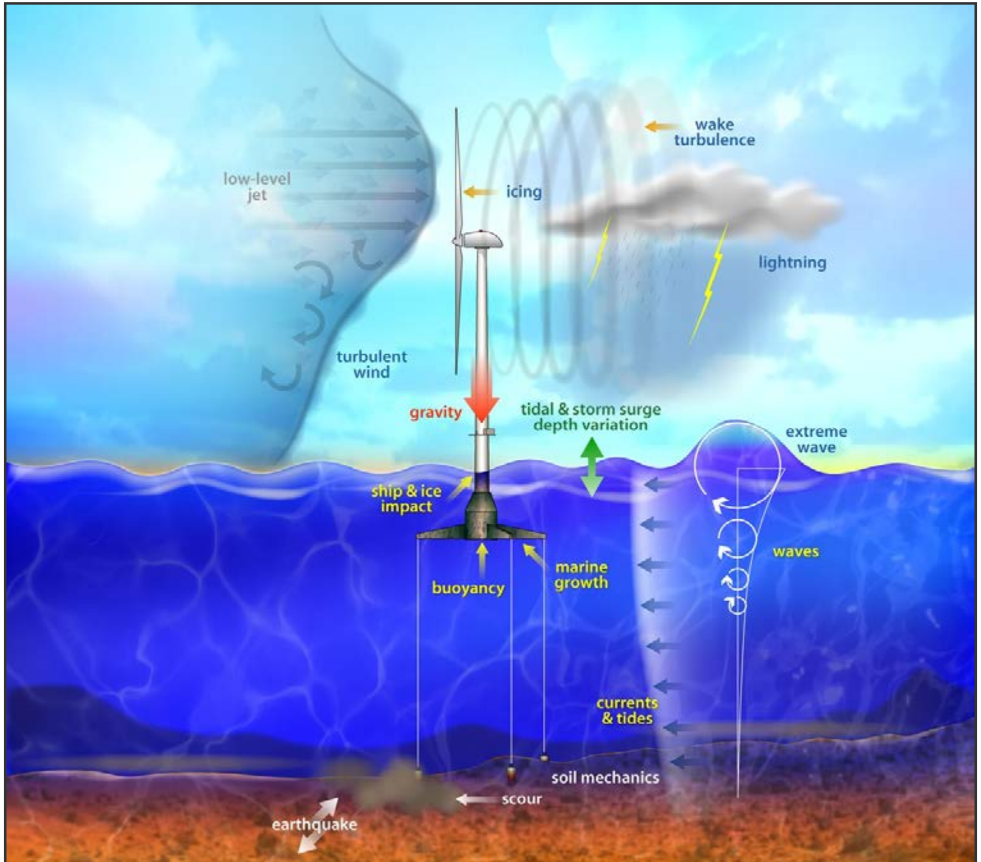
Participants
- NREL
- Sandia Labs
- ORNL
- Univ. of Texas



NREL 5-MW turbine simulation **("coarse", 25-million-node mesh)** under uniform inflow of 8 m/s. The wake is visualized by contours of velocity magnitude of 5.5 m/s. Simulation performed on the NERSC Cori machine.
https://www.exascaleproject.org/exawind-project-demonstrates-blade-resolved-simulation-of-the-nrel-5-mw-reference-wind-turbine/

Team: Lawson, Melvin, Ananthan, Gruchalla, Rood, Sprague

Critical models are required both upstream and downstream



Courtesy Jason Jonkman, NREL

- Weather
- Meso-scale flows
- Plant

Upstream

Turbine

Downstream

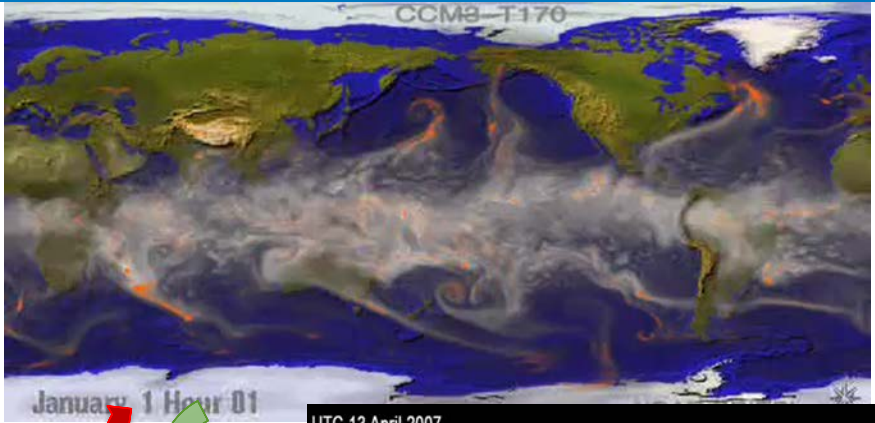
- Subcomponents
  - Foundation
  - Rotor
  - Drive Train
  - Electrical
- Plant
- Grid

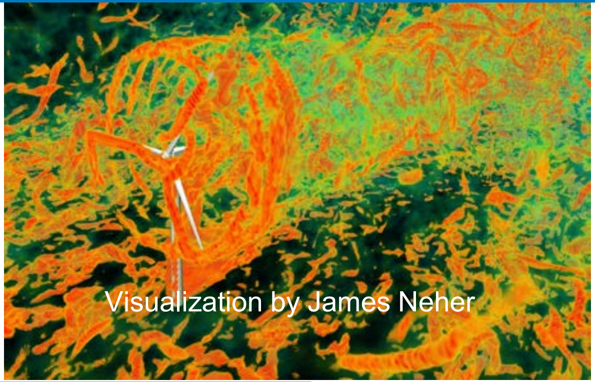
Energy Cascade

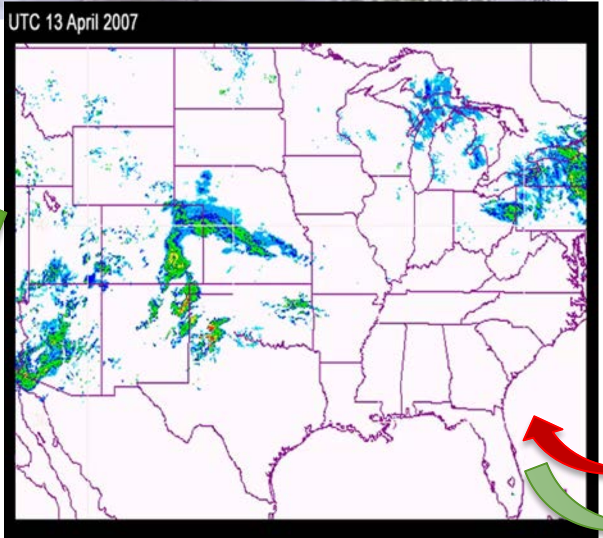
System Optimization

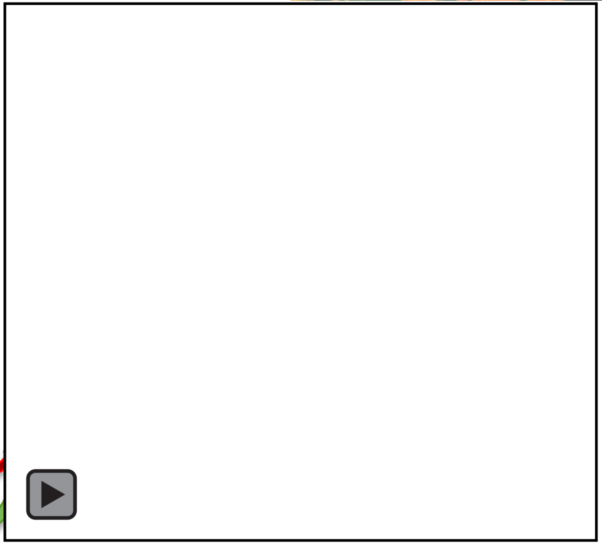
Atmospheric Modeling

Forcing and Transfer of Energy Across Scales









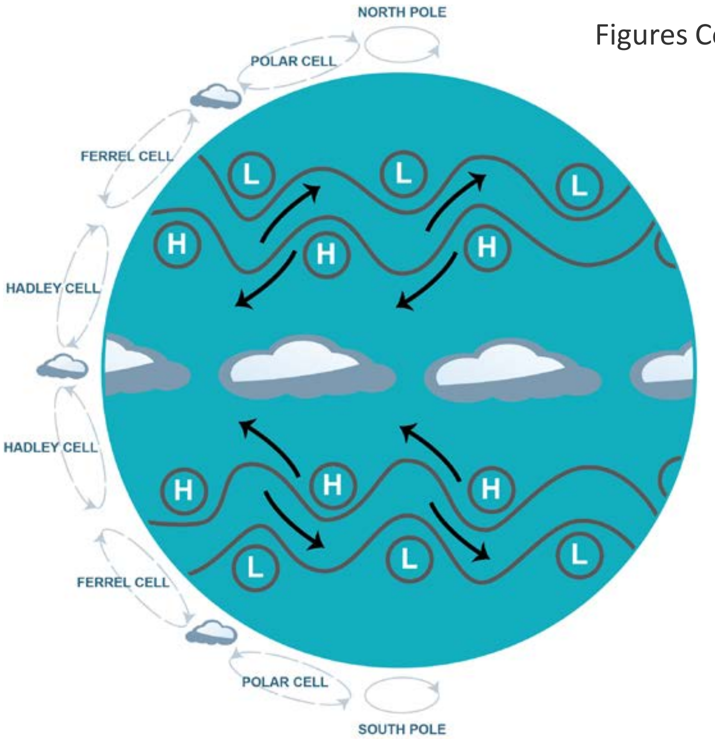
Courtesy Sue Haupt of NCAR and colleagues

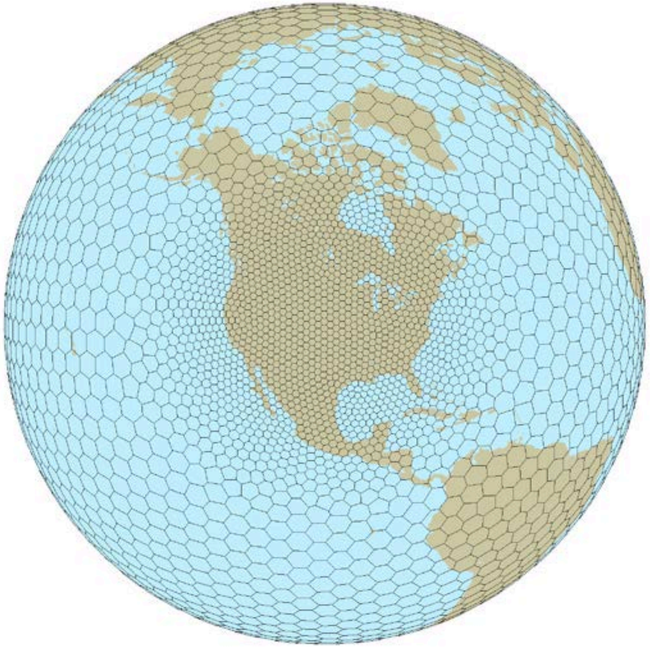
Courtesy Jeff Mirocha, LLNL

Global Weather Phenomena Drive the System

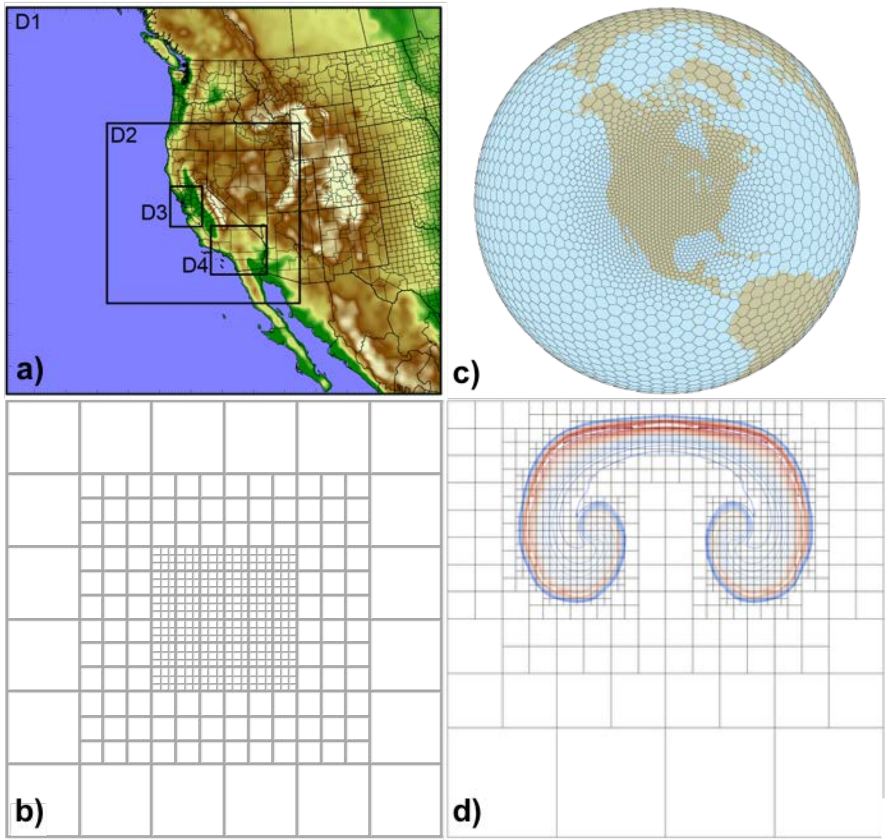
Each of the Scales is discretized – sub-grid models aggregate from physics at finer scales

Figures Courtesy Sue Haupt, NCAR





Example of Nesting in Atmospheric Modelling

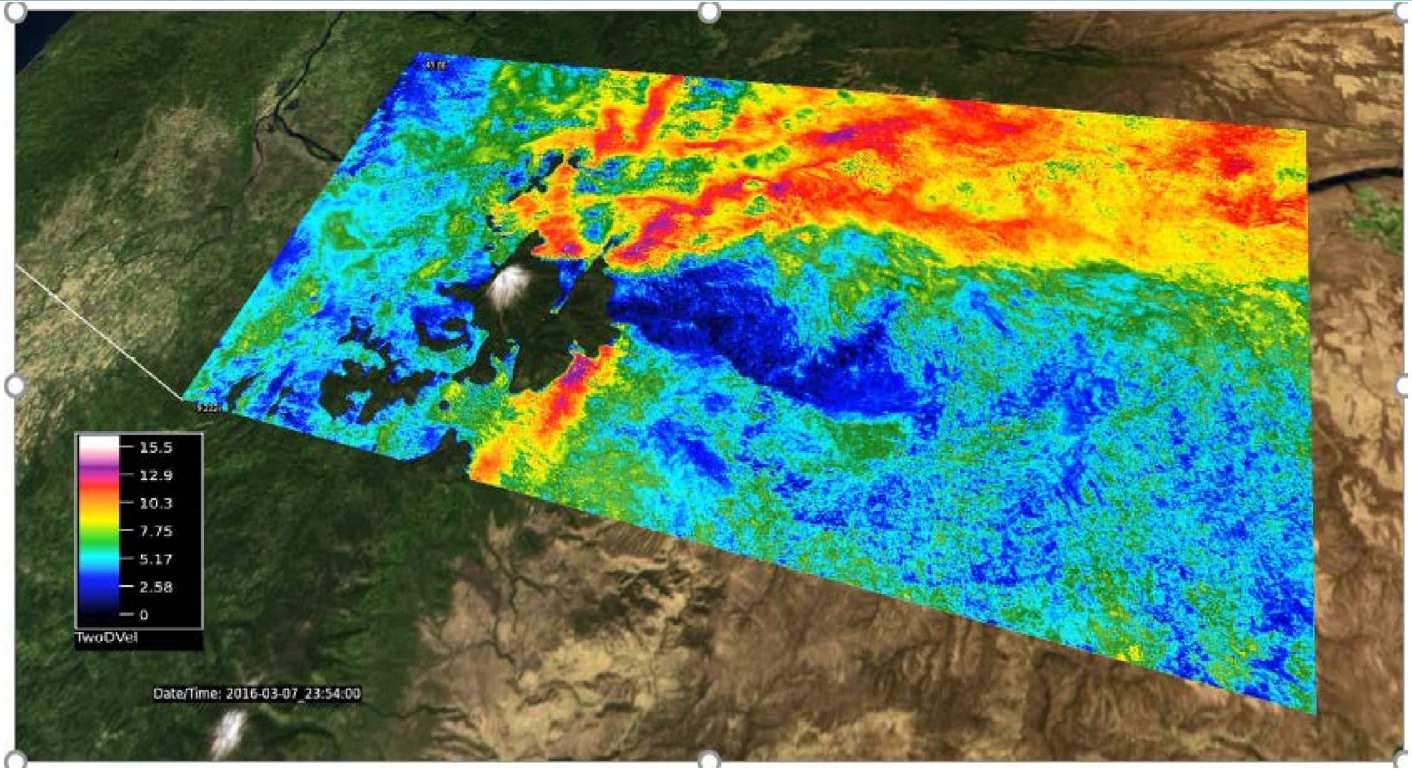


Courtesy Jeff Mirocha, LLNL

- **Models are nested to attempt to resolve the atmospheric flow at finer and finer scales**

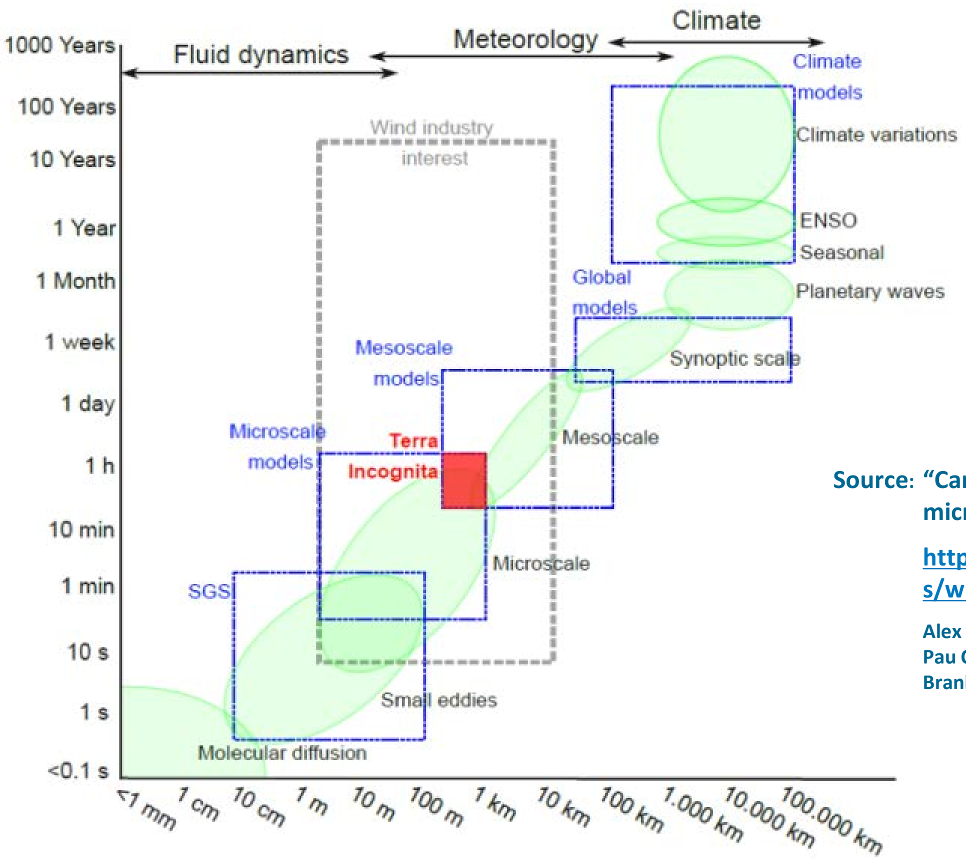
Examples of mesoscale atmospheric model mesh refinement strategies, including grid nesting (e.g. WRF; a,b), Voronoi tesselations (e.g. MPAS; c) and adaptive (e.g. NUMA; d). (Courtesy Jeff Mirocha, LLNL)

Mesoscale to Microscale Coupling in Complex Terrain



Courtesy Branko Kosovic &
Pedro Jimenez, NCAR

Challenges at the Mesoscale, Microscale Interface

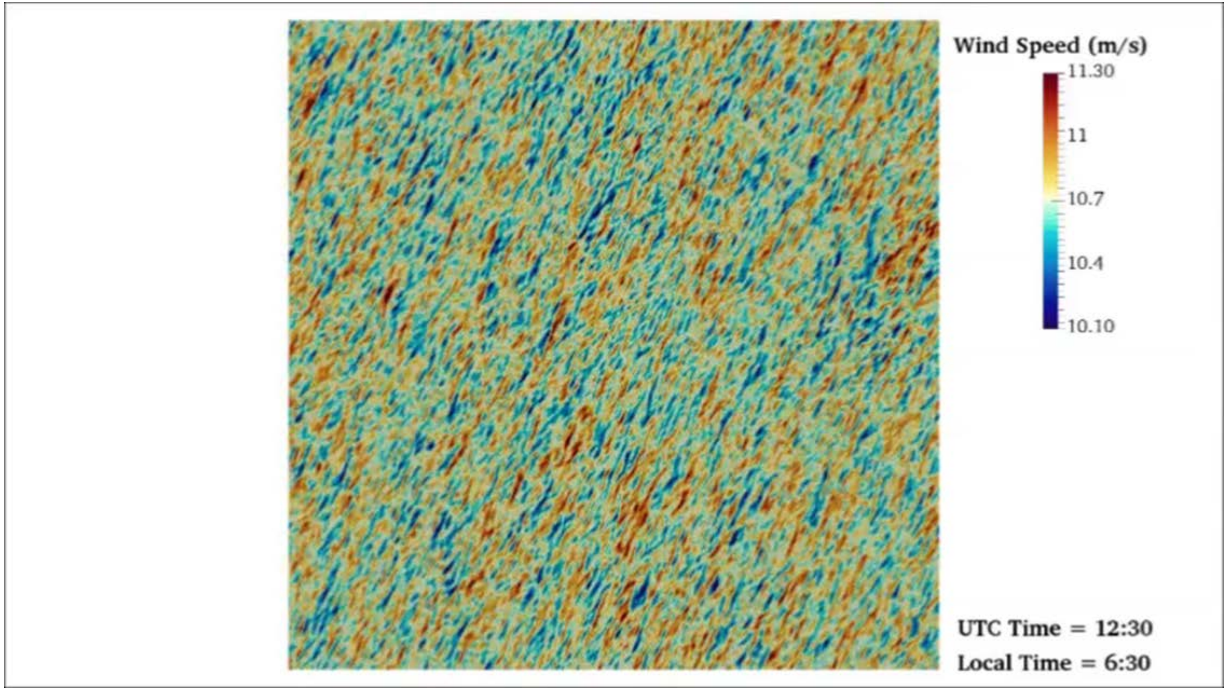


Source: **"Can mesoscale models reach the microscale?"**

http://www.ewea.org/events/workshops/wp-content/uploads/2015/06/LIZCA

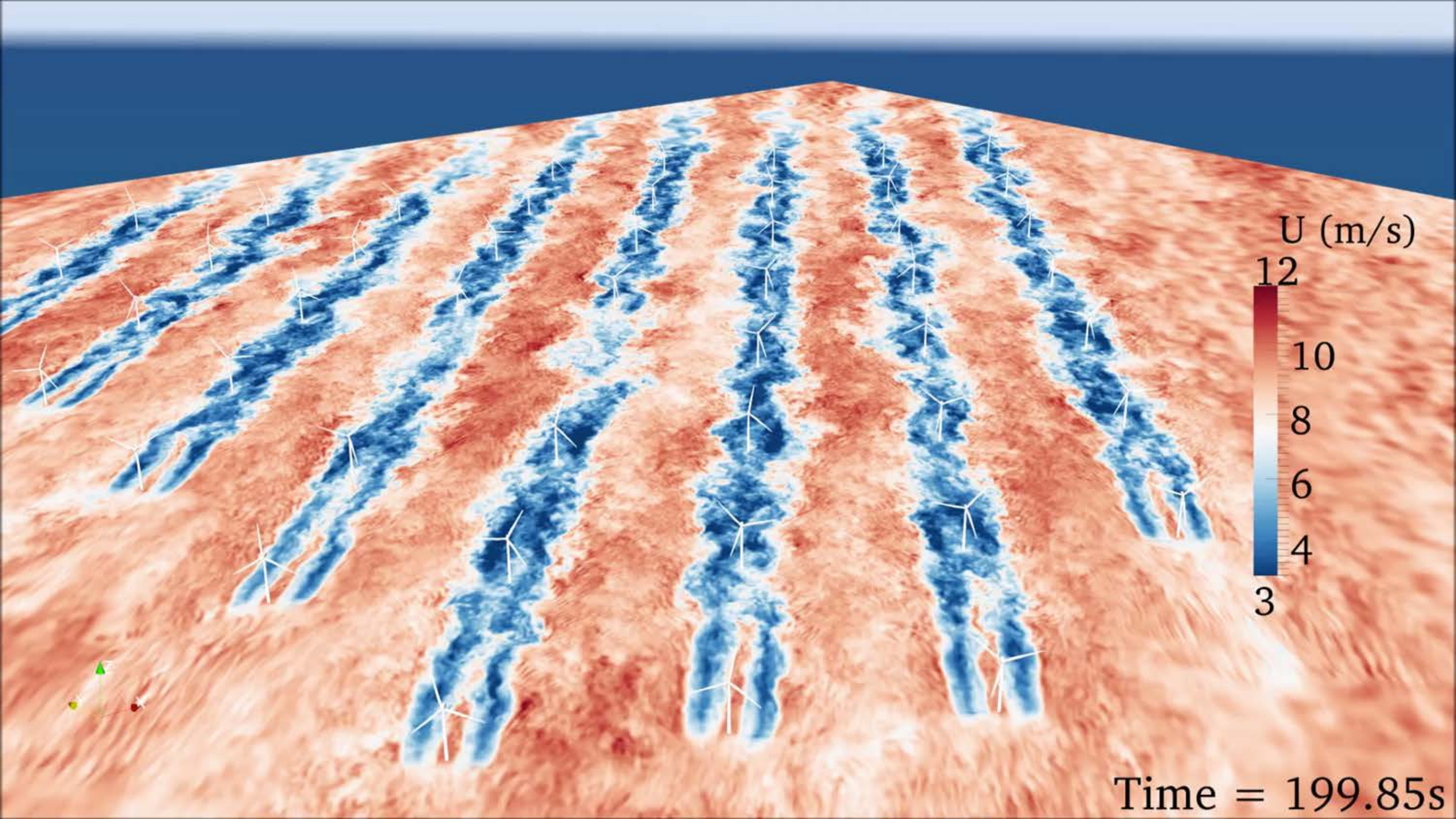
Alex Montornes (Vortex)
Pau Casso (Vortex)
Branko Kosovic (NCAR)

Diurnal Case – SOWFA - Nov 8, 2014

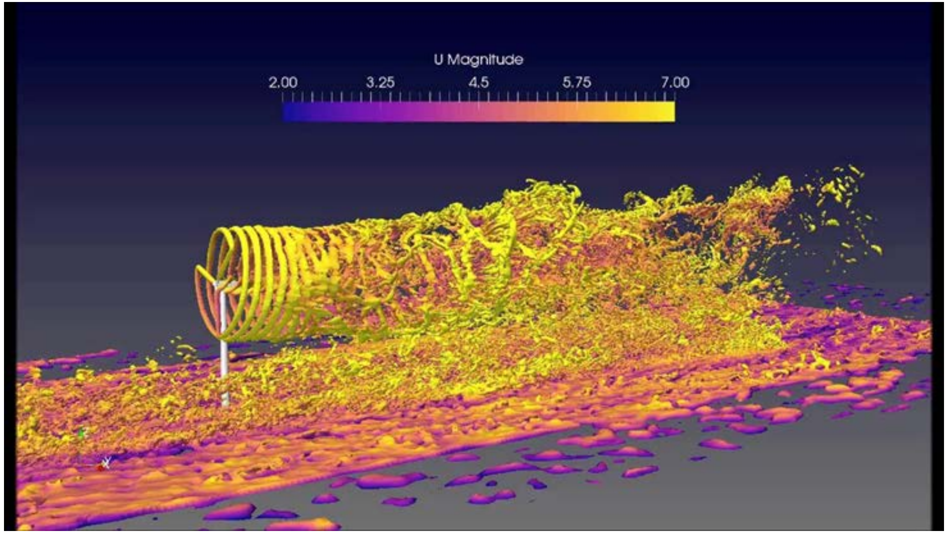


Matt Churchfield, NREL

Wind Plant Flow Modeling


U (m/s)
12
10
8
6
4
3
Time = 199.85s

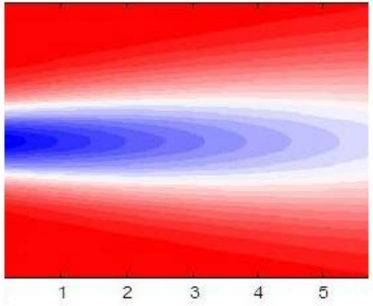
Wakes in Wind Plants



Courtesy Churchfield and Moriarty, NREL

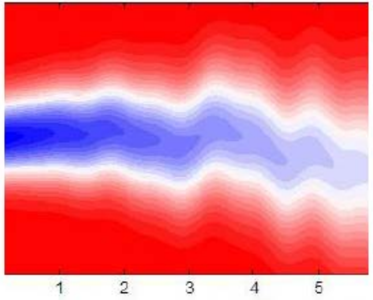
Reproduced with permission from Wind Energy Modeling and Simulation edited by Paul Veers. Copyright 2019 IET.

Average Wake



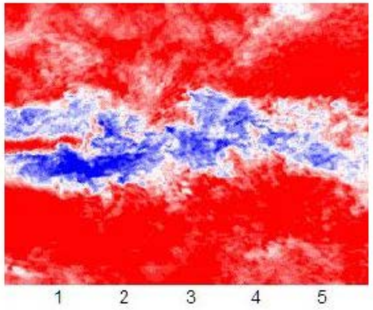
(a)

Dynamic Wake Meandering (DWM)



(b)

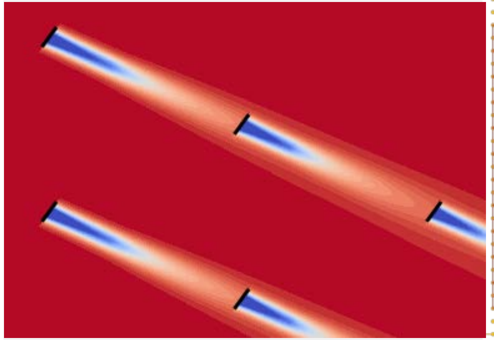
Large Eddy Simulation (LES) Wake



(c)

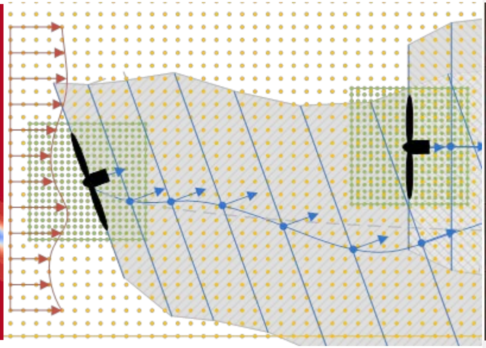
Reduced Order Modeling Tools

FLORIS



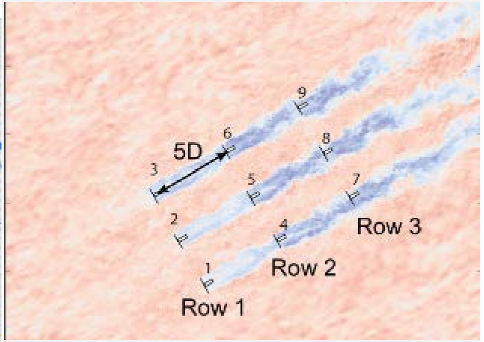
- Control-oriented model
- Runs in fractions of seconds
- Can be used to find optimal control settings and analyze across wind rose to estimate AEP

FAST.FARM



- New code which overlays DWM wakes on pre-computed CFD inflows
- Includes embedded FAST models of turbines
- Runs on few cores, near real time, allowing load suite analysis

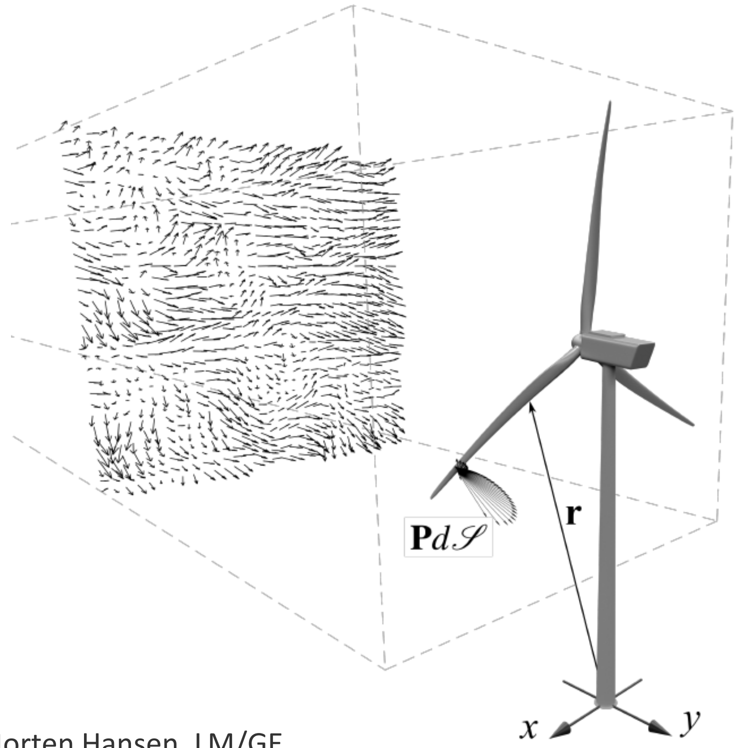
SOWFA



- Wind farm simulator based on large-eddy simulation
- Allows detailed investigation of wake physics, but requires many cores and time to run simulations

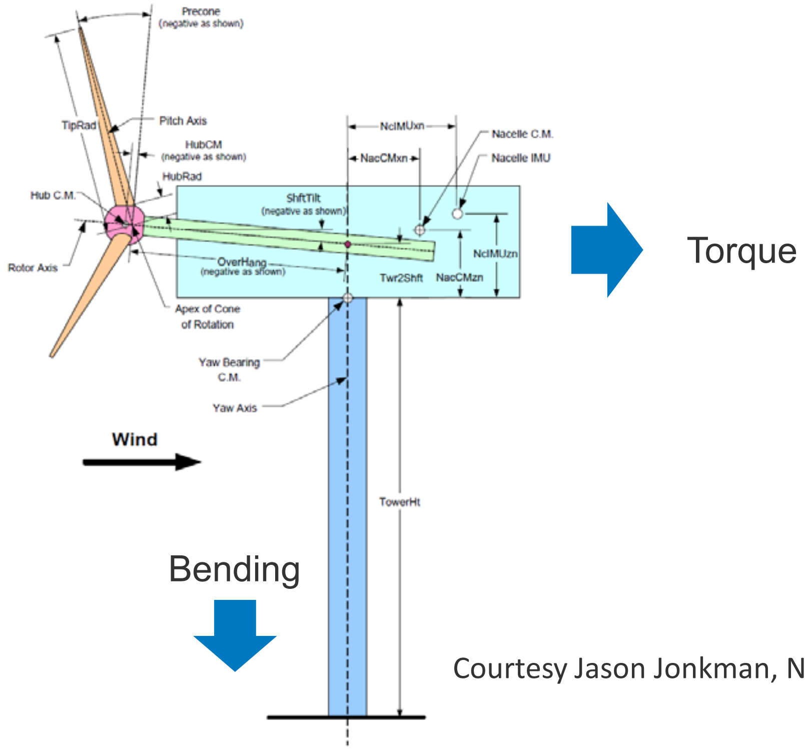
Turbine Subsystems and Design Optimization

Modeling focus has typically begun with the machine



Courtesy Morten Hansen, LM/GE

Reproduced with permission from Wind Energy Modeling and Simulation edited by Paul Veers. Copyright 2019 IET.

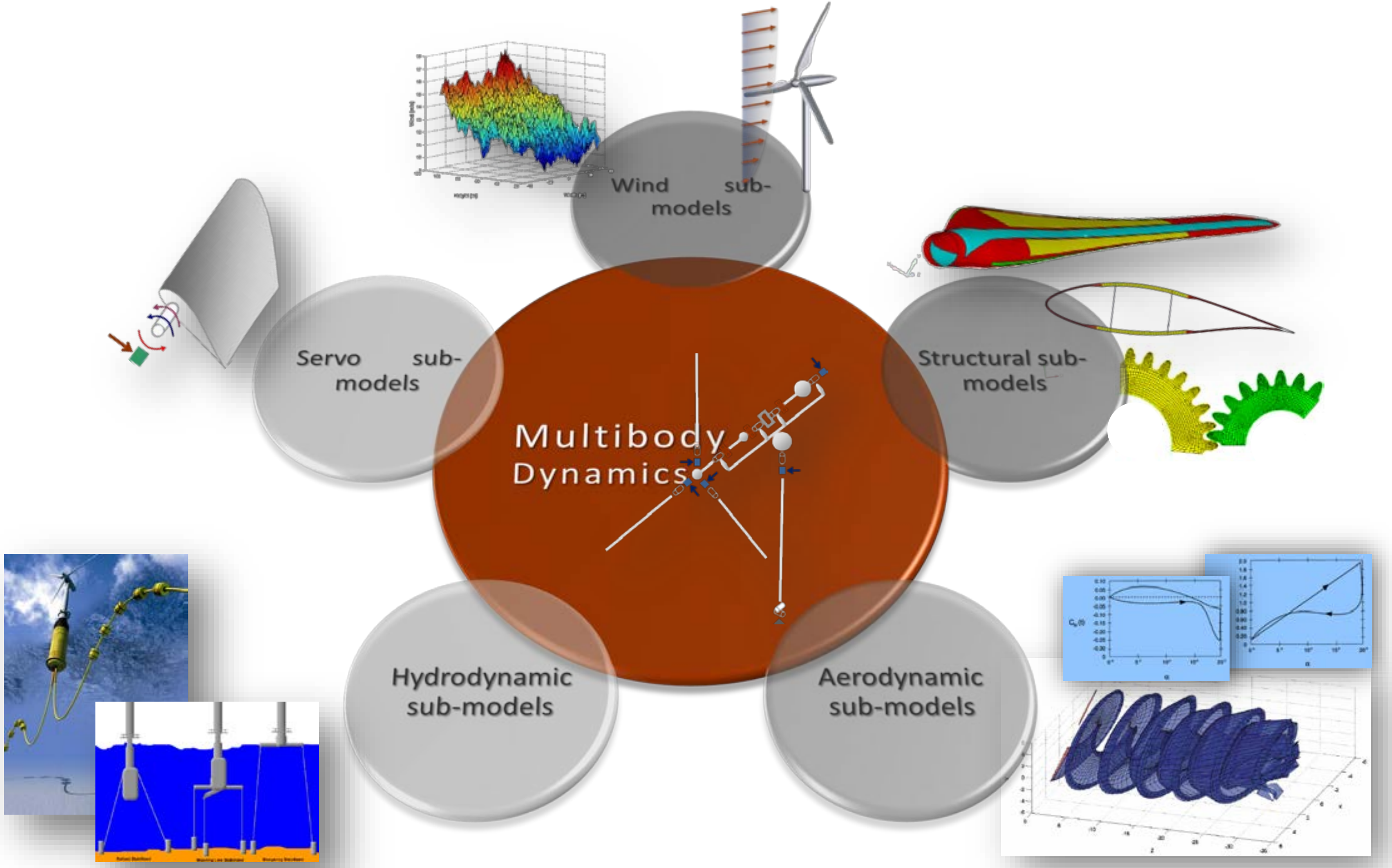


Courtesy Jason Jonkman, NREL

Detailed Aeroelastic Model

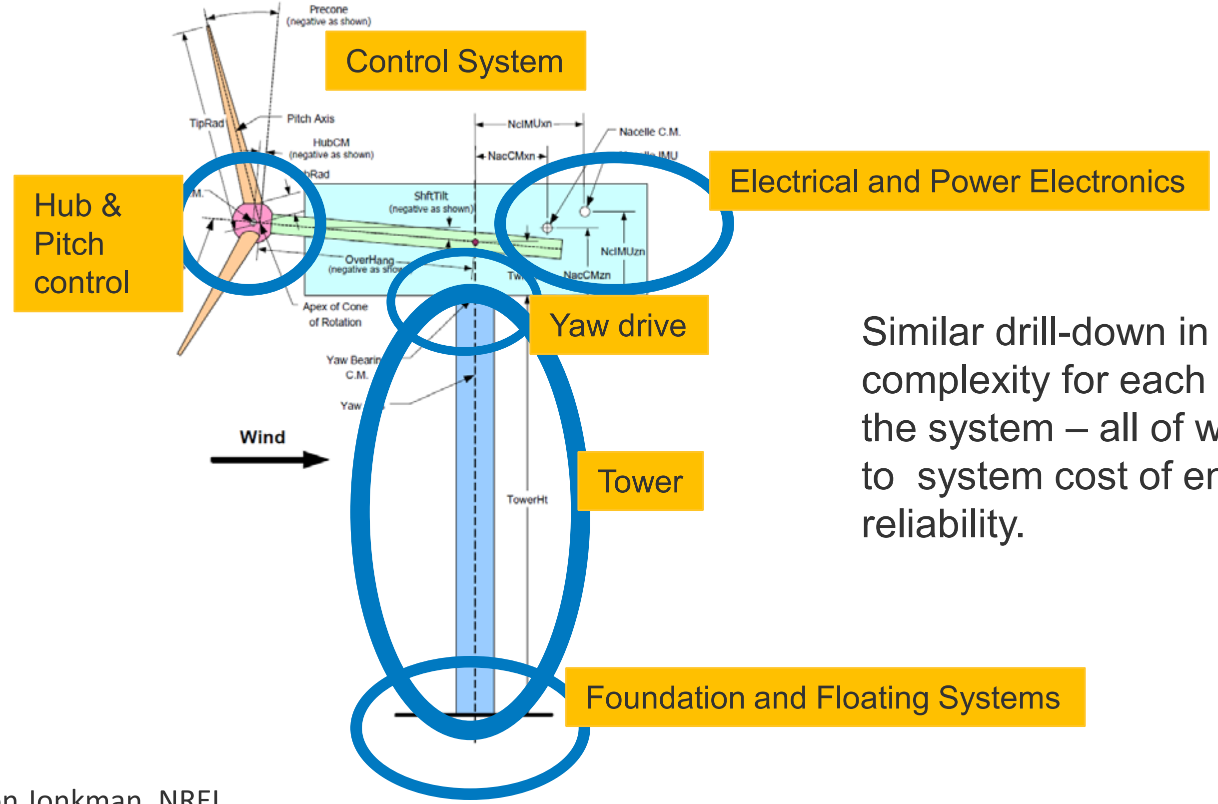
Turbine System Design Optimization

Courtesy Carlo Bottasso,
University of Munich



Reproduced with permission from <u>Wind Energy Modeling and Simulation</u> edited by Paul Veers. Copyright 2019 IET.

Modeling of the Aeroelastic System Depends on Interfaces with all the critical subcomponents



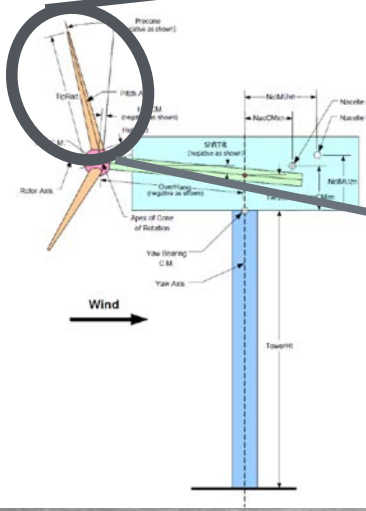
Similar drill-down in scale and complexity for each subcomponent in the system – all of which contribute to system cost of energy and reliability.

Courtesy Jason Jonkman, NREL

Rotor Optimization

Design approach – Modeling Cascade

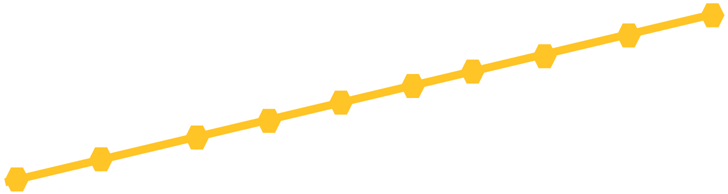
3 dof modal representation of the blade



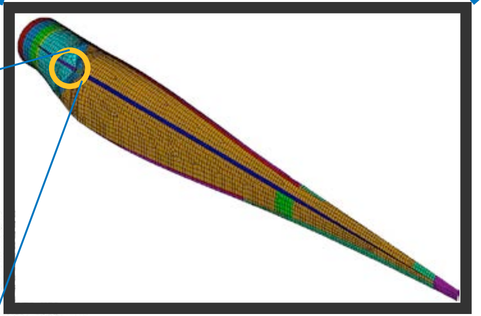
Courtesy Jason Jonkman, NREL

All Loads

Order 100 dof beam model – Internal loads and strains

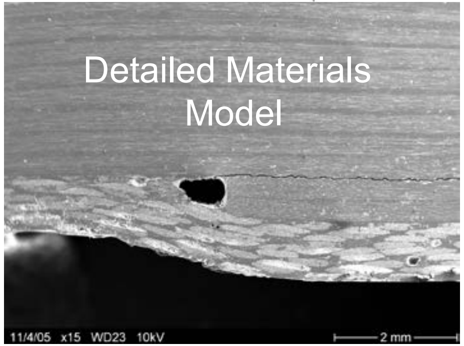


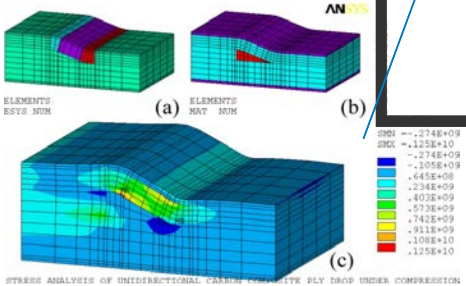
Boundary Conditions: Interface Loads



Order 1,000,000 dof shell model - Buckling

Courtesy Joshua Paquette, Sandia Labs



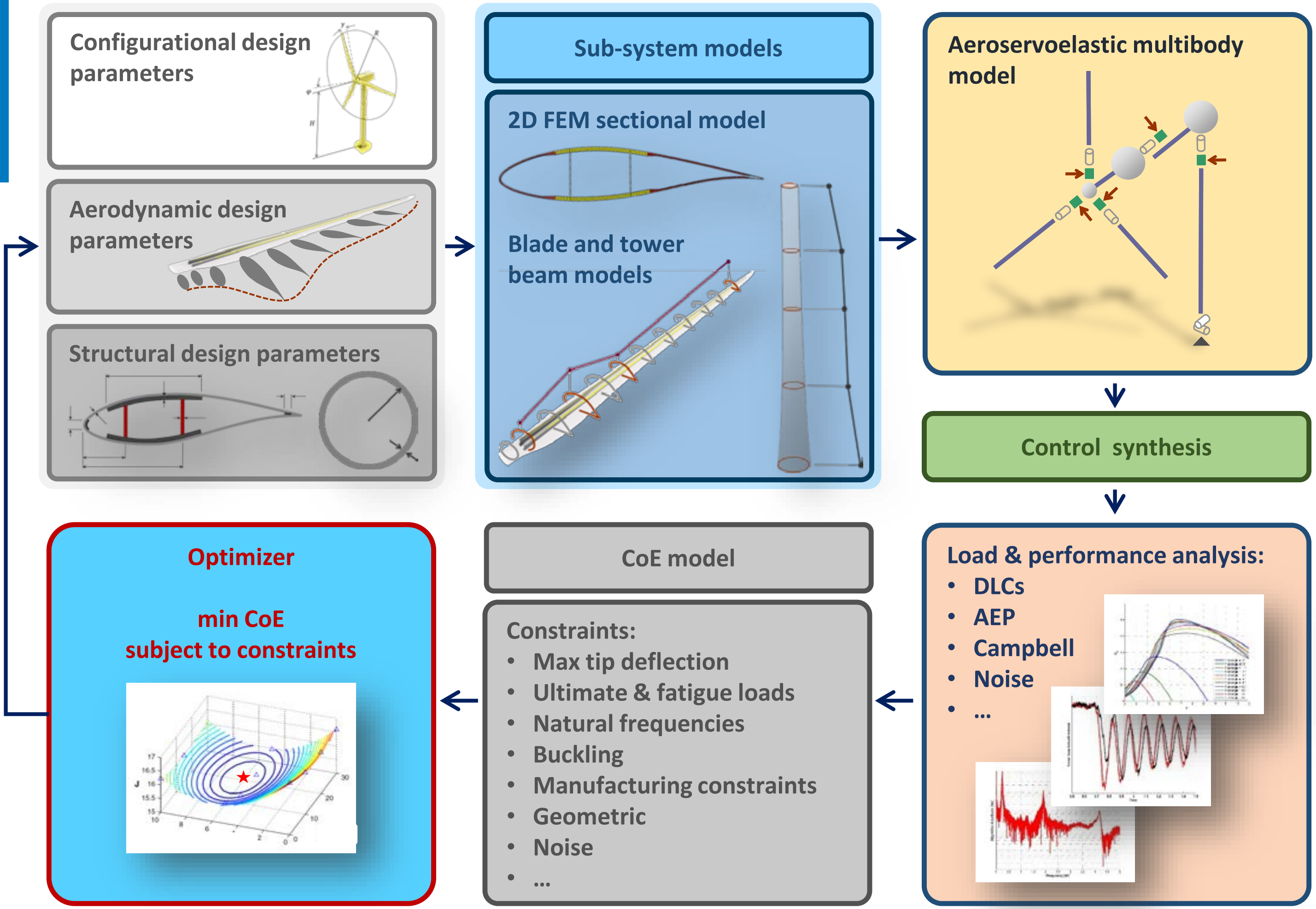


Courtesy Montana State University

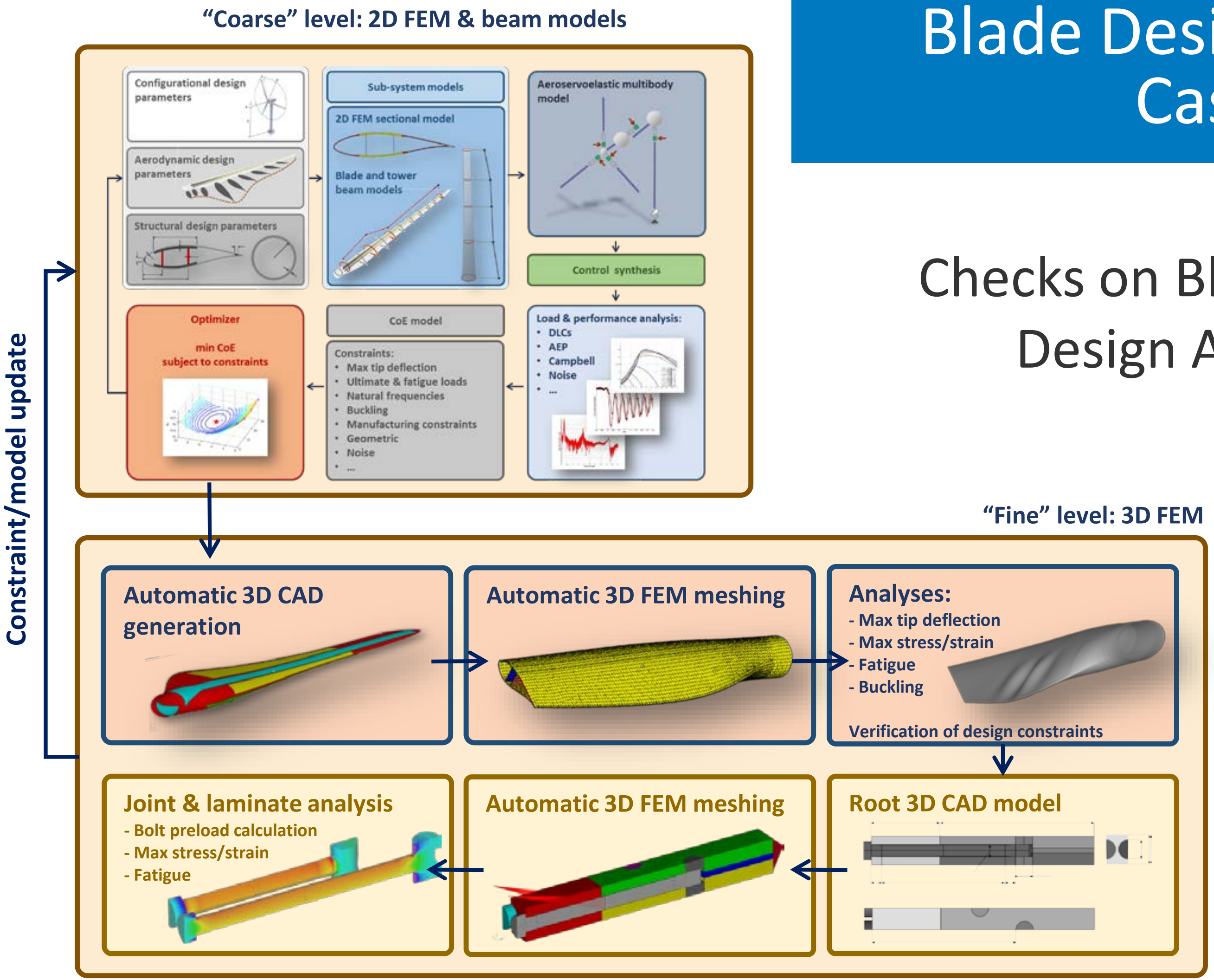
Scales represent different criteria in the design space of wind turbine blades

Rotor Optimization Framework

Courtesy Carlo Bottasso, University of Munich



Blade Design Modeling Cascade



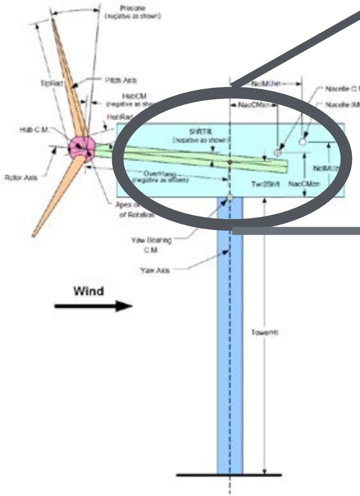
Checks on Blade Nominal Design Adequacy

Courtesy Carlo Bottasso, University of Munich

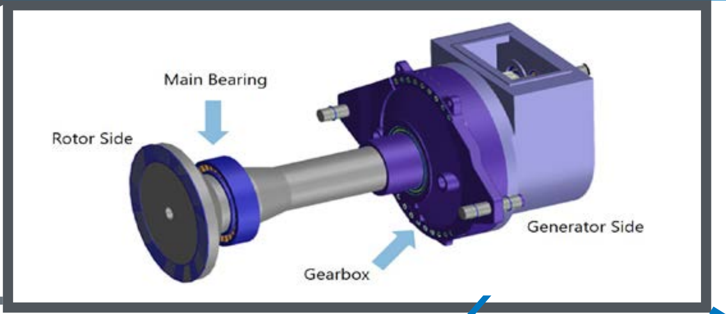
Reproduced with permission from Wind Energy Modeling and Simulation edited by Paul Veers. Copyright 2019 IET.

Drive Train Modeling

Drive Train Design Modeling Cascade



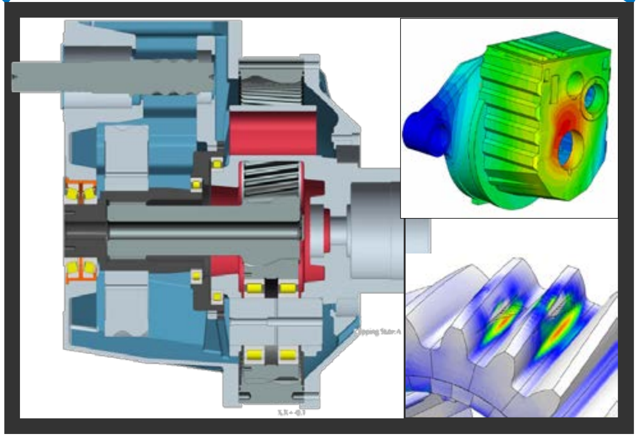
All Loads



Reproduced with permission from Wind Energy Modeling and Simulation edited by Paul Veers. Copyright 2019 IET.

Courtesy Zhiwei Zhang, Romax

Internal Gearbox Loads



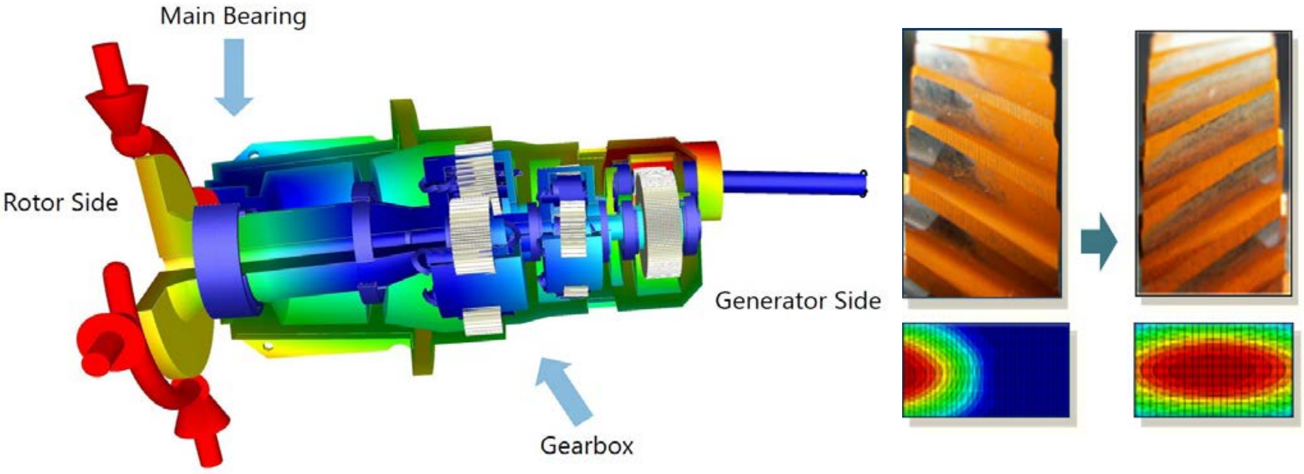
- Aeroelastic models often describe the drive train as a few springs and dampers
- Actual behavior may be much more complex, including nonlinear flexibility and damping

Drive Train Models – Including Flexibility

<u>Drive Train Configuration</u>

- Gear shape
- # stages
- # planets
- location of bearings
- Bearing type
  - CRB
  - TRB
  - Journal

Elastic deformation in the drive system leads to uneven loading on gear teeth and bearings



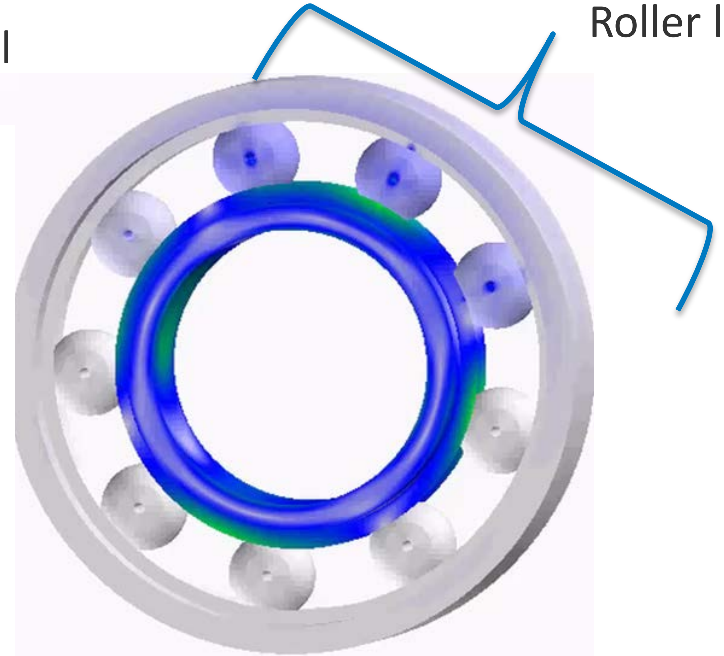
An example of an integrated drivetrain configuration (deflection exaggerated in a RomaxDESIGNER simulation model) [4]

Courtesy Zhiwei Zhang, Romax

Bearing Failures Influenced by Tribology

Load Sharing is never equal

Roller loading zone



Bearing damage is dependent on not only torque and lateral loading, but skidding and friction – requiring detailed bearing models

Movie courtesy Yi Guo, NREL

Offshore Foundations

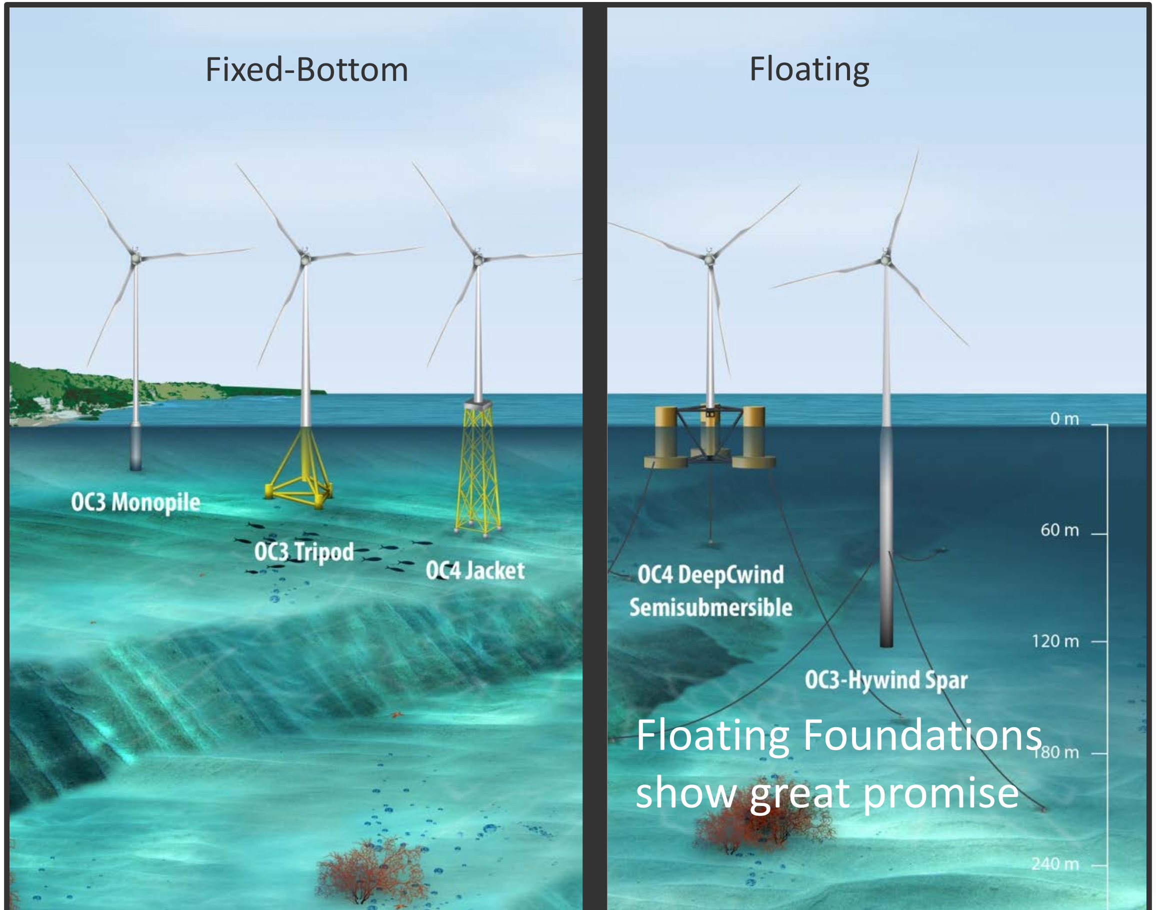
First US Offshore Wind Plant

Map credit: AWS Truepower

Deepwater Wind's Block Island Wind Farm, the first commercial wind farm in the United States, features five GE Haliade 150-6MW wind turbines to come online by end of 2016.

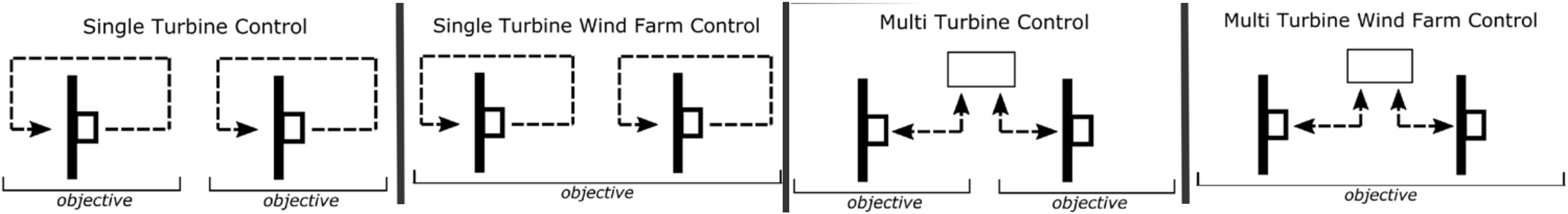
Video courtesy: Paul Veers, NREL

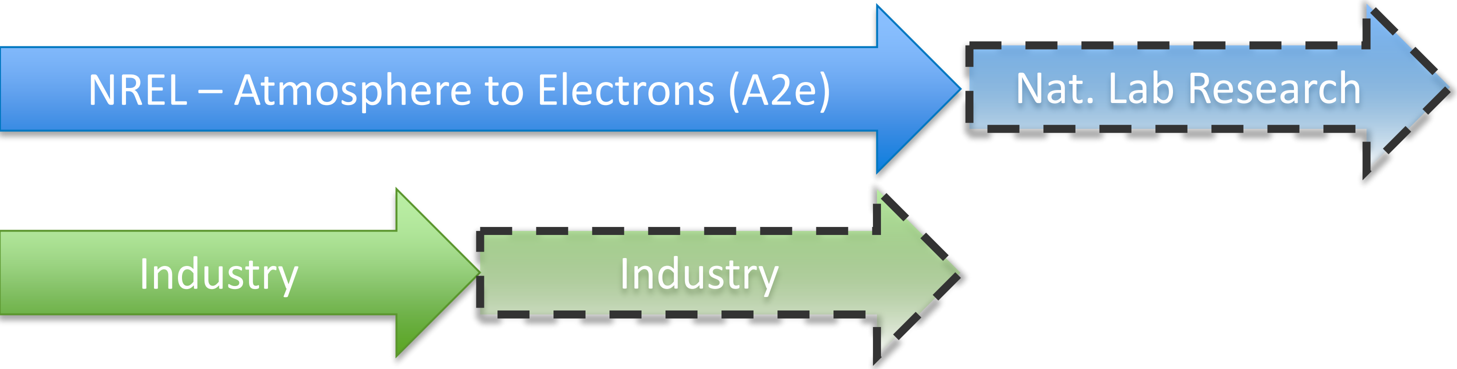
Foundations involve air, sea, and soil interactions



Turbine and Plant Controls

History of Wind Energy Controls

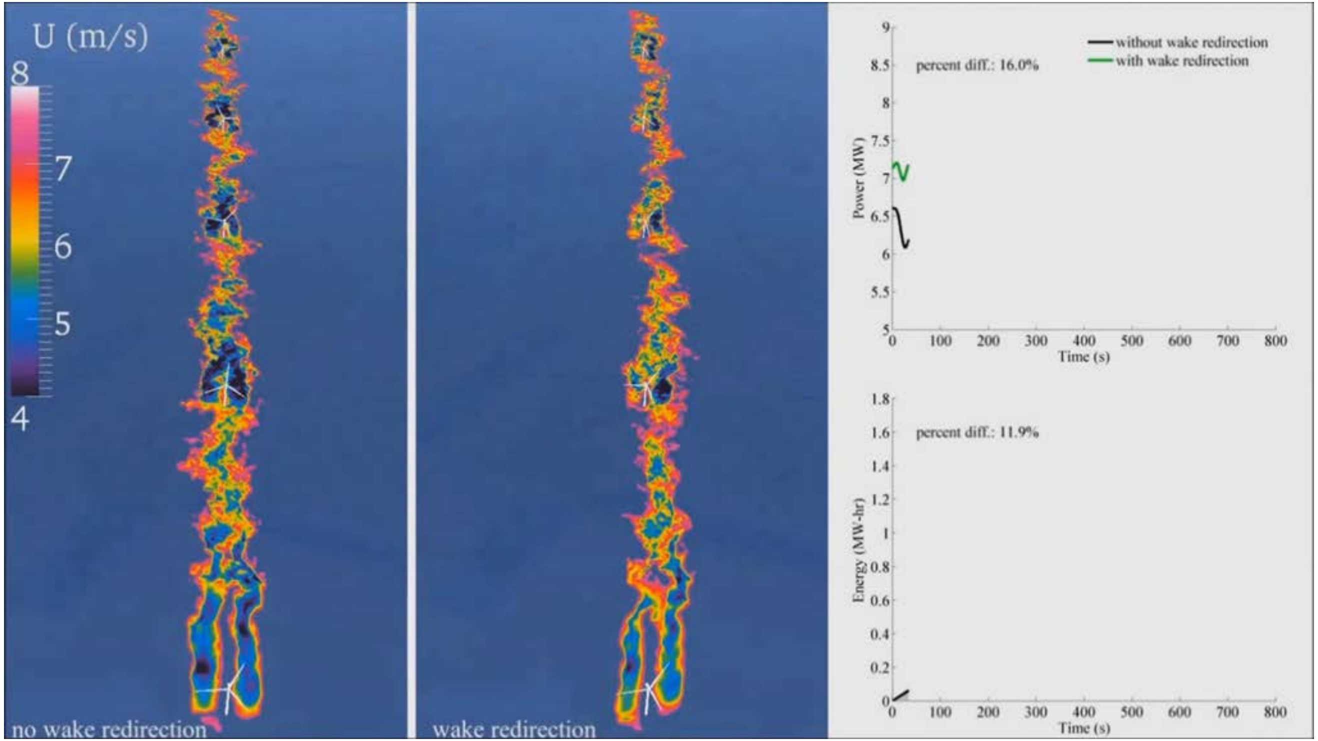




What if turbines could talk to neighboring turbines?

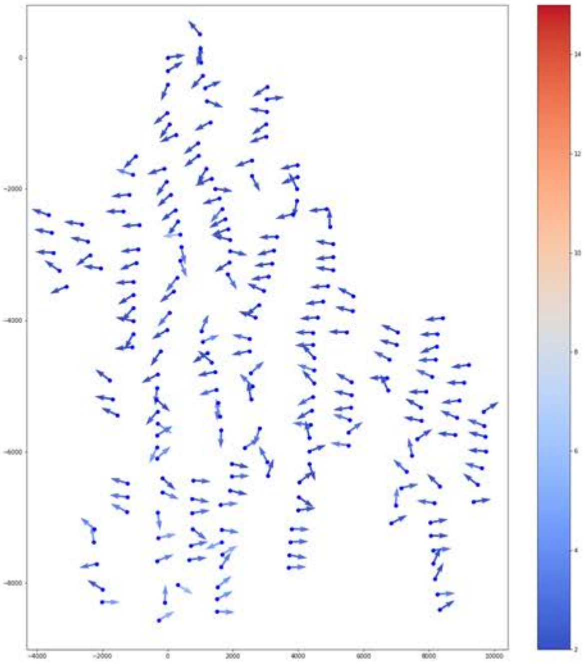
Courtesy Paul Fleming, NREL

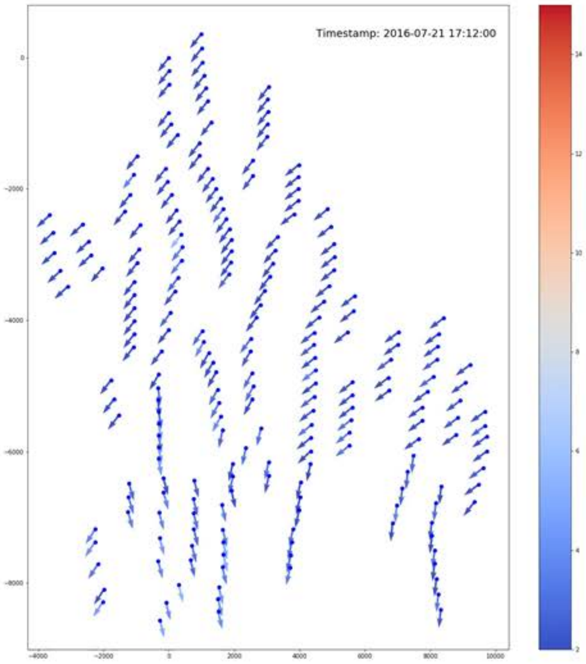
Control Exploration



Courtesy Paul Fleming, NREL

Consensus Control



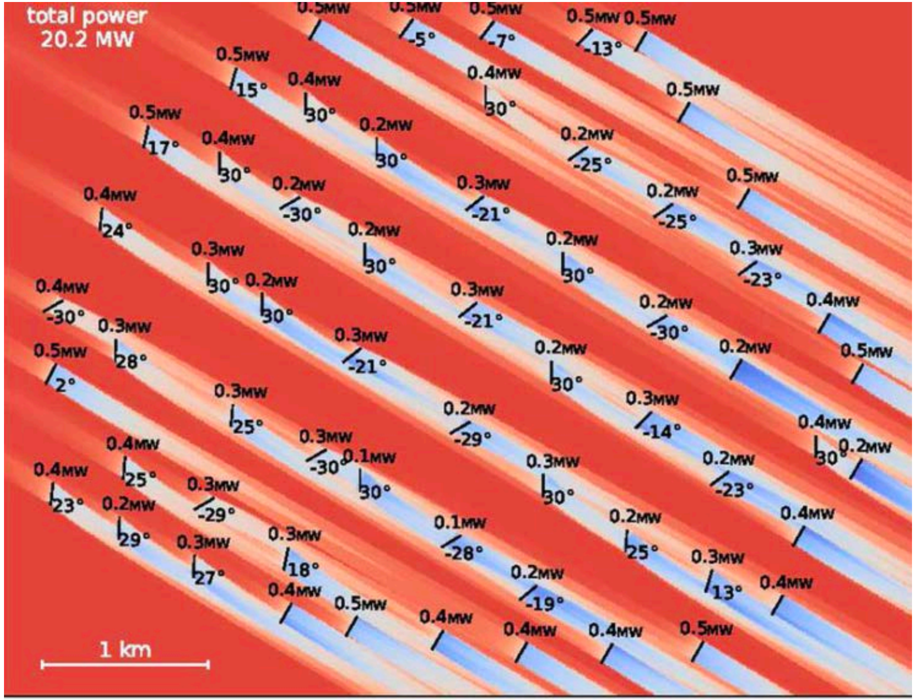


Wind Plant Optimization

Control Analysis and Plant Optimization

Wake models can be used to:

- Design wind farm controllers
- Predict performance of wind farm controllers
- Estimate impact on annual energy production from wind farm control
- However, the LCOE value can be significantly amplified if coupled into the design phase, for example, joined to layout optimization



Reproduced with permission from Wind Energy Modeling and Simulation edited by Paul Veers. Copyright 2019 IET.

Grid Modeling

Grid penetration levels are already very high in the U.S.

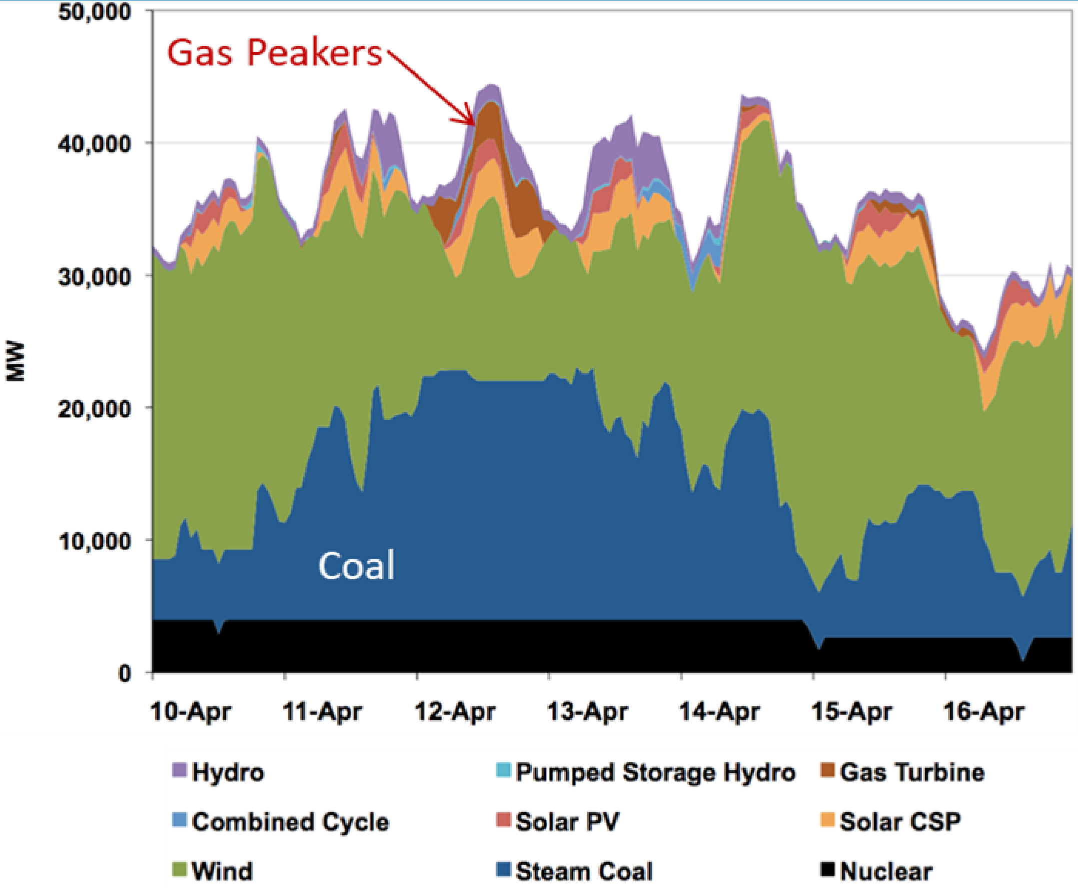
- 15 States exceed 10% of demand with wind energy on average
- 4 States exceed 30%
- One state generates over half of its load

Installed Capacity (MW)				2017 Wind Generation as a Percentage of:			
Annual (2017)		Cumulative (end of 2017)		In-State Generation		In-State Load	
Texas	2,305	Texas	22,599	Iowa	36.9%	North Dakota	58.3%
Oklahoma	851	Oklahoma	7,495	Kansas	36.0%	Kansas	47.1%
Kansas	659	Iowa	7,308	Oklahoma	31.9%	Iowa	43.0%
New Mexico	570	California	5,555	South Dakota	30.1%	Oklahoma	40.9%
Iowa	397	Kansas	5,110	North Dakota	26.8%	Wyoming	26.3%
Illinois	306	Illinois	4,332	Maine	19.9%	South Dakota	25.7%
Missouri	300	Minnesota	3,699	Minnesota	18.2%	New Mexico	19.7%
North Dakota	249	Oregon	3,213	Colorado	17.6%	Maine	19.5%
Michigan	249	Colorado	3,106	Idaho	15.4%	Colorado	17.5%
Indiana	220	Washington	3,075	Texas	14.8%	Nebraska	17.4%
North Carolina	208	North Dakota	2,996	Nebraska	14.6%	Texas	17.3%
Minnesota	200	Indiana	2,117	New Mexico	13.5%	Minnesota	16.7%
Nebraska	99	Michigan	1,860	Vermont	13.4%	Montana	14.8%
Wisconsin	98	New York	1,829	Oregon	11.1%	Oregon	13.5%
Colorado	75	New Mexico	1,682	Wyoming	9.4%	Idaho	10.4%
Ohio	72	Wyoming	1,489	Montana	7.6%	Illinois	8.3%
Oregon	50	Nebraska	1,415	California	6.8%	Washington	8.3%
California	50	Pennsylvania	1,369	Hawaii	6.5%	Hawaii	6.9%
Vermont	30	South Dakota	977	Washington	6.5%	California	5.5%
Maine	23	Idaho	973	Illinois	6.2%	Vermont	5.2%
Rest of U.S.	7	*Rest of U.S.*	6,774	*Rest of U.S.*	1.1%	*Rest of U.S.*	1.2%
TOTAL	7,017	TOTAL	88,973	TOTAL	6.3%	TOTAL	6.9%

- **2017 Wind Penetration by ISO:** SPP: 23.2%; ERCOT: 17.4%; MISO: 7.7%; CAISO: 6.0%; NYISO: 2.7%; PJM: 2.7%; ISO-NE: 2.6%

Courtesy Ryan Wiser and Mark Bolinger of LBNL for data from the 2017 Market Report. https://emp.lbl.gov/publications/2017-wind-technologies-market-report

Wind Plants Need be Actively controlled

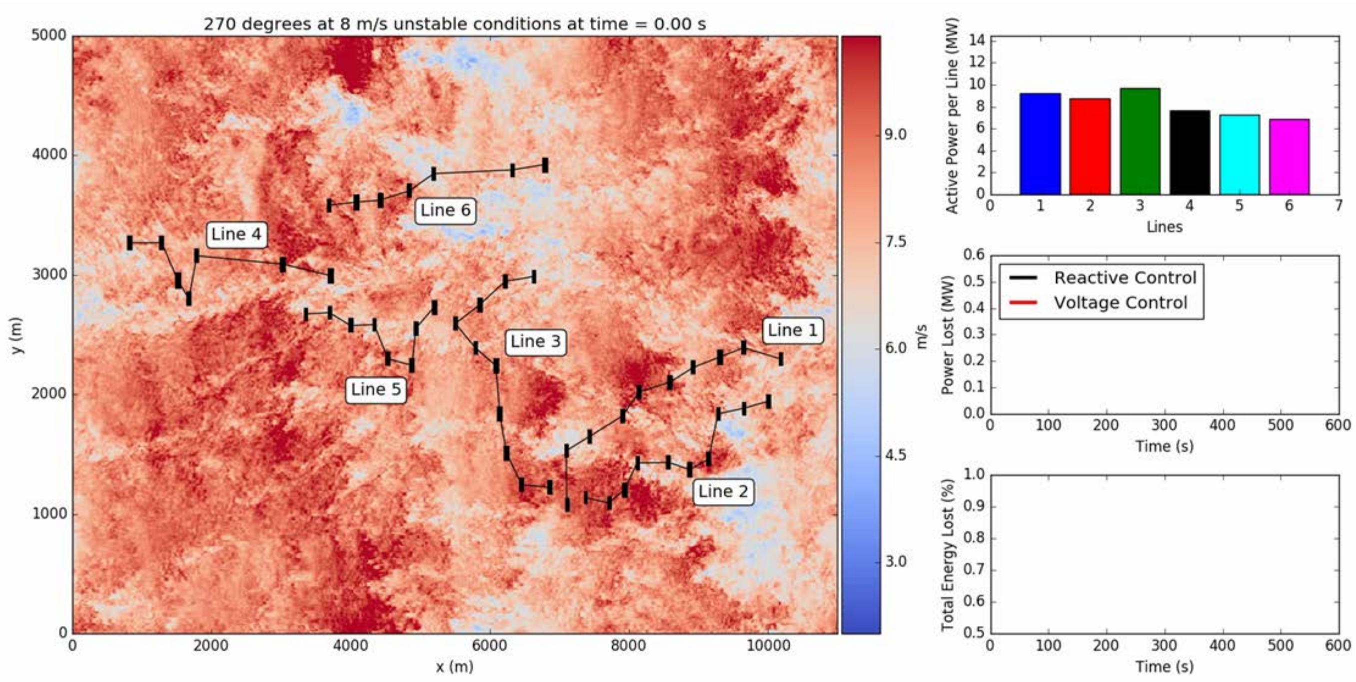


- This is the leading edge of a move away from inertia-dominated generation
- New wind plants will need to provide the ancillary services traditionally supplied by thermal plants

Courtesy Nick Miller, GE

Reproduced with permission from Wind Energy Modeling and Simulation edited by Paul Veers. Copyright 2019 IET.

Wind Plant Hardware in the Loop

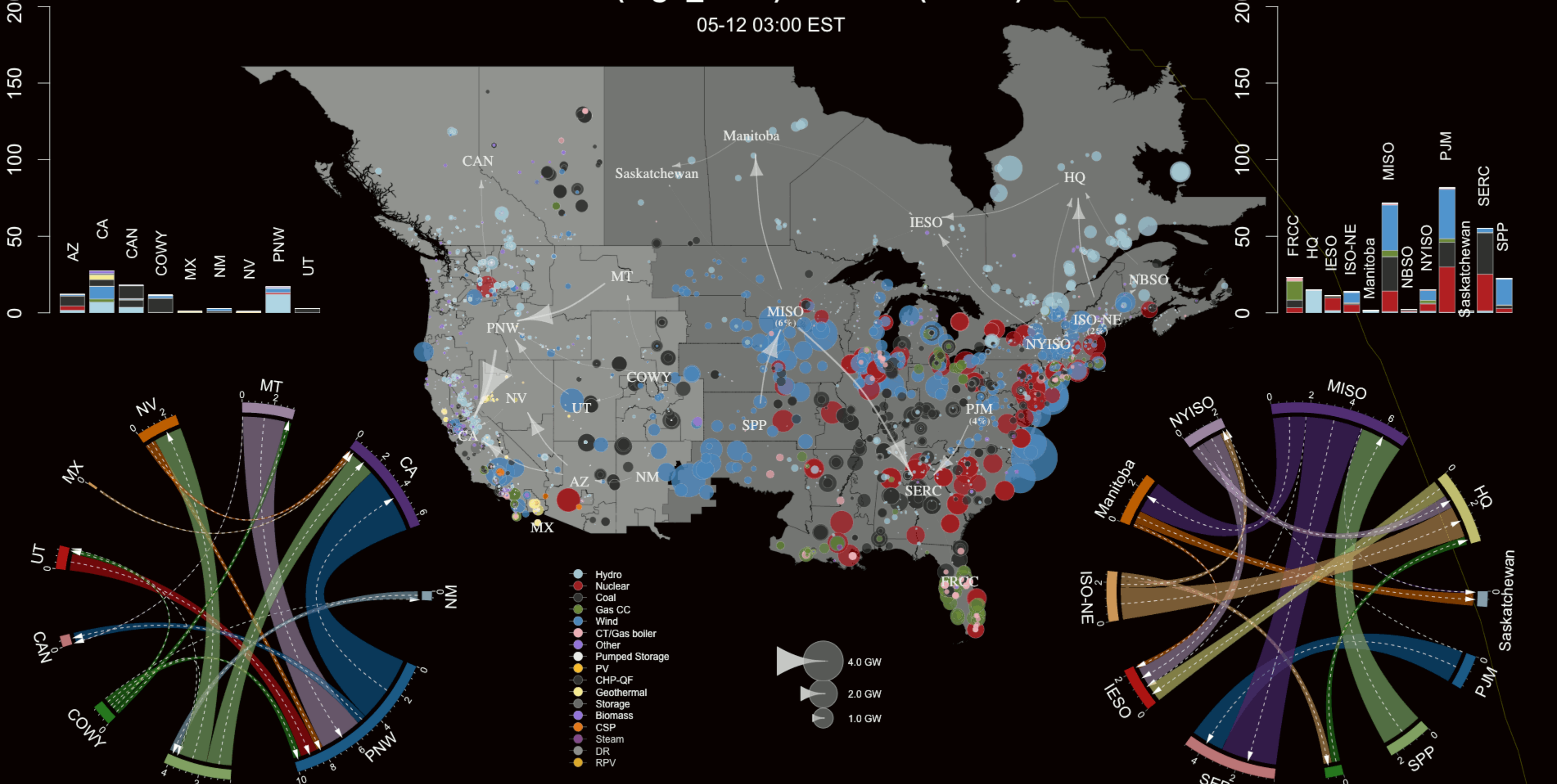


Courtesy Patrick Moriarty, NREL

Optimal electrical control depends on atmospheric conditions and grid

WECC (high_solar) + ERGIS (RTx30)

05-12 03:00 EST



Coluirtesy Beth Clark, NREL

https://www.youtube.com/playlist?list=PLmIn8Hncs7bEl4P8z6-KCliwbYrwANv4p

Final Thoughts on Using Models

- <u>Danish Proverb</u>:

"Det er svært at spå - især om fremtiden"

- <u>English translation</u>:

"It is difficult to make predictions, especially about the future."

Thank You!

paul.veers@nrel.gov