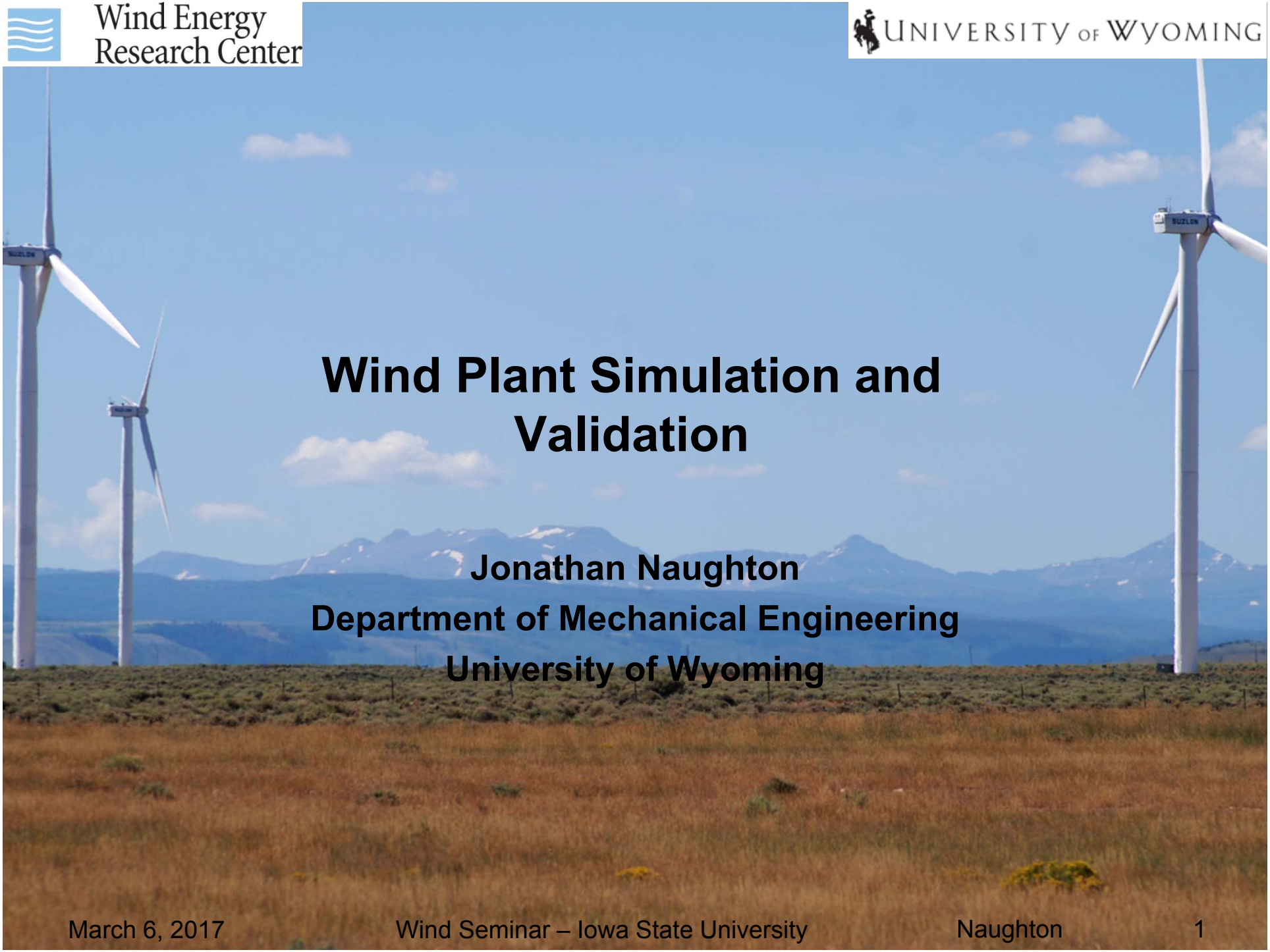


Wind Energy Research Center

UNIVERSITY OF WYOMING

# Wind Plant Simulation and Validation

**Jonathan Naughton**
**Department of Mechanical Engineering**
**University of Wyoming**

# Overview

- Wind's Success
- Wind's Challenges
- Wind Plant Simulation and Validation
- Summary
- Acknowledgements

# WIND'S SUCCESS

Wind Energy Research Center

UNIVERSITY OF WYOMING

# Wind's Success

**Energy Information Administration / Monthly Energy Review Aug 2015**

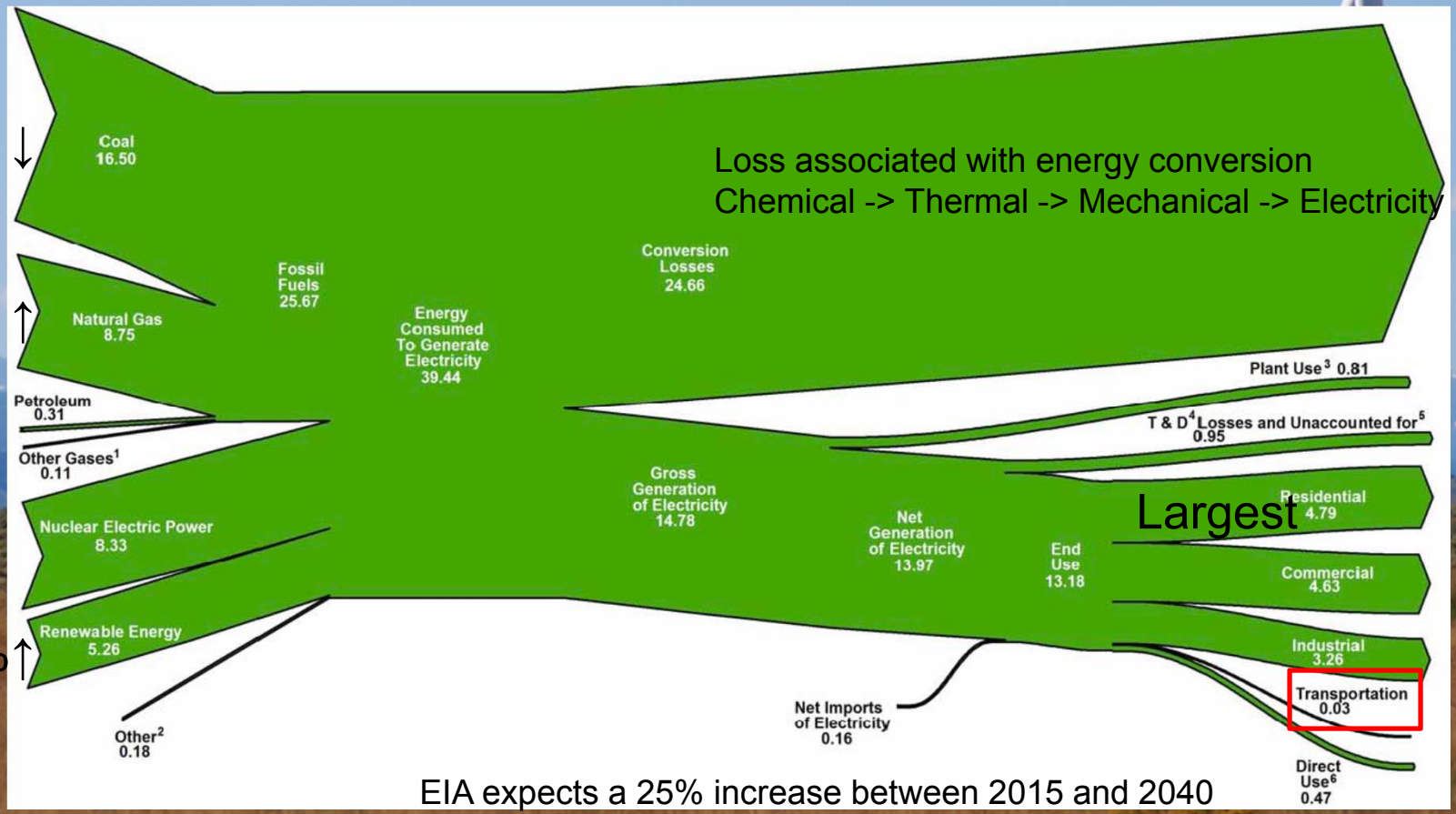
## Electrical Energy

**Annual Energy Outlook 2015**

Sources

End Uses

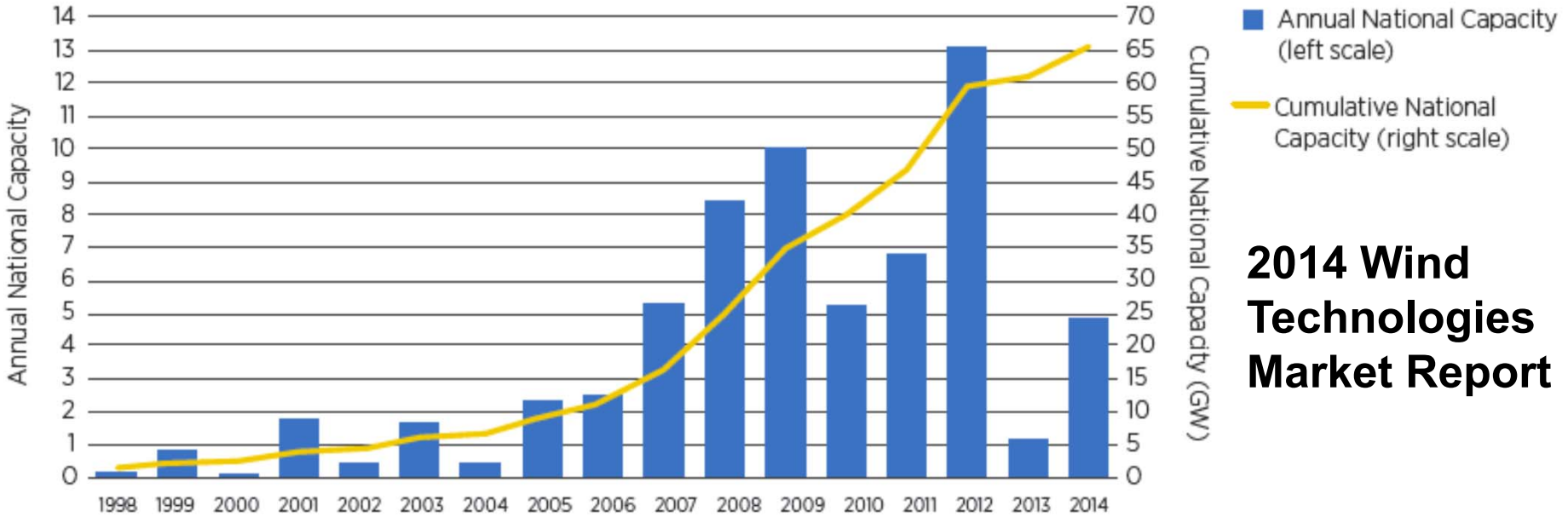
| 2005 | 2013 | |
|---|---|---|
| 52% | 39% | ↓ |
| 16% | 27% | ↑ |
| 20% | 19% | |
| 9% | 13% | ↑ |




EIA expects a 25% increase between 2015 and 2040

Expect changes in both sources and use

# Wind's Success



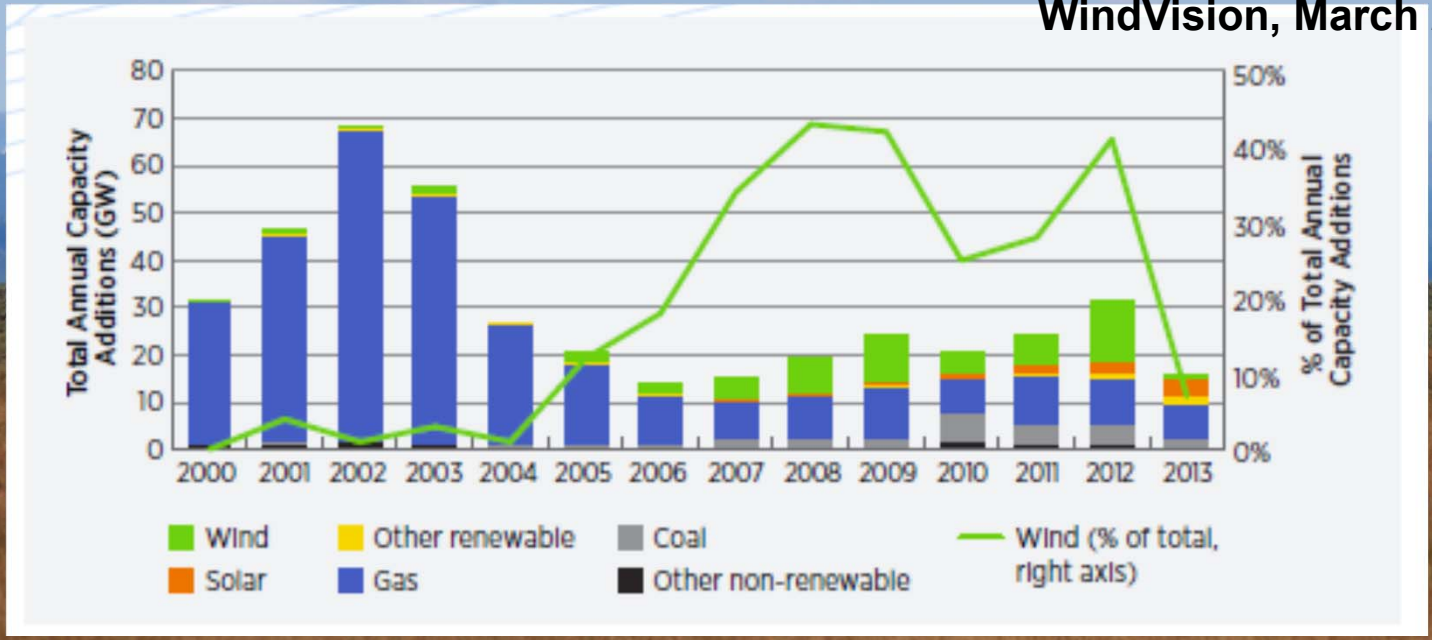

**2014 Wind Technologies Market Report**

- **U.S. installed 8.6 GW of new wind capacity in 2015 and now has nearly 75 GW**
- **In 2016, the US produces >5% of the U.S. electricity.**
- **U.S. produced more power by wind than any other country in the world in 2015.**

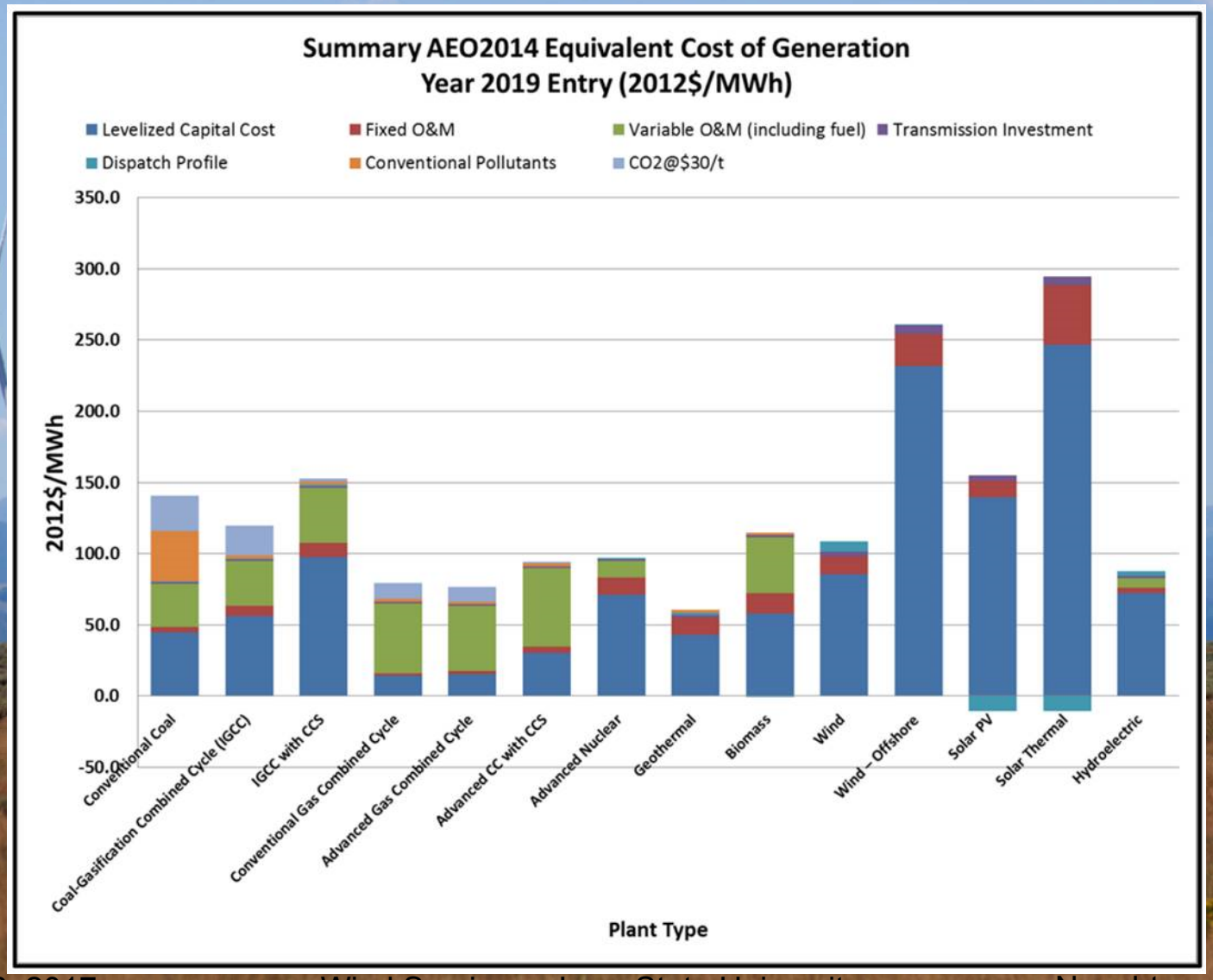
# Wind's Success

- **In 2015, Wind was the largest source of new electricity generation capacity followed by solar (7.3 GW) and natural gas (6.0 GW)**
- **Wind has accounted for 33% of new generation added since 2007 (2014 Wind Technologies Market Report)**

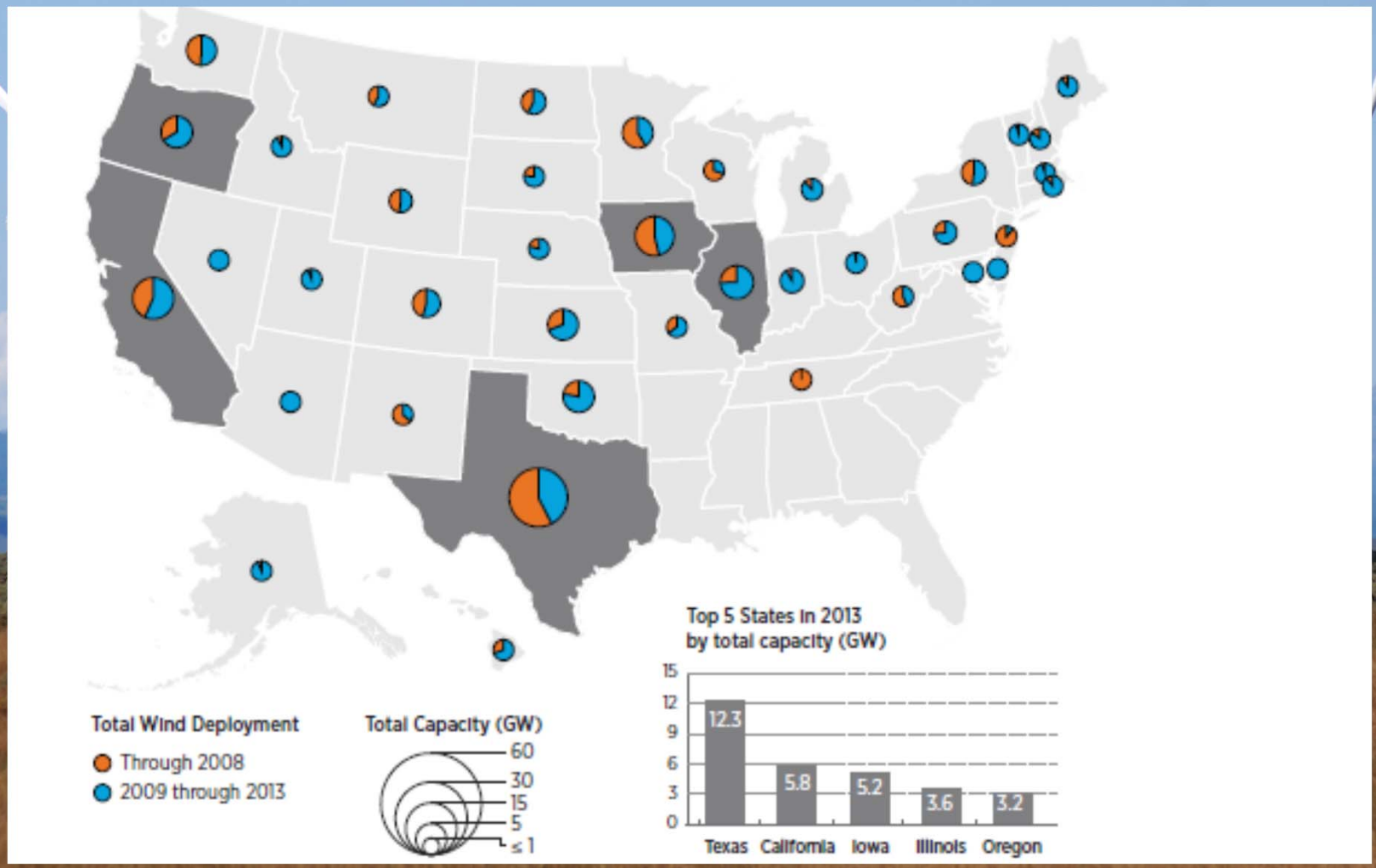
**WindVision, March 2015**



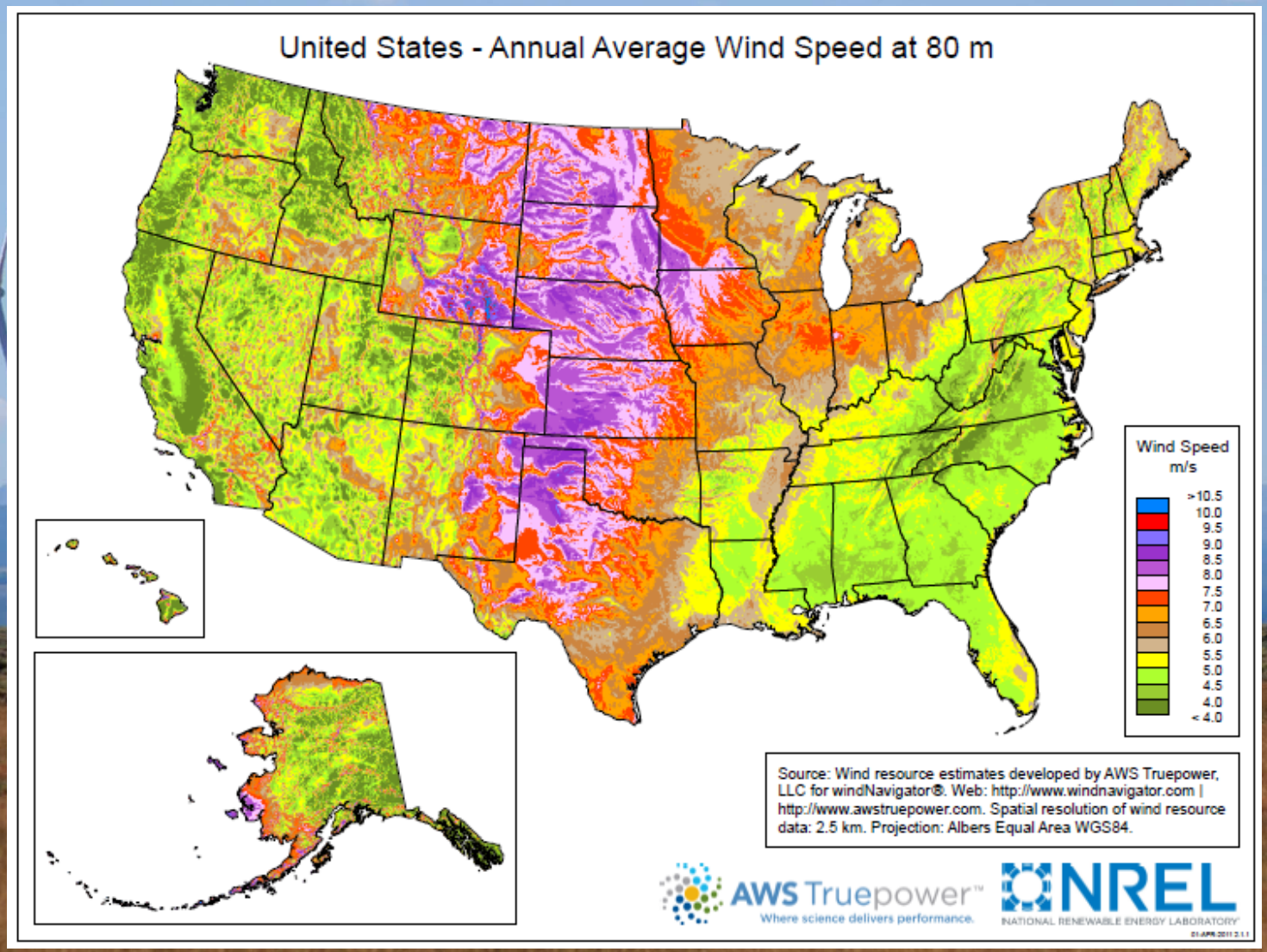
# Wind's Success



# Wind's Success



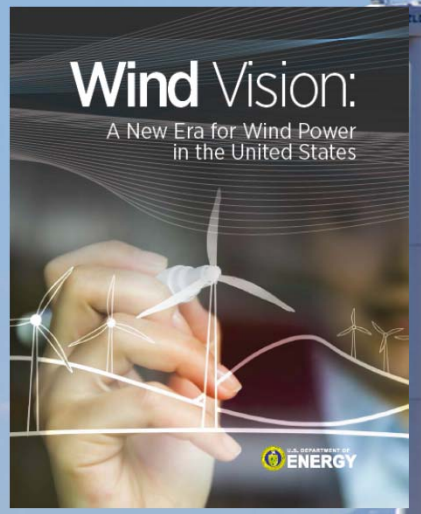
# Wind's Success
# Fantastic Resource

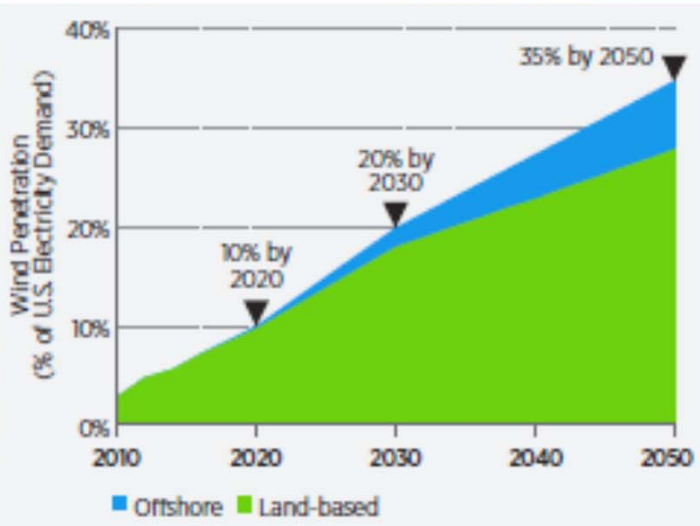


# Wind's Success
# What's Next?

- **Predicted US Electrical Consumption in 2040**
  - Total generation over 5,000 billion kWh
  - 0.9% growth per year
  - Transportation electrification could add more

**WindVision, March 2015**

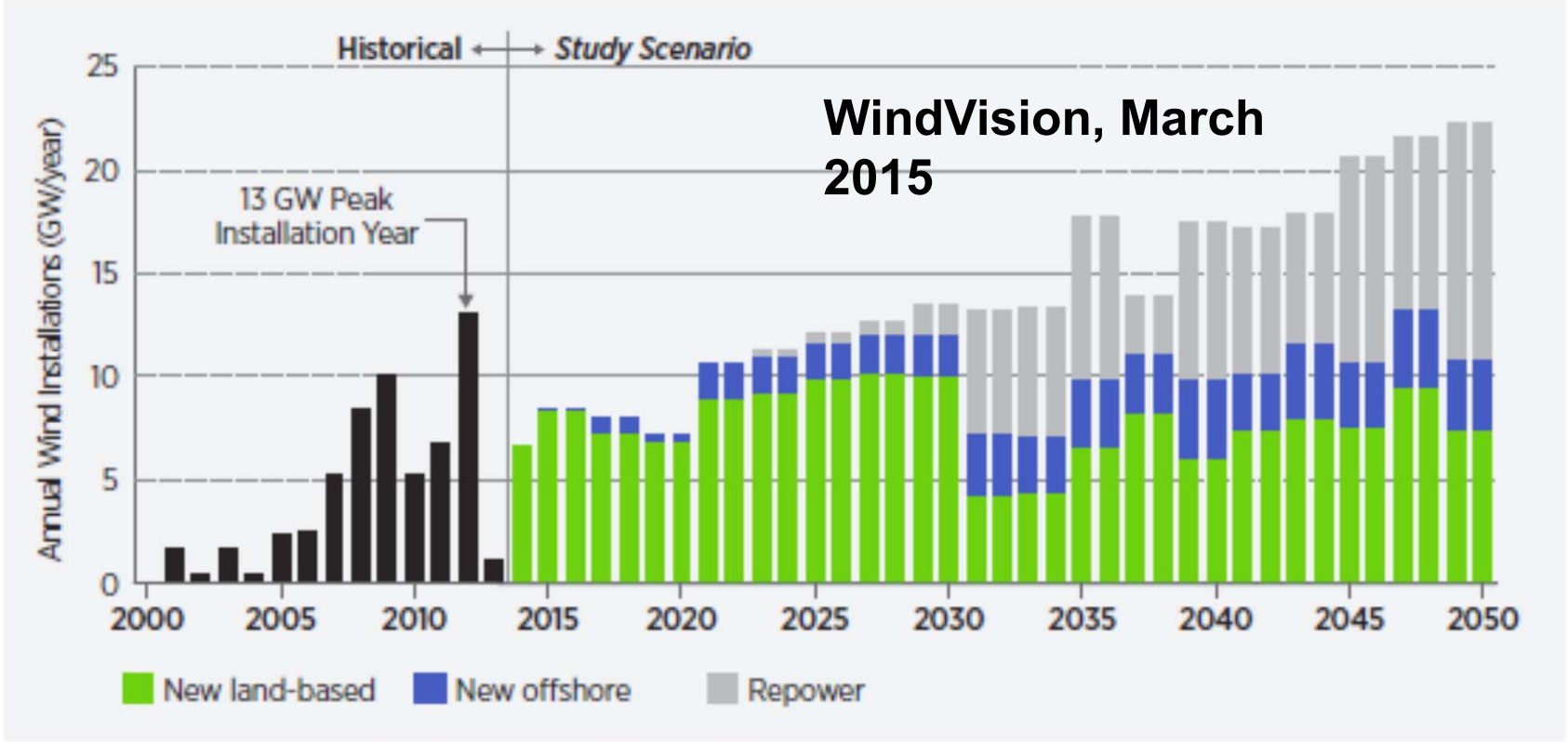



| Cumulative Wind Capacity (GW) | | 2013 | 2020 | 2030 | 2050 |
|---|---|---|---|---|---|
| *Baseline Scenario* | Land-based | 61 | | | |
| *Central Study Scenario* | Land-based | 61 | 110 | 202 | 318 |
| | Offshore | 0 | 3 | 22 | 86 |
| | **Total** | **61** | **113** | **224** | **404** |

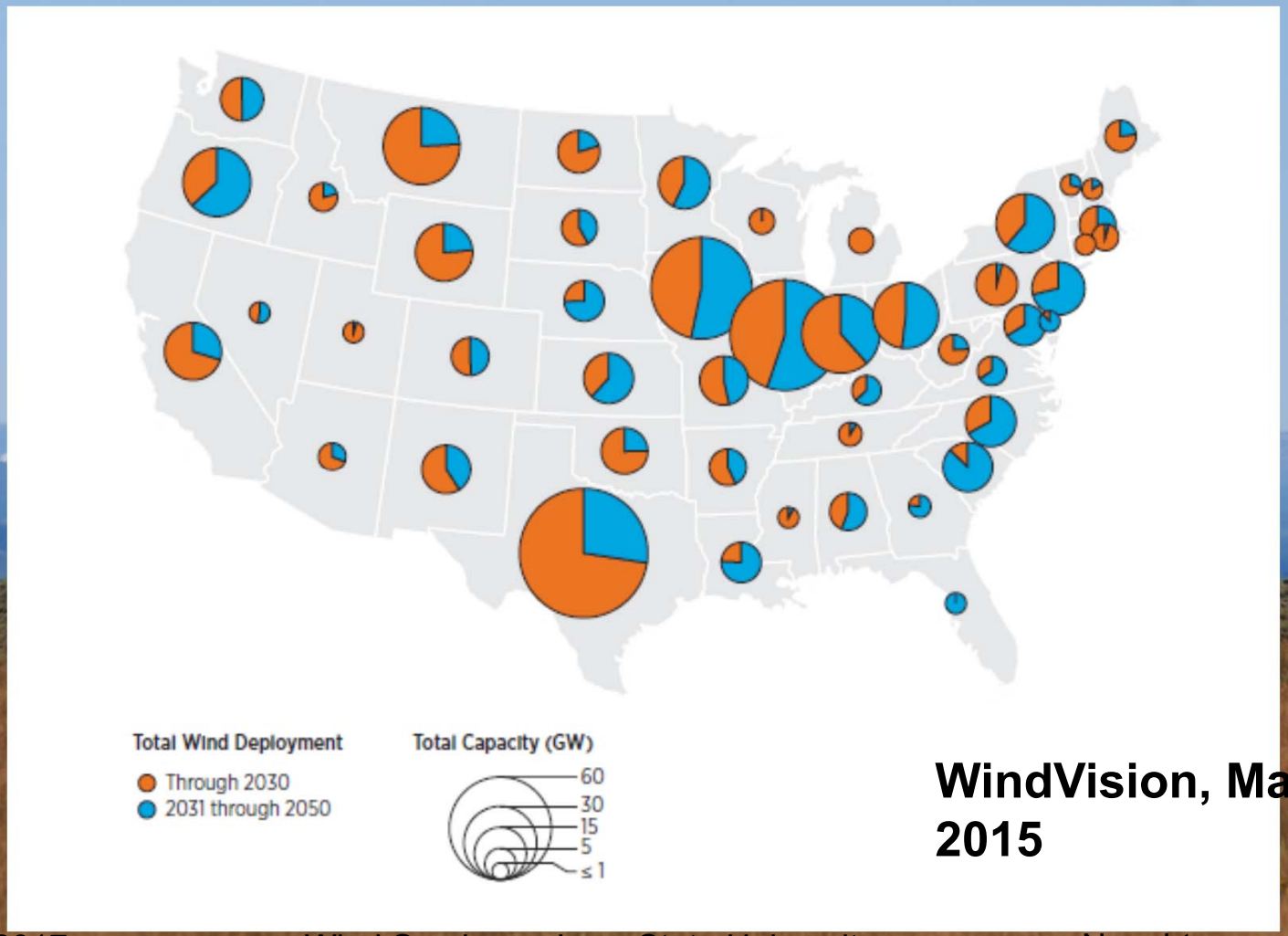
# Wind's Success
# What's Next?

- **Wind will continue to be added at a rate of ~ 10 GW a year for next 35 years**
- **Repowering will start to become a large fraction of this in about 2030**



# Wind's Success
# What's Next?

- **Where will wind be built?**

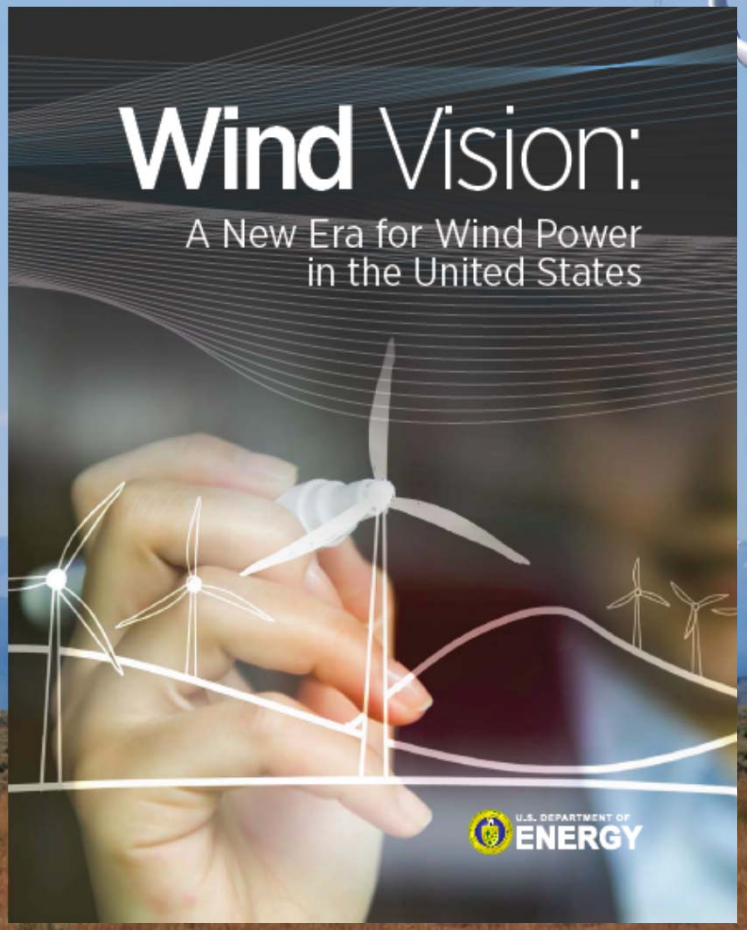



**WindVision, March 2015**

# WIND'S CHALLENGES

# Wind's Challenges
# WindVision

- Resource and site characterization
- Wind plant technology advancement
- Supply chain, manufacturing, and logistics
- Wind power performance, reliability, and safety
- Wind electricity delivery and integration (transmission, load balancing)
- Wind siting and permitting
- Workforce development
- Policy analysis




**WindVision, March 2015**

# Wind's Challenges
# Atmosphere to Electrons (A2E)

# Wind's Challenges
# A2E

- **Plant Performance and Financial Risk Assessment**
  - Assessing the uncertainties and sensitivities in the site assessment models to help facilitate future improvement in modeling and analysis methods.
- **Atmospheric Science Research**
  - Determining how the wind interacts with wind farms at all relevant physical flow scales impacting performance, from regional weather patterns down to the coherent flow structure affecting individual turbines
- **Wind Plant Aerodynamics Modeling**
  - enable the coupling of mesoscale scale and microscale models, allowing for wind inflow simulations at the wind-plant level to be inclusive of larger-scale weather phenomena.
- **Next Generation Wind Plant Technology Development**
  - provide a validated digital environment for evaluation of innovative technologies that maximize energy extraction at the lowest cost of energy.

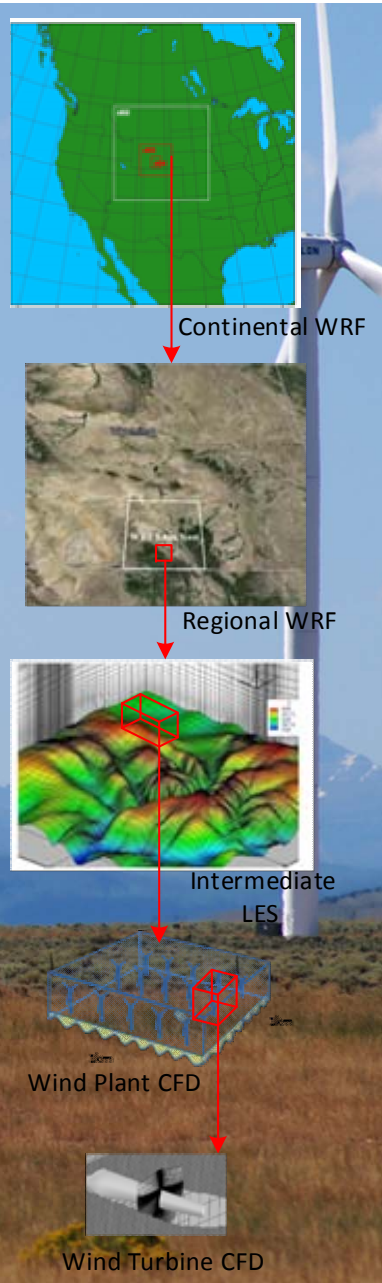
# WIND PLANT SIMULATION AND VALIDATION

# Wind Plant Simulation and Validation Background and Importance

- **Wind turbine technology has matured rapidly**
- **Still need to better understand the environment in which they work**
  - The atmosphere
  - Interaction with other wind turbines (20-30% losses)
  - Effect of complex terrain
- **Challenges for modeling and controlling wind plants**
  - Multi-scale problem
    - **$10^5$ just for the atmosphere (1000 km – 10 m)**
    - **Another $10^5$ for fully resolved turbine blade (10 m – 100 microns)**
  - Complex physics
    - **Multiple fidelity approach required**
    - **Validation at many levels required**
  - Multiple degree-of-freedom problem
    - **Optimization of wind farm output is desired**

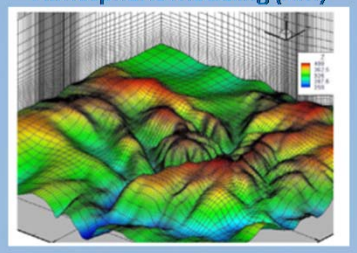
# Wind Plant Simulation And Validation
# Wind Plant Modeling - Objectives

- **Continued development and validation of HPC enabled multi-physics, multi-scale simulations capabilities that enable wind farm simulation and control in complex terrain**
  - Develop and verify tools covering a range of scales
    - **Continental, regional, wind plant, and wind turbine scales**
  - Validate the tools using experimental data
    - **Existing databases**
    - **New wind tunnel and field data**
  - Develop and demonstrate wind plant control

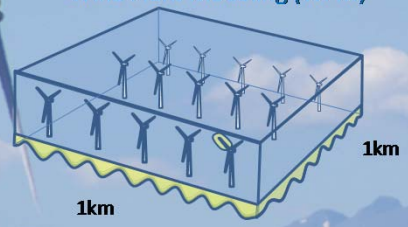


# Wind Plant Simulation And Validation
# Wind Plant Modeling - Tasks and Approach

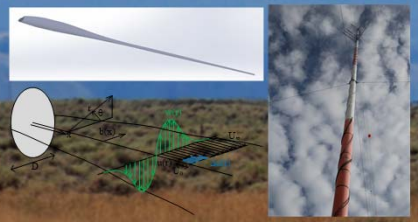
Atmospheric Modeling (AM)



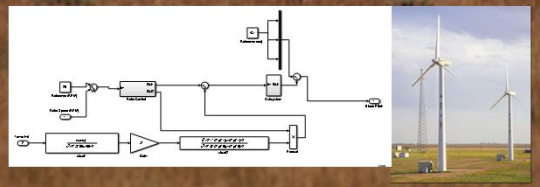
Wind Plant Modeling (WPM)




Validation Studies (VS)

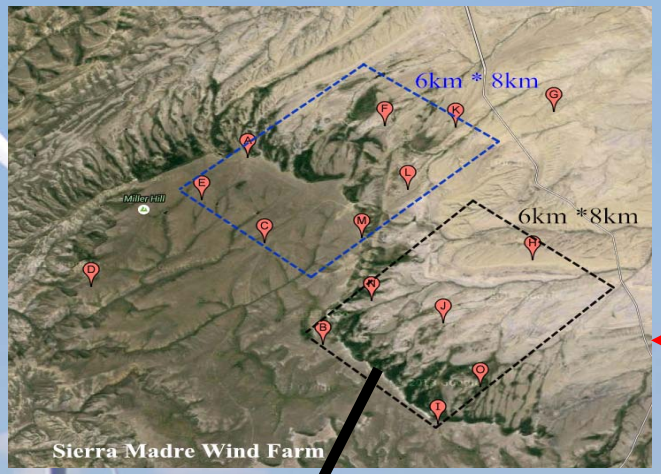


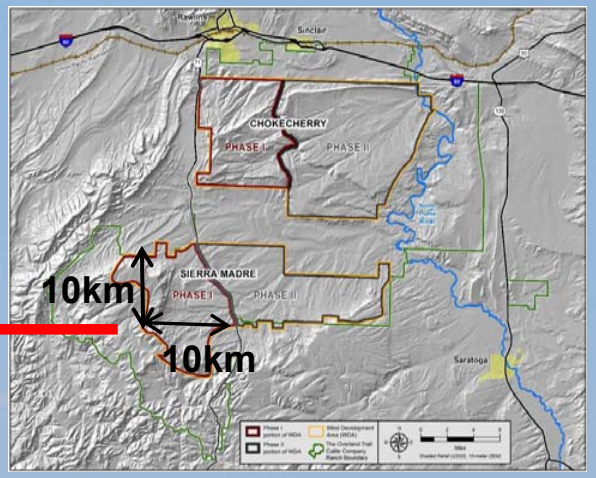
Wind Plant Control (WPC)



- **Develop, verify, and validate tools covering a range of scales**
  - Atmospheric Modeling Task
  - Wind Plant Modeling Task
- **Acquire and organize experimental data for validation**
  - Validation Studies Task
- **Develop and demonstrate wind plant control**
  - Wind Plant Control Task

# Wind Plant Simulation And Validation
## Wind Plant Modeling - Atmospheric Modeling in Complex Terrain

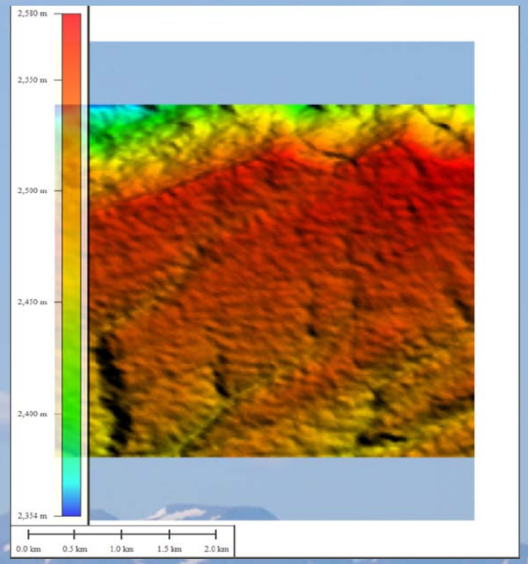



- Demonstrate modeling of wind farm in complex terrain.

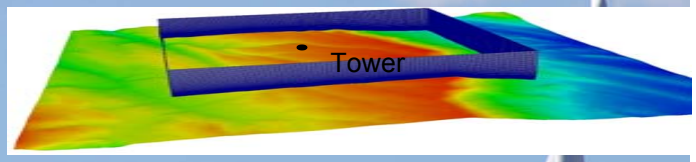
# Wind Plant Simulation And Validation
## Wind Plant Modeling - Atmosphere Modeling in Complex Terrain


Satellite View (2-D)

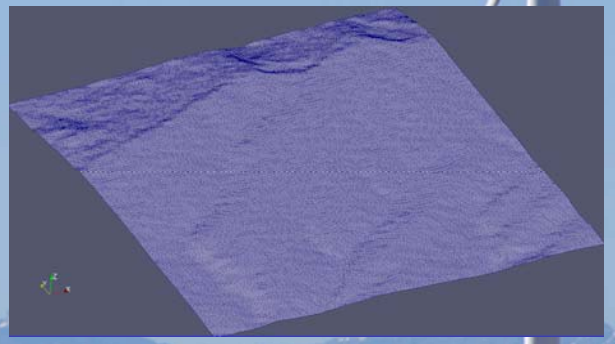



1-arc-second resolution (30m)

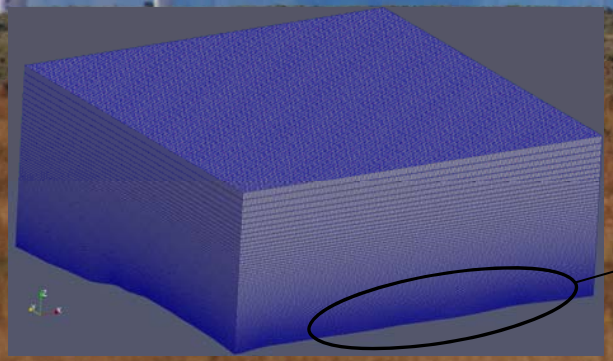
Shuttle Radar Topography Mission (SRTM)

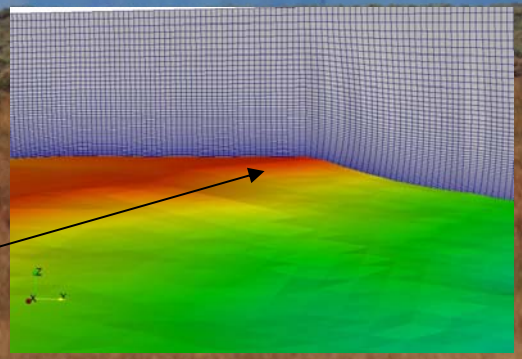



3-D View (stl-surface)



*Body-fitted grid on terrain*
*$\Delta x = \Delta y = 16m$*

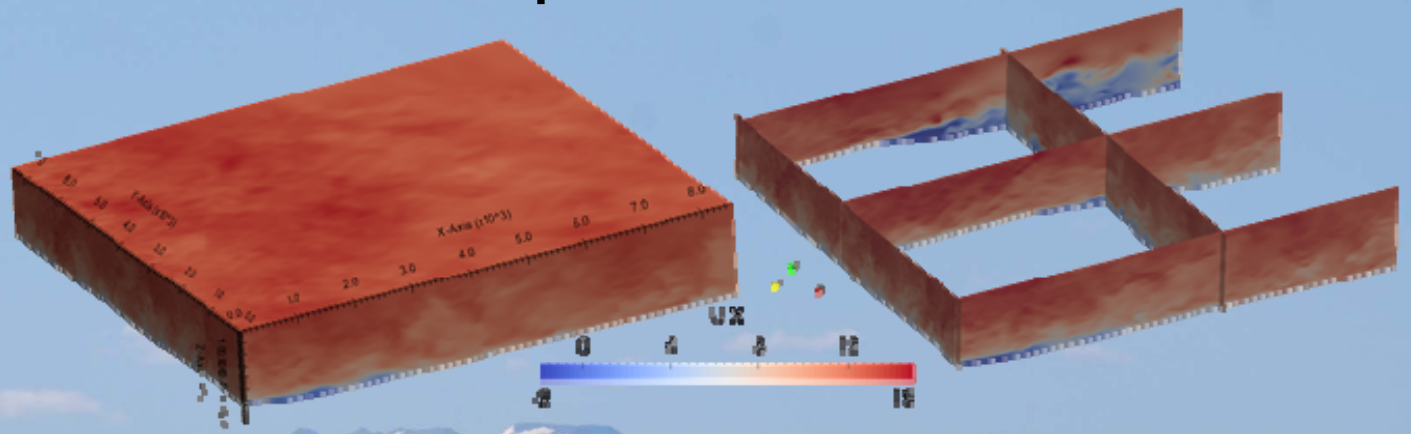




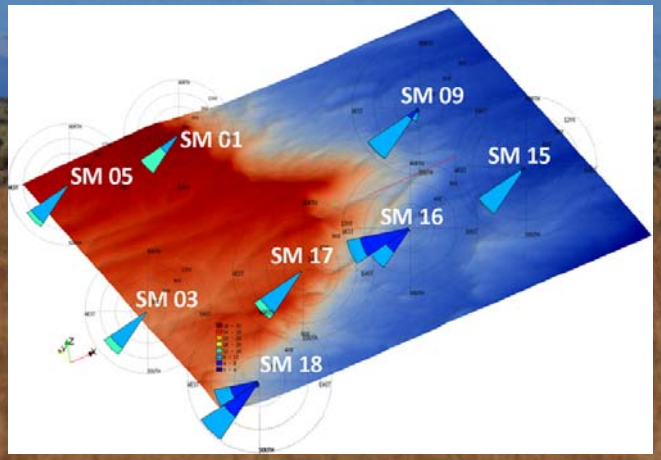
*Vertical grid stretching*
*$\Delta z$ from 5 to 40 m*

# Wind Plant Simulation And Validation
## Wind Plant Modeling - Atmosphere Modeling in Complex Terrain

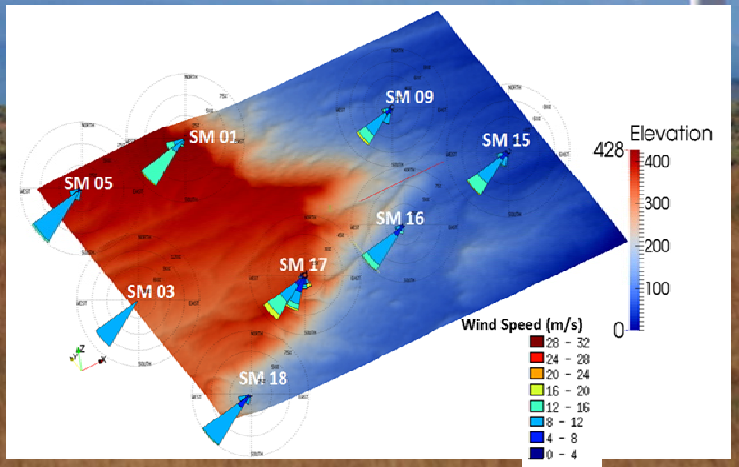
- **Simulate the flow over complex terrain**



Tower data

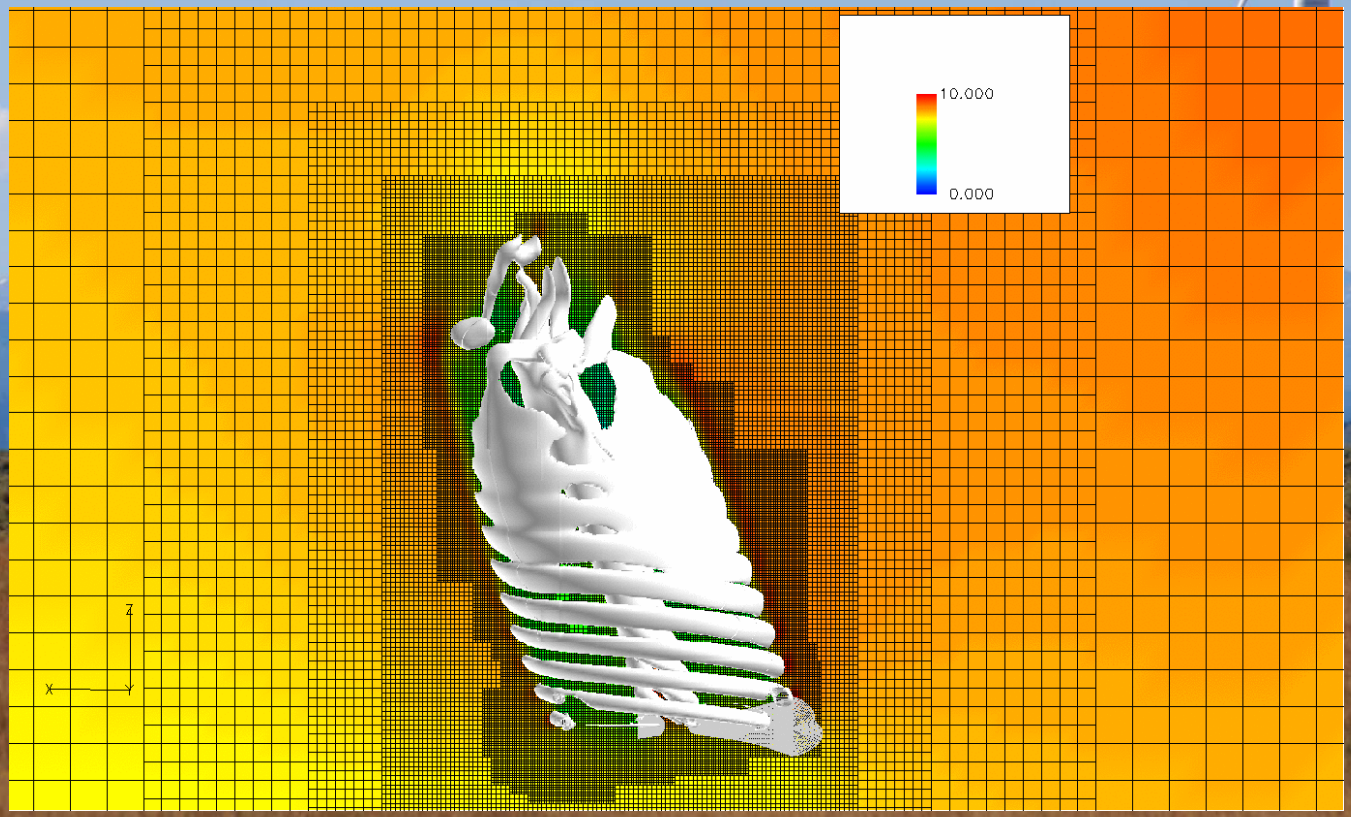



Simulation results



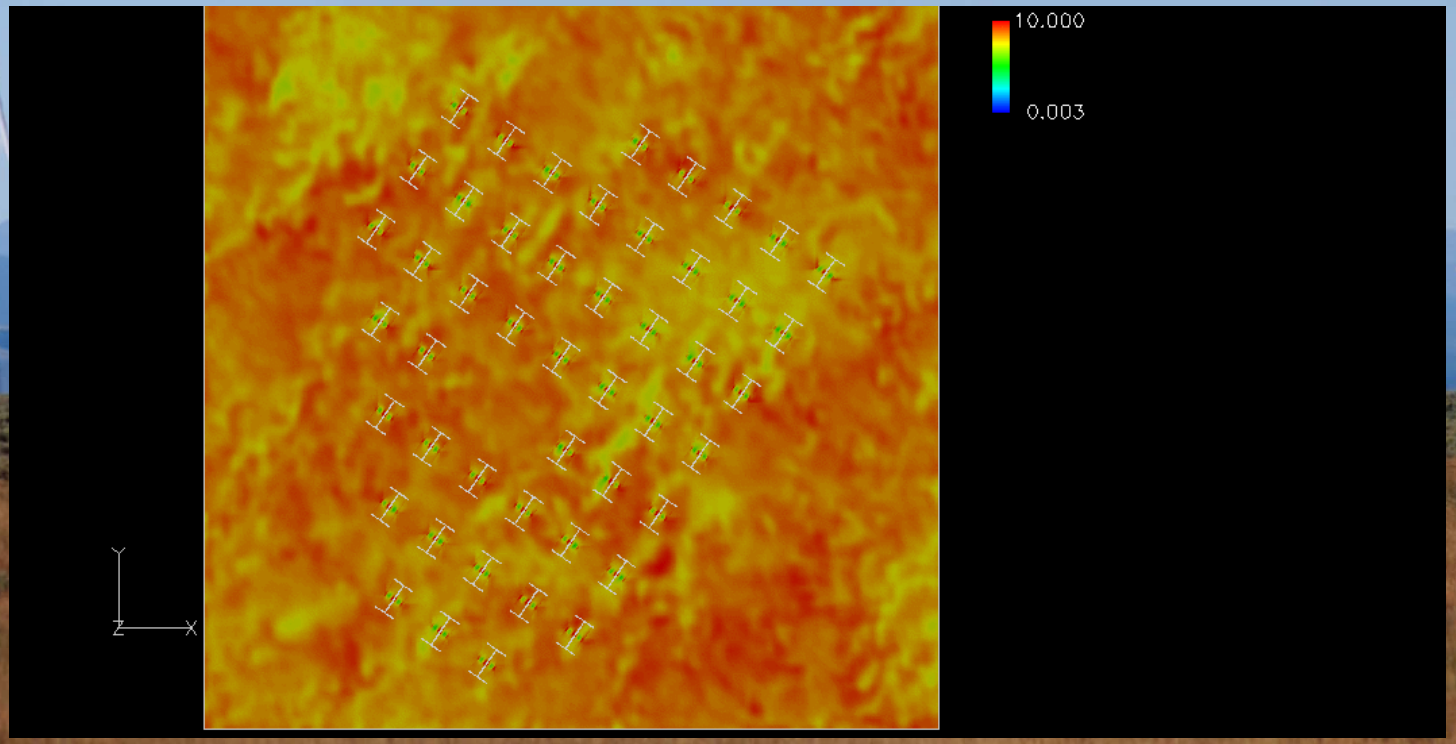
# Wind Plant Simulation and Validation
# Wind Plant Modeling Framework

- **Original simulations demonstrated in Helios**
  - DOD Helicopter Simulation Software



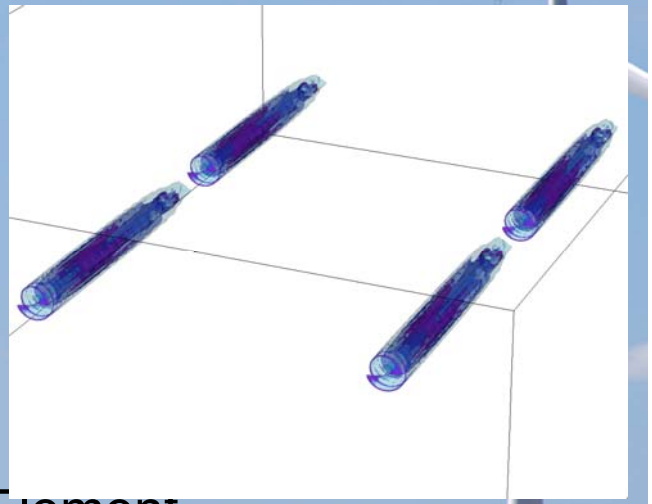
# Wind Plant Simulation and Validation
# Wind Plant Modeling Framework

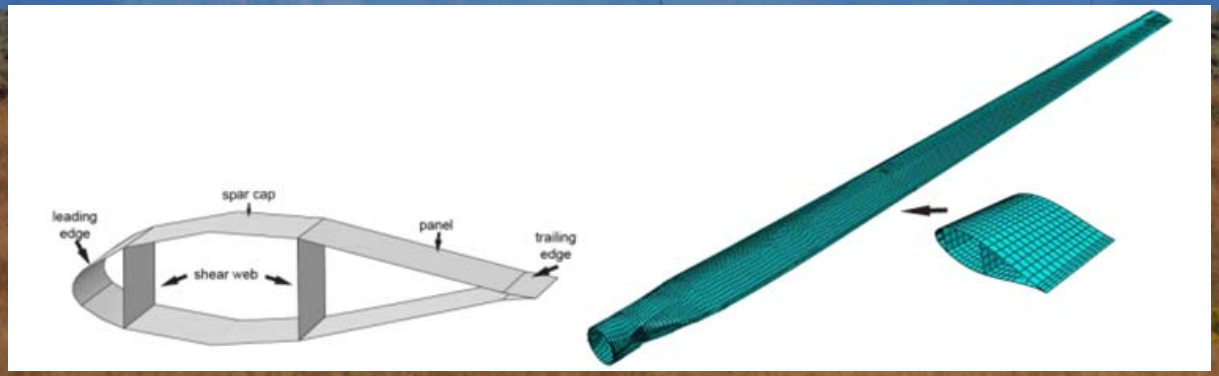
- **Original simulations demonstrated in Helios**
  - DOD Helicopter Simulation Software



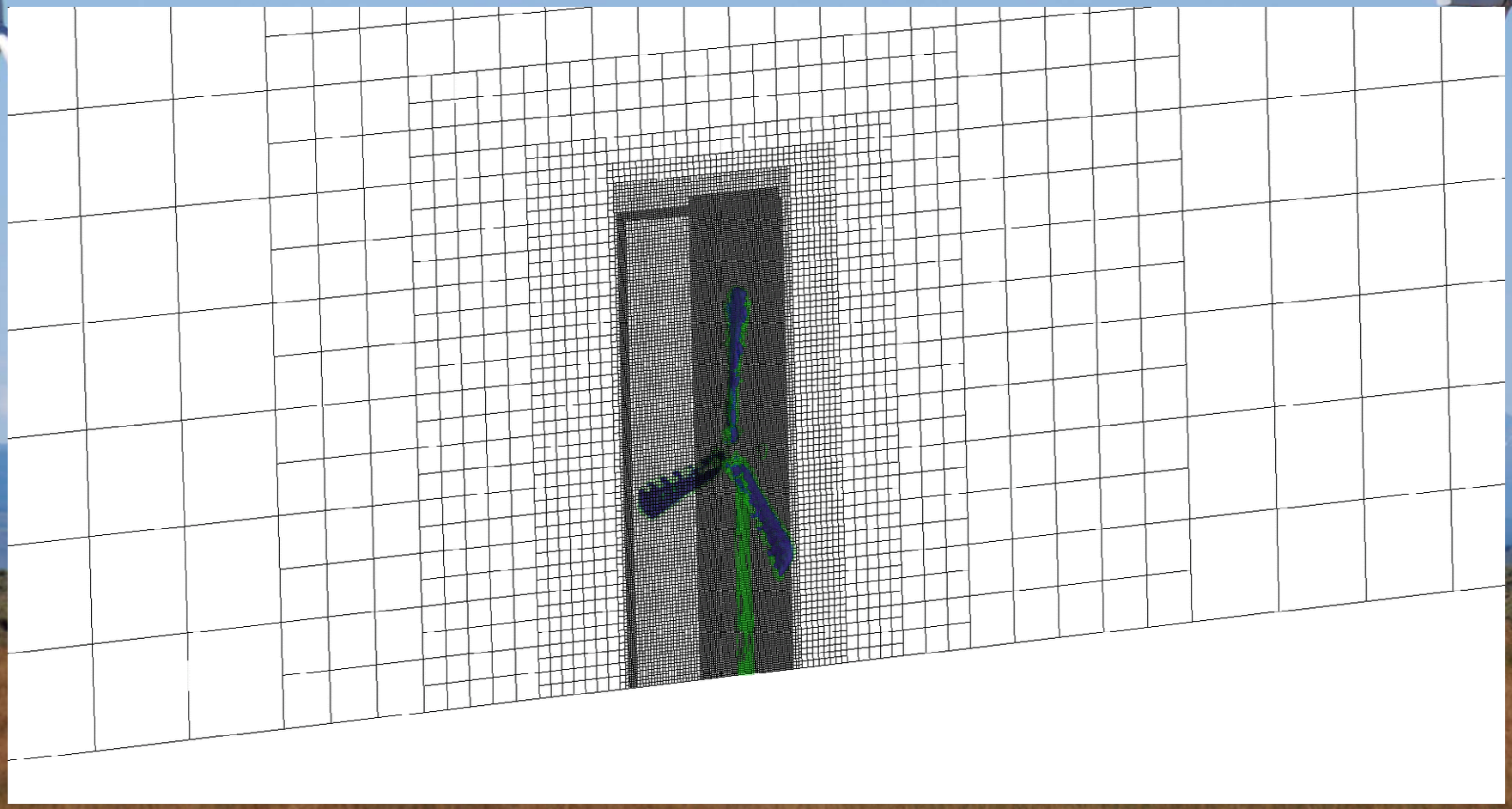
# Wind Plant Simulation and Validation
# Wind Plant Modeling Framework

- **New framework**
  - Near-body solver (NSU3D, DG3D)
  - New high-order off-body solver
  - Overset mesh connectivity module (TIOGA)
  - Adaptive mesh refinement
  - C++ driver for multi-disciplinary framework
  - Structural dynamic effects (Beam and Finite Element Models)
  - Control interface module

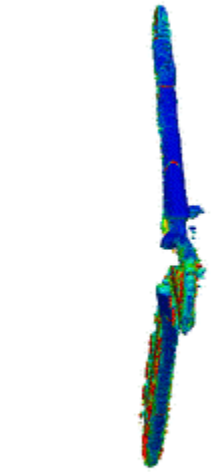




# Wind Plant Simulation and Validation
# Wind Plant Modeling Framework



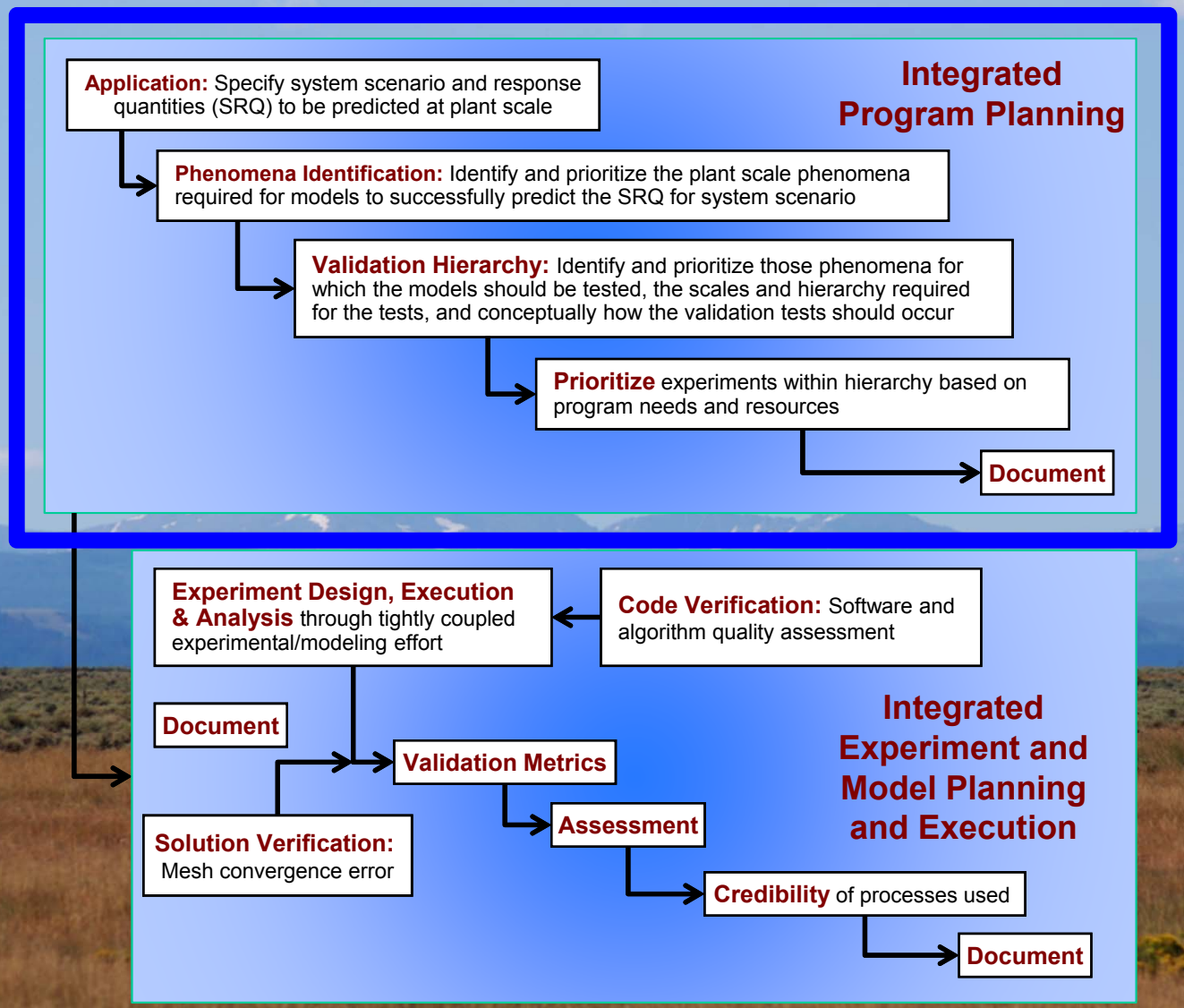
# Wind Plant Simulation and Validation
# Wind Plant Modeling Framework




# Wind Plant Simulation and Validation
# Validation Efforts

- **Validation**
  - The process of determining the degree to which a model is an accurate representation of the real world, from the perspective of the intended uses of the model
    - **Note that validation is not an acceptance/rejection/ endorsement of a model**
- **Verification**
  - Code verification
    - **Software errors or algorithm deficiencies that corrupt simulation results.**
  - Solution verification
    - **Human procedural errors or numerical solution errors that corrupt the simulation**

# Wind Plant Simulation and Validation V&V Process - Framework



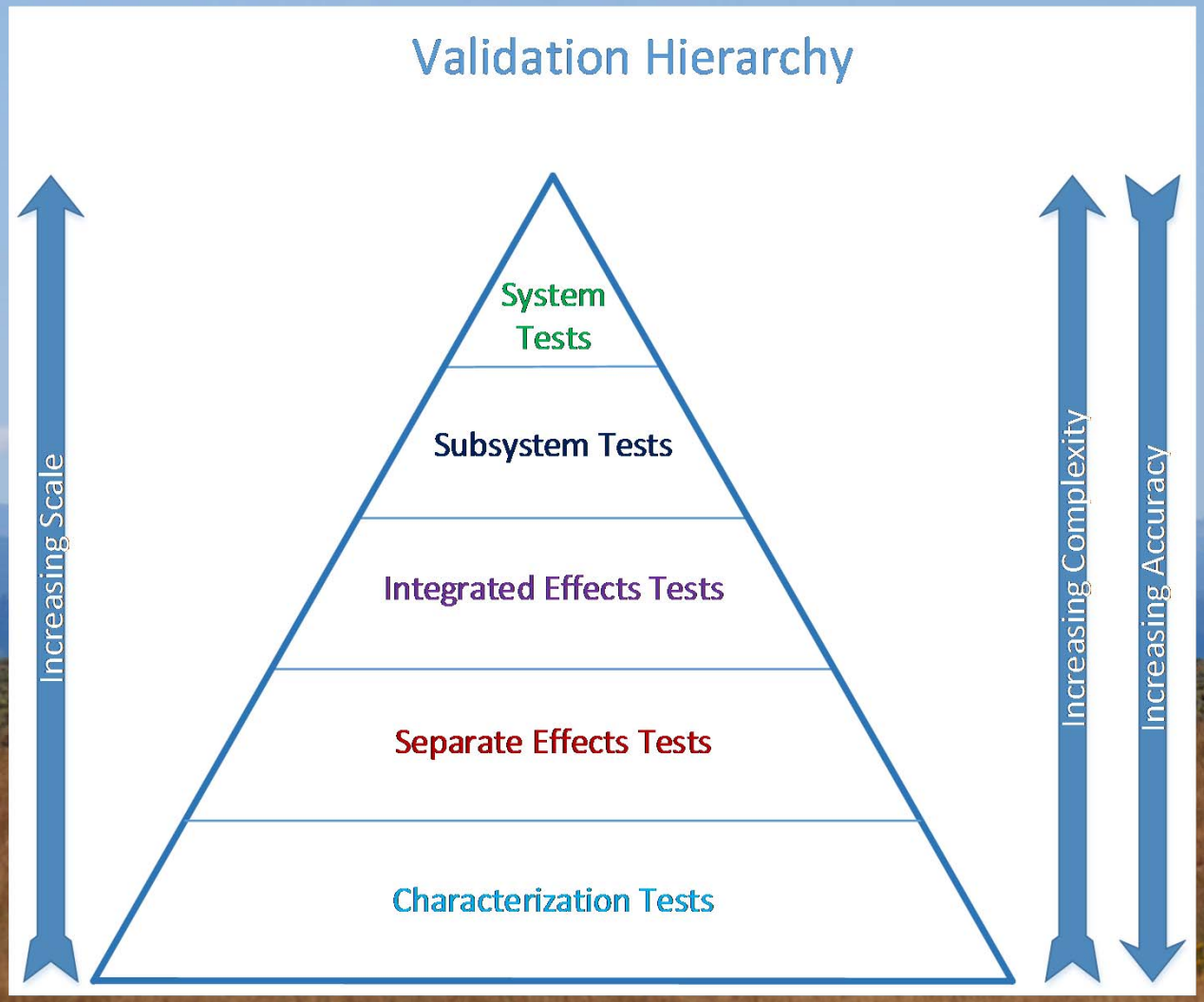
# Wind Plant Simulation and Validation PIRT Development

- **Assemble groups of experts**
  - Several meetings over the past 24 months
  - Wide range of expertise
- **Have the experts identify the physics important to a specific system**
  - Wind turbine
  - Wind farm
- **Have the experts prioritize**
  - How important are the physics to the problem
  - How well do the codes model those physics
- **Take results of several executions and distill into a final PIRT**
- **Use the final PIRT to develop a Validation Hierarchy**

# Wind Plant Simulation and Validation
# PIRT – Wind Plant

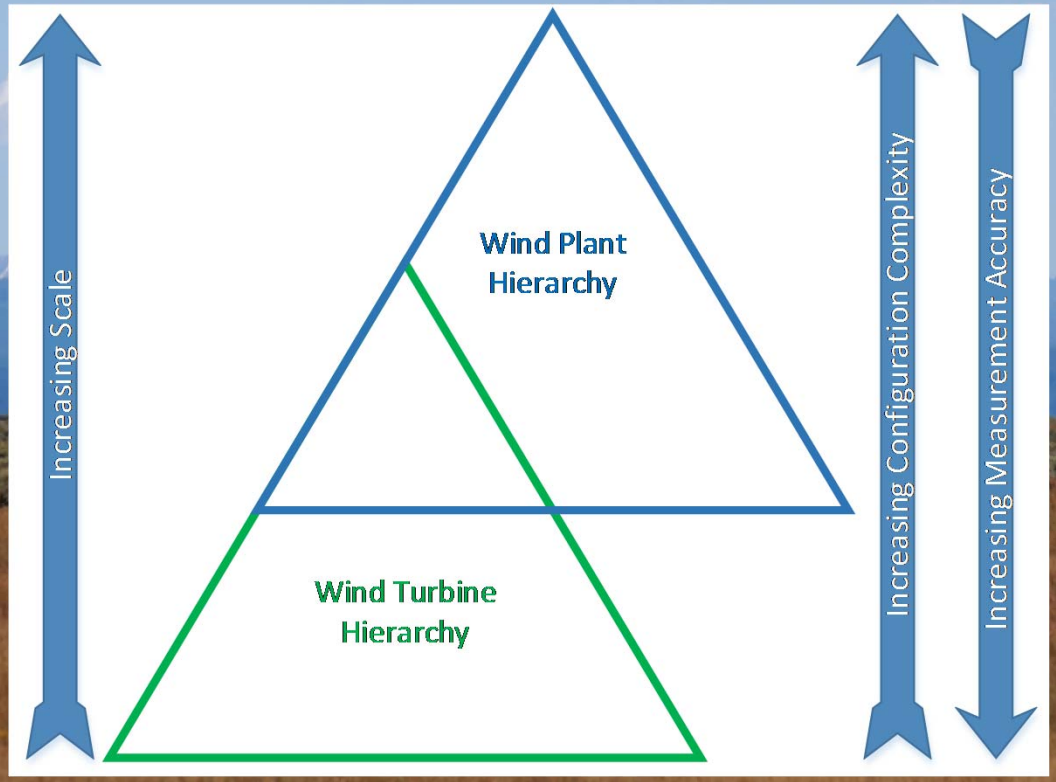
| Phenomenon | Importance at Application Level | Model Adequacy | | |
|---|---|---|---|---|
| | | Physics | Code | Val |
| **Inflow Turbulence/Wake Interaction** | | | | |
| Wind direction (shear/veer/assymetry) | H | L | M | M |
| Turbulence characteristics (intensity, spectra, coherence, stability) | H | L | M | M |
| Coherent turblence structure | H | L | M | L |
| Surface conditions (roughness, canopy, waves, surface heat flux, topography) | H | L | M | M |
| Momentum transport (horizontal and vertical fluxes) | H | L | L | L |
| **Multi-Turbine Wake Effects** | | | | |
| Wake interaction, merging, meander | H | L | L | L |
| Plant flow control for optimum performance | H | M | M | L |
| Wake steering (yaw & tilt effects) | H | L | L | L |
| Wake dissipation | H | L | L | L |
| Wake Impingement (full, half, etc.) | H | L | L | L |
| Deep array effects (change in turbulence, etc.) | H | L | L | L |
| **Other Effects** | | | | |
| Wind plant blockage effects and plant wake | M | M | M | L |
| Acoustic Propagation | H | L | L | L |

# Wind Plant Simulation and Validation
## Validation Hierarchy

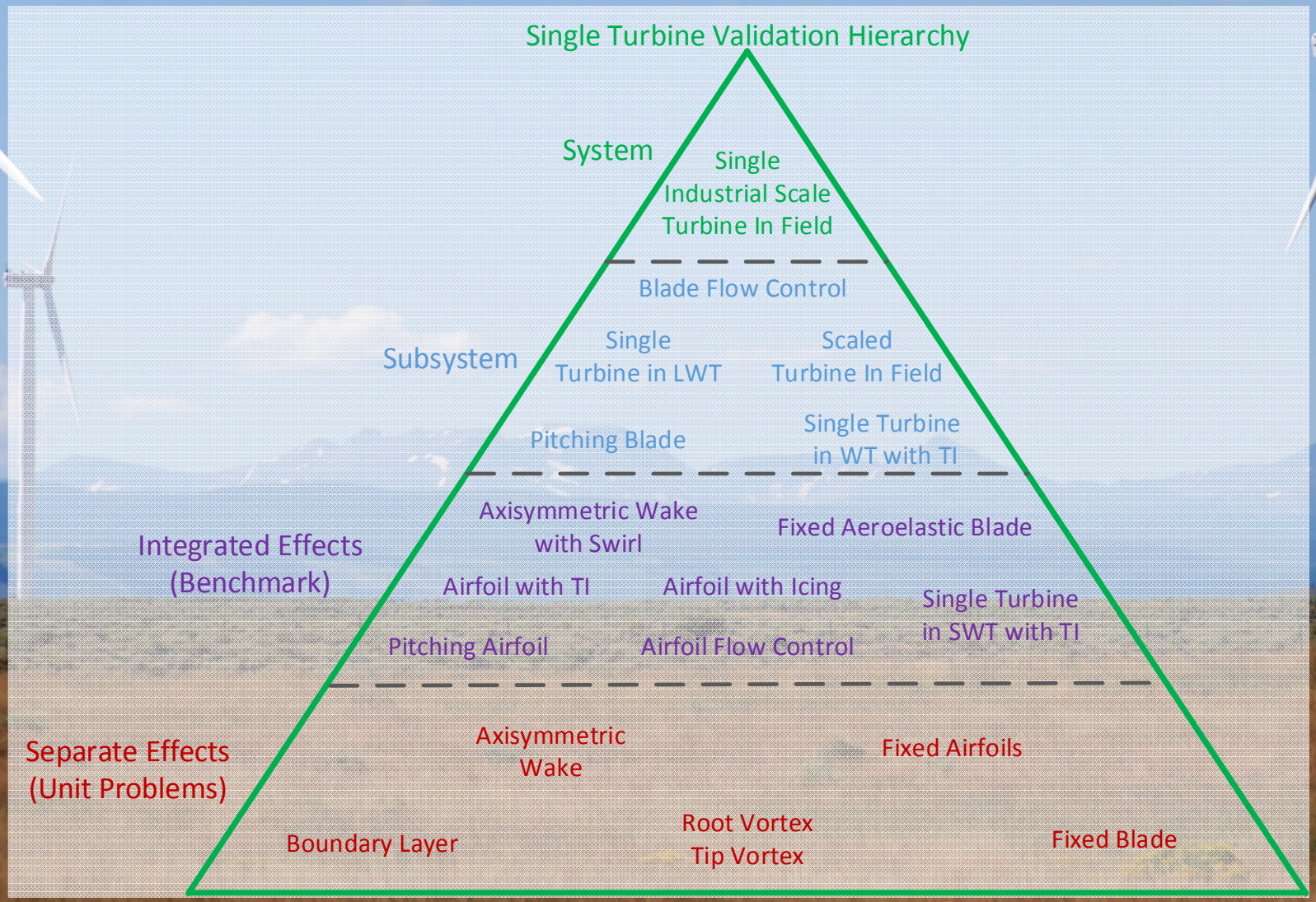


# Wind Plant Simulation and Validation Application to Wind Turbine/Wind Plant

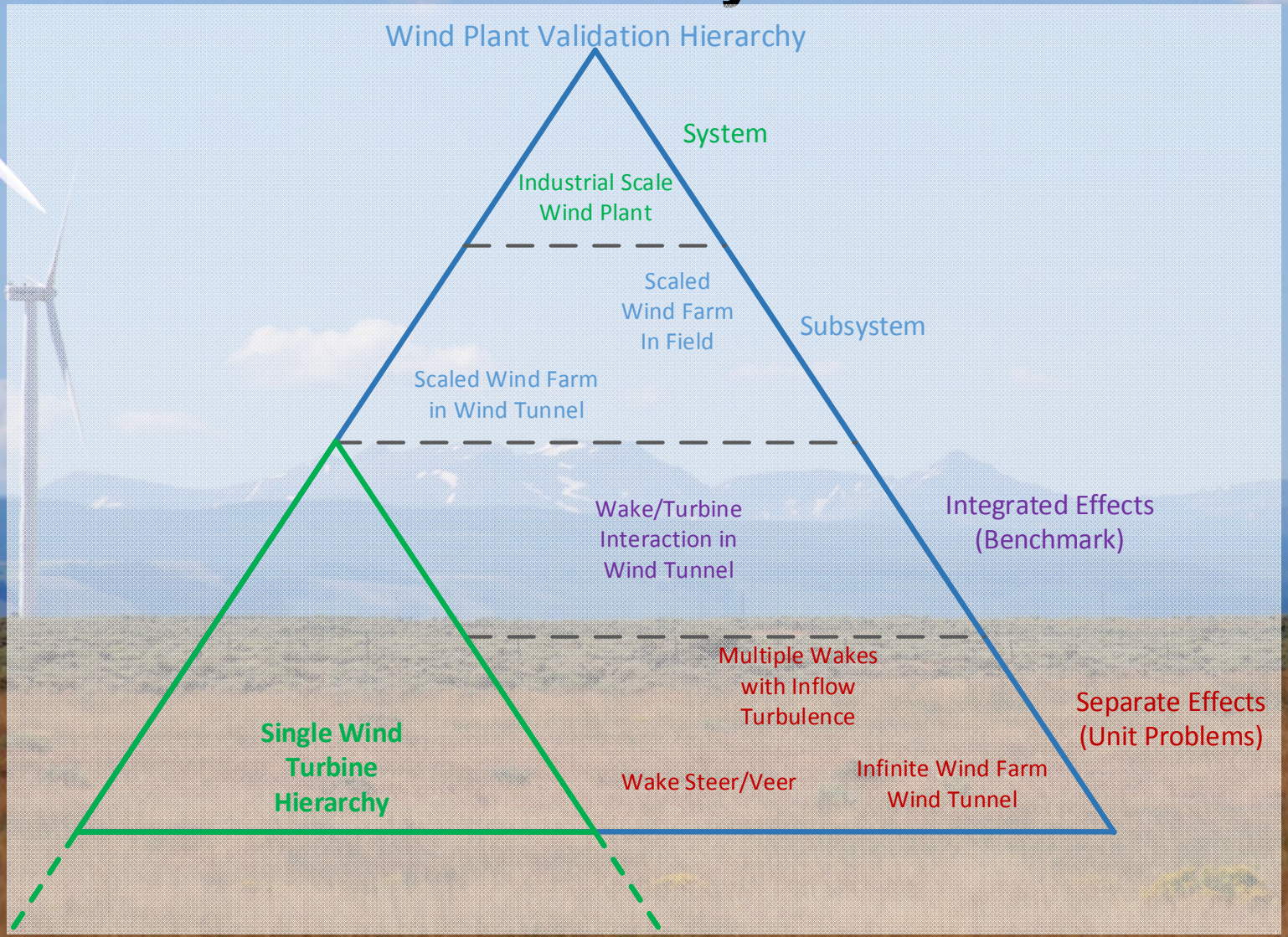
- **Planning steps have been carried out**
  - Wind turbine scale
  - Wind plant scale
- **Important to consider these are not independent efforts**
  - Wind turbine scale is a subsystem of wind plant scale



# Wind Plant Simulation and Validation
## Validation Hierarchy – Wind Turbine

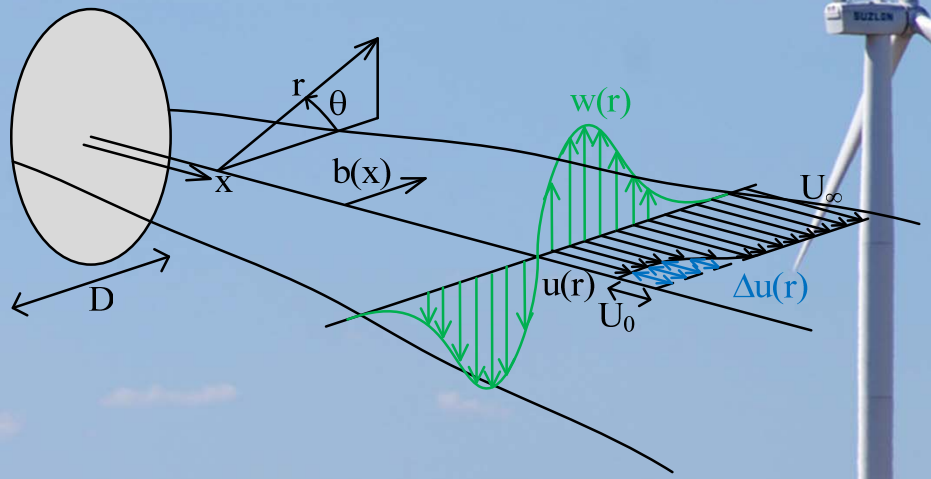


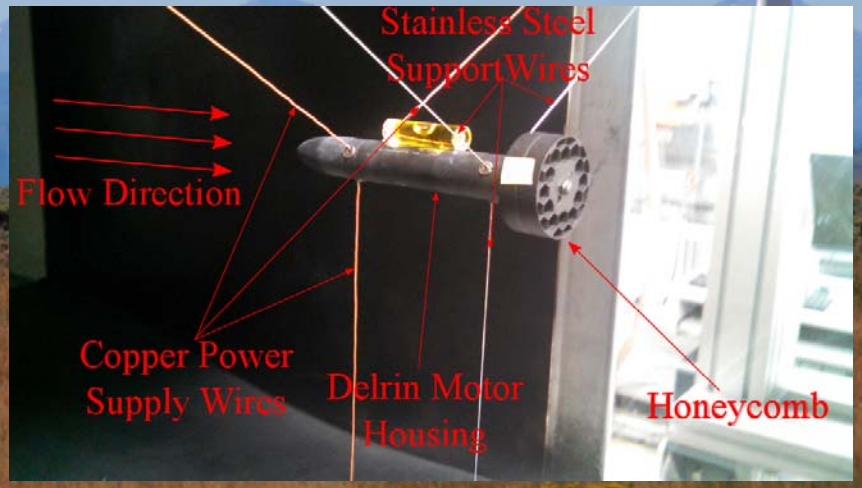
# Wind Plant Simulation and Validation
## Validation Hierarchy – Wind Plant



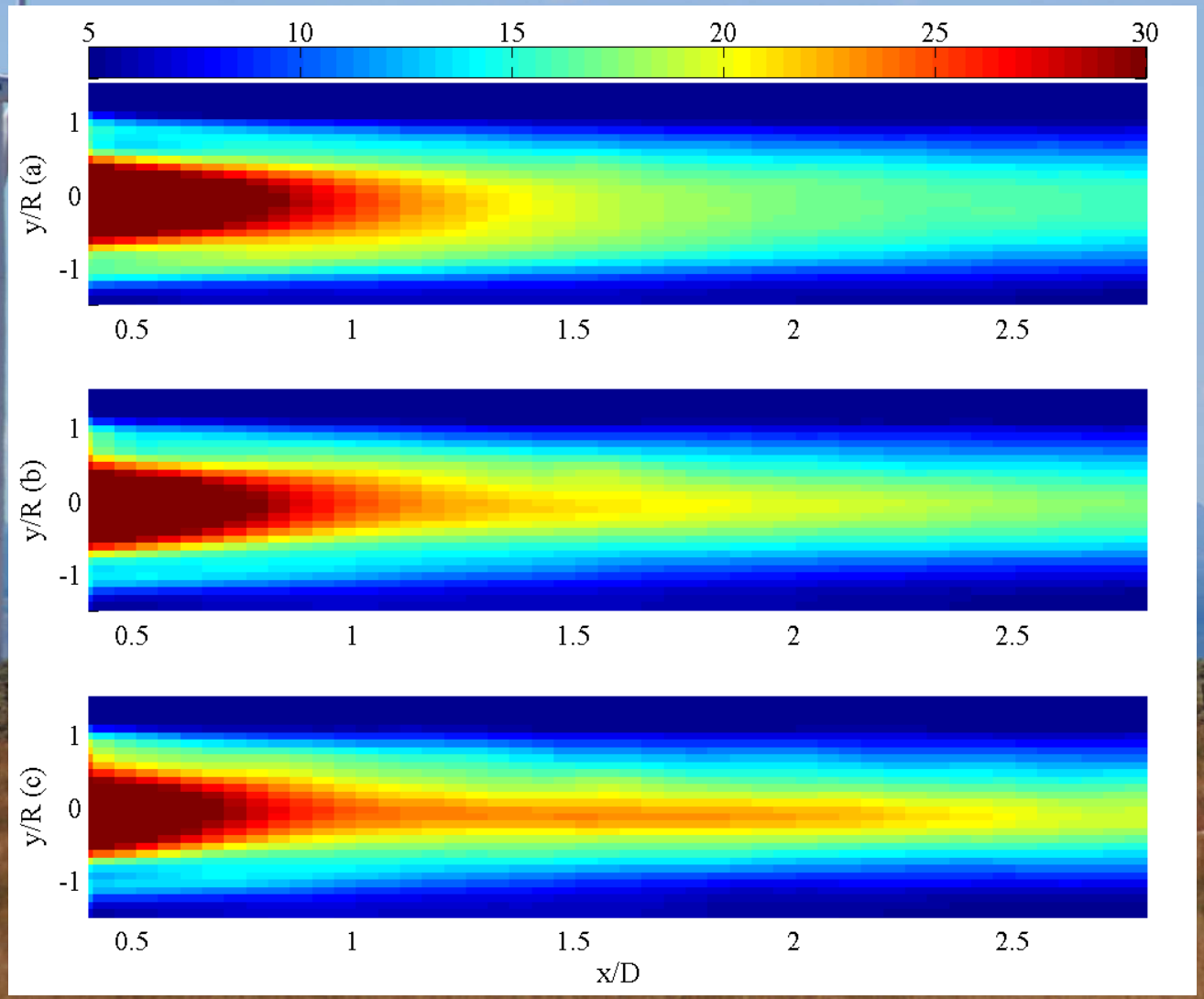
# Wind Plant Simulation and Validation
## Validation Efforts

- **Swirling Axisymmetric Wake**
  - Generate a "generic" wake with swirl relevant for wind turbines
  - Perform "validation" quality measurements in the near wake
    - **Characterize wake and swirl strength**
    - **Characterize flow structure**
    - **Compare/validate theory**
    - **Assess impact of free-stream turbulence**
      - Active grid



# Wind Plant Simulation and Validation
## Validation Efforts

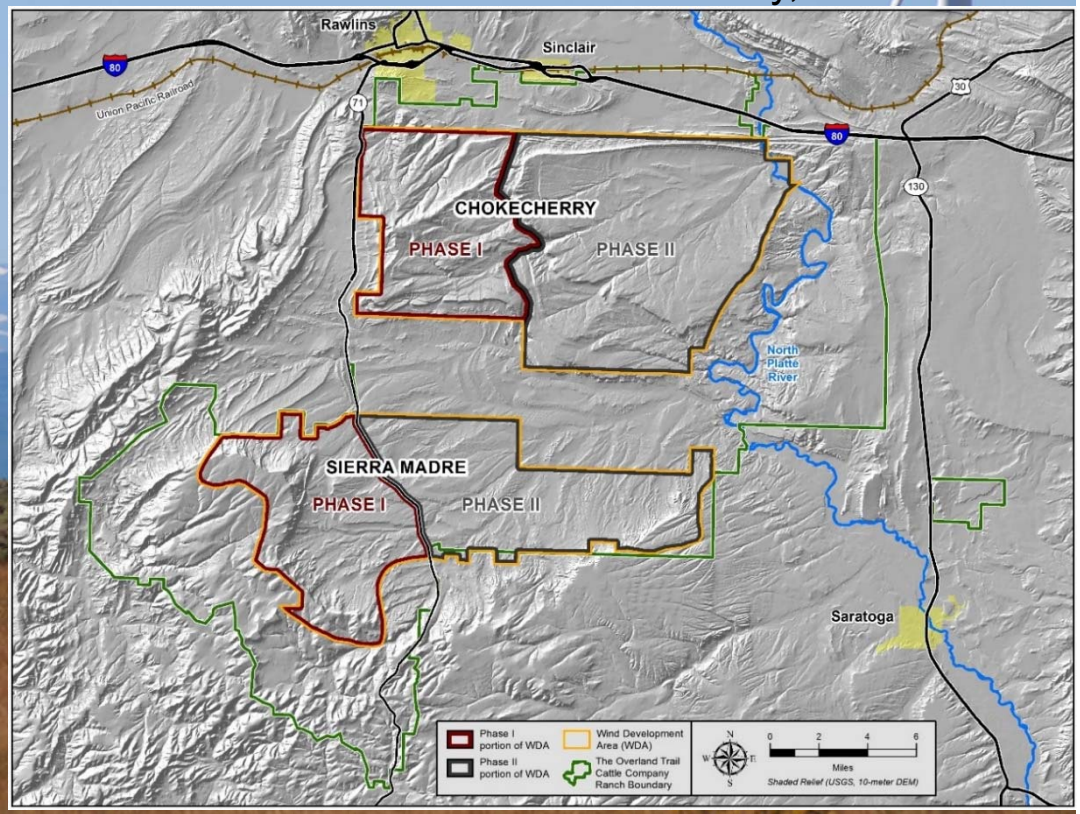



Increasing Swirl

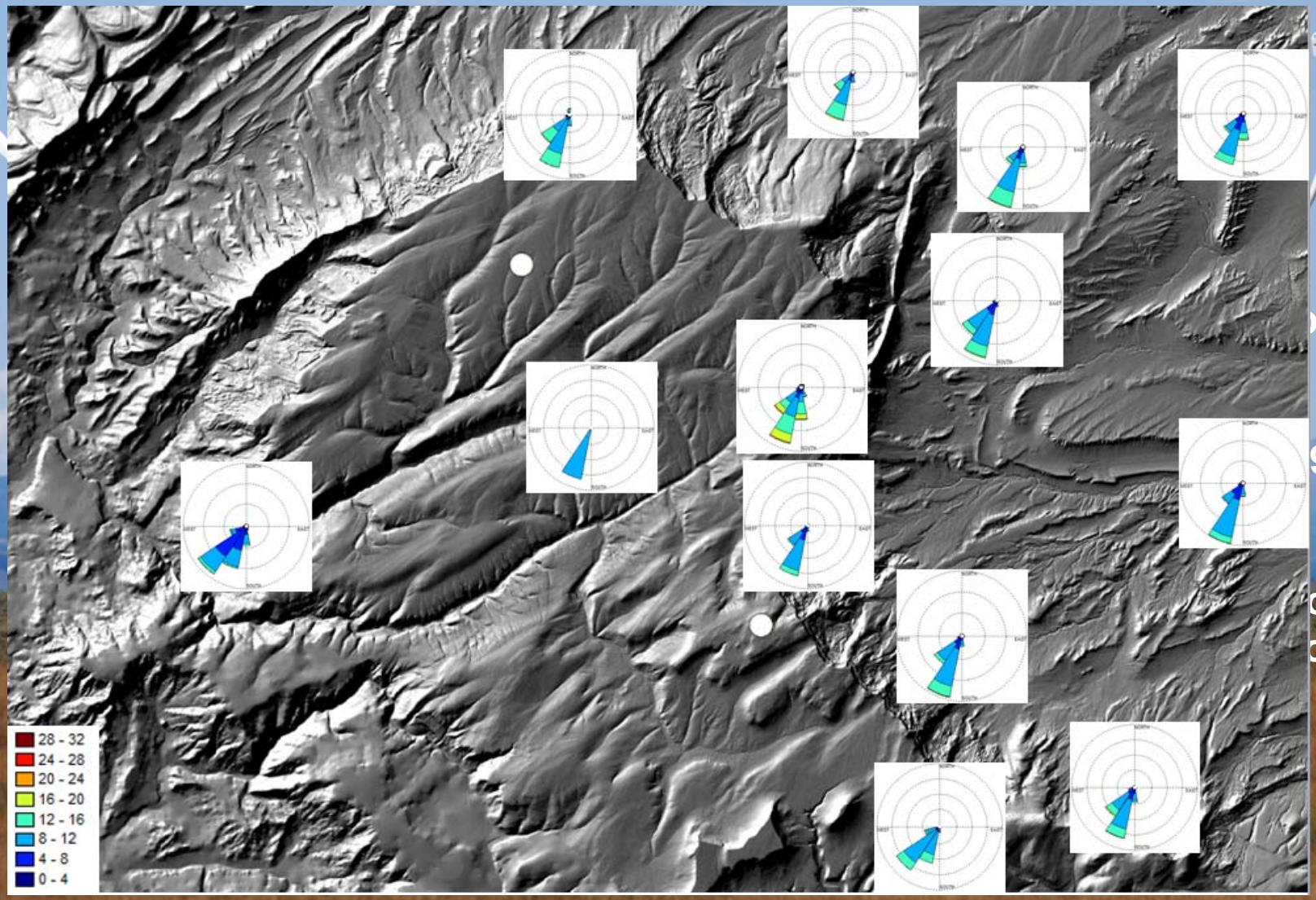
# Wind Plant Simulation and Validation
## Validation Efforts

- **Complex Terrain Data Analysis**
  - Acquire data from CC/SM wind plant development
  - Ensure data suitability for current use
  - Categorize by different quantities
    - **Wind speed, direction,…**
  - Develop validation dataset
  - Obtain better understanding of flows in complex terrain

In conjunction with Power Company of Wyoming, CC/SM Wind Farm in Carbon County, WY



# Wind Plant Simulation and Validation
## Validation Efforts



# Summary

- Wind energy is continuing to grow
- There is still room to improve wind energy – particularly at the plant level
- Models exist that can simulate entire wind plants
- Validation of these simulation tools is needed
- Well planned validation experiments can fill in gaps where little or insufficient data exists

# Acknowledgement


- The wind plant simulation and validation studies work was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, under Award # DE-SC0012671.
- Support for validation and verification work provided by Sandia National Laboratories

- Complex Terrain Modeling – led by Michael Stoellinger, UW ME
- Wind Plant Modeling – led by Dimitri Mavriplis, UW ME
- Work performed by a large number of graduate students.