U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Land-Based and Offshore Wind Plant Technology Characterization and System Cost of Energy Analysis Involving Data Collection, Model Development, and Analysis Activities

Project ID #A2

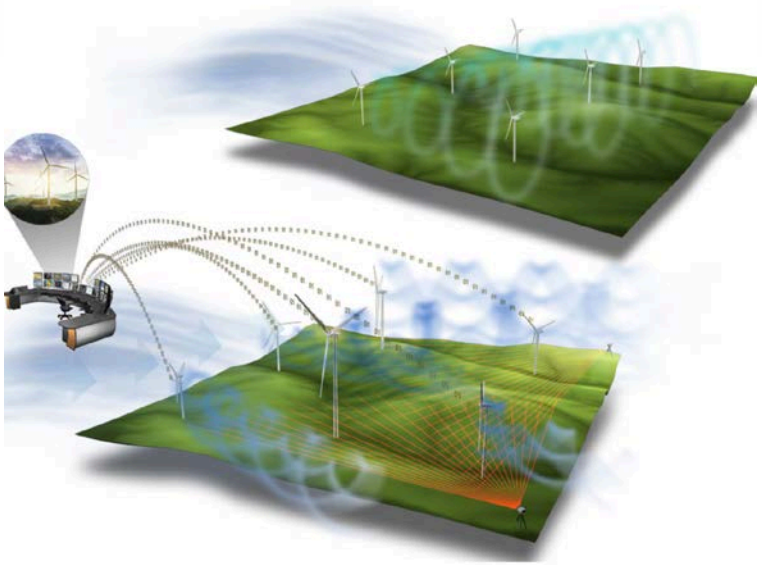


Illustration by Josh Bauer, NREL

Eric Lantz

National Renewable Energy Laboratory

FY17-FY18 Wind Office Project Organization

"Enabling Wind Energy Options Nationwide"

Technology Development	Market Acceleration & Deployment
Atmosphere to Electrons	Stakeholder Engagement, Workforce Development, and Human Use Considerations
Offshore Wind	Environmental Research
Distributed Wind	Grid Integration
Testing Infrastructure	Regulatory and Siting
Standards Support and International Engagement	
Advanced Components, Reliability, and Manufacturing	

Analysis and Modeling (cross-cutting)

Project Overview

A2: Land-Based and Offshore Wind Plant Technology Characterization and System Cost of Energy Analysis Involving Data Collection, Model Development, and Analysis Activities

Project Summary

- **Analyze trends in wind technology** that affect the cost of energy in the U.S. and internationally.
- **Analyze future wind technology research and development (R&D) and cost reduction opportunities**
- **Execute** capacity expansion and (power system) operational **modeling to understand key technology, market, and policy drivers**

Project Objective & Impact

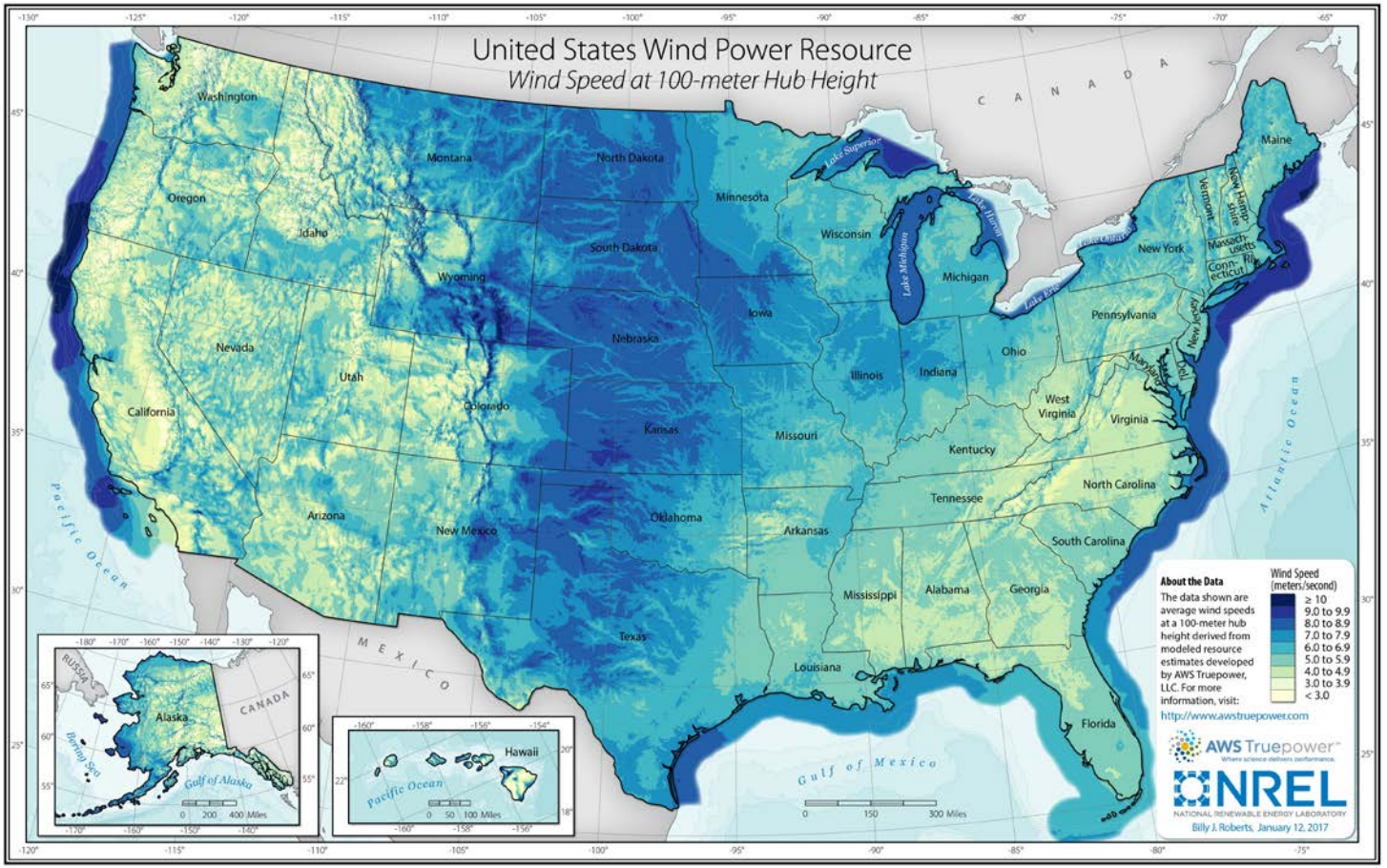
- This project has two principal objectives:
  1. Inform DOE and the public on wind **R&D strategy, priorities, and investments** and;
  2. **Inform public and private sector decision makers and stakeholders around key wind technology, market, grid, and policy drivers**

Project Attributes

Project Principal Investigator(s)
Eric Lantz (Lead) Annika Eberle Garrett Barter Trieu Mai Tyler Stehly
DOE Lead
Patrick Gilman (Lead) Richard Tusing (Senior Advisor) Daniel Beals (Activity Lead)
Project Partners/Subs
Lawrence Berkeley National Laboratory Multiple Wind Power EPC Firms Mowers Consulting IEA Wind Task 26 (Cost of Wind Energy)
Project Duration
2 years: FY17 and FY18

Technical Merit and Relevance

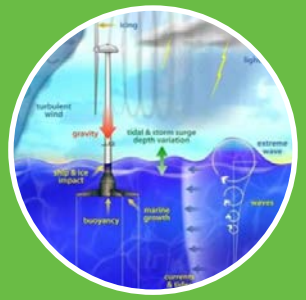
Project Principles: Inform wind technology (land-based + offshore) R&D needs and priorities as well as wind energy integration in to the grid and society, in support of a low cost, clean and abundant energy future.



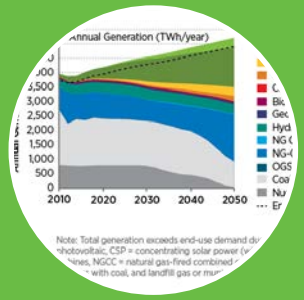
Technical Merit and Relevance

Project Scope: Research spans turbine component modeling to system integration of wind across the United States

Land-based Technology Characterization



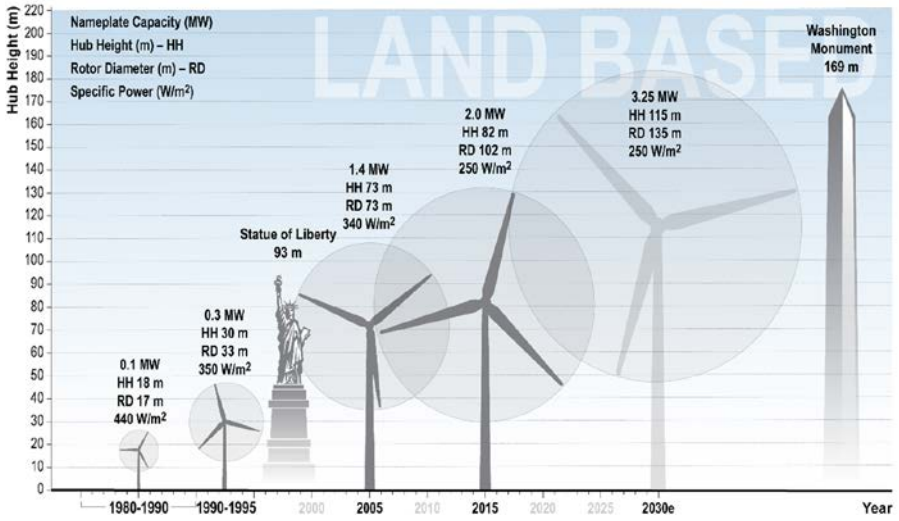
Offshore Wind Technology Characterization



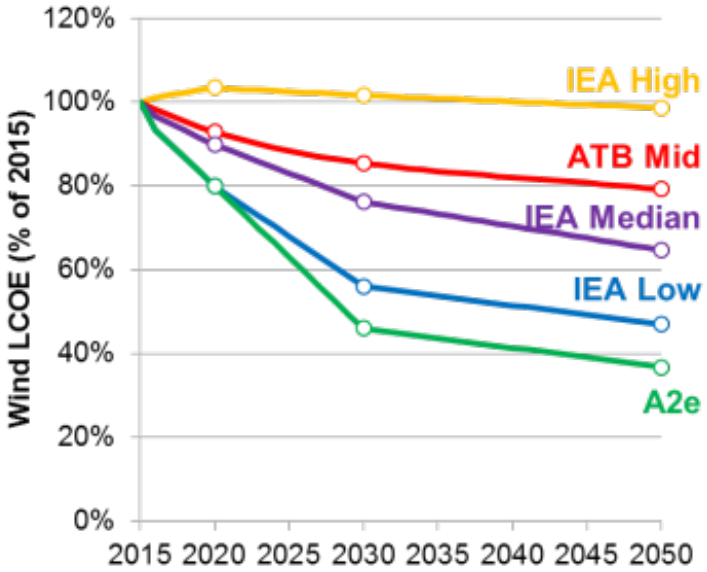
Electric Sector Modeling

Spatial Analysis

Technical Merit and Relevance

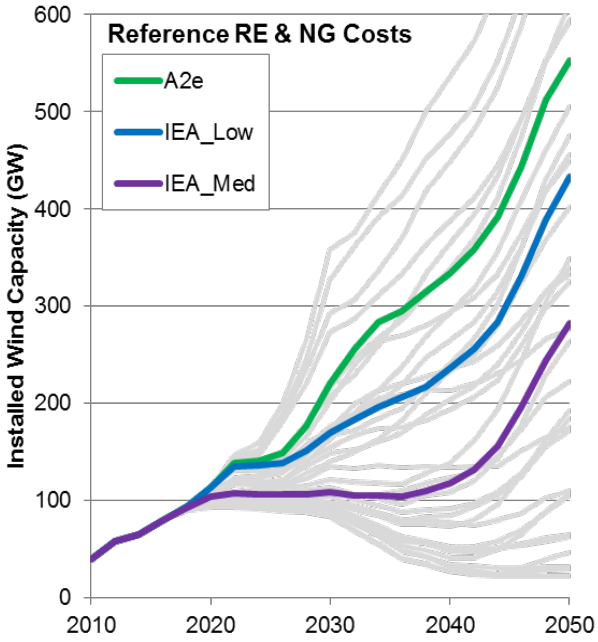


Source: Wiser, Jenni, et al. 2016



Source: Mai, Lantz et al. 2017

Wind technology characterization (land-based and offshore) and spatial analysis feed electric sector modeling



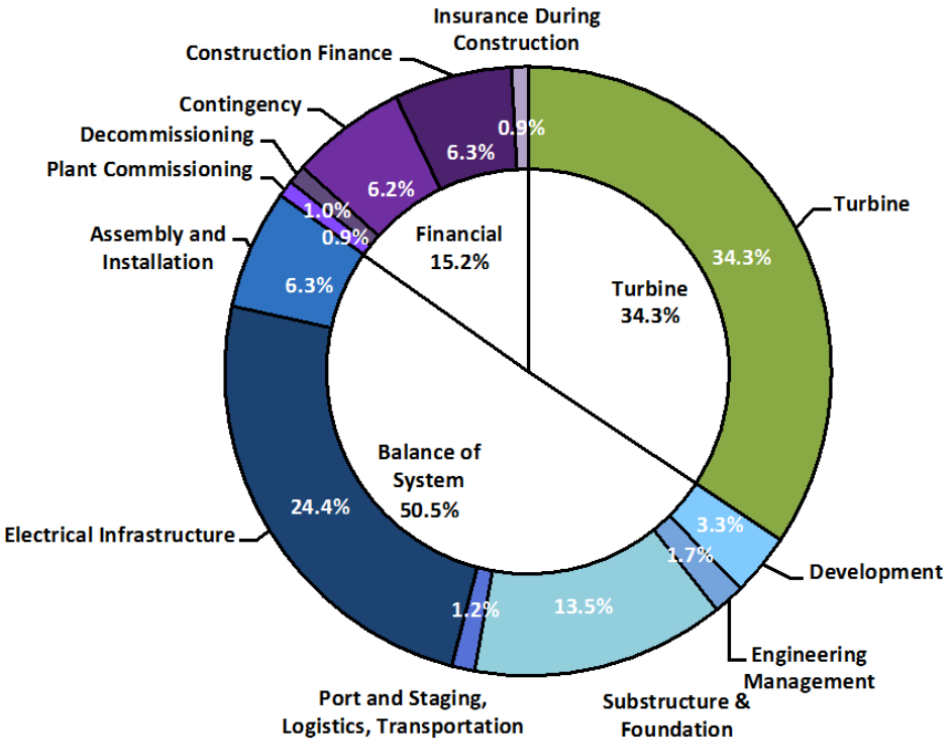
Insights inform research priorities, goals development and an understanding of potential role for wind power in the future energy sector

Technical Merit and Relevance

Work Activities Provide

- **Analytical power to inform** the Wind Energy Technologies Office (WETO) and the public about wind power costs, research and development (R&D) impacts, and the value of wind
- **A means to understand public sector investment** opportunities and to communicate impact
- **A vision for the future of wind power** and an understanding of potential levers that may push the industry forward.

Example Project Outcome:
Project Cost Breakdown for Offshore Wind
(from the 2017 Cost of Wind Energy Review)

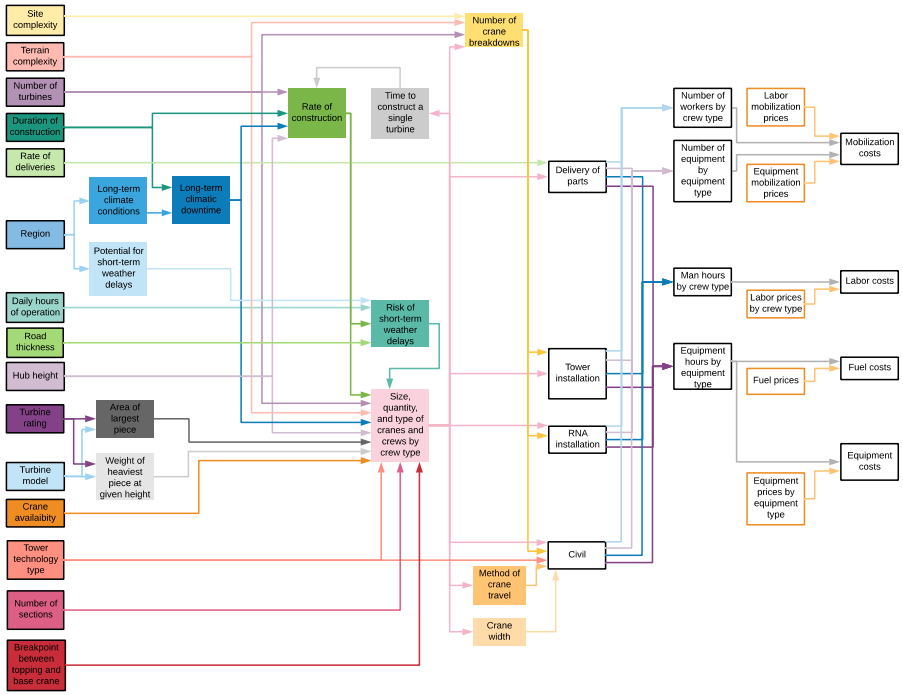


Source: Stehly et al. 2018

Approach and Methodology

Overview

- **As a multi-faceted project, our methods are often tailored to specific research questions**



Process Diagram: NREL Land-based Balance of Station Systems Engineering Model

Core capabilities include:

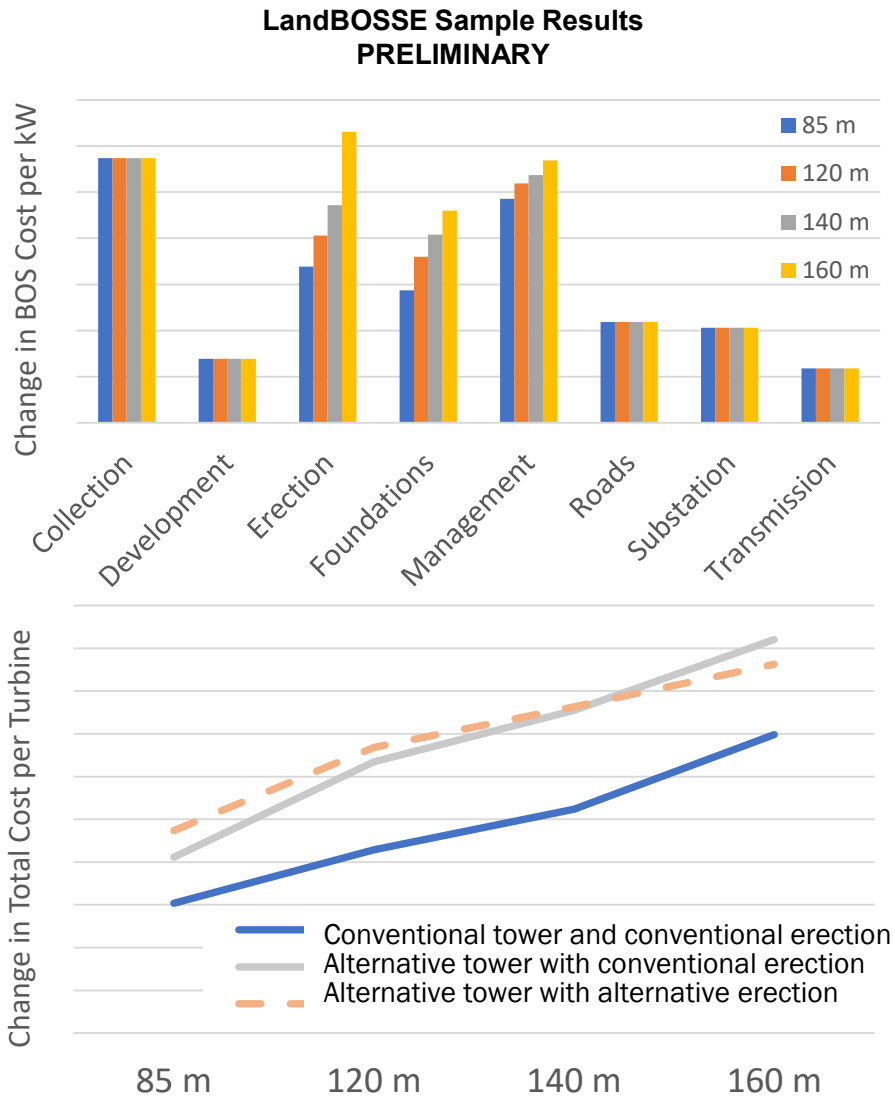
- Techno-economic cost modeling
  - Turbine, balance-of-system, operation and maintenance
- Capacity expansion modeling
  - Regional Energy Deployment System (ReEDS) model
- Cash-flow analysis
  - System Advisor Model (SAM)
- Wind power system analysis
  - Wind-Plant Integrated System Design and Engineering Model (WISDEM)
- Geospatial data science methods, including HPC and machine learning

Approach and Methodology

Technology Characterization Example, Applies to Land-based and Offshore Activities

- **Research Questions**
  - What is the potential impact of turbine scaling on balance-of-system (BOS) costs?
  - How are total capital expenditures impacted by alternative tower technologies (e.g., steel v. concrete)?

- **Process**
  - Evaluate capabilities of existing tools
  - Create new modeling software (as needed) to properly characterize impacts on process components: materials, labor, overhead, equipment, and mobilization
  - Execute model(s) to illuminate costs, sensitivities, and drivers
  - Summarize results for internal or external consumption

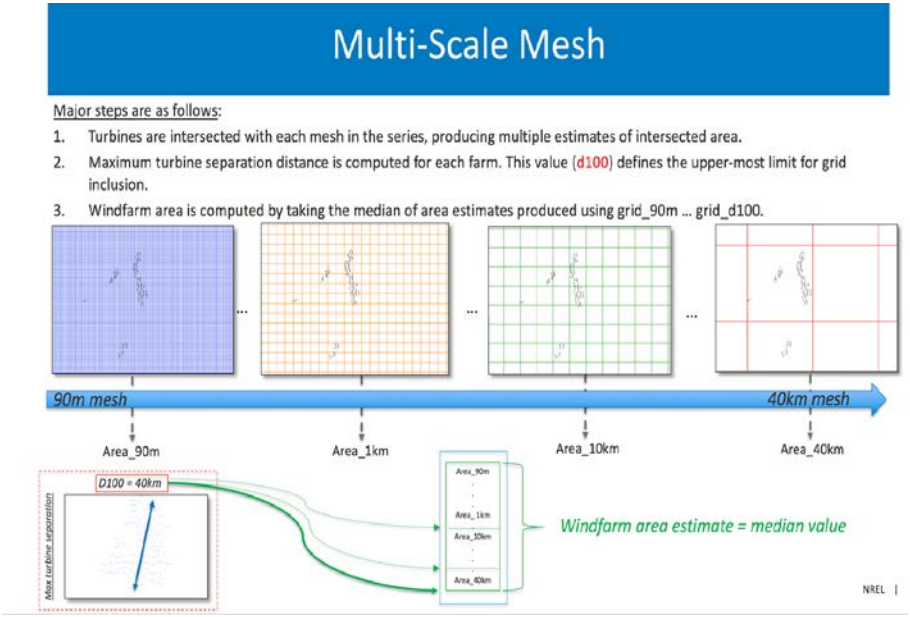


Source: NREL Internal Analysis

Approach and Methodology

Spatial Analysis

- **Research Questions**
  - How do geospatial variables interact with and drive wind plant deployment and layouts?
  - What is the interaction between technology R&D and future turbine and plant design optimization?
- **Process**
  - Gather spatial data on existing wind plants and geospatial variables
  - Develop methods to characterize and correlate wind plant layout with spatial parameters
  - Evolve methods to the point at which one could predict wind plant densities based on spatial variables
  - Validate model results against real world facilities

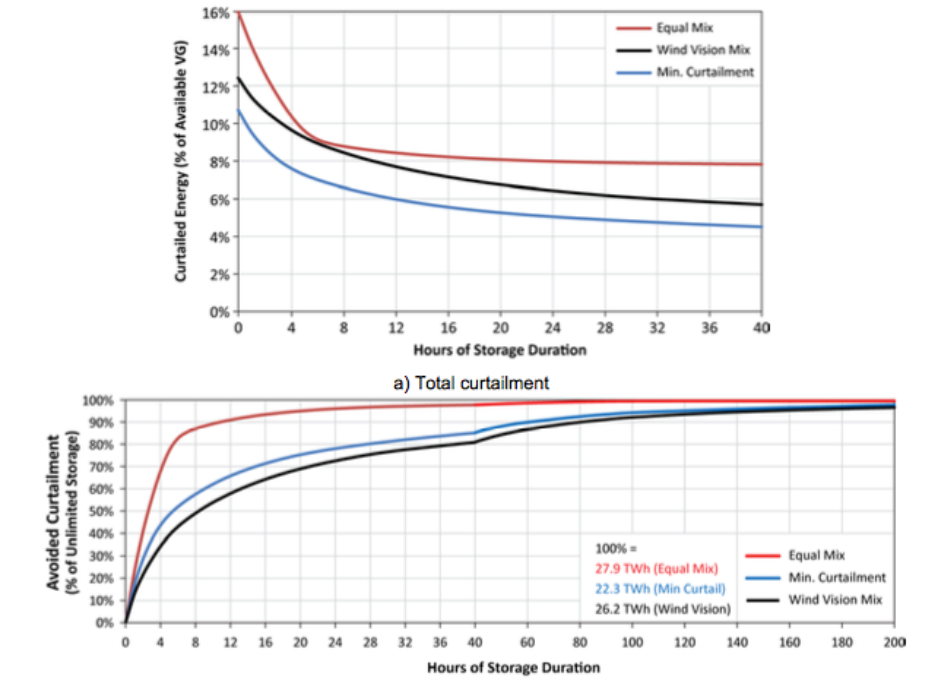


Foundational capabilities such as the ability to predict wind plant density are critical to the long-term vision of predicting optimal wind turbines and facilities for a given location under various R&D futures

Approach and Methodology

Electric Sector Modeling

- **Research Questions**
  - What is the potential deployment opportunity for wind power under an array of market, policy and technology futures?
  - How does the value of wind power change across time and space?
  - How can wind interact with, be supported by, and economically compete with other electric system options?
- **Process**
  - Collect data, develop scenarios, apply the NREL ReEDS model, PLEXOS, REFlex, others to illuminate potential impacts to wind deployment, value and integration ease



b) Avoided curtailment (shown as a percentage of curtailment avoided using an unlimited-duration storage device)—note the different x-axis intervals after 40 hours

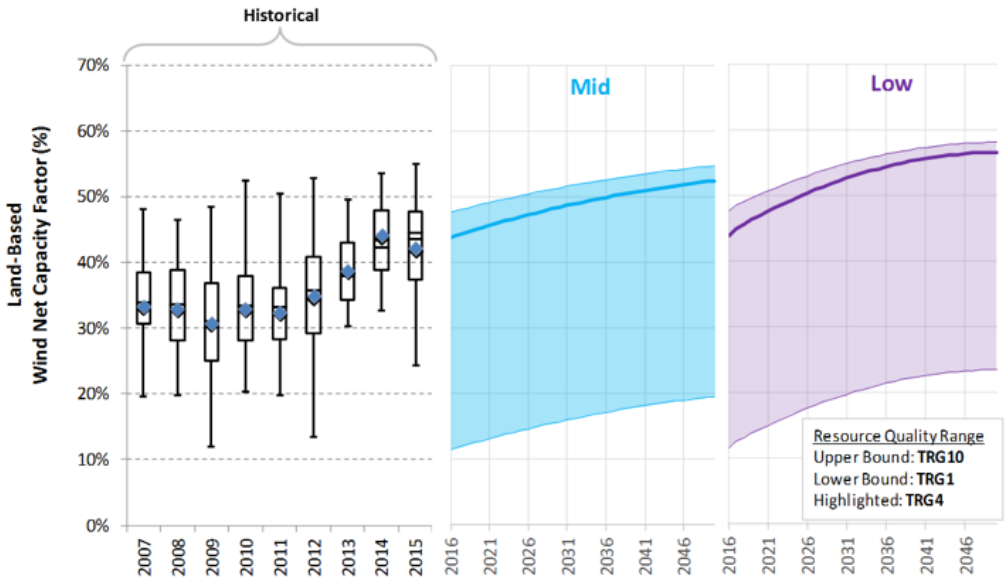
Source: Denholm et al. 2018

Understanding wind in the broader power and energy sectors is a key element of this work; methods/capabilities often applicable to other RE and power generation resources and work is sometimes co-funded across EERE Offices

Accomplishments and Progress

Technology Characterization

- **Goal:** Annual assessment and evaluation of the current and future cost of wind energy
- **Products:**
  - NREL's Cost of Wind Energy Review (published in 2017 and 2018)
    - Provides standardized LCOE estimates (including ranges) for reporting and public use
    - Analysis includes land-based as well as fixed-bottom and floating offshore wind
  - Offshore and land-based wind content for NREL's Annual Technology Baseline (ATB; published in 2017 and 2018)
    - Requires the development of multi-decadal CapEx, OpEx and capacity factor projections

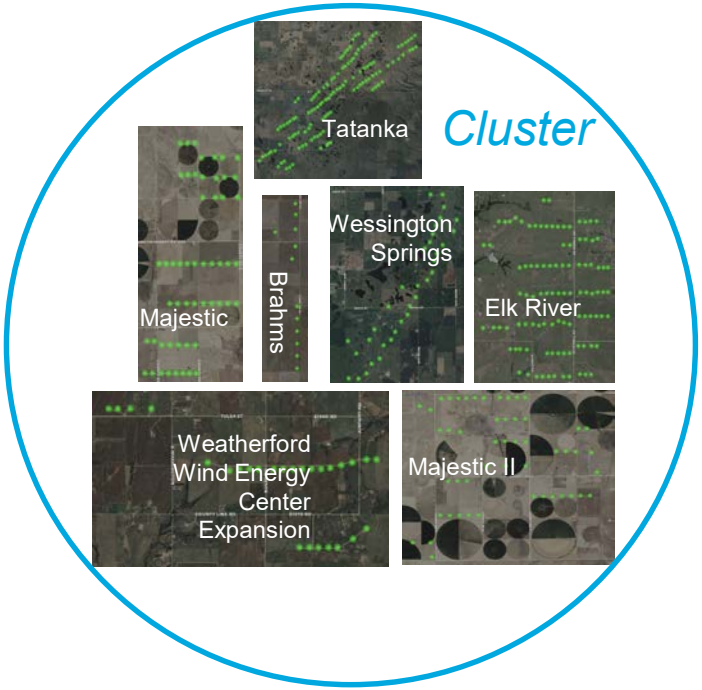


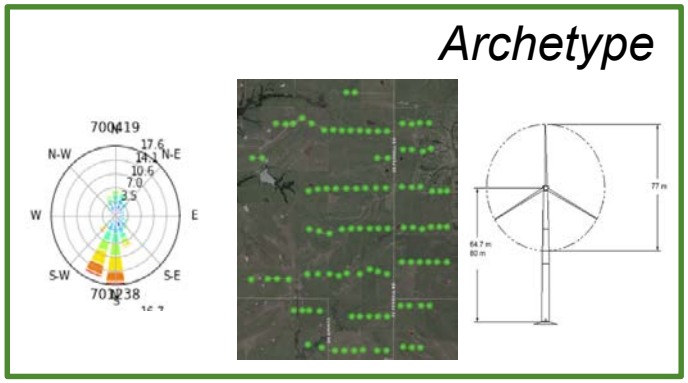
2018 ATB Capacity Factor Ranges - Historical + Projected (http://atb.nrel.gov)

Accomplishments and Progress

Technology Characterization + Spatial Analysis

- **Goal:** Assessment of potential innovation impacts and cost reduction potential
  - Started to develop an approach to expand SMART Wind analysis, which was based on a conceptual wind plant, and allow us to quantify how innovation impacts might change across a more complete range of real-world conditions
    1. Used NREL's System Advisor Model (SAM) to perform nationwide analysis of energy production from existing plants
    2. Developed process and data for creating wind plant *archetypes* to support bottom-up evaluation of A2e innovation impacts
    3. Used Wind-Plant Integrated System Design and Engineering Model (WISDEM) to identify energy production improvement potential and test proof-of-concept approach for wake steering



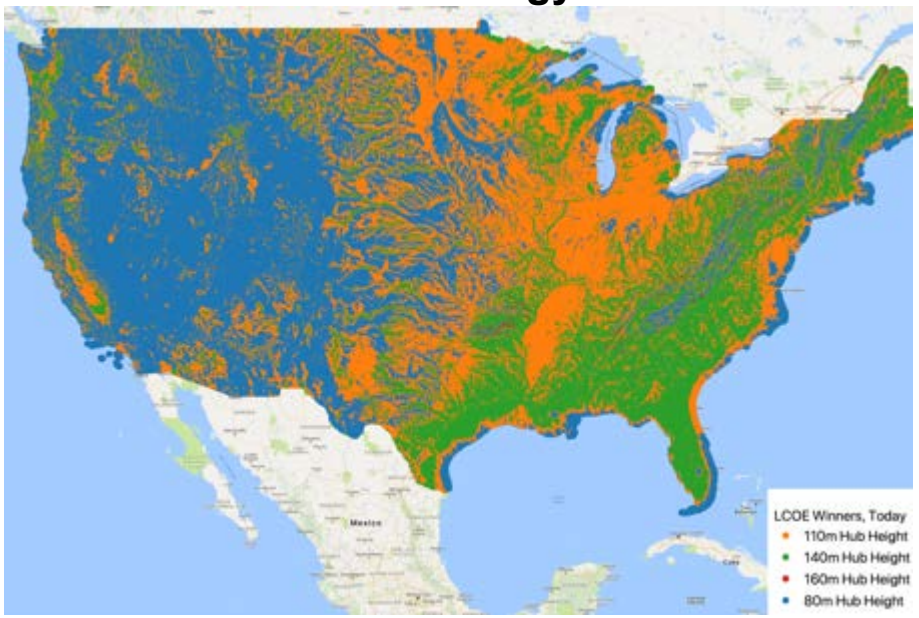


Accomplishments and Progress

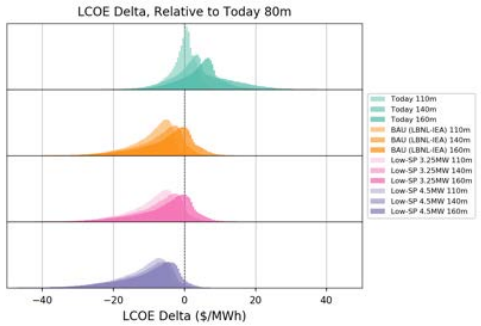
Technology Characterization + Spatial Analysis

- **Goal:** Assessment of potential innovation impacts and cost reduction potential
  - Enhanced supply curve analysis capabilities through code consolidation and efficiency gains, including ability utilize HPC (full supply curve run is now < 2 hours processing time; down from two weeks in 2012-13)
  - Have begun to employ supply curve based technology analysis to innovation questions including lowest cost hub height
  - Plan to document capabilities with forthcoming publications and continue to apply "supply curve" focused perspectives to questions of R&D strategy

Lowest Cost Hub Heights for 2017 Vintage Technology



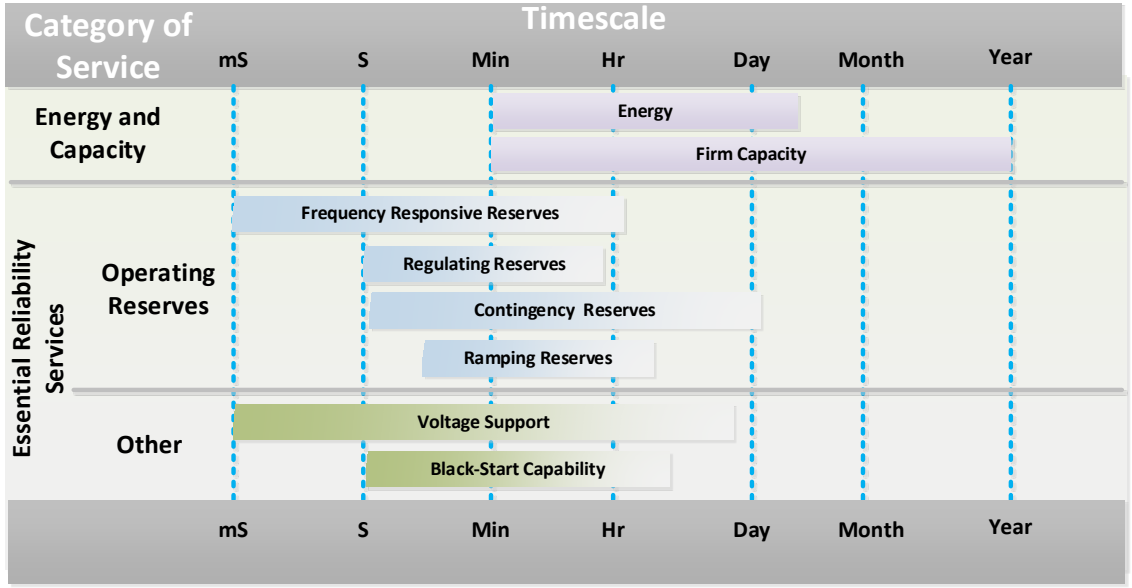
LCOE Differences by Hub Height for Four Conceptual Turbines



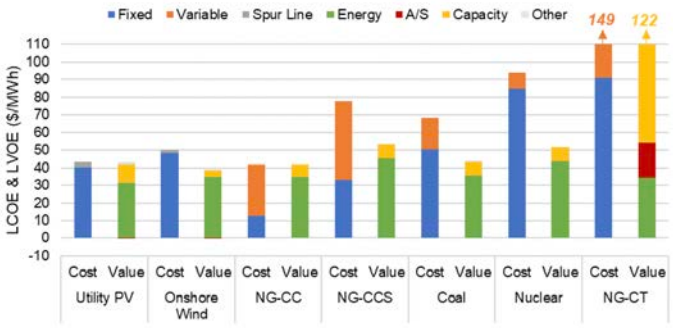
Accomplishments and Progress

Electric Sector Modeling

- **Goal:** Analyze wind power's cost and value as well as its ability to provide essential grid services
- **Products:**
  - ReEDS evaluation of wind power R&D impacts on deployment (published in 2018)
  - Reports on interactions between high wind penetrations, energy storage, and transmission in the U.S. West and wind and storage in ERCOT (published in 2018)
  - Wind Competitiveness Metrics report (draft submitted to WETO in 2018)
  - Introduction to Grid Services report (published in 2019)



LCOE and LVOE estimates by component from an illustrative scenario
include if appropriate per Tier 1

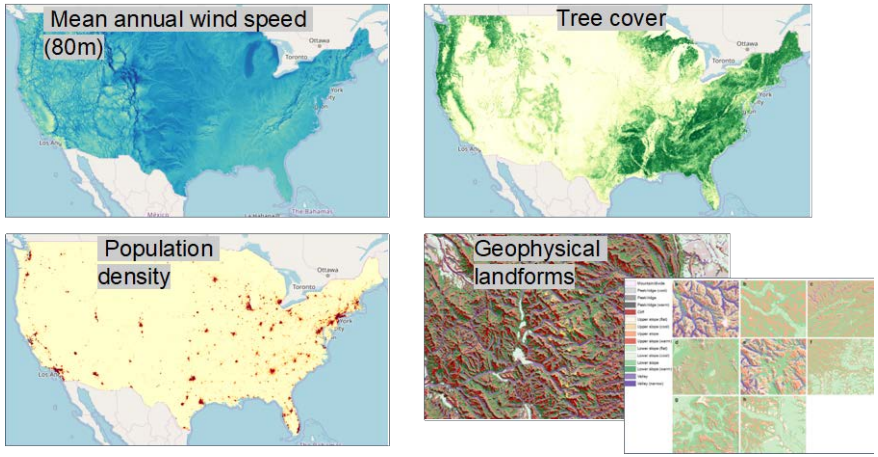


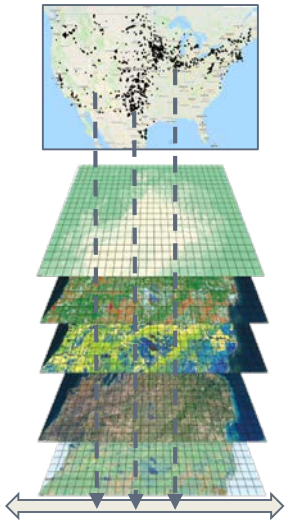
From: An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind (Denholm et al. 2019)

Accomplishments and Progress

Cross-cutting Model Development Activities

- **Data and model maintenance and development**
  - Maintenance, modernization and improvement of NREL's Regional Energy Deployment System (ReEDS) model
  - Expansion of NREL's Wind-Plant Integrated System Design and Engineering Model (WISDEM), an open-source platform for wind energy systems analysis
    - Floating Offshore Innovation Assessment Capabilities Advancement
    - Initial development of a new Land-based Balance-of-System Systems Engineering (LandBOSSE) model within WISDEM
  - Began to develop capabilities to model an "optimal" wind plant for every 2km cell in the Continental U.S., under potential R&D futures

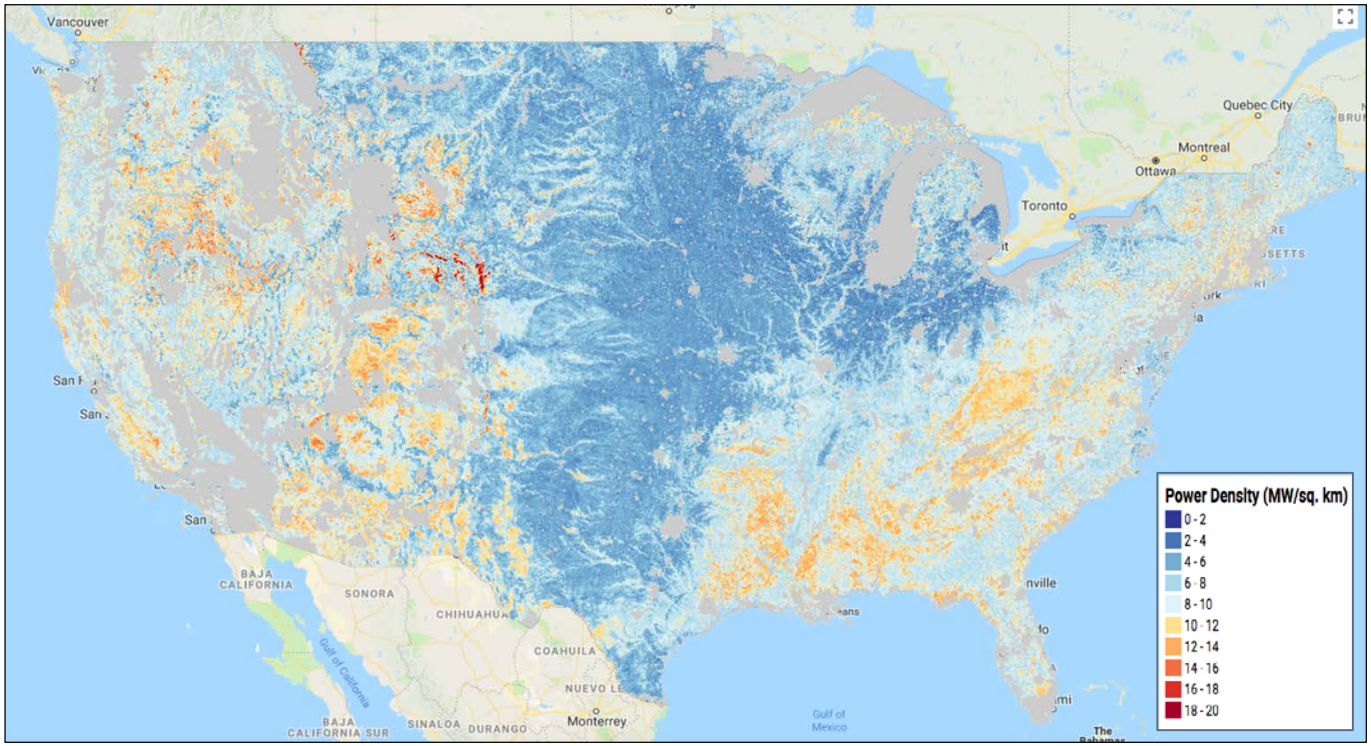




Accomplishments and Progress

Spatial Analysis

- **Goal:** Evaluate potential to model variability in plant power density as a function of spatial inputs, for the sake of predictive plant optimization capabilities
- **Initial Results:**
  - When applying social factors, land-use limitations and policy restrictions, modeled results capture the highly variable operational power density (MW/km^2) of wind plants observed across the country
  - Spatially-explicit predictions of power density based on explanatory geospatial variables, could begin to inform our understanding of future plant types and technology optimums



Accomplishments and Progress:
Sampling of Other Activities and Accomplishments

Evaluation of Wind Plant Exclusion Areas and Siting Policies

- More than 20% of existing turbines fall in areas that historical modeling "excludes"

Capacity Expansion Multi-Model Comparison Activities

- Collaborative effort with the Energy Information Administration, Environmental Protection Agency, and EPRI to share insights and seed model development activities across institutions to better forecast potential variable renewable energy deployment, particularly when considering technology advancement and change

Exploration of Wind and Storage in ERCOT

- The primary value of storage in ERCOT appears to be short-term (hours)

Mesoscale Wind Resource Validation Effort

- Significant differences in mesoscale wind resource datasets and observational data suggest non-trivial uncertainties in our national resource data

IEA Wind Task 26 on Cost of Wind Energy

- International collaborations shed new light on the universality of trends in turbine specific power, nameplate capacity and hub height, along with international offshore wind costs and the value of wind

Milestones and Schedule: FY17-FY18

- Formal milestones listed in narrative summary of project—not repeated here
- Milestones reflect formal annual operating plans established annually
- In practice, this project tends to complete 15-20 deliverables per year, internal and external, beyond formal milestones
- 18 reports and journal articles published over the two-year review period
- Go/no-go decision points
  - FY17 – N/A
  - FY18 – Planned work in Fiscal Year 2018 is anticipated to provide a foundation for the development of new wind power resource exclusions and potentially a migration of all of NREL's ReEDS modeling and analysis work to a new resource dataset. This Go/No Go will facilitate a formalized decision regarding this potential transition and implementation of new wind resource characterization: Go

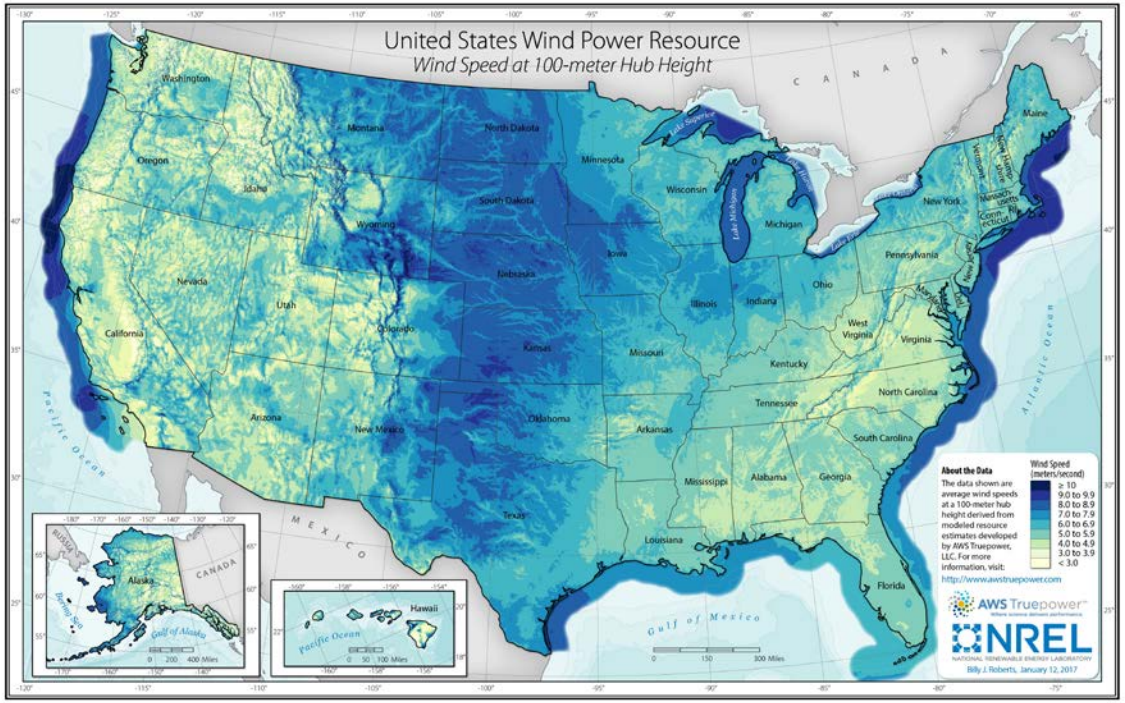
Communication, Coordination, Commercialization

[see: https://www.nrel.gov/research/publications.html]

- Tight coordination and collaboration with other Labs (especially LBNL), international community via IEA Wind, consultancies, and wind industry
- *Average cost per publication is approximately $200k*

Upcoming Project Activities

- Technology and Plant System Level Analysis
  - Land-based
  - Offshore
- Supply curve level analysis
- LandBOSSE model approach to be extended to offshore and Operations and Maintenance cost models
- Further study of Scaling impacts
- Evolution of our Offshore Spatial Cost Model “ORCA”
- 15 MW Offshore Wind Reference Turbine Development



3-5 year goal: optimize wind plants at every resource pixel**, considering logistics, siting and permitting challenges **across an array of R&D pathways