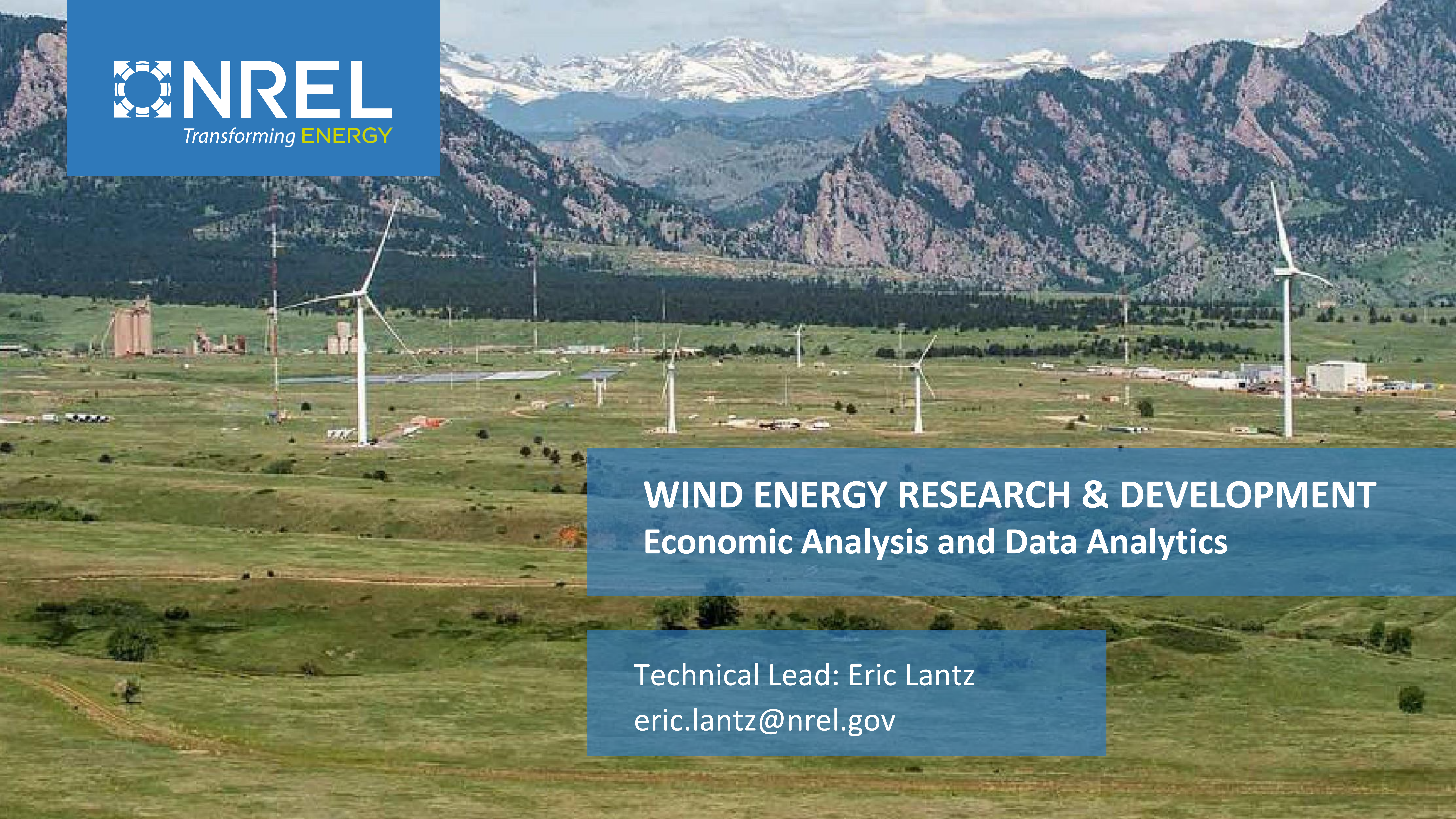
NREL
Transforming ENERGY



WIND ENERGY RESEARCH & DEVELOPMENT
Economic Analysis and Data Analytics

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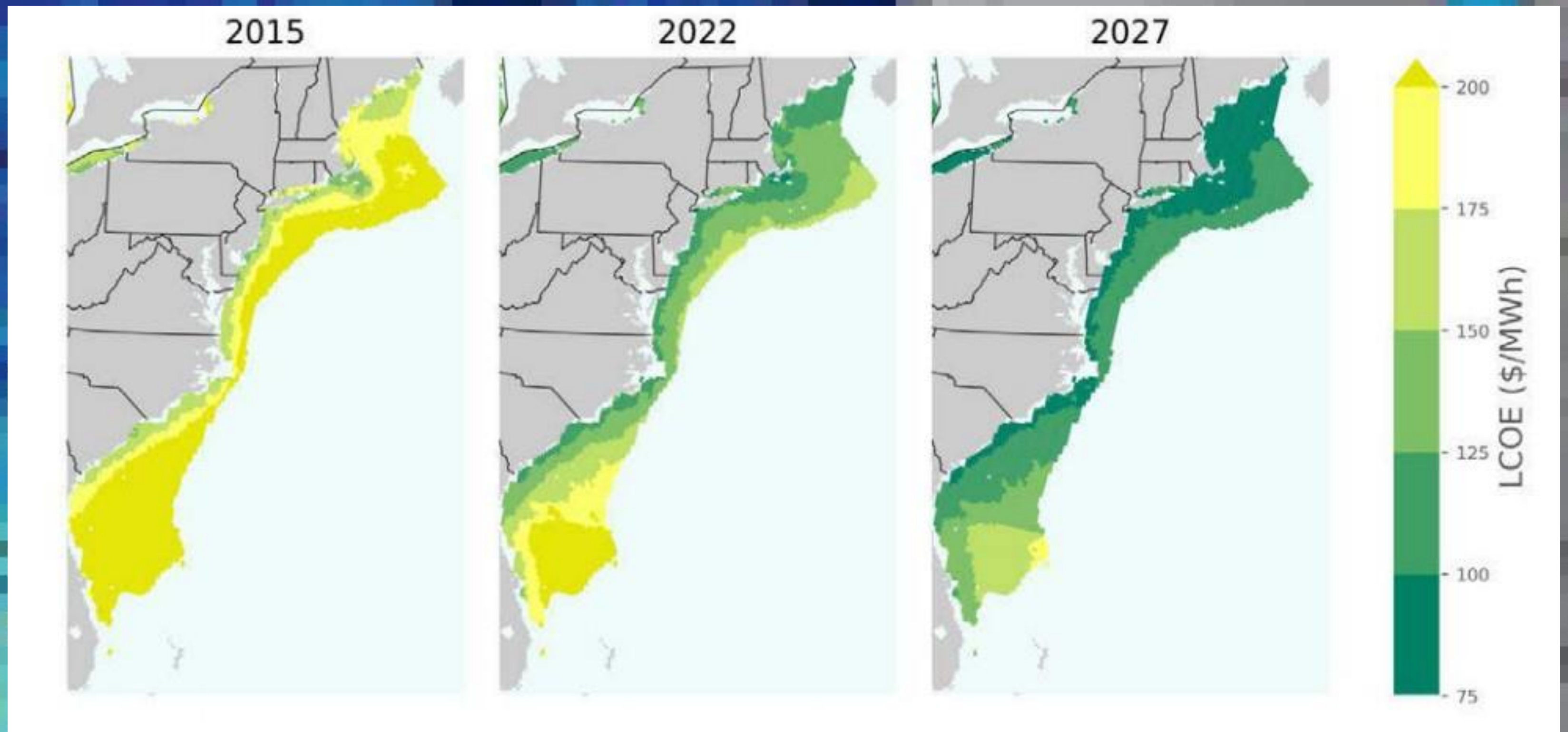

Economic Analysis and Data Analytics

Tracking and analyzing wind energy technology and cost trends and developing engineering and cost models to inform wind energy deployment and integration into the power system.

- NREL informs R&D strategies for the wind industry by tracking and analyzing historical technology trends associated with land-based and offshore projects.
- Engineering and cost models clarify the interplay between technology innovation, system-level tradeoffs, and R&D impacts.
- Capacity expansion and grid operations models inform broader deployment and integration of wind energy into the energy system.

Areas of Expertise

- Historical market and technology trends
- Wind innovation and system design, optimization, and cost analyses
- Future cost and deployment scenarios
- Energy system integration—grid, society, and wildlife.

Economic Analysis and Data Analytics

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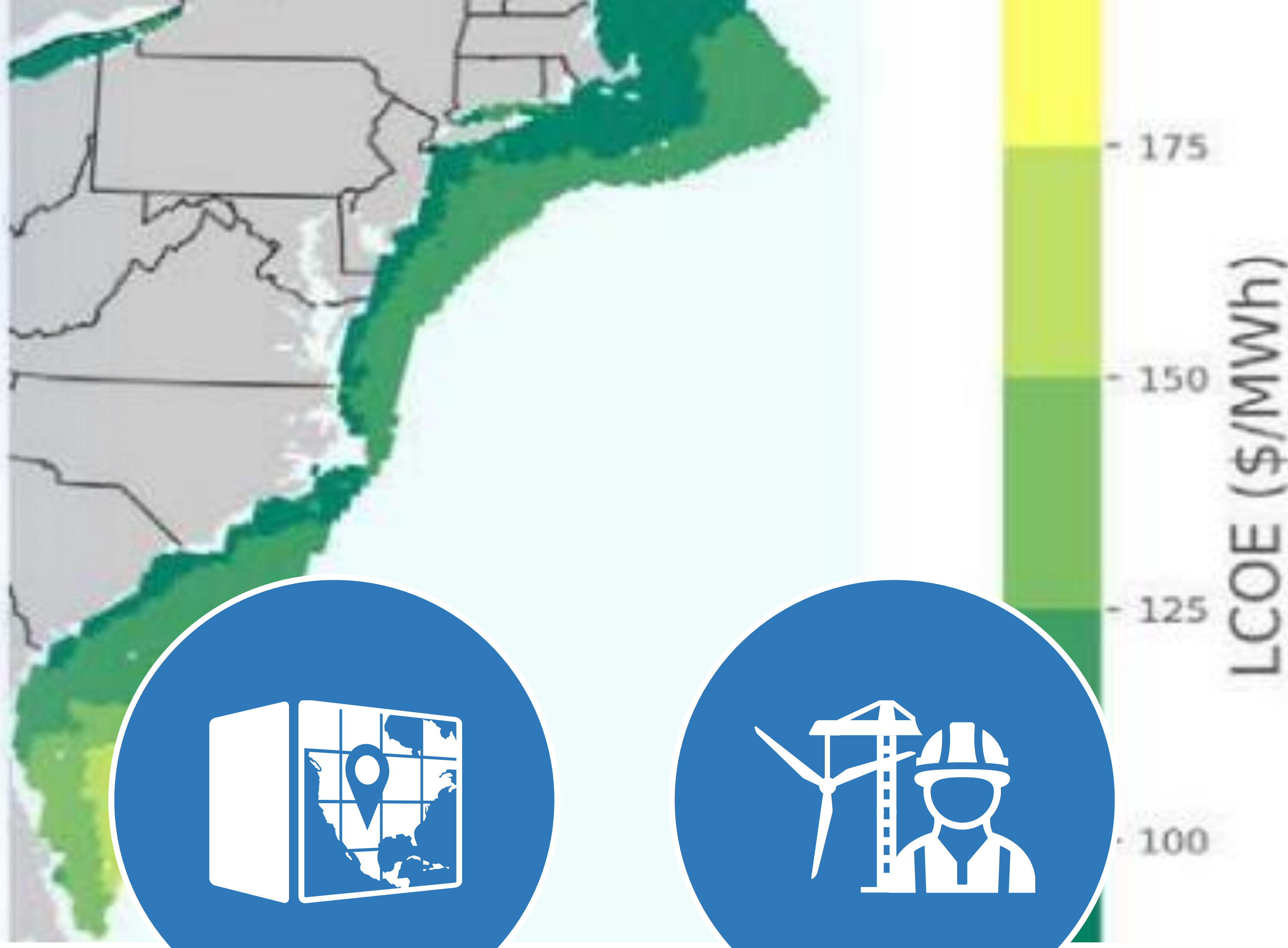


Technoeconomic Analysis

Examining RD&D areas in terms of costs, benefits, risks, uncertainties, and timeframes to evaluate the attributes of wind energy innovations

Digitalization, Artificial Intelligence, and Machine Learning

Creating data-driven machine- learning frameworks that improve the accuracy of wind plant flow models, enhance the models, enhance the resolution of wind resource datasets, and provide fast surrogate models for assessing technology impacts

Wind Energy and the Future Power Grid

Assessing the role of wind in the future energy system by developing high-fidelity models that represent the interactions between technologies, markets, and policies

Land Use and Spatial Analysis

Using vast spatial datasets to understand and inform the potential of wind energy to support the nation's energy needs and to produce maps, analyses, models, applications, and visualizations that inform wind energy planning and production

Jobs and Economic Development Impacts (JEDI) Models

Developing and maintaining economic impact models for land-based wind, offshore wind, and other renewable energy technologies

Technoeconomic Analysis

- Providing technological and economic analysis to address high-priority executive, congressional, industry, and senior management priorities.
- Supporting economic impact research and modeling tools that provide stakeholders with detailed and robust information on technology costs and economic impacts from the development and operation of wind energy in the United States.

Areas of Expertise

- Historical market and technology trends
- Wind technology (turbine, plant, balance of systems) innovation and system design, optimization, and cost analyses
- Plant innovation impacts at regional and continental scales.

Current Projects

Wind Plant System Cost Modeling

TECHNOECONOMIC ANALYSIS

CHALLENGE

Land-based and offshore project developers are faced with a broad range of design options for balance-of-system (BOS) and operations and maintenance (O&M) strategies that can significantly impact the costs, delays, risks, and performance of a project.

APPROACH

NREL researchers developed state-of-the-art, open-source, customizable models, such as LandBOSSE and ORBIT, that evaluate component-level project costs using a bottom-up methodology. These models can be used to evaluate the costs of different logistics and system design strategies and identify critical technological or operational constraints, the impact of weather delays, and potential cost-reduction opportunities.

IMPACT

These models allow NREL researchers to conduct cost-benefit tradeoff analyses with the goal of informing stakeholder decisions on the most promising BOS and O&M strategies for high-performance, low-cost projects.

Current Projects

Evaluating the impact of turbine and plant upsizing

TECHNOECONOMIC ANALYSIS

CHALLENGES

- A trend toward larger turbines and plant sizes has been prevalent in both land-based and offshore wind
- The sensitivity of cost of energy to upsizing trends has not been quantified and it is not clear where, or if, the benefits of upsizing reach a limit.

APPROACH

- NREL analysts have applied the LandBOSSE and ORBIT cost models to evaluate the cost impact of future turbine and plant designs
- NREL led an international collaboration to develop a 15-MW reference wind turbine for use in this type of analysis.

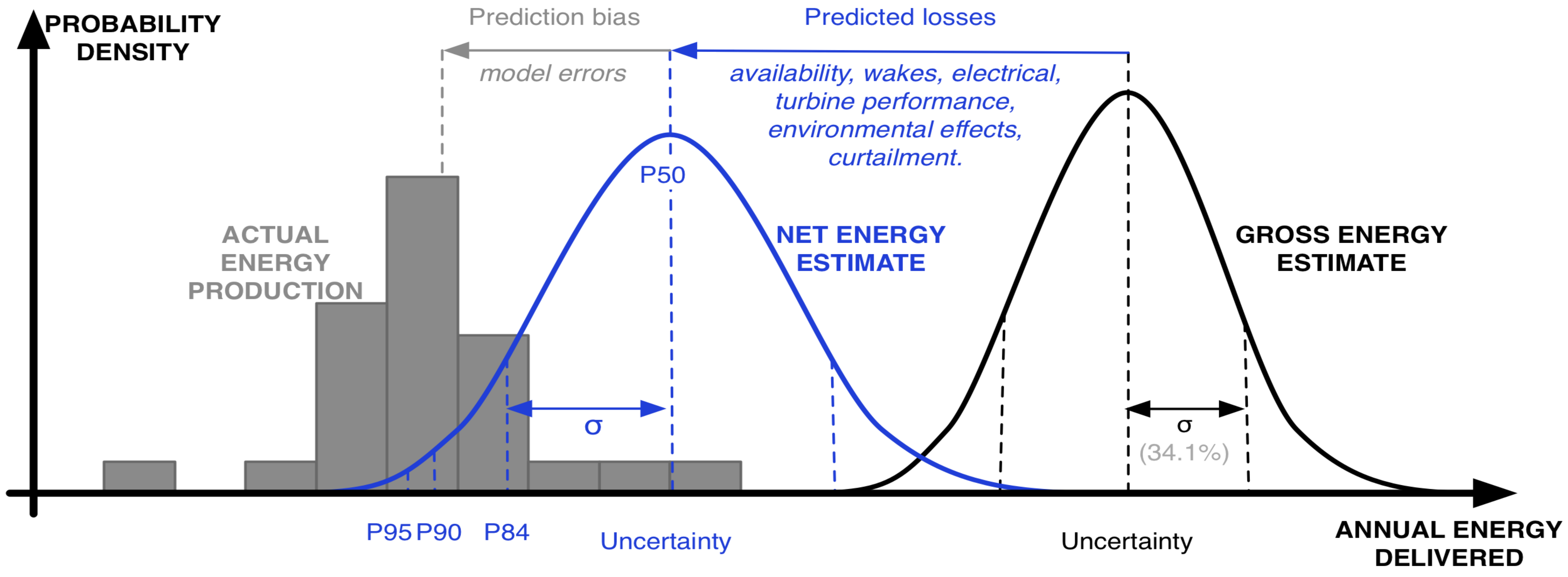
IMPACT

The NREL team is helping industry quantify the magnitude of potential cost savings, identify technology bottlenecks, and align these findings with projected deployment pipelines and state-level energy portfolio planning.

Current Projects

Wind Plant Performance Prediction (WP3) Benchmarking

TECHNOECONOMIC ANALYSIS



CHALLENGE

Understand wind plant underperformance trends, including industry's ability to predict wind plant performance risk for investment purposes.

APPROACH

An unprecedented collaboration—from turbine manufacturers to plant operators to consultancies—benchmarked current methods. This process allowed for the largest data-sharing initiative in the wind industry with the goal of improving performance and fostering much needed data access to spur innovation.

IMPACT

WP3 can reduce financing costs and improve innovation across the industry. NREL has implemented Phase 1 of the benchmark and is continuing to grow the collaboration to more than 30 companies globally.

Digitalization, Artificial Intelligence, and Machine Learning

- NREL aims to realize new levels of efficiency, accuracy, and cost reductions by applying data-driven technological developments in AI and machine learning that are made possible by widespread digitization, Internet of Things (IOT), data science tools, and open data management.

- Our team supports partners with high-performance computing and onsite met towers and turbines to evaluate IOT integrations, edge-computing techniques, and other Industry 4.0 technologies.

Areas of Expertise

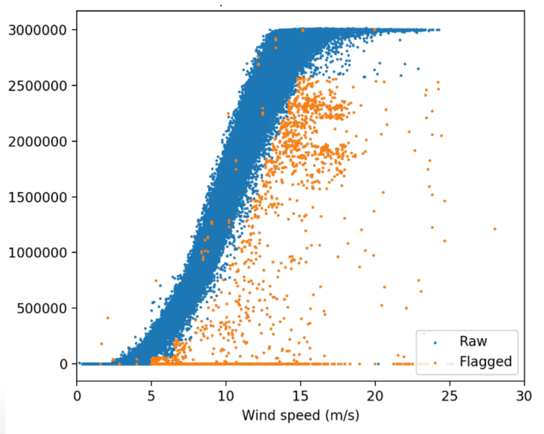
- Machine learning and artificial intelligence
- Open-source big data management and analytics
- Statistics and visualization
- Instrumentation and internet-of-things deployments.

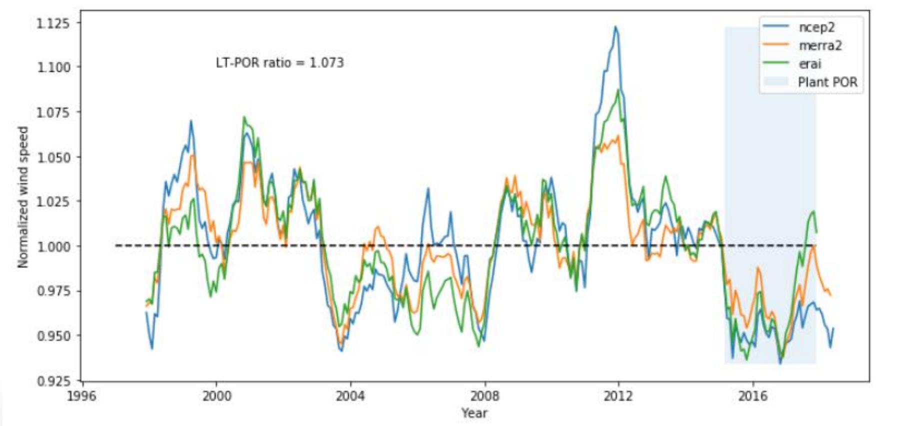
Current Projects

OpenOA

DIGITALIZATION, ARTIFICIAL INTELLIGENCE, AND MACHINE LEARNING

Open OA





CHALLENGE

Develop a universal big-data analytics platform for energy-generation facilities.

APPROACH

NREL researchers and their industry partners created an open-source analytics platform that can harmonize operational data standards and methods across the industry. It includes a variety of data preprocessing, modeling, and visualization toolsets.

IMPACT

OpenOA is being adopted by multiple industry and research partners, including the industry open-data standards initiative known as ENTR. OpenOA and ENTR can help to standardize data and methods across the industry. This can improve efficiency by as much as 80%—and improve accuracy as well.

iea wind

WIND ENERGY DIGITALIZATION
IEA WIND TASK 43

Current Projects

Wind Energy Digitalization
IEA Wind Task 43

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DIGITALIZATION, ARTIFICIAL INTELLIGENCE, AND MACHINE LEARNING

CHALLENGE

Understand the opportunities in wind energy for digital technologies such as:

- Data standards and data sharing
- Machine learning and AI
- Data analytics and visualization
- Open-source tools
- IOT instrumentation

APPROACH

- Work Package 1: Roadmap to identify key opportunities and barriers for industry and research partners
- Technical Area 2: Data Standards
- Technical Area 3: Data Science
- Work Package 4: Digital Wind Resource Assessment
- Work Package 5: Digital Operations & Maintenance

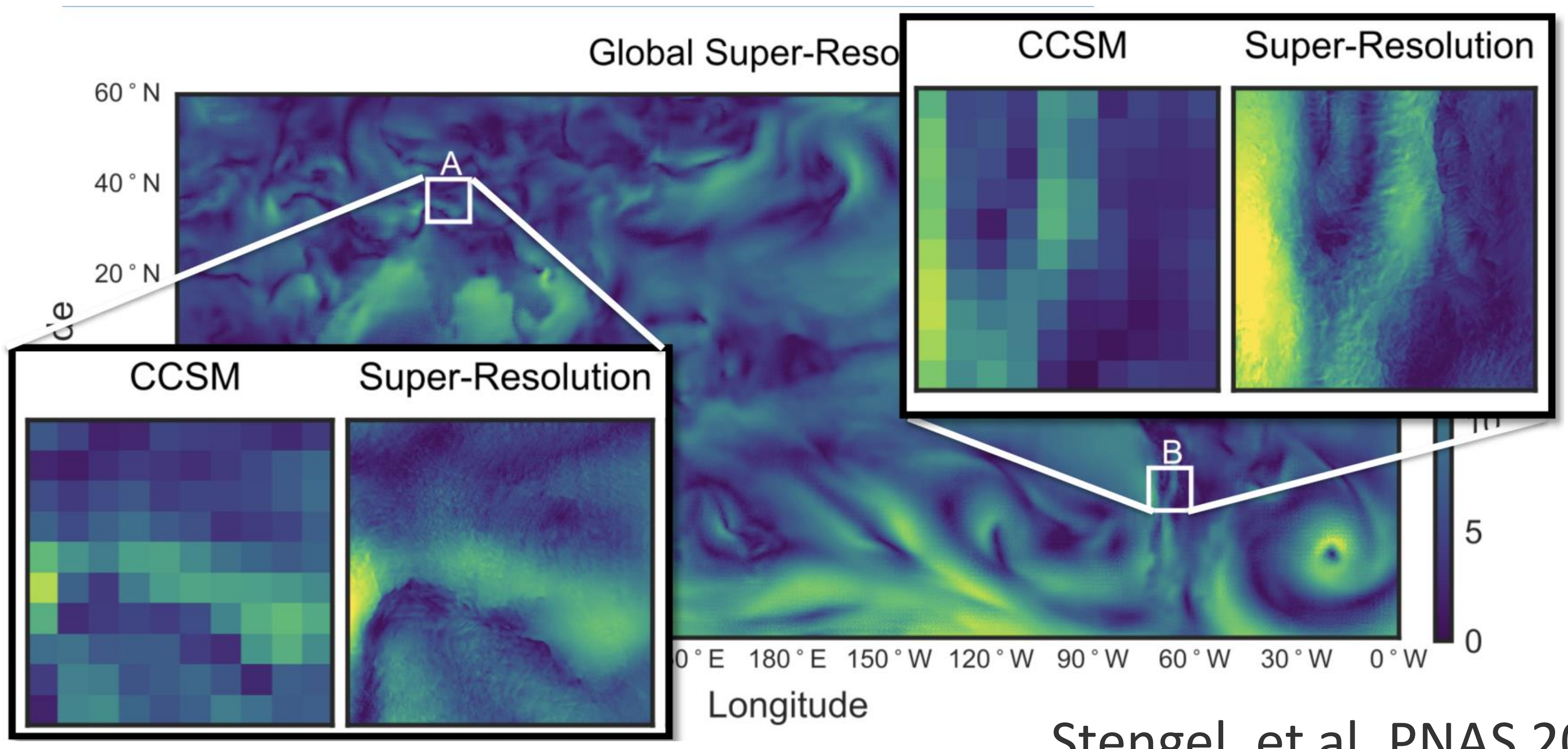
IMPACT

Increased international collaboration regarding digital technologies for the wind industry and best-practice guidelines for application of those technologies.

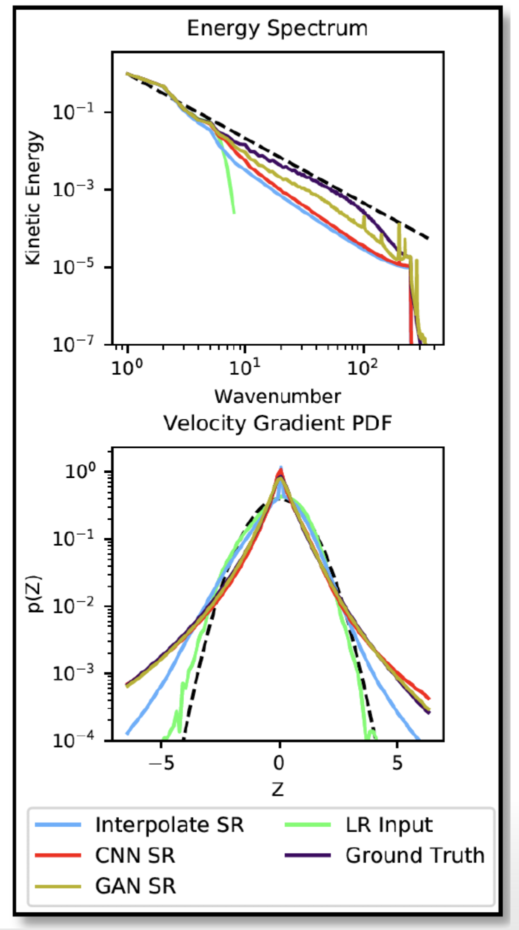
Current Projects

Climate Downscaling

DIGITALIZATION, ARTIFICIAL INTELLIGENCE, AND MACHINE LEARNING



Stengel, et al, PNAS 2020



CHALLENGE

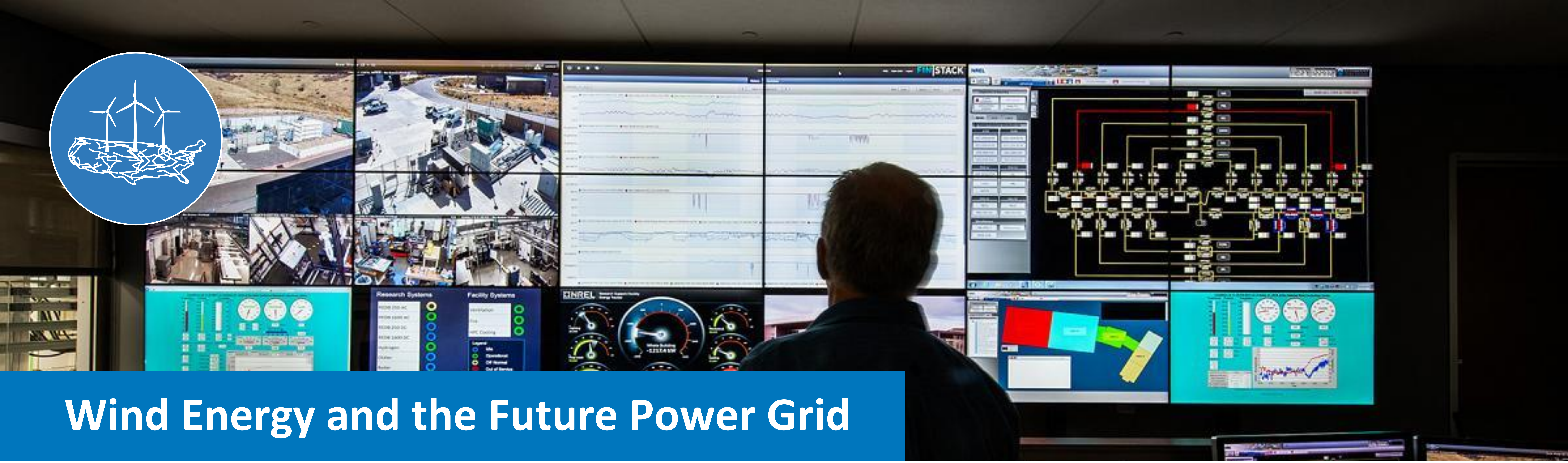
How can researchers enhance data from global climate models to understand the impacts of different climate scenarios on renewable energy resources?

APPROACH

NREL researchers used an emerging, deep-learning technique called super resolution, along with a novel adversarial training formulation, to generate up to 50x spatial resolution enhancements and 24x temporal resolution enhancements, while still preserving important physical properties.

IMPACT

The ability to rapidly generate high-resolution wind fields enables the creation of global wind resource data sets for studying different climate scenarios and provides new mechanisms for inflow generation and mesoscale-microscale coupling.



Wind Energy and the Future Power Grid

- NREL researchers develop and apply advanced capacity expansion and production cost models to study the potential for (and impact of) integrating large-scale renewable energy resources onto the electric power grid.
- We also assess the economic value of wind and its capability to provide a suite of grid services—capacity, energy, operating reserves, and essential reliability services—needed for a reliable grid today and in the future.

Areas of Expertise

- Capacity expansion modeling
- Production cost simulations
- Probabilistic resource adequacy analyses
- Renewable grid integration.

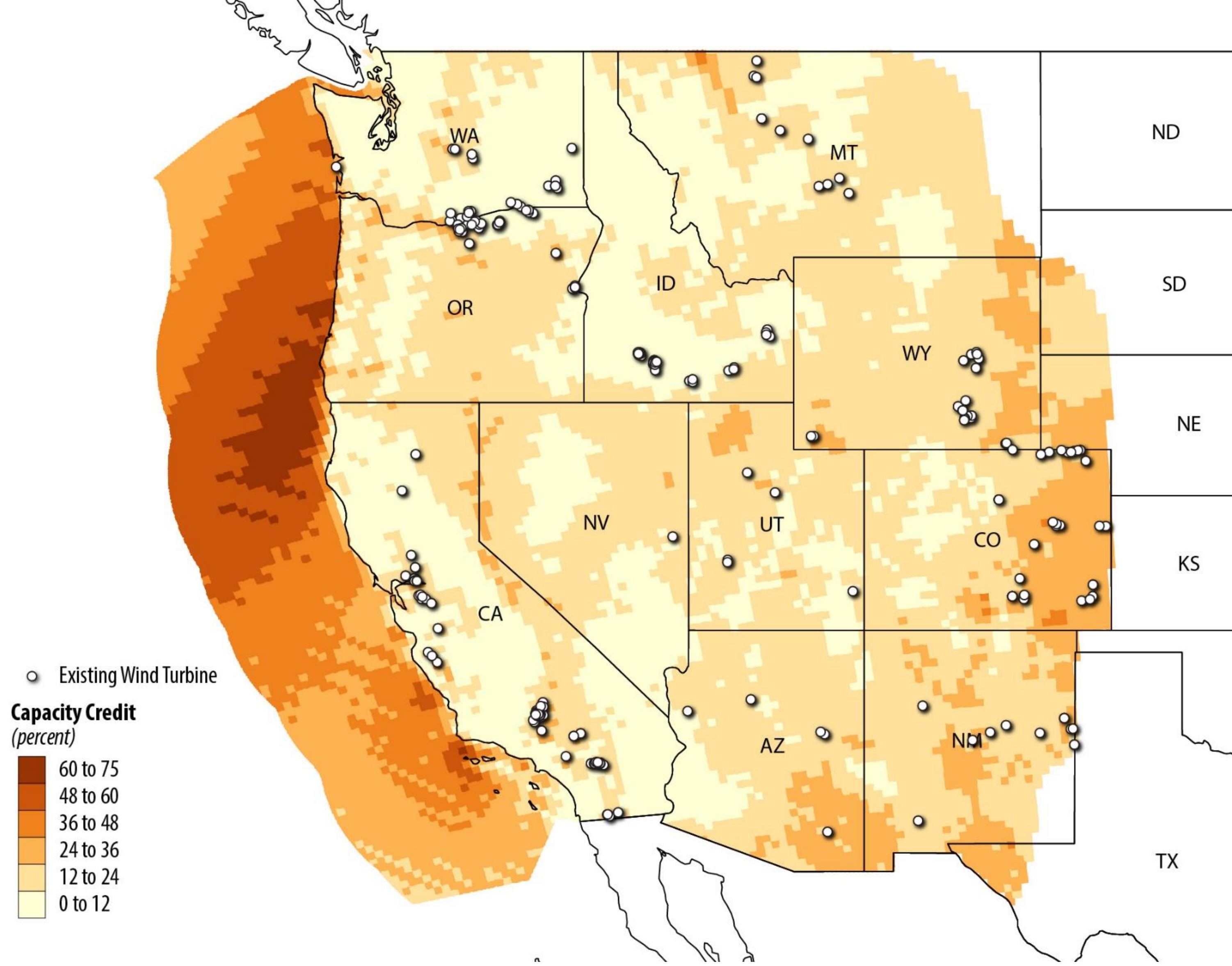
Current Projects

Probabilistic Resource Adequacy Suite (PRAS)

WIND ENERGY AND
THE FUTURE POWER GRID

CHALLENGE

The degree to which wind can contribute to system resource adequacy can vary spatially and with technology design—but is difficult to quantify given complex system interactions.



APPROACH

Using the Probabilistic Resource Adequacy Suite (PRAS) reliability-based tool, NREL researchers systematically estimate the marginal capacity credit for land-based and offshore wind for all sites in the contiguous United States. The tool applies 100,000 Monte Carlo draws of generator outages for each hour across seven weather years to quantify the probability of outages and assess wind plant performance during periods of system stress.

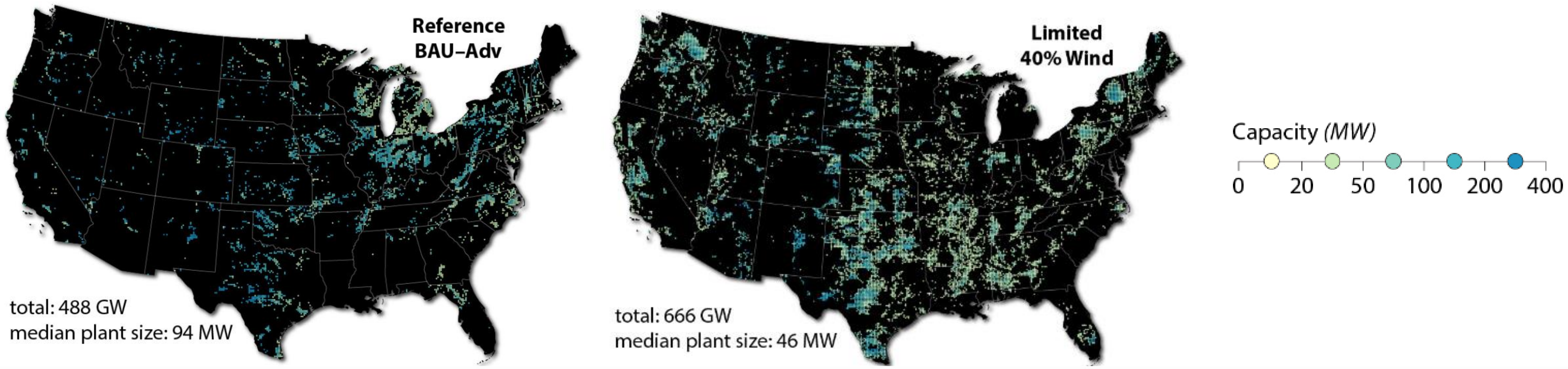
IMPACT

PRAS is an open-source model that extends the state of the art of its class by representing renewables, transmission, and storage technologies.

Current Projects

Regional Energy Deployment System (ReEDS)

WIND ENERGY AND THE FUTURE POWER GRID



CHALLENGE

Projecting future U.S. wind deployment requires models with broad technological and regional scope, but with high fidelity.

APPROACH

The Regional Energy Deployment System (ReEDS) is NREL's flagship capacity expansion model and uses unprecedented spatial resolution, hourly modeling, and high-resolution renewable supply curves to determine the optimal power system portfolio of the future. It is designed to simultaneously compare the life cycle costs and value of multiple grid options—wind vs. solar, transmission vs. storage, local vs. remote resources—to identify the least-cost evolution of the power system.

IMPACT

ReEDS is the analytic framework for NREL's 'Vision' studies—from the seminal 20% Wind study, to DOE's Wind Vision study, and multiple studies today. NREL researchers continue to develop groundbreaking capabilities and have made the ReEDS model publicly available.

Land-Use and Spatial Analysis

Improving the geospatial modeling capabilities for renewable energy potential to build a new foundation of knowledge and understanding that will feed future projections of wind energy potential that consider both emerging turbine technologies and higher-fidelity characterizations of deployment opportunities (e.g., offshore wind, expansion into the Southeast United States) and challenges (e.g., wind power plant saturation, social acceptance, wind-wildlife impacts).

Areas of Expertise

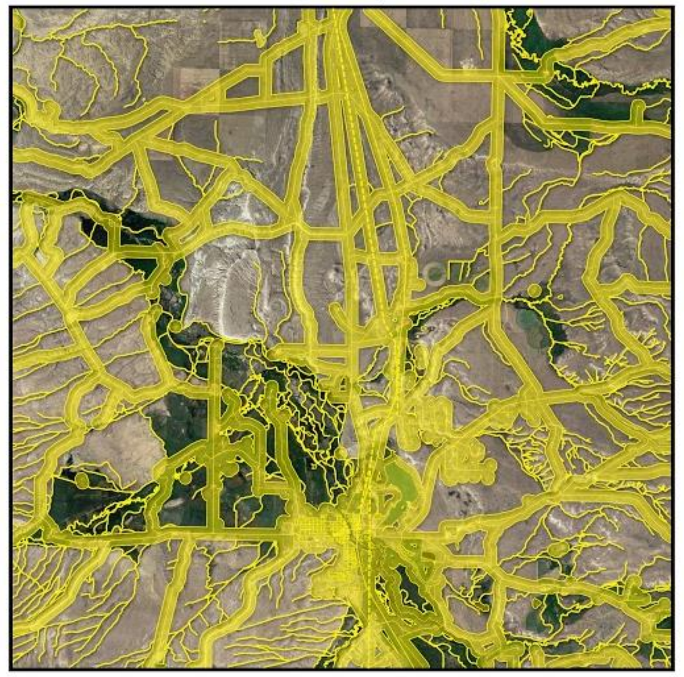
- Spatial statistical analyses
- Technoeconomic supply curve modeling
- Spatiotemporal ‘big data’ high-performance computing and machine learning
- Visualization and mapping
- Machine learning for spatial prediction.

Current Projects

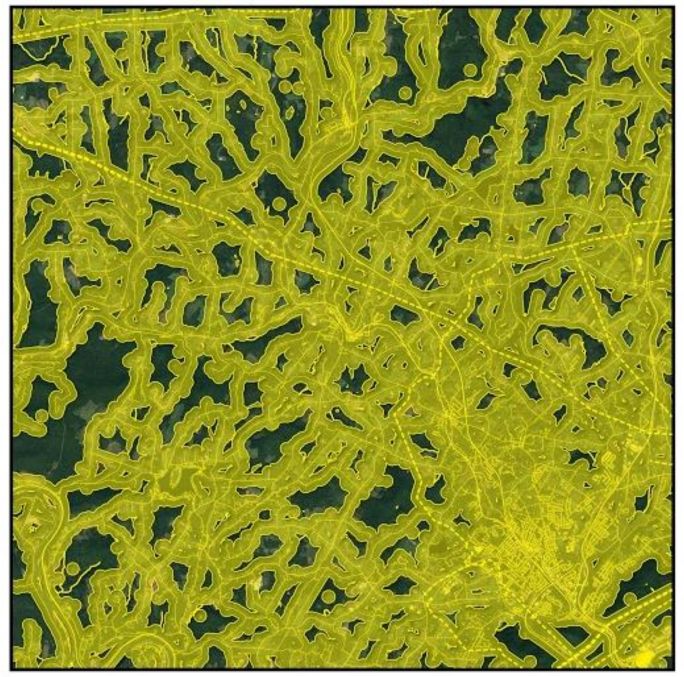
A 21st Century Wind Supply Curve

Bradford, Iowa

Saratoga, Wyoming



Factoryville, Pennsylvania



CHALLENGE

The technical potential for wind in the United States is more than sufficient to meet the electricity needs of the country many times over. Yet, whether high-quality wind energy sites can be developed can impact the future cost and growth of renewable electricity. To assess the developable capacity and generation potential of the renewable resources, i.e., their "supply curve," requires considering local factors, such as those considered by project developers, and a lens for evaluating varying land-use objectives and their interaction with evolving wind energy technology.

APPROACH

The 21st Century Supply Curve is advancing our understanding of wind potential by incorporating unprecedented spatial resolution to capture every building, road, railroad, transmission line right-of-way, documented local siting ordinance (setbacks, height limits), and state wind regulation. It is also advancing our understanding of how varying siting considerations and technology innovation can drastically change wind potential estimates.

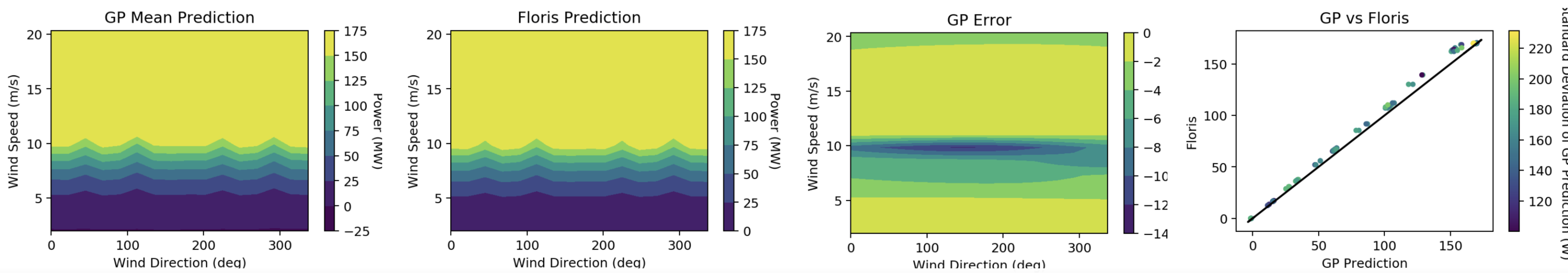
IMPACT

This project has illuminated the critical importance of local siting considerations on national projections of wind deployment through joint research with Renewable Energy Generation and Storage Models. This has resulted in identifying R&D needs to further realize a high wind energy future.

LAND-USE AND SPATIAL ANALYSIS

Current Projects

Wind Plant Surrogate Modeling



LAND-USE
AND SPATIAL ANALYSIS

CHALLENGE

How to quickly assess the impact of emerging wind technologies, such as wake steering, on annual energy production (AEP) and large-scale spatial analysis.

APPROACH

NREL researchers developed machine learning-based surrogate models that predict wind plant AEP using Gaussian processes and convolutional neural nets.

IMPACT

Power output for arbitrary layout arrangements, inflow conditions, and wind plant control strategiescan be computed rapidly over large regions, improving technoeconomicanalysis capabilities.

Jobs and Economic Development Impacts (JEDI)

- NREL develops and maintains economic impact models for land-based wind, offshore wind, and other renewable energy technologies.

- Our team informs state and local communities about the workforce and economic opportunities associated with wind energy development, deployment, and operations.

Areas of Expertise

- Economic impact modeling
- Community economic development
- Wind energy workforce estimation.

Current Projects

Economic Impact Analysis

JOBS AND ECONOMIC DEVELOPMENT IMPACTS (JEDI) MODELS

CHALLENGE

JEDI models inform decision makers by estimating jobs, earnings, gross domestic product, and economic output supported by wind energy. These models enable analysis to increase understanding of workforce and economic development for land-based and offshore wind energy.

APPROACH

NREL researchers are continually improving the capabilities of the JEDI models. Recent improvements include integrating the LandBosse and ORBIT balance-of-system models. Employment and supply chain model assumptions are updated based on industry trends.

IMPACT

Developers and communities use the model to calculate the economic impacts from wind energy projects. For offshore wind, the model is used to understand the workforce and economic considerations from supply chain development and deployment scenarios.

Current Projects

Increasing Stakeholder Understanding

JOBS AND ECONOMIC DEVELOPMENT IMPACTS (JEDI) MODELS

CHALLENGE

Economic impact results require context to adequately inform state or local decision makers. For example, a recent project investigated the characteristics of operations and maintenance (O&M) employment in the United States and how these O&M workforces impact communities near the wind plant.

APPROACH

NREL researchers utilized qualitative and quantitative research methods to gather information from industry and communities. A survey was distributed to several wind plant operators and their workers to collect data on the domestic O&M workforce.

IMPACT

Communities near operating wind plants can make informed decisions with a better idea of what to expect and how their community can maximize economic impacts from wind energy. This research also informs the JEDI models.

Accomplishments & Impacts

NREL's unique expertise in economic analysis and data analytics informs R&D strategies for the wind industry. Examples include:

- NREL created the LandBOSSE and ORBIT balance-of-system cost models to evaluate the impact of technology and process innovations on land-based and offshore wind levelized cost of energy (LCOE). These models have been used to analyze the cost trends attributed to turbine and plant scaling.
- Regional Energy Deployment System (ReEDS), which informs a wide range of electricity-sector research questions—including clean energy policy, renewable energy integration, technology innovation, and other forward-looking generation and transmission infrastructure issues.
- The Renewable Energy Potential (reV) model that dynamically evaluates the nexus between the built and natural environment and renewable energy technology.
- JEDI models that are used by a variety of stakeholders to perform economic impact analyses for project-specific analysis.

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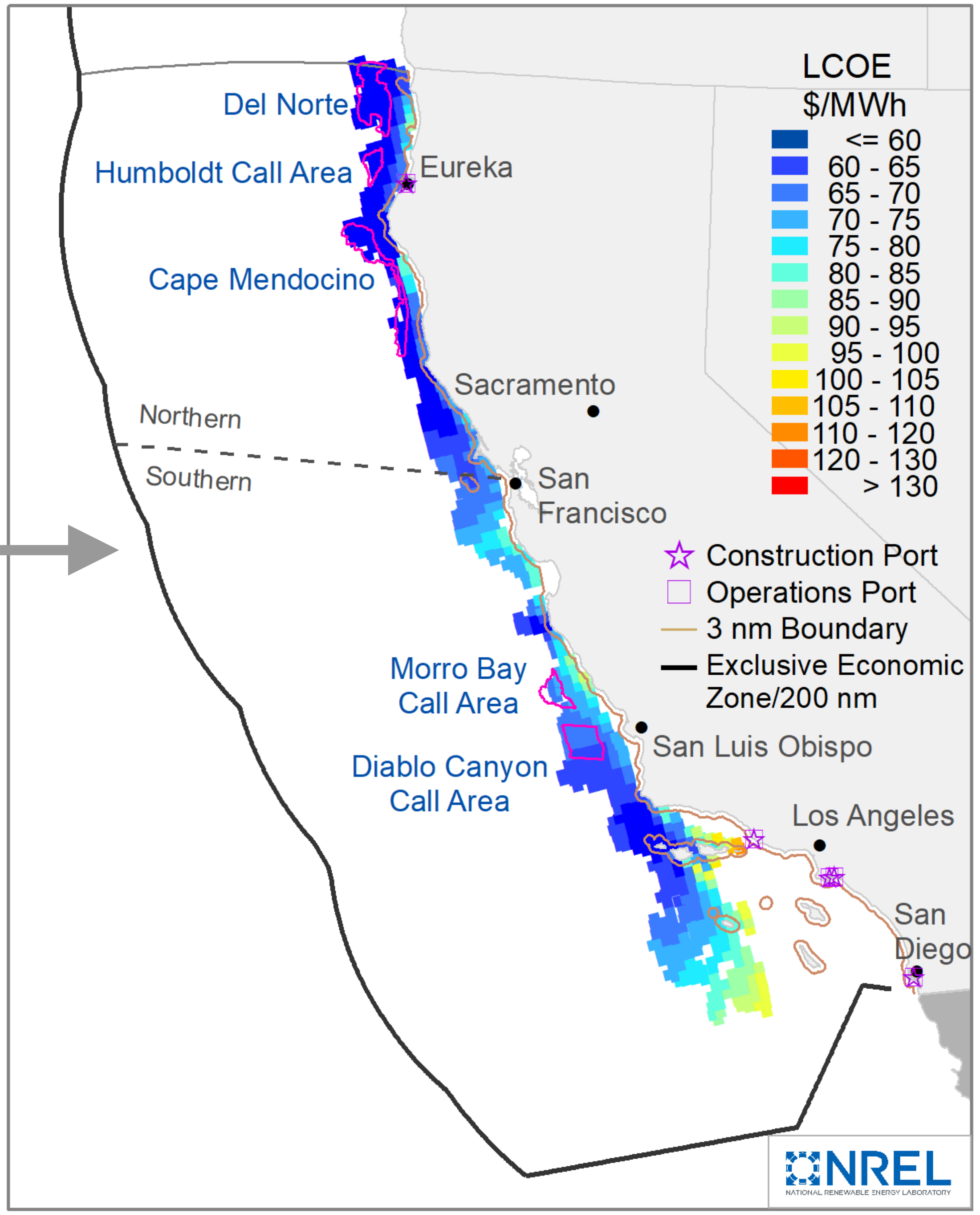

Projected floating offshore wind LCOE in 2032 for the California Outer Continental Shelf. From Beiter, et al, *The Cost of Floating Offshore Wind Energy in California between 2019-2032*, forthcoming.

(More) Accomplishments & Impacts

Machine Learning for Spatial Predictions

- NREL is pushing the boundaries of spatial science by leveraging machine learning to predict variable wind capacity density and wind plant AEP in a geographically continuous space, enabling rapid technology innovation simulations.

Bat Curtailment Strategies and Outcomes

- NREL has developed wind turbine curtailment strategies to avoid bat collision fatalities and has assessed the financial implications of each.