U.S. DEPARTMENT OF
ENERGY
Energy Efficiency &
Renewable Energy

ATMOSPHERE
TO ELECTRONS
U.S. DEPARTMENT OF ENERGY

Atmosphere to Electrons

Enabling the Wind Plant of Tomorrow

Key Objectives of the Atmosphere to Electrons (A2e) Initiative

- Transform today's wind plant operating environment through advanced physics-based modeling, analysis and simulation capabilities
- Revolutionize advanced systems-level control capabilities that adopt flow monitoring and active wake control to mitigate energy and performance losses
- Enable innovative wind plant technologies through an enhanced understating of the wind plant physics.

Illustration by NREL depicting the System Management of the Atmospheric Resource by Turbines (SMART) wind plant of the future to better understand how the Earth's atmosphere interacts with wind plants and maximizing energy extraction from the wind. *Illustration by Josh Bauer, NREL 31411*

Atmosphere to Electrons

Enabling the Wind Plant of Tomorrow

The U.S. Department of Energy's (DOE's) Atmosphere to Electrons (A2e) research initiative is focused on improving the performance and reliability of wind plants by establishing an unprecedented understanding of how the Earth's atmosphere interacts with the wind plants and developing innovative technologies to maximize energy extraction from the wind.

The A2e initiative pursues an integrated research portfolio to coordinate and optimize advancements in four main research areas: 1) plant performance and financial risk assessment, 2) atmospheric science, 3) wind plant aerodynamics, and 4) next-generation wind plant technology. It offers an integrated systems approach to developing the next generation of System Management of the Atmospheric Resource by Turbines (SMART) wind plant technologies necessary to increase wind deployment.

The goal of A2e is to ensure future plants are sited, built, and operated in a way that produces the most cost-effective electrons—in the form of usable electric power—from the winds that pass through the plant. At the heart of A2e is the realization that flow turbulence produced by weather, complex terrain, and turbine wakes impact plant performance. Upwind turbine wakes meander downstream and can impinge on downwind turbines. The wake interaction significantly affects the performance of downwind turbines by increasing fatigue, reducing operational life, and lowering power output.

To address these concerns, A2e aims to develop an unprecedented understanding of the plant operating environment and innovative technologies to maximize energy extraction. The approach incorporates advanced high-fidelity modeling that taps the unique high-performance computational (HPC) resources available within DOE and experimental test facilities at the DOE national laboratories. Scientists from industry, academia, and the national laboratories are working collaboratively across the United States and abroad to create analysis methods, innovative turbine architectures, and advanced plant control strategies that provide wind energy at the lowest possible cost.

Assessing Plant Performance and Financial Risk

The A2e research portfolio is continuously prioritized to identify and execute activities that optimize wind plant performance and lower the overall cost of wind energy. A2e systematically assesses plant performance as well as the analysis methods used to estimate power production and financial return rates for developers and owner operators. The objective is to prioritize the A2e research portfolio based on the largest potential for improving plant performance and lowering levelized cost of energy (LCOE). Prioritization includes establishing the risk and performance uncertainty of new technology, thereby lowering the cost of investment capital and facilitating the deployment of innovative technology.

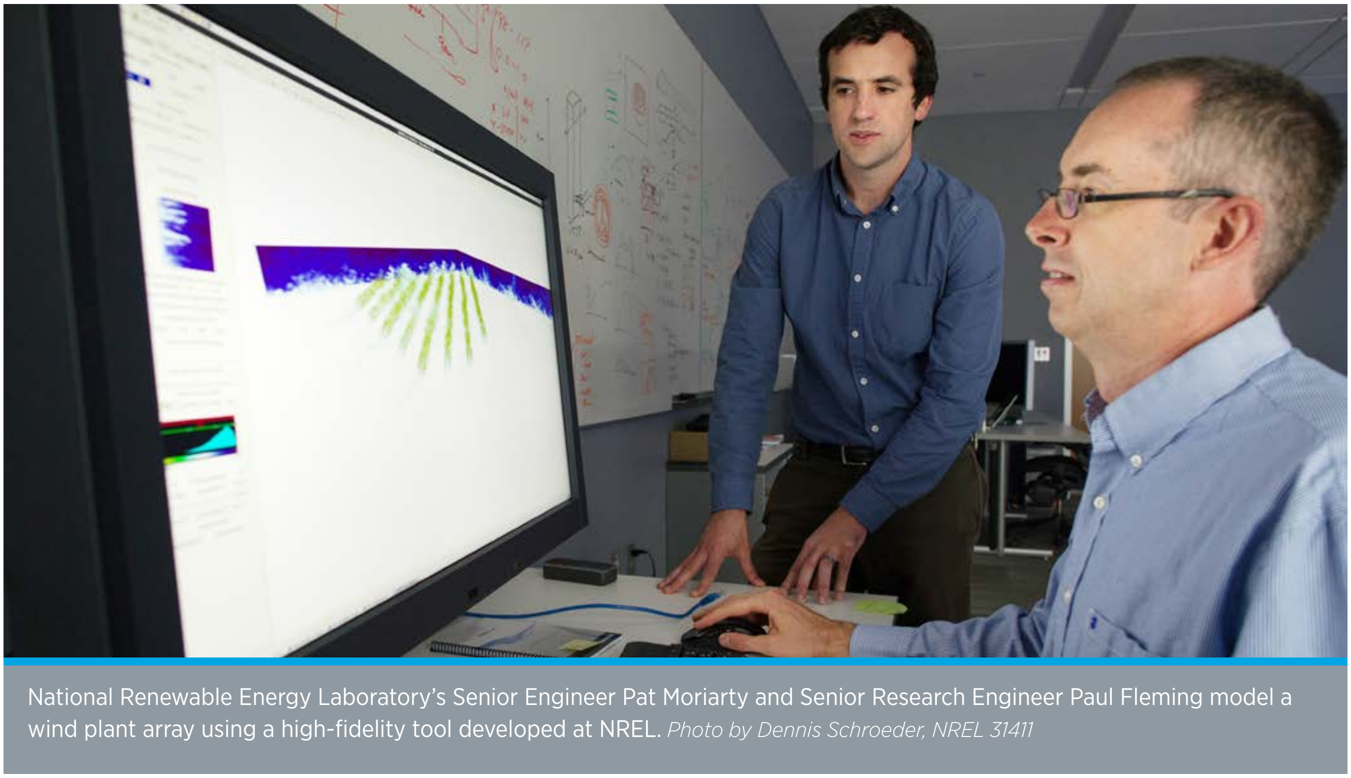
The Performance Risk, Uncertainty, and Finance (PRUF) research area is focused on activities to characterize and reduce the risk and uncertainty associated with developing, investing in, owning, and operating wind plants. Investigators will assess the impact that project uncertainties have on financial structures, cost of capital, cost of ownership, perception of financial risk, and LCOE. PRUF prioritizes the A2e research agenda by linking the uncertainties that drive financial decisions to the physics of wind plant design and operation. Quantifying the performance and operation of existing wind plants is the first step in the assessment process.

The PRUF research collaborative includes research staff from DOE’s Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), and Argonne National Laboratory working in collaboration with DOE and the wind industry to bring together the crosscutting technical and financial expertise required to correlate financial risk, analysis and performance uncertainty, and market impact. PRUF is currently developing a joint industry project with a broad range of wind plant owner-operators and consultants to benchmark pre-construction energy assessments against real performance data and facilitate improvements. The PRUF team is also developing a quantitative framework in collaboration with international standards organizations to describe uncertainties in plant performance and operational cost to inform future A2e research priorities.

For more information contact *Patrick.Gilman@ee.doe.gov*

The Atmospheric Science Challenge

A2e is examining how the wind interacts with wind plants at all physical scales, from regional weather patterns down to the interaction with a single turbine. Researchers are focused on how the regional weather patterns affect the complex



National Renewable Energy Laboratory’s Senior Engineer Pat Moriarty and Senior Research Engineer Paul Fleming model a wind plant array using a high-fidelity tool developed at NREL. *Photo by Dennis Schroeder, NREL 31411*

The 300-MW Stateline Wind Energy Center is located on VanSycle Ridge between the states of Washington and Oregon. *Photo by Larry Berg, Pacific Northwest National Laboratory*

local flows into and around the wind plant in order to develop plant-level control capabilities.

The wind resource is produced by the Earth's rotation and regional weather conditions driven by surface heating from the sun. Fronts, sea breezes, mountain range drainage flows, thunderstorms, and hurricanes are all examples of the diverse and complex atmospheric processes affecting the characteristics of wind plant inflow. Forecasting the wind resource, modeling and monitoring the inflow characteristics, and resolving the internal flow interactions as the wind passes through the plant, are all necessary components in developing wind-plant control strategies for optimized performance and operation.

Wind Forecast Improvement Project

The Wind Forecast Improvement Project (WFIP) is a public/private partnership consortium including DOE, the National Oceanic and Atmospheric Administration (NOAA), and industry to enhance weather prediction models. Preliminary field results from the WFIP project are showing the tremendous potential for improving energy capture estimates. The use of deployed flow monitors to provide better input data to the models would have boosted wind forecast accuracy by up to 15%. Such an improvement would have a significant impact on compensation for owner-operators of wind plants, causing a shift in their decision processes.

The project's goals include improving the accuracy of short-term (day ahead or less) wind energy forecasts and demonstrating the economic value of these improvements. Short- and long-term (week to months) weather forecasts are a vital aspect of coordinating wind plant output with the power grid operators and achieving seamless integration both locally and regionally. Improvements can be achieved by enhancing the representation of physical processes in computer models and using advanced wind monitor data in the forecast predictions.

Accurate models of physical processes are the foundation for weather forecasts and general wind resource assessments. Researchers are improving the physical and numerical characterizations within the models that drive the prediction of hub-height winds and turbulence. Research activities are concentrated on complex terrain (e.g. hills, ridges, manmade structures, etc.), which poses some of the most difficult challenges for inflow resource models. The ultimate objective is to provide highly accurate wind-plant forecast and production estimates and their uncertainties to industry for seamless integration and reduced ancillary service requirements.

For more information contact *Will.Shaw@pnnl.gov*

Wind Resource Monitoring

Monitoring the behavior of the wind resource is critical to operating the wind plant for maximum energy production and cost performance. Accurately measuring the inflow, both spatially and temporally, is also essential in characterizing the wind resource and providing high-fidelity data for validating inflow prediction models. A field-test campaign conducted by DOE national laboratories, NOAA, universities, and industry is assessing a variety of instruments that can be used to measure the wind resources in the atmospheric boundary layer where wind turbines operate. Technologies evaluated include devices that use precision radar, sound waves (SODAR), and lasers (LiDAR).

The WindSentinel™ is a floating LiDAR device that accurately measures wind speed and wind direction offshore at turbine hub-height and across the blade span. *Photo by Noah Golding*

The results from this campaign provide an independent assessment of existing field measurement instrumentation to determine accuracy, resolution, and robustness. All

Aerial photography of the London Array wind farm. *Photo by London Array*

information collected under A2e is being placed in the public domain and is accessible through the A2e Data Access Portal. Based on these results, new instruments will be developed to validate wind-plant inflow models and turbine wake interactions. Owner-operators looking to optimize plant production also require advanced flow monitoring integrated into plant level control systems.

For more information contact *Alana.Duerr@ee.doe.gov*

Mesoscale-Microscale Coupled Modeling

Every wind plant location is unique and requires a site-specific assessment to establish wind turbine type, site layout, and operating conditions that will deliver the optimal cost and performance potential for that location. Assessments start with a detailed inflow characterization to determine both the quantity and flow quality of the wind resource. Mesoscale winds (weather patterns spanning 10-1000 kilometers), in conjunction with the unique site topography, create the wind conditions at the turbines blades (the microscale), dictating turbine performance.

Being able to model both the mesoscale and microscale in a coupled fashion is essential in the site assessment process. Currently, a significant void exists in providing detailed inflow characteristics for wind plants, which is the critical first step in predicting performance. DOE-sponsored research is moving beyond the limitation of the empirical models currently being used and advancing the state-of-the-art in high-fidelity HPC simulations needed by manufacturers, developers, and owner-operators for optimizing wind plant performance.

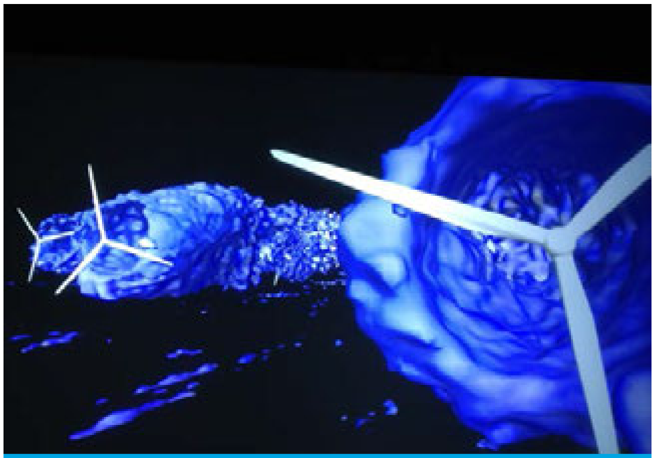
A collaborative of five DOE national laboratories are working under the leadership of the National Center for Atmospheric Research (NCAR) to produce spatially and temporally accurate inflows for wind-plant performance assessment. Advanced high-fidelity, coupled mesoscale/microscale wind simulations are providing new insights into the fundamental physics that couple the mesoscale and microscale wind interactions. The collaborative is using HPC to ascertain the best modeling practices and is establishing a common, unified model development platform that will eventually be incorporated into future wind plant optimization, performance, and reliability determinations.

For more information contact *Will.Shaw@pnnl.gov*

Wind Plant Aerodynamics

Wind plant performance is determined by the inflow, unique site topography, site layout, and the wake flow generated by each turbine. Plants are comprised of multiple turbines, arranged in rows and separated at distances determined by the optimized benefits of energy extraction versus land availability and balance-of-station costs. Understanding how the wind flow is affected by continuously changing weather conditions and influenced by complex terrain is a difficult modeling challenge. Turbulence in the inflow increases with the addition of turbine wakes. How these wakes are produced, interact with the surrounding inflow turbulence, and propagate with the inflow to interact with downstream turbines is unique to wind plants.

These cumulative effects influence the wind plant optimization and performance potential and must all be taken into consideration. Hence, modeling plant performance requires a detailed knowledge of the atmospheric flow conditions, plant inflow characteristics, plant topography, configuration, and turbine performance characteristics. This is a computational science challenge requiring the most advanced modeling and simulation capabilities in existence. The DOE Office of Science has identified inflow and wind plant modeling as a “Grand Challenge” for modern computer science, with multi-scale and multi-physics dependencies requiring exascale computational capability.



Immersive visualization of low-velocity wakes forming behind the turbines in an LES simulation of the Lilligrund wind farm. *Image by Kenny Gruchalla, Nicholas Brunhart-Lupo & Matthew Churchfield, NREL*

Turbine Wake Dynamics Modeling

A by-product of energy extraction by wind turbines is the creation of a wake flow that can persist for kilometers downstream. Wakes have lower speeds and higher turbulence than the surrounding inflow. Wake interaction with downstream turbines results in a decrease in energy production and an increase in the fatigue loads that shortens operating turbine life expectancy. Thus, wake behavior adversely affects the overall plant performance, accounting for up to 9% in energy loss within the plant.

Wake behaviors are difficult to characterize due to their dependency on the turbine characteristics, operating conditions during production and the strong interaction with the microscale turbulence in the surrounding wind. Depending on the operating and flow conditions at the time of inception, the wake characteristics can range from strongly coherent vortices with significant loading impacts downstream to benign, well-mixed flows with minimal impacts. Modeling the wake life cycle within the wind plant, from inception to interaction and final dissipation, is a critical element in determining the extent to which wake behavior can be modified and controlled to enhance overall wind plant performance.

Research scientists at NREL, SNL, Texas Tech University, and the University of Minnesota are working collaboratively to investigate the fundamental aspects of wake generation using advanced computational modeling methods validated with experimental data from extensive field testing. The multi-organization expertise needed to address wake dynamics has resulted in unique research collaboratives and new management paradigms within DOE. Significantly, these collaboratives are forming based on research needs and core capabilities—partnerships that provide the most cost-efficient use of existing government resources. The resulting validated wake physics, based on high-fidelity models, will provide the fundamental insights for developing the advanced controls required for plant-level optimization.

For more information contact *Mike.Robinson@ee.doe.gov*

Next-Generation Technology Development

Achieving optimized wind plant performance requires an unprecedented understanding of the plant operating environment to generate and evaluate innovative technologies that maximize energy extraction at the lowest cost of energy. The A2e initiative integrates high-performance computational modeling with innovative control strategies to demonstrate the next generation of SMART wind plant technologies for optimized performance.

Scientists from industry, academia, and several DOE national laboratories are developing fully integrated research programs to evolve advanced modeling and simulation capabilities and validate the risk and uncertainty of simulation results through targeted testing campaigns. The ultimate goal is to provide a digital technology development environment for industry wherein innovative approaches and technology development opportunities can be evaluated for specific sites with a high degree of assurance in the performance prediction.

A key focus for next-generation technology development is advanced wind plant controls. Today’s utility-scale wind turbine structures are more complex, and their components are more flexible and lighter weight. As turbines become even larger, structural material is often removed to lower the capital cost, resulting in even more flexible and dynamically active designs. Active control is required to mitigate unwanted dynamics and interactions that can result in catastrophic damage and system failures. The challenge facing wind turbine designers is to capture the maximum amount of energy, with minimal structural loading, at minimal cost.

Wind plant performance can be significantly enhanced by actively managing individual turbines to control the flow through the wind plant. Research scientists have shown improved energy capture by yawing turbines upstream and manipulating wakes away from downwind turbines. Minimizing wake interactions through redirection increases the amount of energy captured by the wind plant and decreases the potentially harmful loads experienced by the downwind turbines. By using sensing systems such as LiDAR, coupled with advanced digital controls at the plant level, wind plants can actively monitor the flow field, anticipate wind changes, and modify the flow through redirection to increase performance.

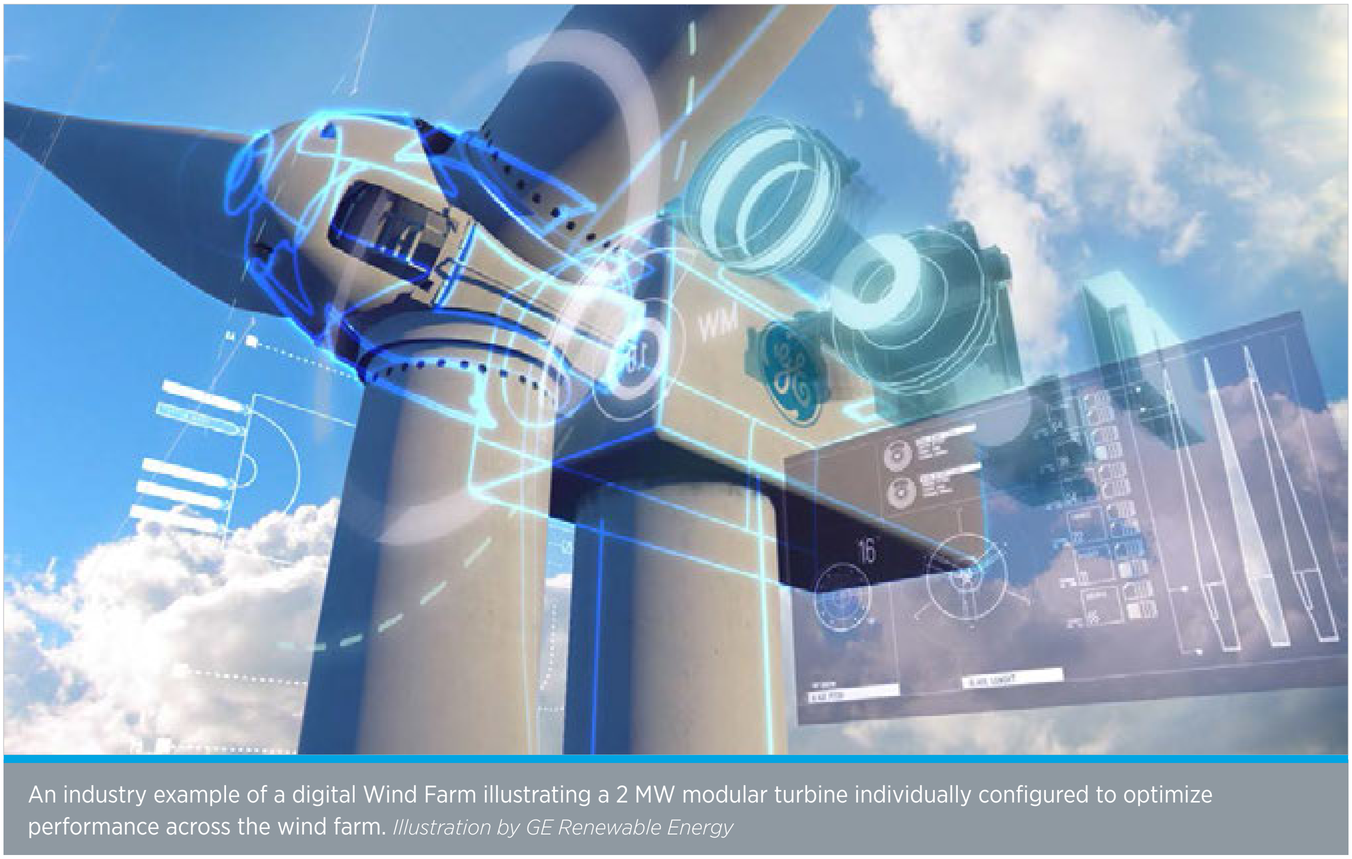
NREL and SNL have formed a research collaborative to develop innovative wind plant control strategies that are experimentally verified and validated. In simulations of existing wind farms, increases in energy capture of 3% have been demonstrated by implementing active yaw control. Increases of 10-17% are possible when turbines are placed in close proximity and with sub-optimal turbine spacing; a typical condition when maximum energy extraction is desired from a limited deployment area. Higher energy gains are predicted in more densely packed arrangements.

Validation of the potential gains from active wind-plant yaw control is expected at the SNL Scaled Wind Farm Technology (SWiFT) facility by the end of 2016. Incorporating system-level operating strategies that rely on active flow monitoring and plant flow control provides the foundation for future SMART wind plant technology development and offers a whole new range of wind plant layout possibilities.

For more information contact *Michael.Derby@ee.doe.gov*

Future Outlook

Attaining future performance goals requires high-fidelity modeling and high-performance computing resources coupled with new state-of-the-art observations to examine and resolve the fundamental physics barriers limiting wind plant cost and performance. Understanding the atmospheric inflow and interaction with large wind farms and facilitating the development of next-generation SMART plant technologies will help achieve future wind penetration levels by lowering LCOE and mitigating technical barriers to wind plant deployment.



An industry example of a digital Wind Farm illustrating a 2 MW modular turbine individually configured to optimize performance across the wind farm. *Illustration by GE Renewable Energy*

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