Quadrennial Technology Review 2015

Chapter 4: Advancing Clean Electric Power Technologies

Technology Assessments

Advanced Plant Technologies

Biopower

Carbon Dioxide Capture and Storage Value-Added Options

Carbon Dioxide Capture for Natural Gas and Industrial Applications

Carbon Dioxide Capture Technologies

Carbon Dioxide Storage Technologies

Crosscutting Technologies in Carbon Dioxide Capture and Storage

Fast-spectrum Reactors

Geothermal Power

High Temperature Reactors

Hybrid Nuclear-Renewable Energy Systems

Hydropower

Light Water Reactors

Marine and Hydrokinetic Power

Nuclear Fuel Cycles

Solar Power

Stationary Fuel Cells

Supercritical Carbon Dioxide Brayton Cycle

Wind Power

U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

Wind Power

Chapter 4: Technology Assessments

***NOTE:** The 2015 U.S. Department of Energy (DOE) Quadrennial Technology Review (QTR) addresses opportunities for the Nation as a whole. As it is not specific to DOE (or any other federal agency), the QTR and this Technology Assessment do not propose nor discuss funding levels or specific funding mechanisms for national RDD&D activities. This Technology Assessment for Wind Power focuses on RDD&D that is specific to wind power. Cross-cutting activities, such as transmission grid integration of clean power sources and grid storage technologies, are discussed in the QTR chapters and Technology Assessments that specifically address those activities, and are not covered in detail in this Technology Assessment.*

Introduction

Wind power has become a mainstream power source in the U.S. electricity portfolio, supplying 4.9% of the nation's electricity demand in 2014.[1] With more than 65 GW installed across 39 states at the end of 2014[2], utility-scale wind power is a cost-effective source of low-emissions power generation throughout much of the nation. The United States has significant sustainable land-based and offshore wind resource potential, greater than 10 times current total U.S. electricity consumption.[3] A technical wind resource assessment conducted by the Department of Energy (DOE) in 2009 estimated that the land-based wind energy potential for the contiguous United States is equivalent to 10,500 GW capacity at 80 meters (m) hub and 12,000 GW capacity at 100 meters (m) hub heights, assuming a capacity factor of at least 30%.[4] A subsequent 2010 DOE report estimated the technical offshore wind energy potential to be 4,150 GW.[5] The estimate was calculated from the total offshore area within 50 nautical miles of shore in areas where average annual wind speeds are at least 7 m per second at a hub height of 90 m. Figure 4.S.1 shows the U.S. wind resources in terms of land-based and offshore average wind speed at 100 m hub height.[6]

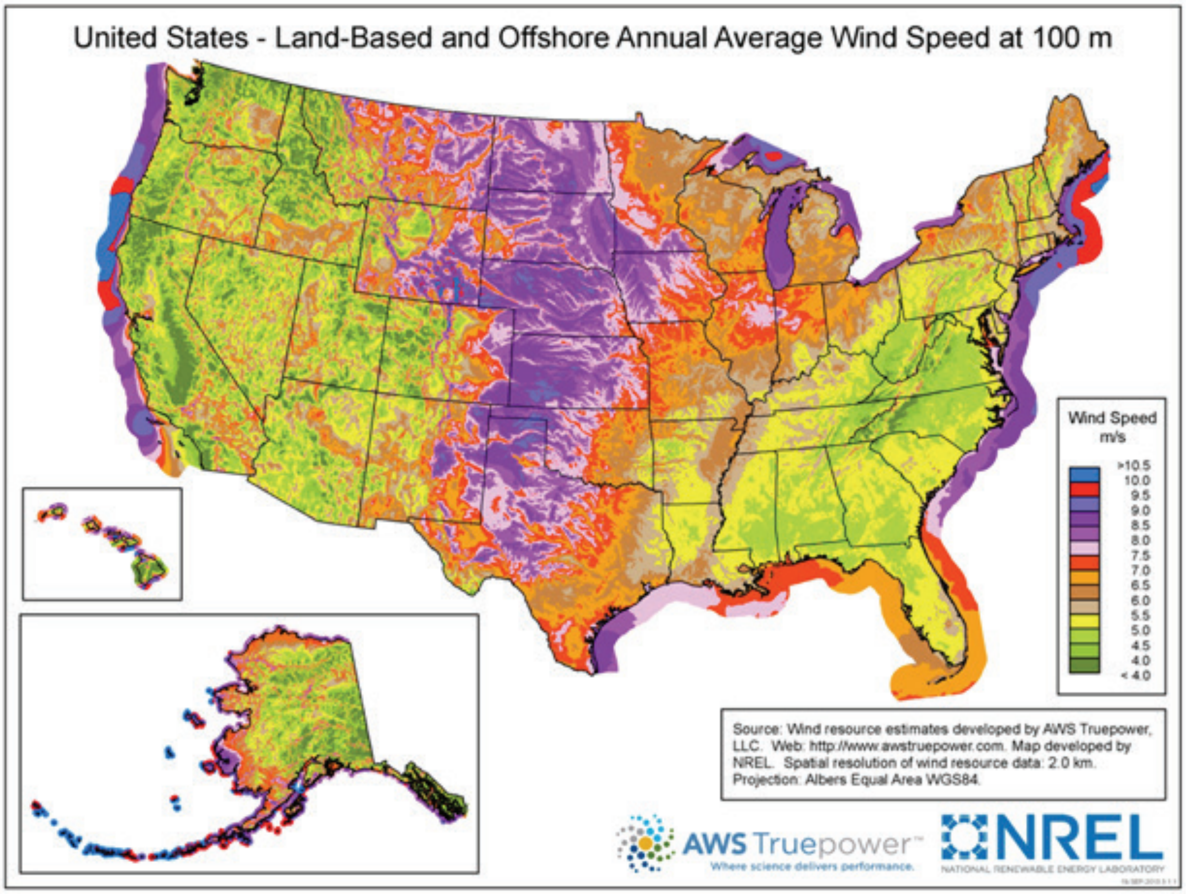
A 2015 DOE analysis, *Wind Vision: A New Era for Wind Power in the United States*, found that through continued innovation in technology and markets, deploying incremental U.S. wind power generation in a U.S. portfolio of domestic, low-carbon, low-pollutant, power generation solutions is both feasible and economically compelling.[7] Further, U.S. wind power could provide greater than 35% of U.S. power requirements with high grid reliability by 2050 but would require concerted actions by all stakeholders to achieve this level of contribution. Three elements critical for enabling further wind deployment emerge from DOE's collaborative analysis and roadmap development:

- Technology improvements to further reduce wind power costs
- Transmission expansion to access high quality wind resources and enhance operation of the electric power system
- Energy market pricing that recognizes the value of low carbon, low emissions power

As wind deployment increases, additional environmental and human use factors may need to be considered and addressed. This includes the potential for new or additional interactions with wildlife, such as birds and bats, as well as effects on their habitats. Additionally, impacts related to human use concerns, such as civilian and military radars, must also be evaluated. Continued research and development (R&D), as well as federal,

Figure 4.S.1 U.S. Wind Resources. This map provides wind developers and policy makers with a representation of land-based wind resources estimated at a 100 m hub height for all 50 states—the 48 contiguous states, Alaska, and Hawaii—as well as offshore resources up to 50 nautical miles from shore

Credit: National Renewable Energy Laboratory



state, and local interagency coordination, on potential impacts and options for mitigation and resolution are required to ensure responsible deployment.[8]

Market Application

Land-based. Land-based wind technology is cost competitive today, without subsidy, in locations with access to transmission capacity in high wind speed locations. Wind is approaching the U.S. Energy Information Administration (EIA) Annual Energy Outlook natural gas-fueled electricity generation projected national average pricing in the next decade, assuming continued demand, cost reduction, and improved market barrier mitigation.

Offshore. The U.S. offshore wind industry is in its very early stages, with no commercial scale offshore wind farms having yet been installed in the nation's waters as of the end of 2014. In order to grow, industry must be able to show that offshore wind generation can be cost-competitive within the unique and regionally diverse physical and market constraints of the United States.

Distributed. Distributed wind can be defined, based on a wind project's location relative to end use and power-distributed infrastructure rather than on technology size or project size; thus, the distributed wind market includes turbines and projects of many sizes.

Market and Other Impacts

Market share. Wind power provided 4.9% of U.S. electricity demand (182 TWh/year) in 2014.[9] With roughly 49,700 TWh/year of potential wind resources over all U.S. regions and offshore,[10] the potential for wind generation is greater than ten times total U.S. electricity end-use of 3,862 TWh/year in 2014.[11]

Environmental and economic impacts. Wind power has very low life-cycle greenhouse gas (GHG) emissions,[12] criteria pollutant (NO_x, SO_x, and $PM_{2.5}$) emissions, and water use. The U.S. wind industry has robust domestic manufacturing capacity and supported an average of 73,000 U.S. jobs in installation, manufacturing, and operations over the past five years (2010–2014), with more than 500 U.S. wind manufacturing facilities in 43 states.[13]

Strategic Priorities

The nation can take action to enable and accelerate widespread U.S. deployment of clean, affordable, reliable, and domestic wind power to promote national security, economic growth, and environmental quality by developing a balanced program of technology planning, research, development, testing, analysis, evaluation, and communication that will increase the viability and acceptance of wind technologies. U.S. innovation in wind technology has over 30 years of demonstrated success, from turbulence models for turbine inflows and wakes (1978–1994) and low wind speed turbine development and demonstration (1995–2008) to offshore wind advanced technology demonstration projects, a multiyear effort begun in 2013.[14]

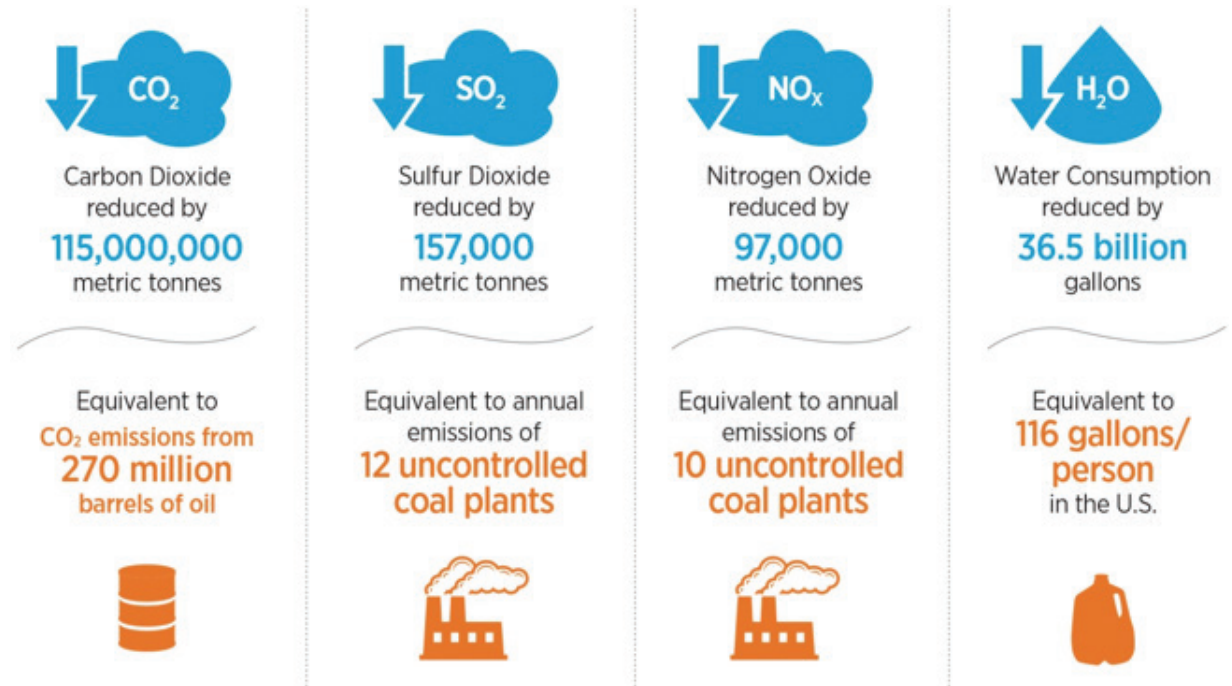
The Role of Wind Power in National Priorities

The U.S. Administration's goal is to generate 80% of the nation's electricity from clean energy sources by 2035; reduce carbon emissions 26%–28% below 2005 levels by 2025; reduce carbon emissions 83% by 2050; lead the world in clean energy innovation; and stimulate jobs and economic growth with a clean energy economy. Figure 2 highlights a sample of estimated environmental benefits realized in 2013 as a function of U.S. wind power generation.

National opportunities exist to improve the performance, lower the costs, and accelerate the deployment of innovative wind power technologies. Associated priorities are electric sector carbon intensity reduction, lower consumer electricity rates, job growth and maintaining a robust wind manufacturing sector, improved grid reliability, and enhanced energy security and diversity. These national opportunities may be framed in five broad categories as follows:

- **Wind plant optimization.** Minimize wind plant cost of energy through wind resource characterization, complex wind plant aerodynamics R&D, advanced plant-level controls development, improved numerical weather prediction and power forecasts, and improved design and operation standards to enhance plant reliability and durability. National priorities may include interagency access to high resolution weather data and leveraging DOE's high-performance computing (HPC) assets for high-fidelity atmospheric and wind plant modeling and data integration efforts; holistic plant design that includes innovative plant control strategies to enhance energy capture, improve reliability, and reduce "levelized" cost of energy (LCOE); and characterization of risk and uncertainty to maximize the financial investment potential of wind plants.
- **Wind turbine components and materials.** Research on advanced materials and key components to improve performance, reliability, and durability; development of new architectures for larger, light-weight turbines that reduce overall mass (reducing costs) and provide access to better wind resources (larger rotors, taller towers) and improved systems performance (capacity factor); improvements in turbine cost, strength, weight, and fatigue to reduce operations and maintenance (O&M) costs and reduce the failure rate for large components, such as blades, gearboxes, generators, and power

Figure 4.S.2 Estimated Reductions in Emissions and Water Use from Wind Generation in 2013[7]



Note: Emissions and water savings calculated using the EPA's Avoided Emissions and Generation Tool (AVERT). 'Uncontrolled coal plants' are those with no emissions control technology.

Source: AWEA

electronics; and transport and logistics innovations to address transportation and installation constraints for large-scale turbine systems and components.

- **Offshore wind technology.** Establishment of a competitive U.S. offshore wind industry through offshore wind system development and demonstration in both shallow and deep water resource areas. In 2012, DOE funded seven offshore wind energy advanced technology demonstration projects to validate innovative technologies to reduce LCOE and expedite development of the U.S. offshore wind industry. Three projects were competitively "down-selected" in 2014 for continued funding and are required to be grid-connected and producing power by the end of 2017.[15] These projects demonstrate features, such as innovative U.S.-developed twisted jacket foundations, hurricane-resilient design, and floating semisubmersible foundations. As of the end of 2014, the U.S. Department of Interior had issued seven commercial wind energy leases on the Outer Continental Shelf, including those offshore of Delaware, Maryland, Massachusetts, Rhode Island, and Virginia.[16]
- **Market acceleration and deployment.** Reducing the cost and impact of market barriers that limit wind deployment, including issues related to potential wildlife impacts, radar interference, workforce development, and public awareness. The nation can leverage existing scientific capabilities and new technology solutions to enable sustainable wind deployment in more locations, focusing on supporting development of monitoring and mitigation tools necessary for the industry to obtain new permits required under the Bald and Golden Eagle Protection Act; compliance with provisions of legislation, such as the Magnuson-Stevens Fishery Conservation and Management Act, the Marine Mammal Protection Act, and the Endangered Species Act; collaboration on using publically available U.S. Interagency Field Test and Evaluation (IFT&E) results[17] to mitigate wind turbine interactions with civilian and military radar; and development of national public acceptance baseline studies to provide

quantitative assessment of the factors associated with public acceptance of wind energy development across the country.

- **Advanced grid integration.** Optimize grid integration (distributed and utility) and transmission for wind systems through integration studies and operational forecasting tool development, including development of grid management and control systems that enable high penetrations of wind with high grid reliability. Opportunities exist for development and deployment of tools to ensure reliable and economic system operations under high penetration levels of wind generation; further integration studies to fully understand the effect of wind on the U.S. power system and support the adoption of effective operational practices; planning and development of new infrastructure to allow access to high quality wind resources; evaluation of system response to uncertainties and electrical phenomena associated with wind power and develop operations practices for system operator use; and improved wind power controls to benefit grid power quality.

Major Challenges

Market challenges include the following:

- Increased need for transmission capacity, including transmission located with access to high quality wind resource sites
- Perceived and actual project risk with respect to performance, reliability, and lifetime
- Market valuation for carbon and criteria pollutant impacts
- Fair, consistently-applied long-term policy stability to spur investment

Technology challenges include the following

- Enabling optimized wind plant operation using advanced sensors and control algorithms capable of utilizing the advanced understanding of atmospheric flows and their interaction with wind turbines to maximize power production while minimizing the impact to reliability
- Development of improved modeling methodologies and disseminating observational data that can advance the state-of-the-art industry wind plant design and siting practices
- Continued reductions of LCOE for land-based and offshore wind plants

National Research, Development, Demonstration, and Deployment (RDD&D) Opportunities

This section describes national opportunities for U.S. wind power technology to achieve widespread market competitive LCOE and improved deployment opportunities for both land-based and offshore wind.

Wind Plant Optimization

Achieving cost parity with conventional electricity generation sources remains a significant challenge that requires an expanded R&D portfolio to exploit performance gains possible from holistic wind plant design and operation. Improving integrated wind plant performance would enable high penetration scenarios where wind power is a critical contributor to the overall U.S. energy mix. Increasing wind's value requires advances in integrated system design and control capability, technology innovation, and operational strategies that reduce performance losses, uncertainties, and the associated risk to achieve the targeted cost reductions. A national R&D program with a strong systems-level perspective will be critical in mitigating various issues currently seen in operating wind plants:

- Wind plant power losses due to turbine wake interactions and other factors may be as high as 20%–30% in modern wind farms.[18]
- $100–$300 million in existing annual system operating costs can be saved through forecasting improvements of as little as 10%–20%.[19]
- Uncertainty in wind flow conditions into, around, and within large, multi-array wind plants result in premature failures and high O&M costs, as well as conservative design criteria and costly designs.[20]
- Uncertainties surrounding project risk can have a significant impact on the cost of money—this is critical for U.S. offshore wind energy deployment.[21]

A national opportunity exists to enable a new generation of "smart" wind plants that are designed and operated to achieve optimized performance through better understanding of the wind resource and the complex flow conditions found within an operational wind plant. Updated and higher-resolution analyses of resource-driven wind plant power losses can better define the scope of this opportunity. Improvements in long-term energy production assessments and short-term operational forecasting capabilities combined with real-time plant-level control strategies utilizing the latest advances in flow monitoring sensor technologies would enable future wind plants to optimize across a wide range of objectives in order to maximize profitability, lower the financial risk of wind plant ownership, and enable seamless integration of wind into the utility grid.

Wind Resource Characterization and Forecasting

Before the wind reaches a wind power plant it begins as part of a much larger, highly complex weather pattern that evolves over hundreds of kilometers and through many different geographic locations and terrains. This airflow is mixed through different altitudes and has characteristics ranging from the macroscale (e.g., large weather formations such as storms) to the microscale (e.g., flow over the wind turbine blades). Wind power plants, therefore, extract power from an extremely diverse, nonuniform, and multi-scale resource. In order to make accurate wind forecasts and to understand wind interactions within wind power plants, stakeholders must understand these large-scale weather patterns, local wind flow characteristics, and physical phenomena that drive the wind. Improved understanding in the underlying physics of the wind resource will lead to more accurate foundational forecast models, regional wind simulations, operational forecasting capabilities, and project siting tools—and hence, more efficient and cost-effective wind power production.

To understand atmospheric inflow development under a wide range of drivers—including weather, terrain, and the air/sea interactions offshore—investments in large-scale field campaigns employing a variety of instruments and observational techniques—including state-of-the-art remote sensing—are needed to acquire high-resolution data on various time scales, both upstream and downstream from the wind plant, as well as volumetric data within a wind plant itself. In the United States, wind stakeholders can leverage high-quality atmospheric data and results from the 2011–2012 Wind Forecasting Improvement Project (WFIP)[22] and the 2015–2016 WFIP Phase II,[23] which will focus on sites that include complex and mountainous terrain, coastal and island terrains, and offshore environments.

These high-resolution weather data sets and simulations may be used to develop high-fidelity wind plant inflow models and foundational forecast models. These atmospheric model improvements would provide the basis for understanding complex and poorly understood atmospheric and oceanographic environments and their effect on wind plant performance. Because the physical phenomena occur at multiple temporal and spatial scales, improved simulation technologies—as well as HPC capabilities—are needed as part of a comprehensive research plan. Stakeholders can continue to work with the National Oceanic and Atmospheric Administration (NOAA) and its partners to improve NOAA's High-Resolution Rapidly Refreshed model to help resolve the complex interaction between wind plants and the physical environment. This model, refreshed hourly, is critical for the wind industry because it provides input for short-term (0–6 hour) and day-ahead plant-scale forecasting models. The atmospheric inflow models can be integrated with wind plant models to optimize plant layout designs, enhance energy capture, reduce risk in electricity generation, and lower the cost of capital investments in wind plants.

Wind Plant Performance

The development and application of high-fidelity modeling tools are critical to informing opportunities in wind plant optimization. Such tools could be developed in a community-based, open-source simulation environment and would enable understanding and accurate prediction of the fundamental physics and complex flow within a wind plant as well as the response of individual turbines to the complex flows within that plant. The objectives of such a high-fidelity modeling strategy would be to evaluate the existing suite of computational tools to characterize their applicability and limitations in modeling wind turbine and wind plant performance and to develop the next generation of HPC modeling capability to accurately resolve the flow within wind plants on complex terrain and under the limits of extreme operating conditions.

Achieving optimized performance would require a significant investment in high-fidelity models and field test campaigns to characterize the operating environment and control potential of modern wind plants. Such tools would need to accurately replicate the complex physical process involved in the extraction of energy from the inflow by a wind plant. These processes include forecasting the inflow resource, quantifying the inflow characteristics, and capturing the subsequent interactions with and among wind turbines, terrain, and other structures as the inflow passes through the wind plant. Initial high-fidelity model development would focus on accurate characterization of the inflow into the wind plant and how turbine rotor wakes develop and evolve. Validating the ability of high-fidelity models to accurately predict the complex flow environment produced by the wind's interaction with the turbines inside a wind plant would require extensive experimental measurement and data collection campaigns at wind tunnels, at scale-sized test facilities, and in full-scale operational wind plants.

Establishing the model accuracy and uncertainties is critical to gain stakeholder trust in the capabilities of the newer models. A comprehensive validation effort would be necessary to quantify and assess any improvements in modeling capabilities. To this end, field and laboratory validation experiments can be used to gather the high-resolution data needed to verify and validate the models. Experimental campaigns can be designed and conducted closely with the model development effort through a formal verification and validation process, such as those utilized within the National Aeronautics and Space Administration and National Nuclear Security Administration, to clearly establish the capabilities and limitations of models that are disseminated to the industry.

Innovative Technology Development

Better insight into the complex flow environment within and around wind plants would inform the development of the next generation of technology improvements to mitigate the underperformance and premature failures observed in existing wind plants. The following are examples of national opportunities:

- **Integrated wind plant control.** Development of controls capability at the wind plant scale could play a crucial role in implementing much of the physics-based understanding of advanced high-fidelity modeling and experimental efforts. Improved knowledge of the inflow and turbine-turbine interaction would enable high-level, site-specific, physics-based optimization of wind power plants for both land-based and offshore applications. Control considerations include energy production, reliability, raw material costs, services to the utility grid, cost of energy, uncertainty reduction, and power density. Developing real-time, wind plant control capability would require innovative, cost-effective flow measurement sensor technology, novel turbine to turbine communication strategies, and high-bandwidth controllers that can optimize over a wide range of variables capable of addressing the grid requirements in conjunction with the performance and plant reliability objectives.

- **Aeroacoustics and propagation.** Human perception and annoyance from wind turbine noise is not well understood. In order to increase the public acceptance of wind and reduce the risk of curtailment for noise considerations, it is necessary to develop a better understanding of the fundamental mechanisms of wind plant noise generation, propagation, and reception through scientific research and to disseminate research results and recommend best practices that will benefit industry and community stakeholders. Primary goals of such an effort would be to provide the scientific basis for long-term advances in wind plant noise prediction and reduction, develop standardized metrics and regulatory models for wind plant noise, and provide an easily accessible and reliable public information warehouse.
- **Integrated wind plant design and analysis.** Integrated wind plant systems design and analysis focus on wind plant optimization through improved plant design capability and better defined design criteria that can be adopted by the industry to design and operate the next generation of wind plants. Such an effort would benchmark any shortcomings of current industry design tools and practices, develop and validate improved models to analyze and mitigate losses from plant wake interactions, and evolve improved design standards that reflect the realistic operational environment and constraints.

Performance Risk, Uncertainty, and Finance

Deployment of wind energy can be facilitated by lowering the real and perceived risk and uncertainty associated with developing, investing in, owning, and operating wind power plants. Opportunities exist to investigate the impact that project uncertainties have on financial structures, the cost of capital, the cost of ownership, the perception of financial risk, and the LCOE for wind. Research in this area would be expected to identify opportunities to reduce financial risk from existing levels and to motivate research programs within the wind research community. The research scope would include uncertainties that are driven by the complex wind flow leading up to and within wind plants and uncertainties that are relevant at the time of financial investment decision, not during early project prospecting or during out-year project budgeting. Improved models to predict inflow with high accuracy would lead to more reliable and cost-effective design, and further research can lead to new and better design standards and methods for verification of site suitability.

By focusing on risk and uncertainty, stakeholders could make a real contribution towards achieving high-level industry objectives by improving the business case and potential returns for investing in wind energy, increasing the profitability of owning and operating wind power plants, encouraging new sources of capital to enter the wind market, and reducing the cost of wind energy.

Industry stakeholders have identified the following as important to such an effort:[24]

- Improve trust, data sharing, and communication among industry stakeholders
- Identify, target, and reduce specific wind plant uncertainties and financial risks
- Reduce the perception of risk and illuminate actual risks to a broad audience
- Improve project financial assessments for current and future wind power plants
- Communicate high value R&D opportunities to the wind research community

Wind Turbine Components and Materials

While the primary focus of industry R&D has expanded to examine wind plants as a whole, it is still necessary to conduct targeted R&D on turbines and their components because they are the energy-producing element of any wind plant energy system. National opportunities in this area include “incubator” programs to promote novel and innovative component R&D that improves overall wind turbine system performance.

Examples of such high-risk, potentially high-reward technologies include superconducting generators, multivariate control systems, active control systems, and rotor blade control surfaces. Expanding the superconducting generator example, it will take several years of low technology readiness level R&D to prove system designs and system reliability to a point where industry might consider designing operational generators of this type. Given the potential of this technology to facilitate cost-effective turbine scaling to levels greater than 15 MW, this is an important area of research.

Specific objectives of such activities would include increasing rotor diameter to increase energy capture, advanced drivetrain development, tower and foundation technologies, and advanced offshore substructure technologies. Expected outcomes of this R&D area would include novel blade and rotor architectures that will allow for longer, lighter blades. These longer blades would allow greater energy capture within a given resource, thereby increasing capacity factor. Advanced drivetrain R&D would result in more reliable, highly scalable drivetrain system, potentially including novel gearbox and generator architectures. Tower, platform, and foundation R&D would look at advanced technologies for on-site or regional manufacturing of land-based wind turbine components as well as cost-effective ways to increase hub height with minimal cost.

Innovation incubators and high risk material and design R&D. Breakthrough innovations are generally considered to be "game-changing" solutions, employing new technologies that cannot be compared to any existing practices or techniques. Innovative companies have learned that mainstream business and marketing structures significantly constrain blue-sky thinking, while autonomous incubators allow creation of new value where none previously existed.[25] An early example of this is the development of interchangeable parts, which revolutionized manufacturing. These were developed at public armories, originally for rifles, under President George Washington.[26] A more recent example is the X Prize Foundation, a nonprofit organization founded in 1995 that designs and manages public technology incubator competitions intended to encourage technological development that could benefit mankind.[27] Elements required for spurring game-changing innovation for wind technology include the following:

- Teams that bring together diverse expertise and skill sets
- Willingness to take a fundamentally different approach with little to no commitment to retaining initial early concepts
- Ability and incentive to attempt high risk innovations
- Strong focus on the end goal and a clear understanding of what is needed to meet it

Examples for wind technology are development of low-cost, high-performance carbon fiber for use in lighter, longer wind turbine blades, reducing blade leading edge erosion, improving component reliability, and developing component materials that are more manageable from a life-cycle perspective, taking into account recyclability and future disposal.

Manufacturing. Next-generation wind turbines under development for land-based deployment (2–3 MW) offer potential economies of scale compared to the current fleet of operating turbines. However, deploying even larger turbines requires overcoming several transportation and logistical constraints that are unique to land-based systems. Innovations such as spiral-welded towers, segmented blades, and modular generators could enable continued turbine scaling. In addition to continuing LCOE reductions from economies of scale, this could also lead to a significant increase in the locations, particularly where there are lower average wind speeds, where cost effective deployment is possible. Due to the high initial costs of financing and prototyping field units, partnerships may be desired among technology developers, project developers, and original equipment manufacturers on the first full-scale demonstrations to manufacture and demonstrate these prototyped units. Activities may include the following:

- Modular component and system designs
- Offshore port on-site manufacturing techniques to enable low-cost, domestic manufacturing solutions
- Offshore floating platform designs and demonstration to withstand extreme weather events (e.g., hurricanes) and support very large turbines of 10 MW and greater

- New rotor manufacturing assembly technologies, including carbon-fiber work geared toward exceeding the strength and stiffness-to-cost ratio relative to conventional materials from an integrated systems approach to blade manufacturing

World-class Test and User Facilities

Full-scale, accredited test facilities and trained engineers capable of developing test methods and conducting full-scale tests are in high demand, but these facilities can be cost prohibitive for any single company to build and operate. The federal government's role has been to provide component and system test facilities that industry can use to validate designs prior to large-scale deployment. This has been especially true for wind turbine blades and drivetrains, where DOE test facilities have been used to perform highly accelerated life testing. These test facilities support collaboration between industry and government on codes and standards development, including components and system design requirements, testing requirements, measurement techniques (load, power quality, and acoustics), modeling techniques, safety concerns, and conformity testing and certification. Opportunities exist for developing generally accepted and state-of-the art test methods and guidelines for interpretation. In addition, development of an experimental database of test results from component tests and load tests from turbines in large wind farms and offshore could help support validation of design methods and further R&D in new technology and upscaling.

DOE has developed a Technology-to-Market initiative to identify and develop strategies to overcome key barriers to the development and success of commercial enterprises built around the Office of Energy Efficiency and Renewable Energy's technologies and initiatives, including wind power.[28] The initiative will help industry stakeholders come into contact with testing facilities available at the national laboratories (e.g., National Wind Technology Center [NWTC] 5-MW dynamometer or the Sandia National Laboratories [SNL] Scaled Wind Farm Technology [SWiFT] facility) and through industry partnerships (e.g., Massachusetts Wind Technology Testing Center or Clemson University's Energy Innovation Center).

The broad user community currently uses DOE test facilities to test various components (e.g., blades and drivetrains) to industry fatigue life standards or to test properties of innovative components that are still under development. Taken together, these test facilities represent a world-class capability unique to the United States. Both domestic and international industry partners as well as the larger international R&D community utilize these facilities. Successful design verification through testing has been critical towards gaining financial community confidence. Availability and access to these test facilities will continue to be important catalysts in advancing wind energy technology development. Table 4.S.1 provides a summary of existing federal wind-related test facilities, along with their intended purpose and status.

Offshore Wind Technology

Offshore wind energy has the potential to be a high-yield renewable energy source near major urban areas that typically have higher than average electricity rates. However, U.S. offshore projects face a daunting array of regulatory steps, installation challenges, and financial uncertainties. Consequently, as of the end of 2014, no projects had yet been installed in this country, delaying the opportunity to tap into the significant U.S. offshore wind resource potential. At the same time, offshore wind is becoming a sustainable economic development engine internationally, particularly in Europe. Many coastal U.S. states, seeking to emulate the European experience, see offshore wind development as an economic driver in revitalizing ports and heavy manufacturing infrastructure, building local supply chains, and creating a steady flow of highly skilled jobs.

Offshore Wind Advanced Technology Demonstrations

A competitive U.S. offshore wind industry requires substantial reductions in costs, timelines, and technical risks. In order for the U.S. to be competitive on a global scale, multiple factors need to be addressed

Table 4.S.1 DOE-Supported Wind Energy Testing and Validation Facilities

Facility	Location	Details	Status
225 KW Dynamometer	Boulder, CO (NWTC)	Small wind turbine drivetrain testing	Operational
2.5 MW Dynamometer	Boulder, CO (NWTC)	Medium-scale wind turbine drive testing; gearbox reliability collaborative research	Operational
5.0 MW Dynamometer	Boulder, CO (NWTC)	Utility-scale wind turbine drivetrain testing	Operational
7.5 MW Dynamometer	Charleston, SC (Clemson U.)	1st Generation offshore wind turbine drivetrain testing	Operational
15 MW Dynamometer	Charleston, SC (Clemson U.)	2nd Generation offshore wind turbine drivetrain testing	Operational
19m Blade Test Stand #1	Boulder, CO (NWTC)	Scale testing of wind turbine blade innovations; scaled evaluation of improved blade testing methods	Operational
19m Blade Test Stand #2	Boulder, CO (NWTC)	Small wind turbine blade testing	Operational
50m Blade Test Stand	Boulder, CO (NWTC)	Utility-scale wind turbine blade testing; full-scale evaluation of improved blade testing methods	Operational
90m Blade Test Facility	Boston, MA (MCEC)	Utility-scale blade testing; three test stands sized for anticipated blade lengths of the offshore wind industry	Operational
CART-2/3 Turbines	Boulder, CO (NWTC)	Controls Advanced Research Turbines (CART): Two 600-KW turbines for advanced control algorithm R&D	Operational
1.5 MW Research Turbine	Boulder, CO (NWTC)	GE 1.5-MW utility-scale wind turbine available to researchers for field testing of innovative technology	Operational
Controllable Grid Interface	Boulder, CO (NWTC)	Simulates electrical grid faults for testing of wind turbine drivetrains	Operational
Grid Simulator	Charleston, SC (Clemson U.)	Research on turbine-to-turbine interactions in wind plants	Operational
SWiFT Facility	Lubbock, TX (Texas Tech Univ./SNL)	Three 300-kW research turbines for turbine-turbine interaction R&D	Operational

concurrently. These factors cannot be addressed by industry alone. By providing funding, technical assistance, and government coordination to offshore advanced technology demonstration projects, DOE efforts are underway to help eliminate uncertainties, mitigate risks, and support the private sector in creating a robust U.S. offshore wind industry. DOE's offshore demonstration projects[29] are commercial ventures for which DOE is providing partial funding in order to facilitate use of innovative technical solutions and to reduce market barriers. These projects are aligned with the National Offshore Wind Strategy[30] jointly announced in 2011 by the Secretaries of Energy and Interior.

The DOE-sponsored offshore wind demonstration program aims to establish world-class technical demonstration and evaluation capabilities in conjunction with commercial developments to support validation of innovative technology, installation methods, and operation and maintenance strategies. These geographically diverse projects will also aid in establishing and validating the infrastructure required for offshore wind plant installation and operation. Projects will incorporate next-generation technologies adapted to the North American environment and operating parameters, consider several innovative offshore foundation types, and address public concerns associated with the concept of offshore wind.

DOE issued the competitive Funding Opportunity Announcement (FOA) U.S. Offshore Wind: Advanced Technology Demonstration Projects in 2012.[31] Projects receiving funding under this FOA are to be commissioned at an accelerated timeframe, followed by a five-year data collection period. In December, 2012, DOE announced seven awardees for the initial phase of the offshore demonstration project. Three Offshore Wind Technology Demonstration projects were down-selected in FY2014 to complete the final engineering design, finalize vendors, and begin procurement and fabrication of major project components, such as foundations and turbines. Cost share will be a minimum of 20% for the balance of the design process and 50% or greater during the subsequent building and operating phases. Awardees will also be required to collect and share with DOE a wide range of data on operational characteristics, wind plant performance, and environmental parameters for the first five years of operations. These data can help validate technology designs and design tools. The three selected projects all demonstrate unique innovations as follows:

- The first will utilize an innovative, U.S.-developed twisted jacket foundation that is simpler and less expensive to manufacture and install than traditional offshore wind foundations.
- The second will install and test a hurricane-resilient design to ensure that offshore wind facilities placed in hurricane-prone U.S. waters are reliable, safe, and cost-effective.
- The third will deploy a floating semisubmersible foundation, demonstrating an innovative solution for deep water wind turbine projects and lowering costs by simplifying installation and eliminating the need for highly specialized ships.

Offshore Wind-Specific R&D

The DOE Offshore Wind Advanced Technology Demonstrations alone will likely not lead to reduction of LCOE to levels competitive with other energy sources. Opportunities exist in crosscutting efforts, including implementing a national offshore “metocean” data campaign, accelerating siting and deployment strategy development for offshore wind plants, optimizing wind plant design and performance for the offshore environment, and evaluating grid integration and electrical subsystem strategies for offshore wind plants.

Market Acceleration and Deployment

National opportunities exist to reduce market barriers to preserve or expand access to quality wind resources. Research can increase the national understanding of wind’s benefits for and impacts on resources of concern; develop mitigation measures to avoid, minimize, or compensate for those impacts; and disseminate objective information regarding these issues to decision makers and the public. Such efforts would in turn lead to more effective siting, reduced timelines, and improved certainty associated with regulatory review, ultimately preserving or expanding access in wind resource areas affected by siting challenges. Areas for potential development can be impacted by public acceptance, radar, and wildlife. Even where wind is already cost-competitive, challenges in any of these areas can be showstoppers. Sixty percent of the available wind resource in the United States (6,300 of 10,500 GW) is coincident with at least one moderate public acceptance, radar, or wildlife challenge.[32]

Environmental and Wildlife Information

The following are examples of activities that could supply decision makers and communities with the environmental and wildlife information they need to make smarter decisions about siting projects in order to capture strong wind resources while minimizing risk to sensitive species and habitats:

- Develop technologies and methods to assess and monitor environmental and wildlife impacts
- Monitor first-generation offshore wind projects for potential impacts
- In collaboration with federal and industry partners, conduct baseline and mitigation studies on wildlife that are of high-priority interest to regulators and the public, particularly eagles, bats, and prairie grouse

Examples of potential initiatives to reduce siting and regulatory uncertainty for developers would provide viable risk mitigation strategies to enhance the geographic area available for development and are given in Table 4.S.2.

Table 4.S.2 Example Environmental and Wildlife Initiatives Designed to Mitigate Market Barriers

Topic	Land-based			Offshore
	Eagles	**Birds**	**Prairie Grouse**	**Impact Characterization and Analysis**
Focus	■ Develop a wide range of quantifiable compensatory and operational mitigation measures to offset/reduce fatalities ■ Develop viable advanced conservation practices to support effective low-risk siting and permitting of wind turbines in eagle habitat ■ Develop effective bat deterrent technologies to reduce fatalities		■ Collect and analyze pre- and post-construction factors to determine long-term impact of wind power on grouse populations ■ Develop and refine tools to predict risk to grouse at current and future developments ■ Develop risk minimization and mitigation tools to offset potential risks	■ Research to evaluate potential environmental impacts ■ Development and testing of monitoring and mitigation technologies and techniques ■ Meta-analyses of impacts
Impact	■ Better understand the relationships between wildlife and wind turbines ■ Develop risk minimization and mitigation strategies to reduce local and population-level impacts to wildlife			■ Better understand environmental impacts and how to measure those impacts
Long-term Outcomes	■ Preserve or expand geographic areas available for development ■ Reduce siting and regulatory uncertainty for developers			

Human-Use Conflicts

DOE conducts RD&D on technologies that will reduce interference from wind turbines on radar systems to minimize impacts on other federal national defense, national security, air safety, and weather forecasting missions. There are national opportunities to leverage partnerships with the Department of Defense (DOD), the Department of Homeland Security (DHS), the Federal Aviation Administration (FAA), and NOAA and—based on successes already achieved through the IFT&E campaigns—to assess and demonstrate radar mitigation technologies at commercial land-based wind facilities, advance modeling and simulation techniques that will facilitate siting new wind facilities in areas with least impact to critical missions, develop algorithms to process radar data to eliminate wind energy interference while maintaining the overall air picture, and explore international collaboration and other pathways to understand how to assess and mitigate the potential effects of offshore wind facilities on various radar systems.

Successful expansion of wind deployment requires more than technical innovation alone. Industry best practices that ensure procedural fairness and access to credible information are critical for public acceptance of wind technologies at the community level. Continued development of GIS tools that provide the industry, stakeholders, and agencies a common platform to look at the potential challenges and benefits associated with wind energy development can increase the transparency and inclusiveness of the development process and potentially lead to better outcomes.[33]

Information Dissemination

WINDExchange is a national Web-based portal for disseminating credible information about wind energy on the national, regional, and local scales.[34] Its purpose is to help communities across the nation weigh the benefits and costs of wind energy, understand the deployment process, and make wind development decisions supported by the best available information. The body of information on deployment challenges includes, among other things, economic analyses, resource assessments, and environmental data. Wind energy technology improvements and market developments provide opportunities to update these resources to ensure that they represent the state of the industry and its opportunities accurately.

Accurate, unbiased information can increase stakeholder familiarity with wind and help them understand the benefits wind offers, both of which are fundamental enabling conditions of technology adoption. Outreach activities structured around RDD&D results, especially technology demonstrations, deliver more direct experience to stakeholders, familiarizing them with real examples that go beyond theory, potential, and models. Methods of dissemination include information graphics, webinars, Web presence, training opportunities, and education programs and projects. These outreach tools are vital to increasing familiarity, reducing uncertainty, and informing policy, siting, permitting, and developer decision making. Over time, as the land-based market further matures, the focus of information resources can be shifted more toward the offshore wind market.

Advanced Grid Integration

Wind energy resources present a number of challenges to grid system planners and operators who are more accustomed to conventional baseload and dispatchable generation. These challenges include understanding the effects of increased penetrations of variable generation, understanding integration costs, developing new grid operating capabilities, understanding and valuing the role of ancillary services from variable generation and storage, and developing new transmission planning tools to help ensure access to high-quality resource areas. Opportunities in advanced grid integration are to remove barriers to wind energy deployment through a variety of activities, including integration studies, model and tool development, and demonstrations of new wind turbine capabilities such as active power control.

Electricity markets in the United States are not currently optimally designed for high penetrations of variable generation. These markets have largely utilized conventional, fossil fuel generation for baseload, intermediate, and peak-load system needs, and as such, they have been structured with conventional generation in mind. As wind penetration levels increase, the near zero marginal energy cost from wind plants can decrease the marginal prices of energy being sold on the grid. This is a result of the wind resource being a no-cost fuel source. Negative prices can be seen during periods of high wind output in conjunction with severe transmission congestion and the inability to further reduce the output of conventional generation on the system, making it difficult for conventional generators to capture sufficient revenue for cost recovery.[35]

Transmission development in the United States is a complex process with a large number of stakeholders seeking to meet a variety of objectives, governed by a large number of regulatory environments, and is currently in a state of flux as new regulations are being passed that allow for the consideration of new criteria in the transmission planning process. Interregional transmission—needed for energy market balancing and vital for wind deployment into high-quality resource areas—is further limited owing to permitting and siting issues. Determining the interconnection-wide effects of transmission development will reduce congestion and open access to high-quality resource areas, thereby reducing a key wind deployment barrier, and will enable more economic operation of the grid on a national scale, thereby reducing consumer costs. Federal Energy Regulatory Commission (FERC) order nos. 890 (2007) and 1000 (2011) have made efforts to improve this cooperation by requiring open, transparent transmission planning processes with rates approved by FERC for the public good; however, national effort may be needed to facilitate transmission expansion. There are opportunities to conduct interconnection-wide integration studies and carry out national system flexibility assessments that would examine generators, transmission, grid operations, and planning, incorporating analysis of economic and technical characteristics to determine necessary infrastructure technological, operational, and market improvements.

Grid System Planning

Grid system planning relates to the evaluation, design, and construction of infrastructure to meet expected system conditions at some future point in time. As additional wind generation is integrated into the system, grid planning will need to adapt to maintain a reliable, economic grid that integrates large penetrations of variable renewable generation under a more probabilistic approach, where tools analyze the system under a wide variety of system states and provide indicators of the level of risk in operating in a given state. The current generation of planning tools and methods used by system planners is not adequate for the evolving nature of the grid. Opportunities for additional grid system planning efforts include the following:

- Supporting the development and deployment of models and tools to ensure reliable and economic system operations under high penetration levels of wind generation
- Conducting integration studies to fully understand the effect of wind on the U.S. power system and supporting the adoptions of effective operations practices
- Supporting the planning and development of new infrastructure to allow access to high quality wind resources

Wind deployment models and tools. Research areas for improving wind deployment models and tools that can be used by grid system planners to enable increased penetration levels of wind include wind generator models and dynamic transmission line rating tools. Development and improvement of complex, accurate and nonproprietary generic wind turbine generator simulation models for power system planning and interconnection have been identified as an area where such efforts could make significant impact. Simulation models and tools are used by grid system planners and others to assess impacts of variable generation addition and also to help evaluate and expand the assumptions used in grid modeling tools to improve flexibility in incorporating wind energy.

Another substantial hurdle to wind power deployment is the response to and management of transmission congestion. Dynamic transmission line rating may help address this. Opportunities exist to analyze the effects of weather, such as ambient temperature and wind, on transmission line ratings and to develop tools to allow system planners to utilize this analysis. The “ampacity,” or maximum current-carrying capacity, of transmission lines is based on a thermal constraint caused when current passes through the conductor and generates heat. This constraint has typically been determined by the material of the line prior to installation, and the current through the line is never permitted to exceed this initial rating. However, weather conditions such as ambient temperature and wind can reduce the temperature of the conductor, which would allow more current on the line, thus providing a dynamic rating of the transmission line capacity.

Wind integration studies. Integration studies are used to determine the effect that evolving generation mixes have on the reliability, operation, and economics of a system. Load profiles of a system at all times throughout a year are time synchronized in relation to the wind generation profiles. Because both load and wind generation profiles are variable, their net impact (or resulting "net load") must be managed by system operators. The scope and scale of U.S.-focused studies, such as the Western Wind and Solar Integration Study[36] and the Eastern Wind Integration and Transmission Study,[37] are such that industry cannot undertake them on its own, but the findings from these studies have identified impacts of variable generation and necessary infrastructure development that can be applied to future grid planning. Going forward, thanks to new wind data sets that are currently being completed, integration studies will have at least 10 years of wind data available to understand integration impacts over longer time frames. These data sets can be incorporated into manufacturers and operators models and control systems, allowing for increased granularity of their modeling capabilities.

Infrastructure development support. The U.S. power system currently consists of three asynchronous interconnections across the country, with vast transmission networks connecting numerous states, regions, and markets within each interconnection. The diverse scope and scale of transmission development require that interconnection-wide benefits be examined.

National opportunities exist to work with a wide variety of stakeholder groups to ensure that wind is reasonably considered in transmission development plans, to support the development of tools to help transmission planners identify locations that are the most beneficial to helping integrate wind into the bulk power system, and to work with regulators and top-level decision makers to help them understand how regulatory efforts can aid in transmission development that benefits not only the wind industry but also the power system as a whole.

Grid System Operations

Grid system operation relates to the adjustment of existing system infrastructure to maintain supply and demand balance plus some level of system reserves. National opportunities exist to ensure the secure and reliable operation of the power system under high levels of deployed wind energy. The introduction of large penetrations of variable generation is increasing the variability and uncertainty of supply to the power system, requiring system operators to adapt their tools and understanding to manage this evolution. Examples of potential grid system operations efforts include the following:

- Evaluating system response to uncertainties and electrical phenomena associated with wind power, developing operations and standard practices for system operators to apply system response principles into normal operation, and improving wind power controls to benefit grid power quality through activities such as voltage ride-through and frequency control
- Evaluating market structures and signals to develop economic wind deployment solutions

Wind plant operations and standards. Opportunities exist to improve the ability for wind plant operators and system operators to utilize wind plants to safely manage the stability of the grid and improve electrical system design standards for safety and protection purposes. This could include working with utilities to update their energy management systems and support operational changes needed to benefit higher wind penetrations, such as reduced scheduling windows. Engagement and training for system operators to implement and utilize new wind forecasting and active power control tools will continue as new tools are developed.

Additionally, active power controls within the wind turbine can allow the turbine to maintain or improve power quality throughout the larger power system by injecting or withholding power during grid stability events. These controls would allow the turbines to actively participate in voltage and frequency regulation in the system.

Grid economic and market structure analysis. Most energy markets and regulations currently in place are not designed for large-scale variable generation sources. For example, it is not well understood how the increasing addition of low-cost energy sources such as wind will impact electricity market prices over the long term, which can lead to other generation sources not earning enough revenue to remain in operation, which can adversely impact system reliability if these generators are mothballed and unavailable during a time of high load and low wind generation.

Forecast errors can be minimizing via reduced scheduling windows, the amount of time for which a generation unit pledges to produce energy at a given level, to lower reserve costs and improve wind plant profitability.

The variability of wind generation, when taken in aggregate, is also reduced as the area of operation increases. The size of balancing authorities (BAs) plays a role in the cost of integrating and operating wind plants. A BA with wind generation on its system will have to balance the net load variability (load minus wind) by using the remaining generation on the system. BAs that manage larger regions, with wind plants spread out over a larger geographical area, will see a reduction in the variability that will need to be accounted for on a per-plant basis, which will reduce operating costs on the system.

Collaboration with DOE's Office of Science

There is significant potential to leverage the expertise and capabilities from DOE's Office of Science (OS) Advanced Scientific Computing Research (ASCR) program to analyzing important physics problems currently facing the wind industry, including access to HPC facilities and development of robust, scalable algorithms.

Potential opportunities include developing joint R&D activities with wind stakeholders along the lines of the Scientific Computation Application Partnerships in High Energy Physics—a collaboration between the OS High Energy Physics and ASCR programs—under DOE's Scientific Discovery through Advanced Computing program. Under such a collaborative, the nation would fund wind domain experts and ASCR would help fully utilize leadership class computing resources as well as providing expertise on topics, such as numerical methods, model coupling issues, code performance, and "exascale" computing readiness for wind applications. Through such an activity, multiyear research plans focusing on multi-scale, multidisciplinary modeling efforts for wind energy could be developed and executed.

Interagency and International Coordination

U.S. wind stakeholders coordinate with many U.S. departments and agencies through working groups, memoranda of understanding, and other formal and informal relationships as well as engagement with international stakeholders through the International Energy Agency (IEA), the International Electrotechnical Commission, and other partnerships. Opportunities exist to enhance and expand this collaboration. Examples of U.S. interagency and international coordination are as follows:

- Wind plant optimization includes national coordination with DOD/Department of Transportation (DOT)/Department of the Interior (DOI) (FAA, DHS) on radar technical solutions and taller towers and with NOAA on resource characterization through WFIP.
- Technology transfer includes national coordination with DOD/DOI (Navy, Bureau of Ocean Energy Management [BOEM]) on offshore wind permitting and IEA on codes and standards.
- Market barrier mitigation includes national coordination with DOI BOEM, the U.S. Fish and Wildlife Service and IEA on wildlife and siting and includes coordination with DOD, DHS, DOT (FAA), and Department of Commerce (NOAA) on wind radar issues.
- Advancing grid integration includes national coordination with DOE's Office of Electricity and FERC on policy, codes, and standards.

Technology Metrics and Impacts

In 2015 DOE released the Wind Vision Report, summarizing multiple analyses conducted to deepen the understanding of U.S. wind power's potential contributions and related impacts.[38] The report finds that deploying incremental U.S. wind power generation in a U.S. portfolio of domestic, low-carbon, low-pollutant power generation solutions is both feasible and economically compelling and that U.S. wind power could provide greater than one-third of the U.S. power generation by 2050 but would require concerted actions to achieve this level of contribution. The *Wind Vision Report* updates and expands on DOE's 2008 report, *20% Wind Energy by 2030*.[39]

The *Wind Vision Report* represents a collaboration of DOE with over 250 wind industry representatives, electric power system operators, environmental stewardship organizations, federal government agencies, research institutions and laboratories, and siting and permitting stakeholder groups to inform actions and options in the development of incremental U.S. wind power. The report finds that, given achievement of technology innovation and related impacts with targeted LCOE reductions, along with favorable market mechanisms and transmission availability, U.S. wind power can sustainably address key societal challenges, such as climate change, air quality and public health, and water scarcity, as a substantial part of the U.S. power portfolio. Wind deployment can provide U.S. jobs, U.S. manufacturing, and lease and tax revenues in local communities to strengthen and support a transition towards a low-carbon economy.

The *Wind Vision Report* analyzes the impacts of wind power supplying the nation 10% of its electricity demand by 2020, 20% by 2030, and 35% by 2050. This *Central Study Scenario* in the *Wind Vision Report* is neither a projection nor target but instead is an analytical scenario for conducting detailed quantitative impact analyses. The *Wind Vision Report Central Study Scenario* analysis demonstrates the benefits of and the actions required for U.S. wind power achieving up to 35% of U.S. power generation by 2050, with the following impacts:

- Reduction of lifetime GHG emissions of U.S. power generation, with significant value of cumulative avoided global climate change damages from 2013–2050
- Reductions of criteria air pollutants (e.g., SOx, NOx, PM2.5 [particulate matter]), with significant cumulative avoided health and economic damages from air pollution from 2013–2050
- Reductions of water consumption and withdrawals by power plants, with significant cumulative water saving by 2050
- Reductions in U.S. electricity rates by 2050
- Energy diversity and reduced natural gas demand rate impacts, with cumulative natural gas demand cost reductions from 2013–2050 and a reduction in the sensitivity of total electric system costs to natural gas price fluctuations in 2050
- Local and regional impacts, including local tax benefits and lease impacts, and addition of U.S. wind related jobs in U.S. manufacturing, operations, and induced employment
- Actual land area within wind plants that is occupied by wind turbines, roads, and other project infrastructure equivalent to less than one-third of total land area currently occupied by U.S. golf courses

DOE tracks the current state of the U.S. wind industry and its technology, cost, pricing, and installation trends and policy and market drivers in its annual *Wind Technology Market Report*. These data informed the *Wind Vision* report and can be used to track the progress in U.S. wind power deployment.[40]

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Acronyms

ASCR	Advanced Scientific Computing Research
AWEA	American Wind Energy Association
BA	Balancing Authority
BOEM	Bureau of Ocean Energy Management
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
DOT	Department of Transportation
EIA	Energy Information Administration
FAA	Federal Aviation Administration
FOA	Funding Opportunity Announcement
GHG	Greenhouse Gas
GIS	Geographic Information System
HPC	High-Performance Computing
IEA	International Energy Agency
IFT&E	Interagency Field Test and Evaluation
LCOE	Levelized Cost of Energy
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrogen Oxides
NWTC	National Wind Technology Center
OS	Office of Science
PM2.5	Particulate Matter (2.5 microns in size or less)
SOx	Sulfur Oxides
SWiFT	Scaled Wind Farm Technology
WFIP	Wind Forecasting Improvement Project

Glossary

Aeroacoustics	Branch of acoustics that studies noise generation via either turbulent fluid motion or aerodynamic forces interacting with surfaces.
Ancillary services	Grid services that support the transmission of electricity from its generation site to the customer. May include load regulation, spinning reserve, non-spinning reserve, replacement reserve and voltage support.
Dynamic transmission line rating	Transmission line capacity ratings calculated in real time based on the transmission line's actual operating conditions, rather than on fixed assumptions as used in conventional static transmission line capacity ratings.
Dynamometer	A device for measuring force, torque, or power, often as a function of rotational shaft speed of the device being measured.
Variable generation	Expected changes in power system generation, with deployment of operating reserves needed if the variability occurs at time resolutions that scheduling resolutions are not prepared for. Wind power is considered variable in that there may be discrepancy between forecast and observed wind resources at a given time.
WINDExchange	The U.S. Department of Energy Wind Program's online hub of stakeholder engagement and outreach activities.