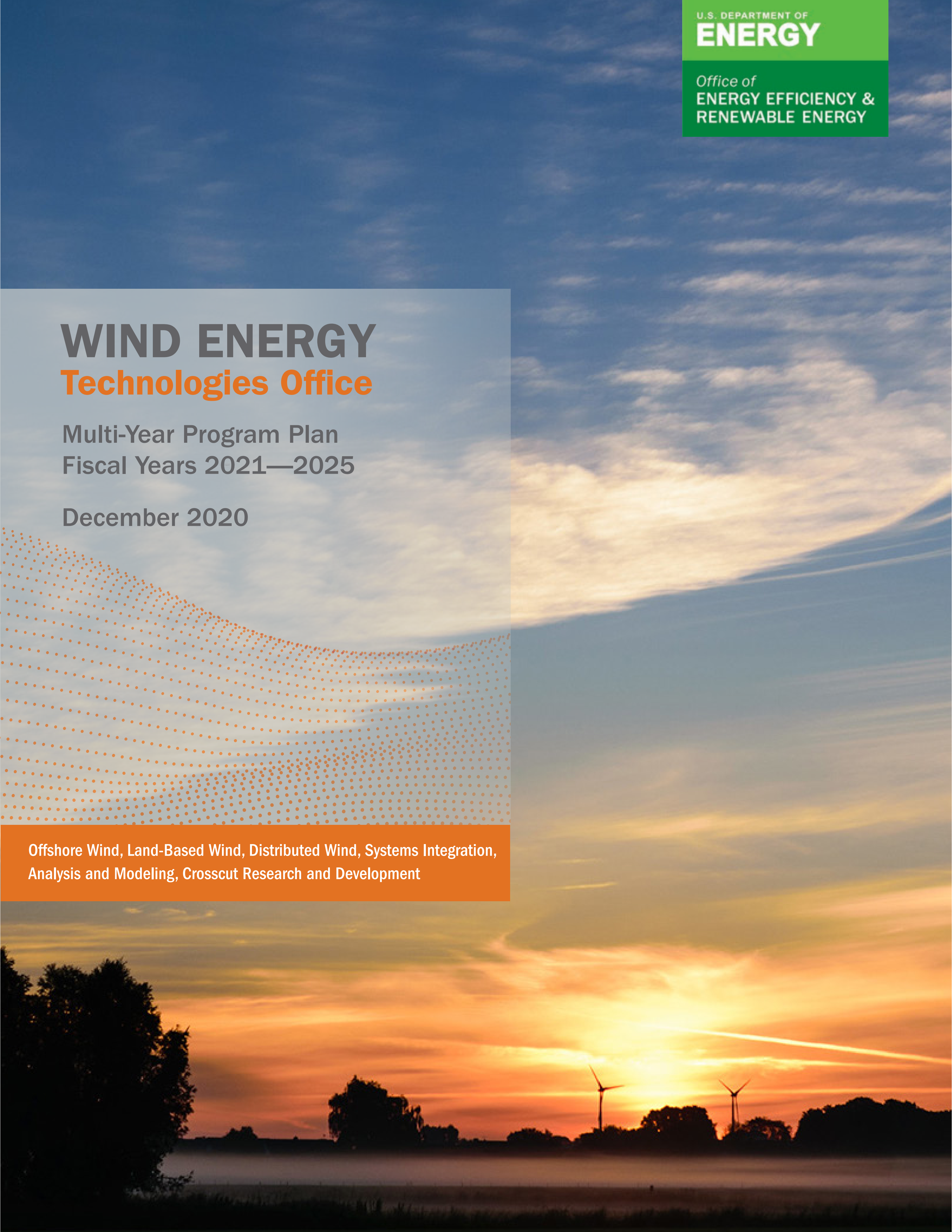

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

WIND ENERGY
Technologies Office

Multi-Year Program Plan
Fiscal Years 2021—2025

December 2020

Offshore Wind, Land-Based Wind, Distributed Wind, Systems Integration, Analysis and Modeling, Crosscut Research and Development

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This 2020 Multi-Year Program Plan for the U.S. Department of Energy's (DOE's) Wind Energy Technologies Office ("the Office") was prepared under the auspices of the Assistant Secretary for Energy Efficiency and Renewable Energy, Daniel R Simmons, and the Deputy Assistant Secretary for Renewable Power, Dr. David Solan.

The plan sets forth a rationale and research strategy through 2025 and beyond, and is intended to comply with Title II, Section 203 of the U.S. Department of Energy Research and Innovation Act of 2018, P.L.115-246, which states that DOE shall "develop a planning, evaluation, and technical assessment framework for setting long-term objective strategic goals and evaluating progress."

The plan was developed under the leadership of the Wind Energy Technologies Office Director, Dr. Robert C. Marlay, and Deputy Director, James Ahlgrimm. It was created and brought to fruition by a "core team," led by Jim Ahlgrimm and comprising Maureen Clapper, Phillip Dougherty, Ivette Gonzalez, Liz Hartman, Alexsandra Lemke, and Rich Tusing. It benefitted significantly from the helpful critiques and guidance of David Solan and Arlene Fetizanan.

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We also thank the National Renewable Energy Laboratory Communications team for final report editing (Sheri Anstedt) and graphics development (Jennifer Breen Martinez).

List of Acronyms

ABL	atmospheric boundary layer
AEP	annual energy production
ARIES	Advanced Research on Integrated Energy Systems
BOEM	Bureau of Ocean Energy Management
CapEx	capital expenditures
DER	distributed energy resources
DOE	U.S. Department of Energy
DDD	Define acronym
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
ESGC	Energy Storage Grand Challenge
FY	fiscal year
GPRA	Government Performance and Results Act
GW	gigawatt
IBR	inverter-based resources
IEA	International Energy Agency
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
m	meter
MIRACL	Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad
MW	megawatt
NOWRDC	National Offshore Wind Research and Development Consortium
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
OpEx	operational expenditures
R&D	research and development
RFP	request for proposals
STEM	science, technology, engineering, and mathematics

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Executive Summary

The Wind Energy Technologies Office ("the Office"), which is part of the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE), plans and executes a diversified portfolio of research and development (R&D) to advance technologies for offshore, land-based, and distributed wind energy, as well as integration with the electric grid. The Office also supports research to understand wind-related siting and environmental challenges. The work is underpinned by investments in atmospheric science and modeling and analysis, and complemented by competitively selected, cost-shared projects carried out in collaboration with industry, universities, and national laboratories.

Wind Energy, Technology, and Challenges

Wind energy is an important part of the U.S. energy mix. In 2020, there are over 100 gigawatts of land-based, utility-scale wind installed across 41 states (Wiser et al. 2020), supplying 7% of U.S. electricity supply (U.S. Energy Information Administration [EIA] 2020). The United States has over 85,000 wind turbines in distributed wind applications across 50 states (Orrell et al.2020). A nascent offshore wind industry is beginning to develop—driven by federal offshore wind lease auctions, complementary state policies, technology innovation, and falling wind turbine prices—but challenged by unique characteristics of U.S. waters. Although utility-scale land-based wind technology is relatively mature, the phase out of the production tax credit in 2020 highlights the importance of continued research and innovation to reduce costs further, so that wind energy can compete and add value to the grid on an unsubsidized basis. Additionally, many remaining sites where wind could be deployed are constrained by an array of environmental and siting concerns. Finally, wind energy's growth has brought attention to the need for advanced technology and controls to support grid resilience and integration of wind with other energy technologies.

Wind Energy Program and Objectives

The Office's research mission, programs, and priorities are shaped by a body of legislation dating back to the establishment of DOE. Of 27 public laws broadly applicable to EERE, many are specifically relevant to wind energy and direct DOE to carry out research and innovation focused on, among other objectives, reducing the cost of energy, decreasing environmental impacts, and advancing renewable generation and delivery.

The Office's R&D program pursues three overarching objectives: (1) reduce the cost of wind energy for all wind applications; (2) enable the integration of substantial amounts of wind energy into the dynamic and rapidly evolving national energy system, including integrated systems with other renewable energy and energy storage; and (3) create siting and environmental solutions to reduce environmental impacts and facilitate responsible wind energy development. The Office invests in early-stage, high-risk research and technology development that is too risky, uncertain, or beyond the means of individual firms in the wind industry, in terms of technical resources or capabilities. The Office also invests in wind-related science and the creation of knowledge, information, and tools to be made widely and publicly available.

Multi-Year Program Plan

The purpose of this Multi-Year Program Plan is to set forth a rationale and strategy to assist research planning and execution. The plan is intended for use as a 5-year guide, encompassing the period from 2021 to 2025, but also includes goals for 2030 in keeping with the longer-term nature of research and technology development. The plan is organized around five research areas: offshore wind, land-based wind, distributed wind, systems integration, and modeling and analysis. It is complemented by a section showing how the Office's research contributes to seven crosscutting EERE and DOE initiatives.

For each of the five research areas, the plan includes: (a) the state of development, opportunities, and challenges; (b) technical goals; (c) strategies and approaches for realizing the goals; (d) research priorities that, in turn, shape a hierarchy of underlying research activities and projects; and (e) expected outcomes of a successful research program.

Research Areas, Goals, and Priorities

Offshore Wind. The research goal is to reduce the levelized cost of energy (LCOE) for fixed-bottom and floating offshore wind by 40 to 50% by 2030. For fixed-bottom offshore wind, the goal is to reduce LCOE from 8.6 cents per kilowatt-hour (¢/kWh), as reported in 2020, to 7.0¢/kWh in 2025, and to 5.0¢/kWh in 2030. For floating offshore wind, the goal is to reduce LCOE from 13.5¢/kWh, as reported in 2020, to 9.5¢/kWh in 2025, and to 7.0¢/kWh in 2030. To accomplish this, there are six research priorities: turbine scaling and light-weighting; advanced manufacturing; whole plant performance and design; science of atmospheric and oceanographic conditions; system installation, operation, maintenance, and reliability; and offshore wind design standards and validation activities.

Land-Based Wind. The research goal is to reduce LCOE by 40 to 45% by 2030, that is, from 3.7¢/kWh, as reported in 2020, to 3.2¢/kWh in 2025, and to 2.3¢/kWh in 2030. The underlying motivation for the research strategy is economies of scale to capture increased amounts of higher-quality wind resources at higher heights above the ground. There are four research priorities: tall wind; innovative wind manufacturing and advanced materials; integrated wind plant dynamics and optimized energy production; and atmospheric science and wind resource characterization.

Distributed Wind. There is significant potential for expanded application for both larger and smaller systems. Larger distributed wind systems are used to produce power at commercial and industrial sites and, in conjunction with other distributed energy resources, to provide balancing support and increased resilience for local grid operations. Smaller distributed wind systems are used at houses, farms, and commercial sites, and can be used to power isolated microgrids in support of military operations, disaster relief, and other applications. The goal for distributed wind research is to reduce the LCOE for a reference 100-kW wind turbine by 50% by 2030, that is, from 10.5¢/kWh, as reported in 2020, to 7.2¢/kWh in 2025, and to 5.0¢/kWh in 2030. There are six research priorities: balance-of-plant costs; wind plant costs and performance; small wind power production risks; hybrid distributed wind systems; design standards; and military and disaster relief solutions.

Siting and Environmental Challenges. Offshore, land-based, and distributed wind are different from one another, with each requiring specialized projects and activities. At a high level, however, the goals and research priorities are similar. The goal for offshore wind is to gain knowledge and develop cost-effective technology and operational strategies to address challenges. The goal for land-based wind and distributed wind is to facilitate the development of solutions, minimize impacts, and enable the efficient siting and operation of wind power plants. For offshore wind and land-based, the three research priorities are: wildlife and environmental impacts and solutions; radar impacts and solutions; and mitigation of use conflicts.

Systems Integration. The goal is to enable cost-effective, cybersecure, reliable, and resilient operation of the energy system with increasing levels of wind. Much of the work is expected to be carried out at DOE's national laboratories, including the recently upgraded 20-megawatt platform for Advanced Research on Integrated Energy Systems (ARIES) at the National Renewable Energy Laboratory. Planned activities focus on five research priorities specific to wind: hardware and controls; hybrids with storage and energy conversions; analysis of transmission adequacy and flexibility; grid reliability support; and physical and cybersecurity.

Modeling and Analysis. The goal is to inform, guide, and enable the planning, execution, and delivery of the Office's research and innovation mission. To realize this goal, there are three research priorities: acquire, process, and provide timely and accurate data from best-available sources; develop models and tools; and carry out analyses that provide insight to decision-making applicable to DOE's R&D investments.

Crosscut R&D. This area focuses on high-priority strategic initiatives. The research aims to accelerate progress by encouraging federal programs to plan and work in concert, parse out tasks, and/or leverage resources. The Office contributes to seven crosscuts on: artificial intelligence; advanced manufacturing; polymer upcycling and recycling; cybersecurity; energy storage; grid modernization; and science, technology, engineering, and math (STEM) and workforce development.

With continued research and technology innovation to drive down costs and overcome grid integration, environmental and siting, and workforce development challenges, wind energy has the potential to serve as a key building block of an affordable, reliable, and secure energy future.

1 Introduction

The Wind Energy Technologies Office ("the Office"), which is part of the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE), plans and executes a diversified portfolio of early-stage research and development (R&D) to advance technologies for offshore, land-based, and distributed wind energy, and its integration with the electric grid. The Office also supports research on siting and environmental challenges and analysis and modeling. This work aims to drive down the cost of wind energy through competitively selected, cost-shared projects, carried out in collaboration with industry, universities, research institutions, and other stakeholders.

Statutory Authorities

The Office's mission, programs, and priorities are shaped by a body of legislative history dating back to the establishment of DOE in 1977. There are 27 public laws broadly applicable to EERE. Below are the statutory authorities that are particularly relevant to the Office.

Selected Authorities Relevant to the Wind Energy Technologies Office	
Public Law	**U.S. Code Reference**
P.L. 95-91, "Department of Energy Organization Act" (1977)	42 U.S.C. 7101
P.L. 101-218, "Renewable Energy and Energy Efficiency Technology Competitiveness Act" (1989)	42 U.S.C. 12001-12007
P.L. 102-486, "Energy Policy Act of 1992" (EPACT 1992)	42 U.S.C. 12005, 42 U.S.C. 13381-13389
P.L. 109-58, "Energy Policy Act of 2005" (EPACT 2005)	25 U.S.C. 3506, 42 U.S.C. 16161, 42 U.S.C. 16181, 42 U.S.C. 16231, 48 U.S.C. 1492
P.L. 110-140, "Energy Independence and Security Act of 2007" (EISA 2007)	42 U.S.C. 17154, 42 U.S.C. 17244, 42 U.S.C. 17337, 15 U.S.C. 657h
P.L. 111-5, "American Recovery and Reinvestment Act of 2009" (ARRA 2009)	U.S.C. Titles 1, 6, 7, 12, 15, 16, 19, 20, 26, 28, 29, 31, 33, 38, 42, 45, and 47
P.L. 115-246, "Department of Energy Research and Innovation Act" (2018)	42 U.S.C. 7139, 42 U.S.C. 16313, 42 U.S.C. 16315, 42 U.S.C. 16352(b), 42 U.S.C. 16391, 42 U.S.C. 16357, 42 U.S.C. 16538

Among the statutes, the Energy Policy Act of 2005 (42 USC 16231, Part 2) is specific to wind energy. It states that the Secretary of Energy shall conduct a program of research, development, demonstration, and commercial application for wind energy, including low-speed wind energy, offshore wind energy, testing and verification (including construction and operation of a research and testing facility capable of testing wind turbines), and distributed wind energy generation.

In addition, the Energy Policy Act of 2005 states that the Secretary shall conduct a "balanced" set of research, development, demonstration, and commercial application programs, including those for the combined use of renewable energy technologies with one another and with other energy technologies. The statute also directs demonstration of the use of renewable energy technologies to assist in delivering electricity to rural and remote locations.

The statute notes a series of national objectives, including:

- Decreasing the cost of renewable energy generation and delivery
- Decreasing the environmental impact of energy-related activities
- Increasing the conversion efficiency of all forms of renewable energy through improved technologies
- Promoting the diversity of the energy supply
- Increasing the export of renewable generation equipment from the United States.

Additionally, the Department of Energy Research and Innovation Act of 2018 (P.L. 115-246) directs the Secretary to identify strategic opportunities for collaborative research, development, demonstration, and commercial application of innovative science and technologies, and to promote collaboration and crosscutting approaches.

Office Programs and Priorities

Collectively, the previously mentioned statutes provide an operating framework for the Office to plan and execute its responsibilities in wind energy research, development, demonstration, and commercial application. The statutes direct DOE to conduct programs of research and innovation focused on, among other objectives, reducing the cost of energy, decreasing environmental impacts, and advancing renewable generation and delivery. The Office also supports EERE's vision and mission.

Accordingly, top-line priorities are to:

- **Reduce the cost of wind energy**, in compliance with statutory direction
- **Create siting and environmental solutions** that aim to reduce environmental impacts and facilitate responsible development and delivery of wind energy resources
- **Enable the integration of substantial amounts of wind energy** into the dynamic and rapidly evolving energy system of the future, including integrated systems with other renewable energy and energy storage technologies, and the electrification of the transportation and building sectors.

EERE VISION AND MISSION

EERE's vision is a "strong and prosperous America that is powered by clean, affordable, and secure energy."

In the context of this vision, EERE's mission is "to create and sustain American leadership in the transition to a global clean energy economy."

These priorities are overlaid across the Office's programmatic structure. This structure has five subprograms in addition to crosscutting activities, as shown next. These represent the "pillars" of the Multi-Year Program Plan's (MYPP's) organization:

- Offshore wind
- Land-based wind

- Distributed wind
- Systems integration
- Analysis and modeling
- Crosscut R&D.

Multi-Year Program Plan

The purpose of the MYPP is to set forth a rationale and strategy to assist research planning and execution aimed at maximizing progress toward wind energy goals within available resources. The plan is intended for use as a 5-year guide, which encompasses the period from 2021 to 2025, but also includes longer-term research goals for 2030.

In this MYPP, each of the wind energy pillars follows with a developmental discussion outlining the state of current development, potential opportunities, and challenges; technical goals that motivate the plan and its level of ambition; strategies and approaches for realizing those goals; research priorities, which shape planned activities and projects; and expected outcomes, should the program be carried out as planned and successful.

Potential for Significant Additional Progress

A retrospective of the Office's history and technical accomplishments suggests that DOE's role in pursuing early-stage, high-risk research and innovation has been pivotal in the wind industry's development and success. Thirty years ago, large-scale wind energy was all but out of reach. Wind power to the grid was nearly nonexistent. The technologies were just not sufficiently developed, and costs were too high.

DOE's research, supported by its national laboratories and in partnerships with industry and universities, sustained over time, contributed to innovations that advanced the scale, efficiency, and competitiveness of wind energy.[1] The Office undertakes its research with support from nine of DOE's national laboratories. In 2020, the Office had active multiyear projects with more than 55 universities, located across 34 states and the Commonwealth of Puerto Rico.

Looking forward, as outlined in this MYPP, there are ambitious new frontiers to explore in offshore wind, particularly in deep water; in addressing siting and environmental challenges; in finding a leadership role for wind in providing a full range of grid services, in addition to power; and in continued innovation with scaling, light-weighting, automated manufacturing, end-of-life recycling, and cost reduction. Progress in these areas, can lead to pivotal developments for the future of wind energy.

[1] Wind Energy Technologies Lasting Impressions. For more information, visit: https://www.energy.gov/eere/wind/downloads/wind-energy-technologies-office-lasting-impressions.

2 Offshore Wind

Offshore wind is a rapidly growing global industry, creating electricity from wind turbines specifically designed to operate at sea, atop either rigid or floating substructures anchored to the seabed. Well-established in Europe, offshore wind generation in the United States provides a significant opportunity to expand and diversify energy supply and help meet future electricity demand. Offshore wind development areas include the Atlantic Seaboard, the Pacific Seaboard, the Great Lakes, and the Gulf of Mexico.

There are two primary types of offshore wind:

- Fixed bottom for shallow water depths (<60 meters [m])
- Floating platform for deep water (>60 m).

U.S. offshore wind projects are developing a variety of different foundations suited to unique conditions at each site.
Illustration by Josh Bauer, National Renewable Energy Laboratory (NREL)

The offshore wind resources off U.S. coasts are substantial. The technical resource potential[2] of offshore wind is more than 2,000 gigawatts (GW) (Musial et al. 2016), including areas in both shallow water with depths of below 60 m or less, where fixed-bottom platforms are typically used, and in deeper water depths of greater than 60 m, where floating platforms are generally needed. For perspective, this 2,000 GW of technical resource potential is more than double the current total U.S. electricity demand (EIA undated). Although there are two offshore wind power plants operating in the United States as of 2020, the announced pipeline of fixed-bottom projects under development is significant and may expand. Floating platforms of various designs are being tried abroad, but none have been installed in the United States. Though the planned near-term U.S. commercial projects are for fixed-bottom locations, approximately 60% of the offshore wind technical resource potential in the United States is at locations in water depths that would require floating platforms.

[2] The technical resource potential is the amount of resource that could potentially be developed using existing technology but excludes areas that are unlikely or cannot legally be developed. For more information, see *Computing America's Offshore Wind Energy Potential* https://www.energy.gov/eere/articles/computing-america-s-offshore-wind-energy-potential.

As an indication of the growing attractiveness of offshore wind, 12 states have recently made power purchase commitments for 28.9 GW for fixed-bottom installations, as of June 2020 (Musial et al. 2020). Of this, BloombergNEF projects that 6.5 GW will be in operation by 2025 (BloombergNEF 2020). Such commitments are contingent upon permitting and compliance with federal, state, and local regulations. The potential for offshore wind—both fixed-bottom and floating—is large, but challenges remain, including:

- Technology needs for continued cost reduction, so that wind energy can become broadly competitive without subsidy
- Finding acceptable solutions to an array of siting and environmental challenges
- Integrating large amounts of offshore wind energy into the electric grid (see Section 5 for more information).

Overlaying these challenges are others that address the fact that many of the offshore development areas in the United States have unique characteristics compared to Europe. Differentiating characteristics include severe weather (e.g., hurricanes), icing, soft sediment and other ocean floor conditions, marine wildlife, and endangered species concerns, competing uses, and community impacts, all with significant regional variations. Many of these challenges can be addressed or mitigated with research and innovation.

Goals and Approaches

For technology research and development, the goal of the Office's offshore research program is to reduce the levelized cost of energy (LCOE) for offshore wind systems with both fixed-bottom and floating platforms. For fixed-bottom offshore wind, the goal is to reduce LCOE from 8.6 cents per kilowatt-hour (¢/kWh), as reported in 2020 (for prior year installations), to 7.0¢/kWh by 2025 (as reported through the end of year). For floating offshore wind, the goal is to reduce LCOE from 13.5¢/kWh, as reported in 2020 (for prior year installations), to 9.5¢/kWh in 2025 (as reported through the end of year).

The approach for realizing cost reduction goals is to identify the top-most cost-contributing elements and find ways to reduce capital costs, improve energy output and operating efficiency, and reduce operation and maintenance (O&M) costs over the life of the investment. These considerations lead to R&D focused on enabling economies of scale, including:

- Light-weighting
- Advances in component designs, materials, and manufacturing
- Better understanding of offshore wind resources and a power plant's interactions with various atmospheric and oceanographic conditions
- Integrated and automated controls for optimizing power plant performance in real time
- Means for ensuring durability, remote inspection and repair, and long-term reliability in the ocean environment.

For siting and environmental challenges, the goal is to develop cost-effective technology and operational strategies to address challenges and inform decision-making. The Office's approach is to identify and focus on the highest-priority offshore wind concerns. These are primarily related to wildlife, the environment, wind-radar interference, and siting research and development. Research in each case is to be tailored to specific needs of areas or regions where development is anticipated. In general, the Office seeks to:

- Create data-driven knowledge that illuminates potential impacts and informs the development of solutions
- Develop potential solutions and, where appropriate, test models and prototypes
- Share results broadly among stakeholders and agencies through workshops, publications, and education.

Research Priorities

The Office developed a joint U.S. offshore wind strategy (Gilman et al. 2016a) in coordination with the U.S. Department of the Interior's Bureau of Ocean Energy Management (BOEM), which has statutory authority for offshore wind permitting, including establishing timelines and offering regulatory certainty (EPAct 2005). DOE is responsible for setting scientific and research priorities in areas that include offshore wind resource assessments, wind power plant technology research and development, and advancing siting and environmental solutions. DOE and BOEM have their remits defined by statute, but in offshore wind there are other federal agencies that have missions, priorities, and responsibilities that intersect with offshore wind development and operation. Effective progress across the federal government requires cooperation, collaboration, and coordination, additionally, with the National Oceanic and Atmospheric Administration, the U.S. Department of Homeland Security, U.S. Department of Defense, Federal Aviation Administration, and the U.S. Fish and Wildlife Service.

For fixed-bottom offshore wind, given the volume of projected near-term, shallow-water installations and the advanced stage of industry technological development, the emphasis for DOE's R&D is aimed at addressing siting and environmental concerns and identifying solutions for wildlife, environmental, radar, and community impacts. Technology research and development activities plan to focus on adapting existing fixed-bottom designs for use in the U.S. market, understanding and avoiding failure modes, and lowering O&M costs.

For floating offshore wind, the industry is at a nascent stage of technological development, robust with competing designs, as the deep-water market continues to mature. R&D is planned to focus on the significant technology challenges; foremost among these are investments that reduce the levelized costs of floating platforms by increasing their size and designing common components for high-volume manufacturing. Planned siting and environmental activities aim to identify affected wildlife species and study the effects of installing and operating ultralarge offshore wind turbines and wind power plants.

In view of these considerations, the Office's R&D program plans call for work in nine research priorities for offshore wind. These are organized as follows into two broad categories: technology research and development and siting and environmental research and development.

Research Priorities – Offshore Wind	
Number	**Description**
Technology Research and Development	
OSW 1	Turbine Scaling and Light-Weighting
OSW 2	Advanced Manufacturing
OSW 3	Whole Plant Performance and Design
OSW 4	Science of Atmospheric and Oceanographic Conditions
OSW 5	System Installation, Operation, Maintenance, and Reliability
OSW 6	OSW Design Standards and Validation Activities

Siting and Environmental Research and Development	
OSW 7	Wildlife and Environment Impacts and Solutions
OSW 8	Radar Impacts and Solutions
OSW 9	Siting Research and Development

Achieving targeted cost reductions is essential to enabling the successful financing and development of ultralarge wind turbine systems that will be economically competitive without subsidies. Planned R&D activities support advanced technology innovation and integrated systems design to increase overall offshore wind plant performance at a significantly reduced cost, enhancing market opportunities and competitiveness.

The National Offshore Wind Research and Development Consortium (NOWRDC) was established in 2018 by DOE and the New York State Energy Research and Development Authority. Each provided $20.5 million to fund high-impact research projects that lower the costs of U.S. offshore wind and support supply chain development. State agencies in Maryland, Virginia, and Massachusetts have since contributed funding to the NOWRDC, resulting in a total investment of around $46 million. The consortium's members include many of the major entities in the offshore wind industry. NOWRDC's first request for proposals (RFP) resulted in 20 awards totaling $17.3 million. Their second RFP was issued in 2020. NOWRDC is working toward financial independence following the end of the DOE award period.

The Office works closely with NOWRDC to develop its R&D roadmap and RFPs, review proposals, and recommend projects for award that further DOE's offshore wind research objectives, leverage its resources, and maximize the impact of federal funding. The Office regularly coordinates with the consortium's leadership to ensure their R&D portfolio complements and does not duplicate DOE's offshore wind R&D activities.

NOWRDC will continue to focus on technology solutions across three R&D pillars defined in the National Offshore Wind Strategy and the consortium's roadmap:

- Offshore wind plant technology advancement, which includes optimizing the performance of wind plants; reducing the costs of turbine support structures (e.g., foundations); developing innovative mooring and anchoring technologies for floating wind; and reducing the cost and risk associated with the transmission and distribution of electricity from offshore wind
- Offshore wind power resource and physical site characterization, which includes comprehensive wind resource assessment and the development of a meteorological ocean (metocean) reference site
- Installation, operation and maintenance, and supply chain, which includes heavy lift vessel alternatives, offshore wind digitization through advanced analytics, and technology solutions to accelerate the U.S. supply chain and reduce siting conflicts.

NOWRDC projects resulting from the first RFP are aligned with the MYPP research priorities in OSW 2 through OSW 5 (see previous table) and SI 4 (Wind Grid Reliability). Future NOWRDC projects are expected to be in similar priority areas with possible inclusion of OSW 9 (consortium research area - technology-focused efforts to mitigate use conflicts).

Technology Research and Development

Planned activities to reduce costs and technology risks for offshore wind over the fiscal year (FY) 2021–2025 time period focus on six research priorities, each with several supporting R&D project areas (described next). The R&D project areas are detailed in the Office's annual project plans.

OSW 1: Turbine Scaling and Light-Weighting

Significant cost reductions for offshore ultralarge wind power plants are possible by aggressively pursuing economies of scale and innovative technologies that target improved energy capture while reducing the weight of integrated systems components. Economies of scale address effectively designing common manufacturing components. Novel technologies, including ultralightweight, superconducting direct-drive generators that are matched to new tower, blade, and platform designs, will leverage scaling innovations that can achieve substantial cost savings.

Technology advancements utilizing integrated system design and targeted component weight reduction are major factors determining reduced LCOE for offshore wind energy. As turbine systems evolve to ultralarge sizes, system designs must take advantage of the mechanical properties of lightweight, high-strength materials. Additionally, advanced integrated systems control of turbines and platforms will optimize plant performance and energy capture and extend the operational life by mitigating loads.

Special emphasis is placed on floating platforms, as breakthroughs in light-weighting and integrating turbine and platform technologies would be highly impactful. Many of these innovations will also apply to fixed-bottom systems.

Technology Research and Development	
OSW 1	Turbine Scaling and Light-Weighting
OSW 1.1	Very Large, Ultralightweight Offshore Wind Turbines
OSW 1.2	Integrated Floating Turbine/Platform Systems
OSW 1.3	Advanced Design, Materials, and Mechanical Systems Research

OSW 2: Advanced Manufacturing

Computer-aided manufacturing processes, including additive manufacturing, are rapidly evolving technologies that harness the power of automation and robotics to reduce labor costs and improve design-to-product life cycle, manufacturing time, efficiency, energy usage, process uniformity, and reproducibility. The use of advanced manufacturing ultimately improves product performance, reliability, and cost. These efforts have the potential to:

- Realize innovative designs of components such as generators, which were previously too complex or expensive to manufacture
- Enable inexpensive production of tooling such as blade molds
- Optimize wind blade manufacturing through processes such as automated fabrication and finishing to reduce manual operations
- Scale lightweight materials for the next generation of very large turbines
- Overcome challenges associated with transportation of very large turbine components
- Enable effective handling of end-of-life recycling and repurposing of materials.

The Office plans to support a strategic collaboration with the DOE Advanced Manufacturing Office, other EERE technology offices, industry, and universities, to leverage world-class DOE capabilities for wind-specific R&D on advanced manufacturing technologies.

Technology Research and Development	
OSW 2	Advanced Manufacturing
OSW 2.1	Industrialization: Designs of Common Components
OSW 2.2	Advanced Manufacturing Methods and Automation

OSW 3: Whole Plant Performance and Design

The energy captured by multiple turbines in a wind power plant is lower than the energy that would be captured by an equivalent number of single turbines operating separately. The flow interactions within a large wind plant are complex, and the interactions between multiple turbines in close proximity to one another lower the overall plant energy production.

Mitigating these impacts requires advanced rotor designs and active turbine and plant control strategies to maximize productivity by minimizing turbine wake interactions, including:

- Active monitoring of the inflow resource
- Wake steering controls
- Wake dissipation management
- Integrated plant-level system controls.

The suite of capabilities being developed is essential for future offshore system designs to achieve the Office's aggressive offshore wind LCOE targets.

Technology Research and Development	
OSW 3	Whole Plant Performance and Design
OSW 3.1	High-Fidelity Modeling of Turbines in Large Offshore Wind Plant Arrays
OSW 3.2	Tools and Analyses for Integrated Offshore System Design
OSW 3.3	Control of Advanced Turbines and Offshore Wind Plants
OSW 3.4	Offshore Wind Plant Technologies Validation

OSW 4: Science of Atmospheric and Oceanographic Conditions

Designing the next generation of offshore wind systems requires an understanding of the extremely complex nature and detailed characteristics of the offshore marine operating environment. Although there are some similarities in physical site conditions in the United States compared to Europe (which has an established offshore wind market), there are key differences requiring scientific assessment because of their implications for wind turbine and power plant design and engineering. In addition, the characteristics of the marine atmospheric boundary layer along the East Coast of the United States are substantially different from the conditions on the West Coast. In general, there is a lack of data describing meteorological and oceanographic conditions at potential U.S. offshore wind development sites. Having site-specific field data quantifying the offshore wind resource characteristics and operating environment is critical for successful development, installation, and operational considerations. Data are still needed to:

- Estimate structural loads on offshore wind turbines
- Better understand the air-sea interactions that impact offshore wind system design and operation

- Improve weather and energy forecast models
- Assess annual energy production of offshore wind power plants.

The data and corresponding site performance assessments contribute to reducing offshore power plant cost and performance risks and therefore also reduce project financing costs.

The wind/wave environment in which offshore turbines operate is driven by weather-related atmospheric events that occur at the mesoscale (>10 kilometers). The actual power plant energy production and loading on individual turbines within the plant are determined by wind and wave characteristics at the wind plant microscale (~10 m). Atmospheric events at the mesoscale affect inflow at the microscale. Thus, to determine wind inflow characteristics, mesoscale events that affect the inflow must be accurately characterized. Moreover, wind characteristics upstream of the wind farm also determine the magnitude and frequency of the waves passing through the farm.

An advanced understanding of the atmosphere and wind flow through the plant will enable better designs for the development of lower-cost wind turbines. With improved design criteria reflecting realistic environmental conditions, new components (blades, towers, and generators) can maximize material and structural efficiency and increase in size. Novel designs may also be employed for next-generation wind turbine technology. Moreover, this improved understanding of atmospheric and oceanographic conditions improves energy forecasting, which is important for seamless grid integration.

Technology Research and Development	
OSW 4	Science of Atmospheric and Oceanographic Conditions
OSW 4.1	Offshore Metocean Characteristics
OSW 4.2	Wind Inflow and Wave Dynamics
OSW 4.3	Lidar Buoys
OSW 4.4	Hurricane Impact Mitigation
OSW 4.5	Offshore Field Data Campaign

OSW 5: System Installation, Operation, Maintenance, and Reliability

The complexity and risks associated with offshore wind installation and related O&M activities require either specialized infrastructure not yet developed in the United States, or a heavy reliance on overseas infrastructure, which would reduce the domestic economic benefits of U.S. offshore wind. Identifying strategies to leverage the nation's existing infrastructure will reduce both capital expenditures and long-term operating costs while increasing domestic economic benefits. To accomplish this, investments in technologies have the potential to:

- Ease the technical challenges of installation (e.g., turbine installation methods that do not require large specialized installation vessels), inspection, and repair methods
- Enable remote monitoring of the health status of turbine components
- Utilize advanced materials and manufacturing methods in innovative designs and products.

Installing, operating, and maintaining the next generation of ultralarge offshore wind turbines will pose unique challenges particularly in the harsh U.S. offshore environment. Research identifying and addressing these challenges will reduce risks and uncertainties tied to the lifetime cost of maintaining and operating fleets of increasingly large turbines. This research informs future materials and manufacturing R&D needs for offshore wind.

As offshore wind turbines become larger, the impact of reliability on O&M costs will increase, becoming even more critical to the cost of energy over the life of the turbine. Because of the harsh offshore environment and expected lengthening of power plant life, reliability and maintenance will become increasingly important. Proposed R&D focused on targeted reliability improvements will be beneficial for existing components as well as encourage increased consideration of reliability of new designs. This has the potential to lower O&M costs and increase safety because there will be fewer personnel conducting O&M in the marine environment.

Technology Research and Development	
OSW 5	Installation, Operation, Maintenance, and Reliability
OSW 5.1	Offshore Wind Reliability
OSW 5.2	Innovative Turbine Installation Methods
OSW 5.3	Machine Health Management Tools
OSW 5.4	O&M Operations Optimization

OSW 6: OSW Design Standards and Validation Activities

The Office continues to develop a comprehensive collaborative R&D program bridging the spectra of science and technology research development needs for offshore wind. Partnerships with industry and other government agencies are essential to accelerate offshore wind development and to develop deep-water offshore wind technologies. Investments in critical R&D initiatives are addressing the expansive technical and development challenges and leveraging needed financial and technical resources beyond the limits of the federal program alone. Developing technologies collaboratively facilitates acceptability and speeds up implementation by the risk-averse electricity sector.

There are many offshore physical science and environmental characteristics (e.g., bathymetry, marine atmospheric environment, air/sea coupling, wave resource) that need to be better understood to define robust design criteria ensuring viable offshore wind technologies, including floating technologies for deep water.

R&D efforts to support coordinated field measurement campaigns to gather the information and operational data needed to develop new technologies for the deep-water environment are planned. Comprehensive, verified, and validated resource information is coupled with the development of international design standards through active International Energy Agency (IEA) engagement to define engineering design criteria and standards ensuring robust technology and mitigating market investment risk. New technology initiatives, including partnerships through the National Offshore Wind R&D Consortium, provide a stream of viable technology research and development options, from components to full operational systems.

Technology Research and Development	
OSW 6	OSW Design Standards and Validation Activities
OSW 6.1	Design Standards
OSW 6.2	Experimental Technology
OSW 6.3	Offshore Wind Cooperative Research
OSW 6.4	Field Data Collection
OSW 6.5	DOE and BOEM Offshore Wind Strategy Update

Siting and Environmental Research and Development

Siting and environmental challenges have had significant impacts on offshore wind development. A portfolio of R&D is planned over the MYPP period to address these needs. These investments are planned to translate into decreased LCOE and reduced project risk while resulting in increased competitiveness and market opportunities for offshore wind energy.

The planned activities are organized as a series of projects supporting three research priorities: wildlife and environmental impacts and solutions, radar impacts and solutions, and community impacts and solutions.

OSW 7: Wildlife and Environmental Impacts and Solutions

Currently there is limited U.S. offshore wind deployment in which to assess operational impacts for siting, wildlife, and the environment. The impacts associated with offshore wind installations include potential effects on migratory birds, marine mammals, and other sensitive species. Similar to land-based wind, there are concerns that offshore wind will affect birds directly (via collision), displace birds from important habitats, or create barriers to their migration. Offshore wind facilities can also pose risks to marine mammals through noise generated during surveys and construction, and particularly during pile-driving activities for fixed-bottom applications.

These concerns result in substantive costs and permitting risks for projects. For example, the issue of noise impacts on marine mammals, especially for the critically endangered North Atlantic right whale, poses the risk of limiting construction windows, resulting in delays and increased project costs. The potential impacts of offshore wind on birds and bats, along with the lack of automated instrumentation to monitor that risk, have been major permitting obstacles for some early U.S. offshore wind projects (Ohio Power Siting Board 2020).

Over the MYPP period, planned activities focus first on mitigating near-term environmental risk from fixed-bottom turbines ready for commercial-scale development in shallow waters of the United States. Leveraging these efforts, R&D is planned to address floating designs and deep-water deployment locations. Over the last 5 years, the Office has funded a suite of work aimed at promoting knowledge transfer on environmental impacts and effective research methodologies from Europe to help identify high-priority research needs for the United States. Monitoring tools have been developed to fill gaps in the current capabilities to assess impact. Over the next 5 years, plans focus on supporting research to fill critical gaps in the understanding of impacts in U.S. waters, with an aim to mitigate/retire risk. This includes evaluating significance of impacts and subsequently developing and validating mitigation tools where need is demonstrated and validating risk models that can be used to predict such impacts with confidence in the future. Ultimately, the Office's R&D program aims to continuously assess the underlying scientific data, mitigate, and monitor with newly developed technologies and tools, and publish these science research findings to facilitate knowledge transfer.

Siting and Environmental Research and Development	
OSW 7	Wildlife and Environment Impacts and Solutions
OSW 7.1	Knowledge Transfer, Scientific Collaboration, Priority Setting
OSW 7.2	Instrumentation for Wildlife Monitoring and Impact Minimization
OSW 7.3	Impact Data Collection to Fill Knowledge Gaps and Retire Risk
OSW 7.4	Impact Data Synthesis and Predictive Model Development

OSW 8: Radar Impacts and Solutions

Wind development located within the line of sight of radar systems can cause clutter and interference, which has resulted in significant performance degradation for some radars. While interference from offshore turbines is likely to be similar to interference in land-based turbines, offshore wind turbines may pose unique impacts to coastal radar systems, given the differences in propagation of radar signals over the ocean versus land, as well as the larger size of offshore wind turbines compared to land-based systems. Planned R&D aims to characterize how offshore wind uniquely impacts sensitive radar systems; develop acceptable mitigations with agencies and industry; and ensure the resilience of future radar systems to wind turbine radar interference.

Siting and Environmental Research and Development	
OSW 8	Radar Impacts and Solutions
OSW 8.1	Characterize and Mitigate the Impacts of Offshore Wind on Marine Radar

OSW 9: Siting Research and Development

The development of offshore wind projects can impact coastal communities, co-users of ocean space, and local economies, including fishing, navigation, and coastal viewsheds. Siting and environmental issues, in turn, influence and affect the suite of technology options and the cost of wind energy. Wind turbines are deployed within social, economic, and environmental contexts. Both turbine design and siting plans would benefit by being informed by an understanding of those variables in order to ensure maximum effectiveness. For example, public perception influences wind turbine design, with potential impacts on turbine height (visibility, airspace impacts), rotor and drivetrain design (noise), wind plant layout (fisheries and navigation safety), floating mooring systems (fisheries), and cable routing.

During the FY 2021–2025 time frame, the Office's R&D efforts are planned to focus on research that characterizes impacts on coastal communities, other uses of ocean space, and economies to develop informed mitigation measures and feedback into the design of future offshore wind technologies. This may include developing smart navigation and aviation lighting systems that activate only when needed, wind power plant layouts that maximize energy production while accounting for navigational safety, and mooring systems that minimize fisheries impacts. In addition to publishing this research, the Office will continue to maintain up-to-date public tools, such as wind resource maps, the National Wind Turbine Database, and databases of relevant research.

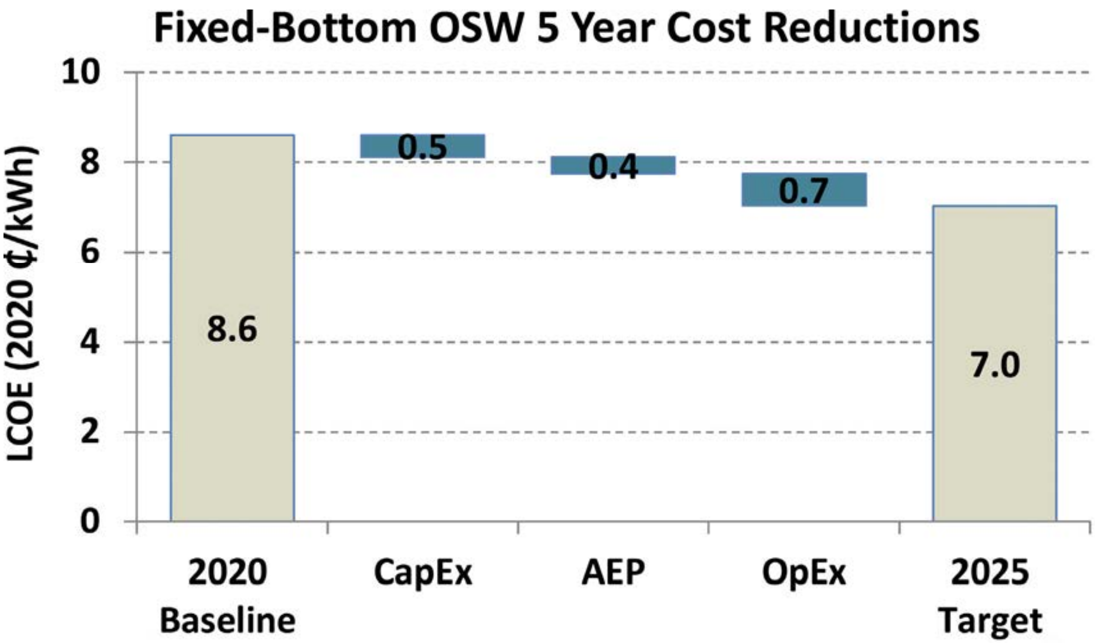
Siting and Environmental Research and Development	
OSW 9	Siting Research and Development
OSW 9.1	Siting Research to Inform Solution Development
OSW 9.2	Siting Data and Tool Dissemination

Expected Outcomes

The technology R&D expected outcomes of the planned activities include the advancement of the next generation of ultralarge wind turbine systems. The diversified nature of the portfolio is planned to also contribute to an array of innovations and technical advances that can reduce capital costs, improve energy production and operating efficiency, increase reliability, and reduce maintenance costs over the life of a wind project.

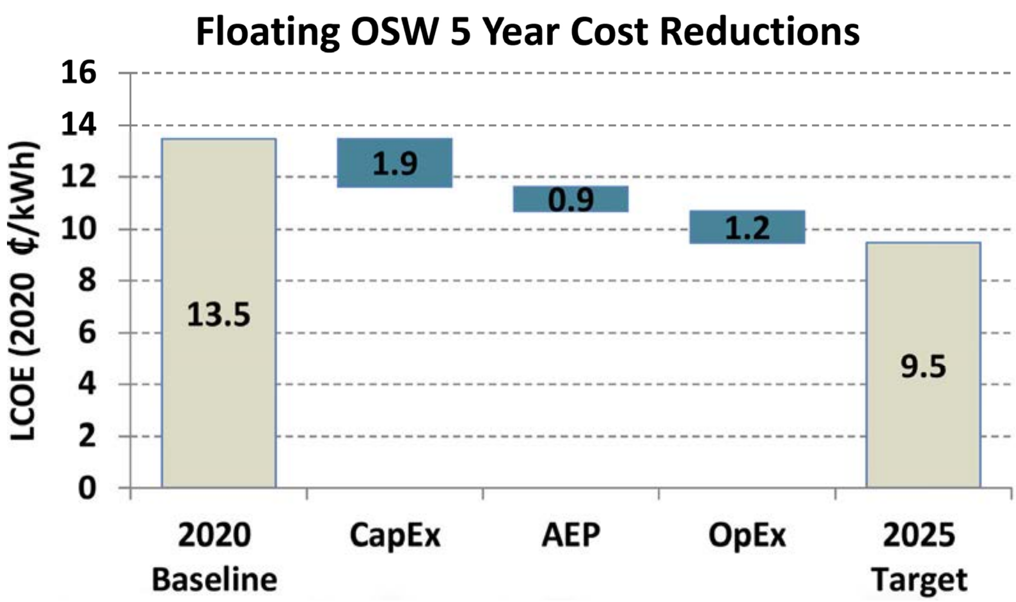
The primary metric for quantifying progress is LCOE. Expected progress is visualized in the following waterfall charts, for fixed-bottom and floating offshore wind. The Office's offshore wind goal is to reduce the LCOE of U.S. offshore wind energy, as follows:

- Offshore wind fixed platform: 7.0¢/kWh in 2025, 5.0¢/kWh in 2030; from 8.6¢/kWh as reported in 2020
- Offshore wind floating platform: 9.5¢/kWh in 2025, 7.0¢/kWh in 2030; from 13.5¢/kWh as reported in 2020



Offshore wind (OSW) fixed-bottom levelized costs are projected to decrease by 21% during the MYPP period. Finance rates, plant useful life, and wind resource assumptions are held constant over the MYPP period.

CapEx: capital expenditures; AEP: annual energy production; and OpEx: operational expenditures



Offshore wind floating platform levelized costs are projected to decrease by 25% during the MYPP period. Finance rates, plant useful life, and wind resource assumptions are held constant over the MYPP period.

These cost reductions also include the impacts of prior R&D that are just now coming to the market. R&D innovations may take multiple years to impact actual market costs because of the time required to complete engineering, manufacturing, and sales cycles.

The siting and environmental R&D expected outcomes are decreased project risk and uncertainty, greater access to wind resources, reduced impacts on communities and the environment, and lower costs. Specifically, over the MYPP period, the research supported is expected to result in validated:

- Offshore wind environmental monitoring and mitigation tools, including automated collision monitoring solutions to monitor bird and bat impacts that can detect at least 80% of strikes with biota and classify targets to species groups over 50% of the time.
- Tools to reduce impacts of noise on marine animals, including tools to monitor marine mammal exclusion zones around construction activities that perform better than human observers, as well as validated noise reduction strategies that reduce overall noise output from offshore wind construction by at least 15%.
- Environmental risk models informed by a greater understanding of offshore wind impacts, including collision risk models validated with empirical data to increase precision in estimates of avoidance rates by at least one significant figure.
- Solutions to offshore wind impacts on high-frequency oceanographic radar and long-range air surveillance radar, informed by a greater understanding of offshore wind impacts on these systems, and including applicable design requirements for next-generation wind turbines.

3 Land-Based Wind

U.S. land-based wind resources are substantial. Assessments of technical resource potential identify more than 8,000 GW (Thresher, Robinson, and Veers 2008) of land-based wind energy potential across all regions of the country. Over the last 10 years, the wind industry has been growing its installed capacity at the rate of 15% per year (Wiser et al. 2020). As of the end of 2019, the United States had 106 GW of installed capacity. Although current capacity is only a fraction of the technical resource potential, wind energy has emerged as an important contributor to the national electric grid, accounting for 7.2% of total U.S. power production in 2019 (U.S. Energy Information Administration 2020).

Wind turbines and power lines stretch across the state of Iowa. These are part of the Eclipse wind project in Audubon and Guthrie counties, owned by MidAmerica Energy.
Photo by Dennis Schroeder, NREL

Research and innovation have been key contributors to wind energy's success. Historically, this broad portfolio of research and development has been aimed at advancing wind energy science and technology. Working with universities and national laboratories, and in collaboration with industry, the contributions of this R&D have proven to be pivotal and underlie many of the recent advancements in scale, efficiency, reliability, longevity, plant optimization, and public acceptance. Collectively, such innovations have enabled wind energy to become an increasingly attractive and competitive option for electricity generation.

If land-based wind energy is to continue its progress and capture more of the resource potential, a number of key challenges need to be addressed. Foremost among these are:

- Continued cost reduction, so that wind energy can become broadly competitive without subsidy
- Finding acceptable solutions to an array of siting and environmental concerns
- Integrating wind energy at increasing scale into the evolving future of the national electric gird (see the Systems Integration section).

Goals and Approaches

Ambitious cost reduction goals have been set for land-based wind from 3.7¢/kWh, as reported in 2020 (for prior year installations) to 3.2¢/kWh in 2025 (as reported through the end of year), and to 2.3¢/kWh in 2030 (Stehly et al. forthcoming). The approach to achieving this goal is to address the highest cost-contributing elements of today's land-based wind technology and operations and reduce them significantly through science, research, and innovation.

The underlying motivation for the research strategy is economies of scale. The quality of the wind resource (e.g., wind speed, wind shear, and wind profile) varies significantly based on location, but is almost uniformly better at higher heights above the ground. Taller towers with larger generators, longer blades, and larger rotor diameters all lead to greater energy capture and lower cost per unit of energy output. But the path to this end is complex and fraught with risks, technical challenges, and uncertain outcomes. Success will require novel designs, light-weighting of massive components, stronger materials, innovative manufacturing, creative transport logistics and construction techniques, real-time monitoring and modeling of wind flows, and dynamic plant optimization. All represent significant opportunities for cost reduction.

For land-based wind siting and environmental research and development, the Office's goal is to facilitate the development of solutions, minimize impacts, and enable the efficient siting and operation of land-based wind facilities. Planned activities are focused on a set of top-most concerns. These are primarily related to wildlife, the environment (land and air), radar interference, and community impacts. Planned research in each case is to be tailored to the following research tasks:

- Create a knowledge base to inform solutions
- Explore and develop potential solutions
- Share results broadly among stakeholders and agencies through workshops, publications, and education.

Research Priorities

The MYPP details R&D to support the following seven research priorities for land-based wind, which are organized into categories of technology and siting and environmental.

Research Priorities – Land-Based Wind	
Number	**Description**
Technology Research and Development	
LBW 1	Tall Wind – Pursuit of Economies of Scale
LBW 2	Innovative Wind Manufacturing and Advanced Materials
LBW 3	Integrated Wind Plant Dynamics and Optimized Energy Production
LBW 4	Atmospheric Science and Wind Resource Characterization
Siting and Environmental Research and Development	
LBW 5	Wildlife and Environmental Impacts and Solutions
LBW 6	Radar Impacts and Solutions
LBW 7	Siting Research and Development

Technology Research and Development

Planned activities to reduce costs and technology risks for land-based wind over the FY 2021–2025 time frame focus on the following four research priorities, each with several supporting R&D project areas.

LBW 1: Tall Wind – Pursuit of Economies of Scale

The Office's pursuit of tall wind systems enables access to higher wind speeds and continued economies of scale for land-based wind turbines that are currently limited by transportation constraints. This project area is focused on innovative designs that leverage new materials science, and the ability to manufacture and transport taller towers, lighter drivetrains, and larger rotors.

The wind resource is stronger and steadier higher above the ground. Designing wind turbines with taller towers enables the capture of better wind resources. Further, taller towers allow for longer rotor blades, which increase the swept area of the rotor and capture more energy. As a result, taller towers and larger rotors make wind energy economically competitive even in areas with low wind speeds.

Developing the scientific understanding and technical innovations to enable the designs of tall wind turbines has a significant impact. By increasing hub height from the current average of 90 m to 140 m, the expanded rotor area supports a net capacity factor increase of 30% for U.S. land-based wind power (Lantz et al. 2019). These systems expand resource potential by 67%, or the equivalent of 700,000 more square miles, which is an additional area comparable to roughly one-fifth of the United States (Zayas et al. 2015). Although there are LCOE benefits possible with increases in turbine size and operating height, the size and design of these components have been limited because of transportation and installation constraints.

In the 2021–2025 time frame, research campaigns are planned for innovative designs that will capture greater economies of scale and R&D activities to:

- Enable next-generation turbine components that are larger, lighter, and more reliable
- Overcome transportation and on-site logistic constraints associated with larger components
- Enable efficient O&M for larger turbines through prognostic health management tools, standardized data, advanced inspection, and repair techniques supported by artificial intelligence and robotics.

Technology Research and Development	
LBW 1	Tall Wind – Pursuit of Economies of Scale
LBW 1.1	Next-Generation Drivetrain Design and Reliability
LBW 1.2	Taller Towers
LBW 1.3	Transportation and On-Site Logistics
LBW 1.4	Wind Plant O&M for Larger Turbines

LBW 2: Innovative Wind Manufacturing and Advanced Materials

Planned R&D for next-generation turbines includes advanced materials, new emerging manufacturing techniques, (such as additive manufacturing and three-dimensional [3D] printing), and design for repurposing of wind components, with a specific near-term focus on the reuse of blade materials. Enhanced U.S. manufacturing and automation will significantly reduce the manual labor typically involved in manufacturing wind components. These advancements allow for manufacturing of components at larger scales at lower costs, leading to global economic competitiveness and technology leadership. R&D for new blade materials that can withstand harsh environments and integrated solutions to address damages from lightning strikes are planned to lower costs for maintenance over the lifetime of the wind turbine.

Technology Research and Development	
LBW 2	Innovative Wind Manufacturing and Advanced Materials
LBW 2.1	Manufacturing Automation for Turbine Components
LBW 2.2	Wind Blade Advanced Composites Research: Light-Weighting
LBW 2.3	Durability and Damage Tolerance for Wind Blades
LBW 2.4	Improve Recyclability and Redesign of Turbine Components

LBW 3: Integrated Wind Plant Dynamics and Optimized Energy Production

The wind inflow interactions within the wind power plant are complex. Before reaching a wind plant, air travels from multiple directions over uneven terrain, hills, and vegetation. As the moving air interacts with the turbine rotors, nacelles, and towers, energy is extracted, and wake flows are created behind each turbine. These wakes are highly turbulent and extend downstream with the wind. The wind turbulence, wakes, and adverse interactions contribute to reductions in captured wind energy and reduced reliability of the overall wind plant, both of which increase costs.

Improving wind turbine aerodynamics and structural and controls models allows turbine developers and wind power plant operators to reduce these interaction losses, increase energy production, and improve the overall reliability and longevity of wind power plants. High-performance supercomputers can model these interactions with full physical representations in more complex equations, thereby capturing the detailed characteristics needed for innovative design advances.

Industry does not typically have the models or the computing resources to conduct these types of simulations, nor do they have the capabilities to develop this type of analysis. DOE's expertise and capabilities have a unique role in contributing to improvements in this area and mitigating industry design risk. Advances in high-fidelity modeling are then used to calibrate and improve lower-fidelity models and algorithms used by industry in new engineering designs and plant control strategies.

Continued technology innovation in designs and their application to very large land-based turbines will be essential to reduce costs and improve performance of wind power plants. Turbines and air-flow-responsive plant controls assist in mitigating wake interaction losses and turbine loads, and advanced aeroacoustics for social acceptance are all part of the comprehensive list of activities to ensure future development of large turbine systems.

Technology Research and Development	
LBW 3	Integrated Wind Plant Dynamics and Optimized Energy Production
LBW 3.1	High-Fidelity Model Capability Development
LBW 3.2	Design Tools and Analysis for Integrated Systems
LBW 3.3	Active Resource Monitoring and Advanced Turbine and Plant Controls
LBW 3.4	Aeroacoustics
LBW 3.5	Verification and Validation

LBW 4: Atmospheric Science and Wind Resource Characterization

Assessing and optimizing wind power plant performance first requires an understanding of atmospheric science and the physical phenomena that drive power production. It then requires assessing both the individual turbine and turbine-to-turbine interactions impacting plant performance. Characterizing and quantifying the underlying physics drive the development of deterministic high-fidelity models of atmospheric inflow conditions. These models operate today on DOE's supercomputers and are the basis for achieving optimized system-level wind power plant performance. Such models and computational design capabilities can be used by industry for plant-level integrated system designs.

Understanding the complexities of the environment in which wind plants operate, in high-resolution detail, is critical to understanding the nature of the wind resource. The atmospheric boundary layer (ABL) is the lowest part of the atmosphere, and as a result, is in contact with the Earth's surface. At about 1 to 2 kilometers thick, the ABL is in constant motion because of both mechanical friction with the Earth's surface and thermal gradients driven by the difference in temperature between the ground and the air above. It is within this tumultuous environment that wind power plants must operate. Thus, an improved understanding of the wind resource will allow for more accurate weather models, regional wind simulations, operational wind energy forecasting capabilities, and wind project siting tools. R&D plans in this area aim to improve these models and simulations to create better representations of atmospheric physics, as well as collect the data required to validate these modeling and simulation capabilities.

As land-based wind expands with taller turbines and very large rotors, turbine interactions with the ABL will be within a new realm not previously examined. Rather than the near-surface viscous layer common to wind energy deployment to date, these larger turbines will operate in the mixing layer of the ABL and be subject to new flow physics and characteristics including nocturnal jets, gravity interactions, and different turbulence structures and spectra. Previous operating characteristics and assumptions will need to be re-examined to ensure proper design and operability in the new environment. Wind power plant interactions with the atmosphere include dynamic coupling of very large rotors that must be designed to minimize loads and mitigate risk.

Technology Research and Development	
LBW 4	Atmospheric Science and Wind Resource Characterization
LBW 4.1	Large-Scale to Small-Scale Model Transformation
LBW 4.2	Coupling Atmospheric Boundary Layer to Inflow for Turbine Design and Performance

Siting and Environmental Research and Development

The Office's R&D efforts to address land-based wind siting and environmental impacts focus on three research priorities, each with several supporting R&D project areas planned for the MYPP period. These investments are planned to translate into increased accessibility to wind resources by creating options for developers to use for environmental and siting challenges.

LBW 5: Wildlife and Environmental Impacts and Solutions

Wind power can directly and indirectly affect bat and avian species, many of which are protected by state and federal laws such as the Endangered Species Act,[3] Migratory Bird Treaty Act,[4] and Bald and Golden Eagle

[3] 16 U.S.C. §1531 et seq. Ch. 35 1973. https://uscode.house.gov/view.xhtml?path=%2Fprelim%40title16%2Fchapter35&edition=prelim
[4] 16 U.S.C. 703-712; Ch. 128 1918. https://uscode.house.gov/view.xhtml?req=granuleid%3AUSC-prelim-title16-chapter7-subchapter2&edition=prelim

Protection Act.[5] A large portion of potential U.S. wind capacity overlaps with wildlife and environmental impacts considered to be potentially sensitive to wind energy development.

To permit wind facilities in compliance with state and federal environmental laws, developers and operators of wind energy facilities must assess the likelihood of, and where necessary, mitigate (i.e., avoid, minimize, or compensate), potential impacts of their proposed project on protected species. Over the last three decades, DOE research, conducted in partnership with industry, other federal entities, and nongovernmental organizations, has greatly improved the understanding of impacts and identified potential solutions for a range of issues. There remains an existing and evolving need for effective technological solutions and for research to inform solution designs. As wind energy technology expands its geographic reach and technologies evolve, wildlife impacts will grow and change. For example, as larger turbines designed to operate in lower wind speeds are deployed, the relative cost of operating speed adjustments designed to protect bats will grow and affect deployment potential. In addition, the challenge of creating effective ultrasonic bat deterrents that cover the larger rotor swept areas associated with tall wind are needed.

To understand how to mitigate environmental impacts in a cost-effective manner, R&D is planned to create a knowledge base, develop siting solutions, and share results. It is important to specifically invest in peer-reviewed research to inform, design, and validate technologies and methods to reduce environmental impacts of land-based wind. During the FY 2021–2025 time frame, major R&D project areas are planned to focus on:

- Research to inform and refine solutions to reduce bat mortality at wind farms. This research includes focusing on understanding the drivers of risk to bats to inform solution design, improving and validating deterrent technologies, and improving smart curtailment strategies.
- Research to minimize risk to eagles at wind farms by developing micrositing tools based on advanced computational fluid dynamics modeling, improving deterrent stimuli, and increasing the number and affordability of impact minimization technologies utilizing integrated hardware and artificial-intelligence-based software solutions.
- Evaluation of impacts of wind energy on grouse species to expand siting opportunities.

Throughout this period, efforts are planned to convene stakeholders and aggregate and synthesize the state of the science to ensure solution development is informed by state-of-the art research.

Siting and Environmental Research and Development	
LBW 5	Wildlife and Environmental Impacts and Solutions
LBW 5.1	Reduce Siting Restrictions and Curtailment Costs by Reducing Bat Mortality
LBW 5.2	Facilitate Permitting and Minimize Wind Plant Take of Eagles
LBW 5.3	Evaluate Wind Impacts on Prairie Grouse

LBW 6: Radar Impacts and Solutions

Wind energy development located within the line of sight of radar systems can cause clutter and interference, which at some radars has resulted in significant performance degradation (Karlson et al. 2014). As wind turbines continue to be installed, and as advances in wind energy technology, such as tall wind, enable wind farms to be deployed in new regions of the country and offshore, the probability for wind development to

[5] 16 U.S.C. 668-668c. https://uscode.house.gov/view.xhtml?req=granuleid%3AUSC-prelim-title16-chapter5A-subchapter2&edition=prelim

present conflicts with radar missions, including air traffic control, weather forecasting, homeland security, and national defense, are also likely to significantly increase.

To ensure the effective coexistence of radar missions and future wind energy development, new technologies to mitigate wind turbine radar interference are planned. Moreover, because existing radar systems serve multiple missions across several agencies, collaboration across the federal government is needed to develop and gain acceptance for these technologies. Under a memorandum of understanding signed in 2014 and building off of the successful U.S. Interagency Field Test and Evaluation program's radar mitigation testing campaigns, a consortium of federal agencies (co-led by DOE and the U.S. Department of Defense) established the Wind Turbine Radar Interference Mitigation working group to develop and deploy such mitigations where required.

During the FY 2021–2025 time period, planned activities include developing radar mitigation approaches for the following three R&D project areas, as determined through the "Federal Interagency Wind Turbine Radar Interference Mitigation Strategy" (Gilman et al. 2016b) effort adopted by DOE and the other memorandum of understanding agencies:

- Improving the capacity of government and industry to evaluate the impacts of existing and planned wind energy installations on sensitive radar systems
- Developing and facilitating the deployment of hardware and software mitigation measures to increase the resilience of existing radar systems to wind turbines
- Encouraging the development of next-generation radar systems that are resistant to wind turbine radar interference.

Siting and Environmental Research and Development	
LBW 6	Radar Impacts and Solutions
LBW 6.1	Improve Government and Industry Capacity to Evaluate the Impacts of Wind Turbines
LBW 6.2	Pilot Mitigation Initiative to Develop and Facilitate the Deployment of Radar Solutions
LBW 6.3	Collaboration in the Development of Next-Generation Radar Systems

LBW 7: Siting Research and Development

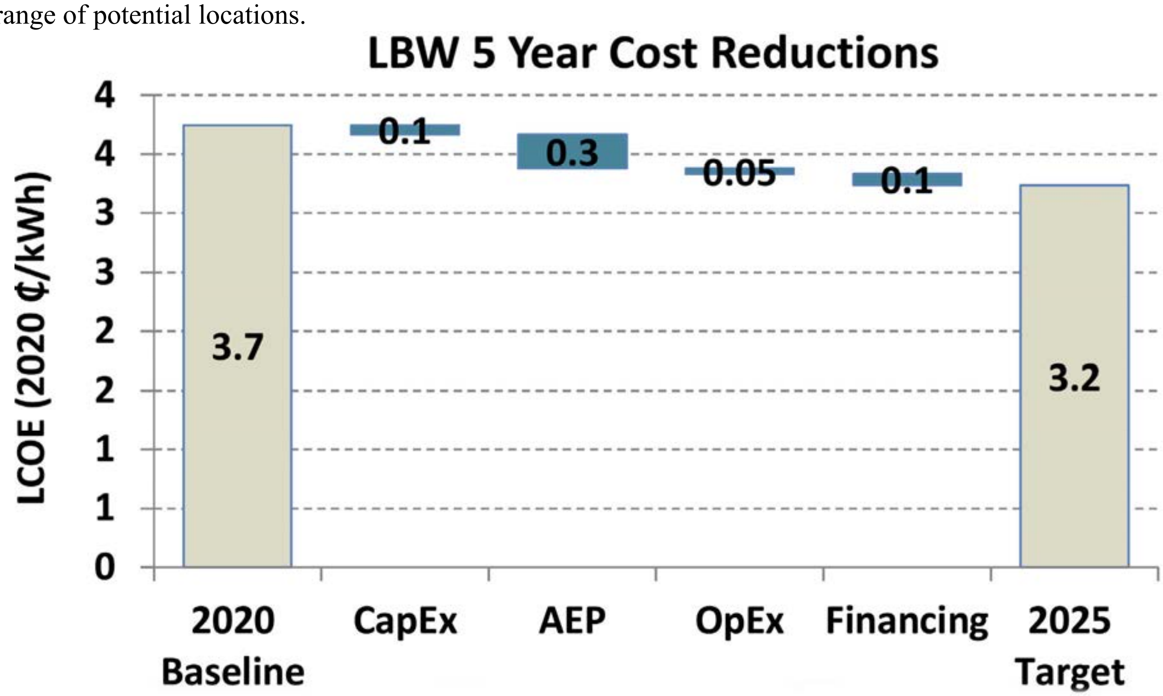
The development of wind projects has impacts on the communities in which wind farms are sited—including visual impacts, additive noise, and changes in land use—and can affect local economies. Siting considerations impact technology options and the cost of wind energy. Wind turbines are deployed within social, economic, and environmental contexts, thus turbine design and siting need to be informed by an understanding of those variables in order to be maximally effective. For example, public perception can present technical design constraints for wind turbines and plants, ranging from turbine size (visibility), lighting (visibility), rotor and drivetrain design (noise output), and limits on equipment/crane size and type (road and land damage).

During the FY 2021–2025 time frame, the Office's R&D efforts plan to focus on research that characterizes locational impacts on communities and economies to develop informed mitigation measures and feedback into the design of future wind technologies (e.g., development of aviation lighting that only activates when needed, turbines with reduced noise footprints, improved noise models, craneless installation techniques, and modular turbine components). In addition to publishing this research, the Office will continue to maintain up-to-date public tools, such as wind resource maps, the National Wind Turbine Database, and databases of relevant research.

Siting and Environmental Research and Development	
LBW 7	Siting Research and Development
LBW 7.1	Siting Research to Inform Solution Development
LBW 7.2	Siting Data and Tool Dissemination

Expected Outcomes

As supported by the land-based wind technology research areas during the 5-year MYPP period, these activities collectively reduce LCOE, supporting the nearly 50%-by-2030 cost reduction goal, for the broadest range of potential locations.



Land-based wind (LBW) levelized costs are projected to decrease by 24% during the MYPP period. Plant useful life and wind resource assumptions are held constant over the MYPP period.

While no single innovation will drive a large change in overall LCOE, the integrated set of innovations is anticipated to yield the Office's land-based-wind LCOE goals of 3.2¢/kWh in 2025 and to 2.3¢/kWh in 2030; from 3.7¢/kWh, as reported in 2020.[6]

As supported by the siting and environmental research and development areas over the MYPP period, the planned research and related activities are expected to facilitate the development of solutions, minimize impacts, and enable the efficient siting and operation of land-based wind facilities. These solutions are expected to lead to a reduction in siting constraints. Specifically:

[6] All future LCOE costs are expressed in 2020 dollars, and therefore do not have inflation-adjusted values for future periods. LCOE does not fully capture all costs and impacts to the economy, such as grid integration costs, supporting transmission requirements and value, and external factors, such as improved health reduction costs.

- Optimized bat deterrent technologies and smart curtailment strategies that reduce impacts, costs, and siting constraints associated with bat impacts, including bat deterrent technologies that reduce mortality by at least 50% for vulnerable species (*myotis*, plus three species of tree roosting bats that experience the greatest rates of mortality at wind farms)
- Smart curtailment strategies that result in < 1% loss in annual energy production while maintaining bat protection equal to or greater than blanket curtailment strategies
- Eagle impact minimization technologies, including eagle detection and deterrence or informed curtailment systems that have both greater efficacy and lower cost than the current state of the art (human observers triggering manual turbine shutdowns)
- Reduced siting constraints associated with grouse species based on a better understanding of impacts, including data on impacts on grouse species that significantly overlap with areas of wind development, leading to either a reduction in assumed risk in permitting processes or identification of options to reduce impacts or develop compensatory mitigation options
- Siting R&D that leads to the development of technical solutions, including improved noise models to enable improved siting of turbines around communities
- Validation of mitigation measures such as infill radar systems and signal processing upgrades, particularly for terminal and long-range air surveillance radars
- Incorporation of resilience to wind turbine interference as a key design requirement in Spectrum-Efficient National Surveillance Radar and other next-generation radar development programs.

4 Distributed Wind

The Office differentiates distributed wind from land-based wind in that the latter provides power and services primarily to the transmission grid at utility scale. Distributed wind, by contrast, typically provides power for on-site demand or to support local distribution networks.

Organic Valley, shown here in Cashton, Wisconsin (America's largest cooperative of organic farmers and one of the nation's leading organic brands) became 100% renewable powered in 2019. ***Photo courtesy of Organic Valley***

Accordingly, distributed wind is defined in terms of the technology's application, rather than its size. The following attributes are used to characterize wind systems as "distributed":

- **Proximity to end use**. Wind turbines that are installed at or near the point of end use for the purposes of meeting on-site energy demand or supporting the operation of the existing distribution grid.
- **Point of interconnection**. Wind turbines that are connected on the customer side of the meter (also known as behind the meter), directly to the distribution grid, or are off-grid in a remote location.

Distributed wind energy systems are commonly installed at, but not limited to, residential, agricultural, commercial, industrial, and community sites. The size of the turbines can range from a 5-kW turbine at a home to multimegawatt turbines at a manufacturing facility or connected to a local distribution system.

In the United States, there is approximately 1.1 GW of distributed wind capacity installed as of 2019 (Orrell et al. 2020). Applications may be found in all 50 states. There is significant potential for expanded application for both larger and smaller distributed wind systems (Lantz et al. 2016). Larger distributed wind systems are finding uses at commercial and industrial sites and, in conjunction with other distributed energy resources (DERs), as providers of balancing support for local grid operations and added resilience to critical infrastructure (as back-up power) when bulk power systems may be interrupted. Smaller distributed wind systems may be designed for residential applications, small agricultural or commercial operations, or rapid deployment to power-isolated microgrids in support of military operations, disaster relief, and other applications. Demand for small wind systems overseas has also been a significant driver of U.S. distributed wind manufacturing. The Office's support for research and innovation, in collaboration with industry partners, has contributed to more efficient designs and significant LCOE reductions, and in some cases, by 50% or more.

Today, distributed wind provides important benefits to many users, often in rural and remote areas. However, the realization of distributed wind's greater potential nationwide is impeded by a number of challenges. Because distributed wind does not enjoy the advantages of purchasing tens or hundreds of turbines, its equipment costs are often higher than utility-scale wind power plants. A lack of standardization and repeatability in towers, foundations, installation methods, and power electronics also raise turbine and balance-of-system costs, particularly for smaller turbines (Jenkins et al. 2016). The costs for permitting and connections to local distribution networks can also be significant (Orrell and Poehlman 2017). Because state-of-the-art methodologies for accurate wind resource assessment are too costly for distributed wind projects, current distributed wind site assessments are often based on rules of thumb, resulting in errors in system performance forecasting, and eroding consumer and investor confidence. Similarly, accurately, and cost-effectively forecasting distributed wind system performance is critical for informing the controls required for hybrid system operation and optimization. Finally, distributed wind is a nascent and fragmented industry comprising numerous small and independent businesses that would benefit from overcoming the challenges and realize the industry's technical potential.

Goals and Approaches

The goal of the Office's distributed wind research program is to reduce LCOE. For a reference 100-kW wind turbine, the goal is to reduce LCOE from 10.5¢/kWh, as reported in 2020 (for prior year installations), to 7.2¢/kWh in 2025 (as reported through the end of the year), and to 5.0¢/kWh in 2030.

Planned approaches for realizing these goals are, in general, to target reductions in the higher cost contributing elements of distributed systems and to improve system performance. More specifically, plans include:

- Standardization of balance of plant (all elements of a distributed wind plant outside of the turbine and tower systems themselves) and installation to reduce capital costs
- Improving turbine performance to cost-effectively increase energy production
- Improving turbine performance forecasts to reduce energy production risk
- Developing low-cost active monitoring, controls, and communication technologies to improve reliability and allow for the provision of needed grid services and integration with other DERs
- Developing design standards and fostering related international technical collaboration.

Research Priorities

Distributed wind R&D addressing technology development has the following six research priorities in the MYPP period.

Research Priorities – Distributed Wind	
Number	**Description**
Technology Research and Development	
DW 1	Reduce Balance-of-Plant Costs Through Technology Solutions
DW 2	Reduce Wind Plant Costs and Optimize Performance for Distributed Applications
DW 3	Reduce Power Production Risks for Small Wind Technology
DW 4	Hybrid Distributed Wind Systems
DW 5	Develop Design Standards
DW 6	Military and Disaster Relief Solutions

Technology Research and Development

Planned activities to reduce costs and technology risks for distributed wind over the FY 2021–2025 time frame focus on six research priorities, each with several supporting R&D project areas.

DW 1: Reduce Balance-of-Plant Costs Through Technology Solutions

In the United States, there are over 18,000 authorities having jurisdiction and more than 3,000 electric utilities (Ardani et al. 2015). Many of these jurisdictional authorities and electricity providers do not have standardized building permit and inspection processes or interconnection procedures that consider the different scales of wind energy development. Even in places where distributed wind is economically viable, technical challenges and regulatory burdens limit its deployment by increasing balance-of-plant costs (Orrell and Poehlman 2017) and limiting industry development of and access to markets. In addition, a lack of standardization and repeatability in towers, foundations, installation methods, and power electronics also raises turbine and balance-of-system costs, particularly for smaller turbines. Developing standardized, application-driven processes and technical solutions can create access to new markets for distributed wind.

Wind Innovations for Rural Economic Development (WIRED) is a crosscutting initiative focused on enabling the development and adoption of distributed wind energy systems, particularly in rural electric utility service territories and communities. The WIRED initiative has two areas of focus:

- Innovations to enhance resilience and reliability of rural electric utilities through integration of hybrid distributed energy systems utilizing wind
- Balance-of-system cost reduction through standardization to greatly simplify adoption by utilities.

The WIRED initiative is aimed to build capacity with local and regional stakeholders on the technical characteristics pertaining to the different scales of wind energy development, which can increase access to new potential locations.

DW 2: Reduce Wind Plant Costs and Optimize Performance for Distributed Applications

For small- and medium-scale (<1 megawatt [MW]) wind turbine technology), there are major gains to be made in terms of performance improvements and cost reductions by integrating and expanding upon the innovations developed over the past 10 years for larger machines, particularly with regards to low-specific-power rotors, advanced controls, standardization of balance-of-plant systems, and installation processes (distributed wind megawatt-scale cost reductions are addressed in the Land-Based Wind section.)

The Distributed Wind Competitiveness Improvement Project is a periodic solicitation in which manufacturers of small- and medium-scale wind turbines are awarded cost-shared subcontracts and technical support via a competitive process. Main focus areas include developing designs for increased energy production and grid support, conducting turbine and component testing to national standards for verification of system performance and safety, and developing advanced manufacturing processes to reduce hardware costs. The goals of the project are to make wind energy cost competitive with other DERs and increase the number of wind turbine designs certified to national testing standards. Over the prior periods, the Competitiveness Improvement Project has yielded major successes, including awardees who have achieved LCOE reductions of nearly 50% within a single project improvement cycle, developed advanced controls and power converters enabling distributed wind to integrate with other DERs to provide grid services, and achieved design certification through testing to national performance and safety standards.

DW 3: Reduce Power Production Risks for Small Wind Technology

Accurately and cost effectively predicting power performance of a distributed wind system, particularly those using small- and medium-scale wind technology (<1 MW) at a specific location, is a technical challenge that will continue to reduce the confidence of U.S. consumers and policymakers in distributed wind systems if left unaddressed. On average, certified small wind systems are producing 90% of the energy estimated prior to their construction, and uncertified small wind systems are producing 58% (Orrell et al. 2019). Measurement-based wind resource assessments employed by the utility-scale wind industry are high in cost and involve long time frames. Thus, small wind installers and developers often use rule-of-thumb methods and simplified model-based approaches. These approaches create uncertainty and tend to overestimate energy production, leading to underperformance. Improved resource assessment and siting processes and tools would reduce costs by correctly sizing distributed wind systems, increase a buyer's confidence in the technology, and greatly improve wind's ability to be included in hybrid and microgrid systems (including in infrastructure resilience, relief, and military applications) where predictability and reliability may be attributes valued above cost.

The Distributed Wind Tools Assessing Performance effort supports collaborative R&D with industry. This effort is planned to improve resource characterization capabilities, and thus reduce project performance uncertainty. The scope of work will use high-fidelity modeling tools to identify where, when, why, and how wind resource assessment modeling tools are failing to provide accurate information. These tools are not routinely used by industry because they are expensive and computationally intensive. Once sources of error are identified, the Distributed Wind Tools Assessing Performance effort seeks to address them by extracting the important physics and flow patterns and making related code available through a simplified open-source format. The resulting product will be a validated, publicly available application tool and independently verified model that will strengthen stakeholder confidence, improve integration into local grids, and reduce LCOE.

DW 4: Hybrid Distributed Wind Systems Supporting a Resilient Grid

Distributed wind systems, including wind-centered hybrid systems (with solar or storage), can be an affordable, accessible, and compatible DER option that enhances the capabilities of local grid operations and supporting resilient infrastructure.

The Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project addresses developing three technology solutions:

- **Accurately Value Grid System Contributions from Wind as a DER**. Advancing the representation of distributed wind in grid modeling tools to better characterize distributed wind's techno-economic performance in, and value to, microgrids, hybrid DER installations, distribution grid systems, and transactive energy systems
- **Advancing Controls for Hybrid Systems in DER Applications**. Demonstrating the advanced grid support functions of wind turbines in grid-connected and isolated microgrids and increasing the availability of wind turbines through fault-tolerant controls

- **Understanding and Guarding Against Cyber Threats**. Conducting research and developing methodologies to understand cyber vulnerabilities, develop threat-resilient supervisory control, and achieve greater, measurable resilience with wind integration in microgrids and distribution systems.

DW 5: Develop Design Standards

To better compete in exports to international markets, U.S. small- and medium-scale wind technology manufacturers need national design standards that are harmonized with international design standards. Engagement with domestic and international collaborators is needed to evolve and improve wind turbine design standards (International Electrotechnical Commission 64100) and grid safety standards (Institute of Electrical and Electronics Engineers 1547), as applied to wind technology used in distributed applications

Wind turbine certification to design standards has been critical to increasing the reputability of smaller wind technologies in the marketplace and is now typically required to be eligible for financial incentives such as feed-in tariffs abroad (Orrell et al. 2019) and the U.S. Investment Tax Credit (Gilman 2015). However, as wind technology has evolved, technical gaps have emerged in the standards. The design tools used to evaluate technologies against the standards are out of date, and the certification process is limiting innovation and the economic competitiveness of wind as a DER. Standards development is planned to explore new approaches for turbine certification that allow for incremental improvements on certified platforms without requiring full recertification while improving design tools and enhancing standards to appropriately address different turbine size classes.

DW 6: Deployable Distributed Wind Systems

To fulfill their primary mission, forward-operating bases of the U.S. Armed Forces and disaster relief agencies require a reliable supply of energy. Diesel generators are deployed to power operations in-theater. Unfortunately, fuel resupply missions for these generators are expensive and become enemy targets, resulting in casualties. A retrospective analysis related to fuel resupply in Afghanistan and Iraq from 2003 to 2007 estimated a casualty rate of one person for every 24 fuel resupply convoys, and that at least 3,000 military personnel and civilians were killed or wounded while conducting fuel delivery operations (Eady et al. 2009).A similar study analyzed the cost for delivering fuel in an operational environment and determined that it was between $100 and $600 per gallon (i.e., up to $25,000/barrel of oil), depending on the range of the battle space.

Rapidly deployable wind and wind-hybrid systems have the potential to reduce fuel requirements of forward-operating bases as week as battery loads for troops in the field, but current technologies are not designed for these applications (Naughton et al. 2020). Defense and disaster deployable turbines efforts focus on driving innovations that enable rapidly deployable wind energy technology. Efforts include work with the military and relief services to develop mission-specific wind turbine design requirements. Once the design space is defined, wind turbine models will be developed to analyze and characterize the design options available for operational and relief applications and to identify the most promising design features. Future collaboration with defense and relief agencies could include soliciting commercial turbine offerings for evaluation based on operational energy design requirements. Additionally, commercial providers could be solicited to respond to a call for prototype design concepts to specified operational requirements.

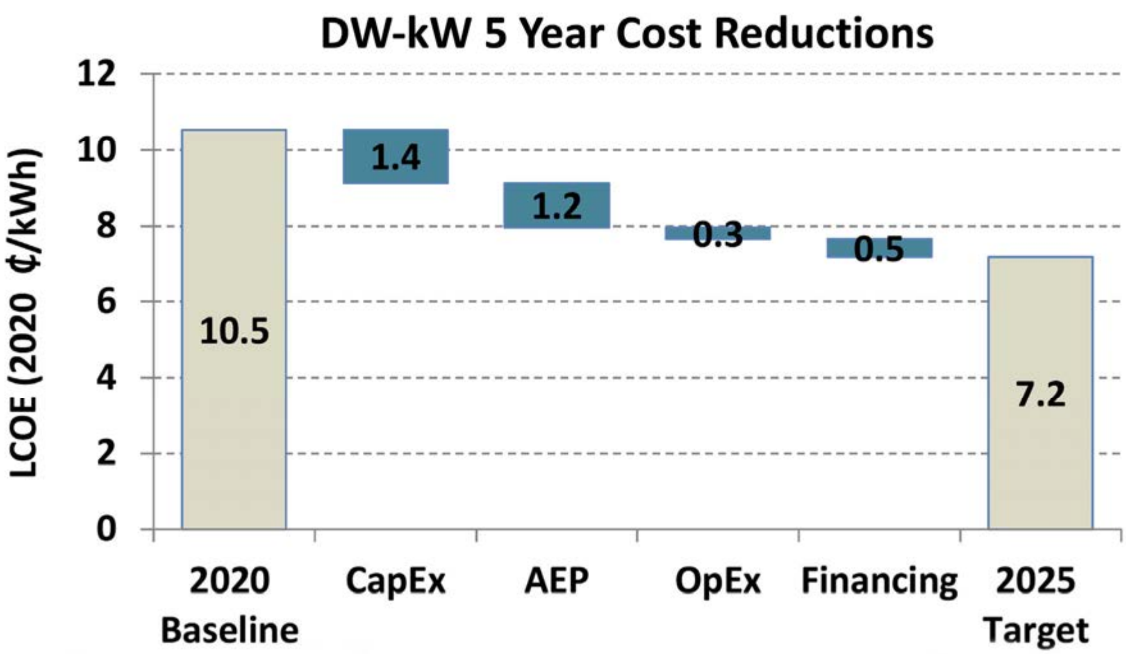
Expected Outcomes

Relative to recent growth trends for other DERs, such as solar photovoltaics and storage, wind technology remains a largely underutilized DER because of higher costs and deployment challenges. Research and development can advance wind technology to a more cost competitive and complementary DER option through cost reductions, performance improvements, accurate energy production forecasts, and smart controls.

The expected outcomes of distributed wind technology R&D investments are:

- Standardized balance-of-plant and installation for distributed applications to reduce capital costs
- Improved turbine performance and increased energy production in distributed wind applications
- Accurate, low-cost turbine performance forecasts to reduce energy production risk for customers and investors, and inform system control schemes
- Integrated, low-cost active monitoring, controls, and communication technologies to improve reliability and allow for the provision of needed grid services and integration with other DERs
- Nationally and internationally accepted design standards supporting consumer confidence and ensuring access to U.S. and global markets
- Rapidly deployable distributed wind systems to support defense and disaster response operations
- Advanced distributed wind systems will provide enhanced services to electricity distribution networks and microgrids and be easily integrated with other DERs into hybrids systems. These advancements can enable distributed wind to realize its potential to provide local economic benefits, particularly in rural communities, and strengthen the resiliency of rural distribution grids.

These distributed wind R&D projects collectively support the cost reductions in the distributed wind-kW design. For a reference 100-kW turbine, the goal is to reduce LCOE to 7.2¢/kWh in 2025, and to 5.0¢/kWh in 2030, from 10.5¢/kWh, as reported in 2020.



Distributed wind (DW)-kW (21–100 kW) levelized costs are projected to decrease by 17% during the MYPP period. Plant useful life and wind resource assumptions are held constant over the MYPP period.

These cost reductions also include the impacts of prior R&D that are just now coming to the market. R&D innovations typically take multiple years to impact actual market costs, given the amount of time required to complete engineering, manufacturing, certification testing, and sales cycles.

5 Systems Integration

Over the past few decades, wind has grown wind from a novel source of energy that was not well understood and represented a share of less than 0.1% of U.S. electricity, to a mainstream source of energy today, with a share of more than 7% of U.S. electricity production in 2019. Future energy systems will be different from today's electric grid. The shifting mix of generation sources and storage, and continued demand for a reliable, resilient, and secure grid are driving requirements for new R&D solutions. Energy systems integration, with the grid as the backbone, must anticipate and provide for solutions that will accommodate a range of future energy system scenarios, challenges, and opportunities.

The Flatirons Campus substation at NREL is part of the Power Generation Upgrade Project, which is changing the source of utility power at the Flatirons Campus from the distribution network that feeds businesses and houses to the transmission network that ties all the power plants and substations together. *Photo by Dennis Schroeder, NREL*

Considerations to take into account for wind energy systems integration include:

- **Increased variability and uncertainty.** Future energy system designs require more system flexibility, including addressing variability from diversified sources, including wind and wind-hybrid systems.
- **Growing demand for a reliable and resilient grid.** Inverter-based resources (IBRs), such as wind, solar, and batteries, respond differently to grid balancing requirements and disturbances than conventional generators. This new grid operating paradigm has raised concerns about grid stability and resiliency. On the other hand, wind energy could provide much-needed grid support (EERE undated), such as synthetic inertia (National Renewable Energy Laboratory [NREL] undated) and primary frequency response (Loutan et al. 2020), even when a system is under significant disturbance.
- **Demand for transmission adequacy and flexibility.** Although future energy systems may become more distributed and decentralized, transmission infrastructures are still required to facilitate the growth of the bulk power transfer. Beyond transmission expansion and upgrades, existing transmission capacity could be better utilized with technologies such as dynamic line rating and smart switching to mitigate congestion and reduce curtailment.
- **Need for cybersecure energy systems.** Virtually all modern sources of power depend on integrated control systems, data, monitoring, communications, and related technologies. Their security has become

an increasingly important and urgent matter. Wind power plant cybersecurity will need to be strengthened to ensure a secure energy system today and in the future.

Goals and Approaches

The goal of systems integration is to enable cost-effective, cybersecure, reliable, and resilient operation of the energy system with increasing levels of wind. The approach is to plan for and execute a robust portfolio of wind systems integration R&D focusing on the highest-impact technology gaps and opportunities.

Wind systems integration R&D must align with other crosscutting R&D initiatives, including DOE's Grid Modernization Initiative and the Energy Storage Grand Challenge (ESGC). The Office's R&D planning has coordinated with multiple R&D organizations and stakeholder organizations with shared equities in an integrated, cost-effective, reliable, resilient, and cybersecure electric grid for today and in the future.

Much of the success in wind integration research can be attributed to the world-class testing facilities at national laboratories, including the recently upgraded 20-MW platform for Advanced Research on Integrated Energy Systems (ARIES) at NREL. Our strategy is to continue leveraging those facilities to conduct research, development, and at-scale field demonstration to validate the expected outcomes.

Research Priorities

The scope of the research focuses on utility-scale wind connecting to bulk electrical systems. It also includes hybrid systems with wind and other generation or storage technologies.

Planned activities within the systems integration R&D portfolio focus on five research priorities to address future wind integration challenges, as shown next.

Research Priorities – Systems Integration	
Number	**Description**
Technology Research and Development	
SI 1	Wind Hardware and Controls
SI 2	Wind Hybrids: Storage and Conversions
SI 3	Analysis of Wind Transmission Adequacy and Flexibility
SI 4	Wind Grid Reliability Support
SI 5	Wind Physical Security and Cybersecurity

Technology Research and Development

Each of the five technology R&D priorities has multiple supporting R&D projects planned for the MYPP period. Descriptions of the more significant R&D projects are included here.

SI 1: Wind Hardware and Controls

Wind and other IBRs are asynchronous. Although fundamentally different from synchronous generators, IBRs can be properly controlled to provide similar and more responsive grid support functions (NREL undated) that have traditionally been provided by synchronous generators (EERE undated). Those functions are commonly known as grid services (e.g., frequency support, ramping and balancing, and voltage support services) (Loutan et al. 2020).

For future energy systems with increasing shares of IBRs, it is critical to experiment and advance technologies to enable wind's capability to provide a full suite of grid services, both during normal grid operation and when the power system is under disturbance or stress. Research is also needed to improve hardware design in support of advanced control functions and reduce integration costs.

Planned activities in the research priority of wind hardware and controls are included as follows.

Technology Research and Development	
SI 1	Wind Hardware and Controls*
SI 1.1	Grid-Forming Capability Development
SI 1.2	Grid-Following Control Enhancement for Stability Support
SI 1.3	Wind Control Standardization and High-Fidelity Model Development
SI 1.4	New Wind Converter Design
SI 1.5	Cost-Effective Offshore Electrical Components

* The research activity may apply to both wind energy systems and wind-hybrid energy systems.

SI 2: Wind Hybrids: Storage and Conversions

Planned research activities will focus on two types of wind-hybrid energy systems:

- **Energy-storage-based hybrid systems**. These are wind power plants that can be co-located virtually (physically separated, but coordinated systems) or physically integrated with equipment and controls that are shared on-site with other generation resources, such as solar plants or storage systems (i.e., batteries).
- **Conversion-based hybrid systems**. These are hybrid systems that use wind energy to produce other forms of energy, including hydrogen, methane, or other renewable liquid fuels (e.g., methanol, ethanol, or aviation or marine fuels) for either resale or use in storage systems. Such systems will require new R&D for wind power plant designs with shared power electronics and development of open-source code for joint control systems.

There is a wide range of storage and conversion technologies that may work with wind. R&D gaps exist in data, models, and tools to design cost-effective hybrid systems. In addition, when a wind hybrid system includes another weather-based generation technology, such as solar, the integration of a combined wind and solar forecast into operations at the plant level is a new research area.

Technology Research and Development	
SI 2	Wind Hybrids: Storage and Conversion
SI 2.1	Data, Models, and Tools Development for Wind Hybrid Design
SI 2.2	Wind Hybrid System Forecast

With proper control, a wind hybrid system can provide a full suite of grid services to make it a dispatchable generation. In the MYPP period, this capability will be demonstrated at scale at NREL's ARIES.

SI 3 Analysis of Wind Transmission Adequacy and Flexibility

Grid studies are essential for power system operators to better understand how to manage increasingly higher penetrations of variable wind power. This is particularly important for offshore wind as nearly 30 GW has secured power purchase agreement and the development pipeline is significant.

Analyzing transmission scenarios can improve the understanding of transmission needs, both on land and offshore, for integrating large amounts of offshore wind to existing transmission infrastructure. The outcomes, including models and tools, could help inform transmission planners to understand the value of transmission to future wind deployment. R&D is also planned to address wind curtailment by evaluating a suite of flexible transmission technologies to better utilize transmission capacity.

Technology Research and Development	
SI 3	Analysis of Wind Transmission Adequacy and Flexibility
SI 3.1	Transmission Scenario Analysis for Future Offshore Wind Integration
SI 3.2	Wind Curtailment Mitigation with Flexible Transmission Technologies

SI 4: Wind Grid Reliability Support

Wind systems integration requires analysis and validation to ensure reliable and resilient grid operation with increasing levels of wind and wind hybrid systems providing a full suite of grid services. The planned research activities will be conducted in a simulated or real grid environment, such as NREL's ARIES, with various generation mix scenarios to:

- Validate wind controls to support reliable and resilient grid operation, including interactions with other IBRs and grid devices, such as flexible AC transmission systems devices
- Evaluate system performance in normal operating conditions and under various types of contingencies
- Improve existing or develop new analytic tools to meet system monitoring and control needs for high amounts of IBRs.

Research activities are further divided to address the key grid operational requirements, as follows.

Technology Research and Development	
SI 4	Wind Grid Reliability Support
SI 4.1	Providing Grid Services from Wind for Grid Flexibility
SI 4.2	Maintaining Grid Stability with High Levels of IBRs
SI 4.3	System Black Start with Wind

SI 5: Wind Physical Security and Cybersecurity

Cybersecurity for integrated control systems and related technology has become increasingly important. The 2020 "Wind Energy Cybersecurity Roadmap" outlines key challenges and research activities to identify, protect, detect, respond, and recover. Aligning with DOE's Cybersecurity MYPP, the Office's wind cybersecurity R&D strengthens critical wind technologies and systems; facilitates engagement and partnerships with industry, academic, and government stakeholders to ensure that research addresses changing needs; and ensures that new wind energy technologies, including both hardware and software, are designed with cybersecurity in mind.

Planned research activities in this area during the MYPP period are as follows:

Technology Research and Development	
SI 5	Wind Physical Security and Cybersecurity
SI 5.1	Wind Plant Cybersecurity Assessment
SI 5.2	Wind Plant Cyber Intrusion Detection and Response
SI 5.3	Wind Plant Physical and Cybersecurity Protection

Expected Outcomes

If successful, the planned systems integration R&D will make available new knowledge and advanced technologies that will enable wind energy to provide increasing amounts of flexible, reliable, and secure power to the grid. Specific outcomes are expected to include:

- Megawatt-scale demonstration at ARIES and validation of sustained grid operation for more than 2 hours, with greater than 80% of power contributed from wind, solar, and batteries. In addition, this demonstration will validate the concept of a dispatchable wind-hybrid-storage system that provides both power and a full range of grid services.
- Demonstrated grid system stability in sustained operations, validated at scale, in a power system that is configured with at least 75% of its power contributed by varying combinations of inverter-based solar and wind generation and energy storage.
- Demonstrated grid system recovery at ARIES to validate the black-start capability from wind or wind-hybrid systems.
- Completion of a cybersecurity exercise at a national laboratory, with participation from various wind industry stakeholders.

6 Analysis and Modeling

Analysis and modeling underpin the rationale for and strategic direction of the planned activities of the Office and its R&D programs. Analysis and modeling activities (e.g., data collection, modeling, tools development, and analysis) collectively form an integrated and coherent information system with an on-demand capability that is connected to ongoing and emerging trends. Further, these activities inform, guide, and enable the Office to plan, execute, and deliver efficiently on its research and innovation mission.

Business woman in a large room in front of a virtual data array and wind power plants.
Photo courtesy of iStock

Selected examples of activities organized under analysis and modeling include:

- Setting, tracking, and reporting on programmatic 5-year and 10-year goals under the Government Performance and Results Act (GPRA) (2011)
- Characterizing wind energy technologies, documenting trends, benchmarking performance, and identifying new and emerging technology developments
- Performing techno-economic analysis on potential cost reduction pathways to identify and help prioritize DOE R&D funding
- Analyzing scenarios, including benchmarks and expected outcomes, under varying assumptions
- Analyzing wind's value to the electric grid as a provider of system services.

The scope of analysis and modeling is sufficiently robust to support the Office's areas of responsibility in offshore wind, land-based wind, distributed wind, and the integration of wind energy with the electric grid and other forms of energy supply, demand, and storage, collectively known as systems integration. Analysis and modeling also support the Office's initiatives in the area of siting and the environment, illuminating the scope and scale of potential impacts and guiding research and innovation toward solutions.

In addition to informing the research and products internally, analysis and modeling provides objective and trusted sources of information. The Office's analysis and modeling efforts are guided by principles of transparency, integrity, quality, replicability, open-source code (when possible), and confidentiality when data may be sensitive or proprietary. Accordingly, its databases, modeling, studies, reports, and other products are sought after and accessed by numerous external users. These include federal agencies, state and local governments, utilities, industry, universities, nongovernmental organizations, and international governmental organizations.

Goals and Approaches

The primary goal of analysis and modeling is to inform, guide, and enable the planning, execution, and delivery of the Office's research and innovation mission. A related and ancillary goal is to share information with others who may benefit from its availability and, in turn, guide and facilitate the expansion of wind energy in the United States. In order to realize these goals, analysis and modeling activities include the following:

- Acquire, process, and provide timely and accurate data from best-available sources
- Develop models and tools that represent a full range of wind generation technologies, operations, interactions, and their potential impacts, including those related to systems that interface with the electric grid
- Carry out analyses that provide insight to decision-making applicable to DOE's R&D investments.

Research Priorities

Research priorities for analysis and modeling are motivated by their related goals and approaches. Maintaining and strengthening analysis and modeling capabilities is planned, with the primary aim of strengthening its core data and sources, improving modeling and support tools capabilities, and expanding analysis on priority topics, such as grid integration, as well as other topics as directed by Congress and the Administration.

Research Priorities – Analysis and Modeling	
Number	**Description**
Analysis and Modeling (A&M)	
A&M 1	Data
A&M 2	Models and Tools
A&M 3	Analysis

A&M 1: Data

Accurate, detailed, and timely data lie at the core of the Office's analysis and modeling activities. Plans include collecting data for all wind types—offshore, land-based, and distributed wind—as well as for wind grid operations, as detailed in the Systems Integration section. Data collection includes wind cost, performance, investment, operational and market information, as well as wind-siting-related content relative to wildlife, radar interference, the environment, and communities. These data are collected, in part, to comply with congressional reporting requirements.

The use of these data also supports analytical activities needed by the Office and others in DOE, and to inform the public and respond to inquiries. Historically, the Office has played a unique role in providing neutral and unbiased information on wind technology that is not generally available through other public or private sources. One example is the aggregation of proprietary and confidential information into publicly available benchmarks.

A&M 2: Models and Tools

Multiple models are used to represent the range of wind system designs, performance, and operations. Models range from simple spreadsheet tools to complex systems engineering and electricity system models that require substantial allocation of supercomputing resources to run. Models include electricity sector capacity expansion, systems engineering, grid system dispatch and operations, and techno-economic analysis models. DOE models and visualization and other tools also help to enable exploration and appreciation of key analyses by nontechnical users. Planned activities call for an enhanced and expanded suite of models to support a full range of research priorities, as detailed in the other sections of this plan. A few selected examples of planned activities across a variety of wind research priorities include:

- Expanding models to address the details required to support wind scaling and economies of scale pathways, particularly offshore
- Updating the model representation of energy storage and wind storage hybrids under systems integration
- Developing models to assess the ability of land-based and offshore wind to provide a full suite of grid services from wind and wind-hybrid systems
- Geospatial modeling of wind siting considerations in support of environmental and siting research efforts.

Such models support the ability to assess potential impacts and evaluate wind's potential contribution to the electricity system at higher spatial and temporal resolutions. They can also lead to a better understanding of the cost and value proposition of wind technology, under realistic simulations, and indicate how wind energy production may interact with storage and other components of the grid. As a general practice, models developed under A&M will, wherever possible, be released as open-source software to ensure transparency and replicability, and to garner suggestions for improvement. In these ways, models gain credibility and reliably inform design and investment.

A&M 3: Analysis

Analysis is used to inform the potential direction and impact of scientific research and technology innovation. Analysis characterizes offshore, land-based, and distributed wind technologies based on historical trends and future innovation potential. It is conducted to illuminate the potential future cost and value of wind power and maintain a view toward potential energy sectors of the future while considering an array of technology and market conditions. Analysis is key to the identification and formulation of a scientific research and technology development strategy. In addition, analysis provides market and cost benchmarks for wind technology and helps inform public and private sector investment in wind technology and related innovation opportunities.

Planned activities include the use of engineering and cost model analysis to enhance the understanding of the interplay between wind technology innovation, wind-power-plant system-level trade-offs, and R&D impacts. These insights will inform DOE's understanding of potential U.S. competitiveness and better position U.S. industry and business in the global marketplace.

Expected Outcomes

Analysis and modeling are expected to provide objective, timely, and high-quality data and analysis on the rapidly evolving state of the wind industry and its technology, performance, and costs. Data and analysis will identify technology trends and emerging developments and help to evaluate and prioritize wind energy technology R&D innovation opportunities. In the area of grid and systems integration, analysis and modeling activities are expected to improve the knowledge base of factors associated with wind energy and its increasing role in the electric sector and wholesale energy markets. In general, analysis and modeling will provide detailed information in the form of publicly available data, models, and analysis to facilitate informed investment decisions across the wind and electric sector industries. In sum, the data collection, modeling and tools development, analysis, and communications will provide information and insights upon which the Office will execute its programs.

7 Crosscut Research and Development

The R&D that the Office carries out is not just motivated by its own programmatic objectives, but also advances several broader DOE- and EERE-wide initiatives. Such initiatives, known as "crosscuts," span organizational elements, share common goals, and are expected to benefit from synergistic cooperation.

Crosscut R&D focuses on high-priority strategic initiatives. The research aims to accelerate progress by encouraging programs to plan and work in concert, parse out tasks, and/or leverage resources. The Office participates in seven crosscuts defined by the Office of Management and Budget, as shown in the following table.

R&D collaboration is not unique to these crosscuts and can be found in virtually all of the Office's R&D activities. Additionally, as found in the Appendix, the section titled Wind Test Facilities and Research Centers highlights unique, world-class platforms for wind industry research and testing initiated with funding from the Office.

Goals and Approaches

The goal for crosscut R&D is to enhance the value of the summed R&D investments beyond the level that would otherwise occur if each cooperating entity were to invest independently. The approach is to work together with other entities, parse out tasks where merited, leverage resources, exchange information, share results, and accelerate progress on common problems that, in turn, will advance Office objectives and build toward an expanded wind energy future.

Research Priorities

The plan outlines seven research priorities for crosscut R&D, as follows.

Research Priorities	
Number	**Description**
Crosscut Research and Development	
CC 1	Artificial Intelligence
CC 2	Advanced Manufacturing
CC 3	Polymer Upcycling and Recycling
CC 4	Cybersecurity
CC 5	Energy Storage Grand Challenge
CC 6	Grid Modernization
CC 7	STEM and Workforce Development

Crosscut Research and Development
Planned activities are targeted to support the crosscut initiative's technical approach. During FY 2021–2025, seven research priorities will be supported, each containing several R&D project areas.

CC 1: Artificial Intelligence
Artificial intelligence has the potential to transform nearly every sector of technology. Today, it is being applied to accelerate the pace of discovery in a wide variety of areas including energy, materials science, national security, emergency response, and transportation. The high value of expansive, independent data sets is open to evaluation from multiple perspectives and disciplines (e.g., weather, materials testing, environmental

effects, and wildlife), providing new insights and technology development pathways. Further, open-source data and collaborative models are just two examples that provide new insights and technology development pathways. The Office plans to aggregate and analyze large data sets using high-performance computing, and incorporate robotics, machine learning, and other artificial intelligence methods to several planned activity and project areas, as indicated next.

Crosscut Research and Development	
CC 1	Artificial Intelligence
CC 1.1	Wind Plant Performance and Controls
CC 1.2	Operations and Maintenance Optimization
CC 1.3	Next-Gen Technology Development and Manufacturing
CC 1.4	Siting and Environmental Impacts

Planned artificial intelligence R&D activities will advance and extend ongoing artificial intelligence initiatives in machine learning, neural networks, robotics, and other areas with the aim to accelerate computationally intensive modeling simulations and develop new methods for pattern recognition in complex systems. Planned R&D activities include:

- Use pattern recognition algorithms to quantify trends and physical relationships in large and disparate operational wind power plant data sets to identify performance enhancement and cost improvement opportunities in integrated system operation and maintenance
- Building on the recent success of the artificial intelligence turbine blade simulation algorithms, incorporate trained neural networks to segment large wind plant system simulations into smaller artificial intelligence computational components— accelerating high-fidelity modeling simulation times by an order of magnitude
- Build on current work with the National Center for Atmospheric Research to generate rapid operational wind and power forecast predictions from new neural-network-based weather forecasting models that operate faster than real time
- Develop artificial intelligence neural networks trained on pre and postoperational wind farm performance data, coupled with pattern recognition algorithms, to identify causal relationships impacting performance uncertainty
- Enable design optimization and innovation for advanced manufacturing and 3D printing
- Develop automated detection and classification software to monitor birds and bats around wind installations.

CC 2: Advanced Manufacturing

Planned activities include strategic collaboration with DOE’s Advanced Manufacturing Office, other EERE offices, industry, and universities, to leverage world-class DOE manufacturing capabilities at the national laboratories. These activities will reduce LCOE through advanced manufacturing and materials innovations for wind turbine components.

Crosscut Research and Development	
CC 2	Advanced Manufacturing
CC 2.1	Wind Blade Advanced Composites Research for Light-Weighting
CC 2.2	Advanced Wind Blade Manufacturing for Light-Weighting
CC 2.3	Hybrid Concrete Tall Wind Tower
CC 2.4	Advanced Generator Additive Manufacturing
CC 2.5	Additive Process Materials Research

The Office participates in and leverages R&D and partnerships developed through the Institute for Advanced Composites Manufacturing Innovation. Planned research seeks to develop advanced composite materials and processes, including development of carbon-fiber composites for lightweight wind blades that maintain needed performance; advanced manufacturing processes such as 3D printing of blade core materials; fusion joining of thermoplastic wind turbine blades; and additive designs of advanced generators. The Office plans to continue partnerships and collaborations on materials and manufacturing R&D for wind blades to enable light-weighting and manufacturing automation.

CC 3: Polymer Upcycling and Recycling

Polymer upcycling and recycling strives to ensure the efficient, full-life cycle use of materials, water, and energy to eliminate waste and optimize the use and reuse of all resources through a domestic supply chain. The concept also includes planning for end of life (e.g., recycling or reuse) in the front-end design and fabrication of material.

For the wind sector, polymer upcycling and recycling pertains primarily to the repurposing and reuse of wind turbine materials. Planned R&D aims to advance the cost-effective recycling and reuse of wind blade materials, such as fiberglass, carbon fibers, and thermoset adhesive materials. In the United States, wind turbine blades are currently sent to a landfill at the end of the technology life cycle. Therefore, development of recycling, reuse, and/or redesign innovations can alter the current end-of-life scenario for such components. Three R&D innovation priorities have been identified to support recycling and reuse of domestic materials: materials separation technologies, materials recycling technologies, and blade designs for materials reuse.

Crosscut Research and Development	
CC 3	Polymer Upcycling and Recycling
CC 3.1	Repurpose Wind Turbine Blade Materials
CC 3.2	Reuse and Design of Wind Components to Avoid Critical Rare Earth Materials (with the Advanced Manufacturing Office)
CC 3.3	IEA Task on Wind Blade Recyclability

DOE analysis is currently ongoing to quantify blade waste, as well as R&D to enable cost-effective recycling of existing fiberglass blades, and advanced manufacturing techniques for better recyclability of future blades. Planned future research will emphasize R&D technology innovations applicable to wind technology development and manufacturing. Examples include a) coordinating with the Advanced Manufacturing Office and the Reducing Embodied-Energy And Decreasing Emissions (REMADE) Institute to increase the use of secondary materials (e.g., metals, fibers, polymers, and electronics), b) coordinating with the DOE Critical Materials Institute on reuse and design for avoidance of critical rare-earth materials, and c) initiating an IEA technical R&D task on recyclability options for wind turbine blades.

CC 4: Cybersecurity

White House Executive Order 13800 directs federal agencies to support cyber risk management efforts for critical infrastructure and to work with the energy sector to identify, protect, detect, respond to, and recover from cyberattacks targeting energy infrastructure. EERE's cybersecurity R&D is guided by the Executive Order and the National Institute of Standards and Technology Framework for Improving Critical Infrastructure Cybersecurity, and will leverage other National Institute of Standards and Technology standards and the investments of other federal agencies.

The "Roadmap for Wind Energy Cybersecurity" aligns with EERE's Cybersecurity MYPP (EERE 2020). Planned activities in this area aim to strengthen critical wind technologies and systems; facilitate engagement and partnership with industry, universities, and government stakeholders to ensure early-stage research accurately tracks the dynamic needs of operational technology cybersecurity; and ensure that new wind energy technologies, including both hardware and software, are designed with cybersecurity in mind.

Crosscut Research and Development	
CC 4	Cybersecurity
CC 4.1	Validation of Models, New Controls, and Approaches
CC 4.2	Establish Wind Plant Reference Architecture and Validate Mitigation Strategies
CC 4.3	Assess Cyber Threats and Develop Process for Monitoring

Planned R&D in cybersecurity includes:

- Support the validation of models, new controls, and approaches to cybersecurity in the microgrid and distributed generation environment through the multilab MIRACL project
- Establish wind power plant reference architecture and set up a power system co-simulation environment to conduct wind plant cybersecurity assessment and validate mitigation strategies
- Collaborate with the Office of Cybersecurity, Energy Security, and Emergency Response's Cybersecurity for the Operational Technology Environment (CYOTE™) program to conduct cyber threat assessment and develop specific tactic, technique, and procedure insights for monitoring.

CC 5: Energy Storage Grand Challenge

DOE's Energy Storage Grand Challenge (ESGC) builds on its extensive resources and expertise to address energy storage technology development, commercialization, manufacturing, and workforce challenges. The vision for the ESGC is to create and sustain global leadership in energy storage utilization and exports, with a secure domestic manufacturing supply chain that is independent of foreign sources of critical materials, by 2030. The ESGC focuses on a broad range of storage technologies, including bidirectional stationary and mobile electrical storage, chemical and thermal storage, as well as flexible generation and controllable loads.

Wind energy R&D interests crosscut with ESGC in the area of flexible generation and controllable loads. The Office plans research to enable cost-effective wind storage hybrid systems and to provide a full suite of grid services. Key opportunities for R&D innovation are to identify cost-effective hybrid options for wind; design, control, and demonstrate wind hybrid systems; and align grid operation with wind hybrid systems.

Crosscut Research and Development	
CC 5	Energy Storage Grand Challenge
CC 5.1	Wind Plant Performance and Controls
CC 5.2	Operations and Maintenance Optimization
CC 5.3	Integration of Wind with Storage

R&D projects aim to:

- Develop and validate controls designed to utilize wind as part of a hybrid system to provide full plant dispatchability and a complete range of reliability services to the bulk power system, including storage and generation
- Enable a grid-forming capability of wind alone and wind with battery systems
- Increase wind power plant operational flexibility by co-optimizing controls to include operational modes that minimize wake losses, maximize value streams for grid services, and reduce O&M under varying grid service operating modes
- Enable cost-effective, secure, and reliable integration of wind with DERs, such as storage, to increase power system resilience and provide grid services using the multilab, distributed wind MIRACL.

CC 6: Grid Modernization

The goal of the Office's systems integration R&D is to provide innovative solutions supporting the seamless integration of high wind energy penetration into the grid. The Office has a long history of supporting projects in the Grid Modernization Initiative through the Grid Modernization Laboratory Consortium, a strategic partnership between DOE and its national laboratories to collaborate on grid modernization. The consortium promotes partnerships with state and local agencies, industry, and other federal agencies. Future R&D planned by the Office includes integration studies, modeling, demonstrations, and assessments at both the transmission and distribution levels while collaborating with utilities to facilitate adoption of best practices.

Crosscut Research and Development	
CC 6	Grid Modernization
CC 6.1	Wind Grid Reliability Support: Grid Flexibility, Stability, Resiliency, and Security
CC 6.2	Validation of Models, New Controls, and Approaches

Current and planned multiyear grid modernization projects include:

- **Grid Services**. Integrated controls allow wind-storage hybrid systems to make trade-off decisions on electricity delivery (e.g., send to energy markets, delay timing to serve a higher capacity market, or precurtail to provide grid services). Integrated controls may also interoperate with ultracapacitors and battery storage, balancing operations with market returns.
- **MIRACL**. The Microgrid, Infrastructure Resilience and Controls Launchpad is an example of crosscutting R&D targeting grid integration of distributed wind energy. MIRACL supports the validation of models, integrated system controls, and microgrid cybersecurity for distributed generation environments. MIRACL will enable cost-effective, secure, and reliable integration of wind with DERs to increase system resilience and enhanced grid services.

CC 7: STEM and Workforce Development

During the MYPP period, the Office's strategic actions to support Science, Technology, Engineering and Mathematics (STEM) education and workforce development plan to continue to focus on the following activities:

- Providing national-level assessment of workforce education needs, anticipated growth of the industry, and gaps in current and future educational programming
- Convening industry, training programs, labor groups, and educational institutions to identify pathways to address workforce and STEM gaps
- Catalyzing STEM programing and workforce efforts through seed funding of curriculum development, STEM programs, and other workforce development activities.

Crosscut Research and Development	
CC 7	STEM and Workforce Development
CC 7.1	Conduct a Workforce Gaps Analysis
CC 7.2	Convene Industry and Workforce Training Partners
CC 7.3	Catalyze Wind Workforce Education Programs

Texas Tech University students Alex Benitez (left) and Katie Alexander (right) work on their wind turbines prior to performance testing at the 2018 Collegiate Wind Competition in Chicago.
Twelve student teams competed in the event.
Photo by Werner Slocum, NREL

Planned future STEM and workforce development activities for land-based and distributed wind are aimed at understanding national wind workforce educational needs, and efforts to help bridge identified gaps. Offshore wind requires a uniquely qualified workforce. Given both the potential for rapid workforce growth and the nascent state of the domestic offshore wind industry, there is a need to ensure that educational programs are graduating students with engineering and science expertise in offshore wind, in addition to growing the current workforce of skilled offshore wind technicians.

The Office is participating in a broader DOE opportunity providing a combined $20 million in FY20 funding, across DOE programs, for the University of Tennessee to create a 5-year interdisciplinary program focused on research and development in evolving technical fields. This funding, which expands the partnership between the university and Oak Ridge National Laboratory, supports the Administration's Strategy for STEM Education by developing a more diverse energy workforce with the skills needed by 21st century employers.

The Office also plans to continue the Wind for Schools project, which provides K-12 learning opportunities, as well as the Collegiate Wind Competition for undergraduate university students. The Office also remains active in the North American Wind Energy Academy, which provides graduate-level wind energy educational opportunities, including WindU, an international multiuniversity consortium in wind energy graduate education.

Finally, over the next 5 years, the Office will aim to increase the breadth and depth of its university-based research by developing and implementing a multifaceted strategy of engagement. Although principally aimed at increasing wind-related university research, this University Engagement Strategy (see Appendix) will also help to strengthen STEM activities aimed at attracting, training, and re-training men and women for professional careers in the wind industry.

Expected Outcomes

The R&D activities illuminated in this section are varied and ambitious. Although each has a specific set of goals, it is expected, collectively, that the crosscut activities will enable researchers to be more productive by working synergistically. Such activities can leverage resources on projects with a broadened scope. Researchers working together on common goals facilitates the exchange of information and stimulates creativity. Cooperation helps to avoid duplication and increases efficiency by parsing tasks and dividing labor. Importantly, it raises research ambition to levels that, otherwise, might not be possible. If the crosscutting initiatives are successful, outcomes will accelerate progress and achieve results beyond that which would occur if the Office were to work independently on its own projects and without the benefit of such platforms.

Program Evaluation

Effective stewardship of the Office's R&D program and investments requires continuous information on progress, results, and outcomes. Information enables Office management to gauge effectiveness of its operations in a timely manner. Topics evaluated may include budgeting, planning of research projects to be conducted at national laboratories or competitively solicited, program implementation, identification of needed corrections or improvements, analysis of outcomes, and accounting and documentation of benefits and successes for reporting to higher levels of management, or for external communications.

The Office relies on its program and project managers to carry out monitoring and evaluation functions as a matter of standard routine. Such processes are significantly enhanced by the Office establishing goals, metrics, milestones, and expected outcomes for its subprograms and projects; sharing results among and seeking critiques by technical experts in workshops and selected professional fora; and scheduling regular reviews by external and independent peers.

Selected examples include:

- **LCOE**. The Office of Management and Budget monitors performance of the Office's programs against established technical annual and long-term performance targets, as specified in the GPRA. The Office uses modeled LCOE, in addition to other metrics, to set targets and evaluate R&D progress, and is responsible for monitoring progress against quarterly milestones aligned to these targets. The Office also reports on annual performance targets established in congressional budget requests.

- **Milestones**. For R&D activities focused on grid systems integration and environmental and siting challenges. The Office sets milestones and expected outcomes to measure progress, as outlined in previous sections.

- **Peer Reviews**. Rigorous, independent peer reviews take place every 2 years in alignment with EERE guidance and best practices. They are designed to ensure and enhance the management, relevance, effectiveness, and productivity of R&D projects, and to evaluate the overall Office strategy. Representatives from industry, national laboratories, academic institutions, and nongovernmental organizations that received funding from the Office during the review period are required to participate in the review process. Panels of independent reviewers are tasked with reporting their findings to DOE, and a summary of the peer review is made public.

- **Merit Reviews**. EERE national laboratory guiding principles require all offices to merit review direct-funded national laboratory R&D projects. With only limited exception, all laboratory projects are evaluated prior to funding the projects. Merit review panel members are subject matter experts that provide an independent assessment of the technical/scientific merit of a proposal prior to the funding decision by senior program staff, allowing DOE to sustain world-class science and technology ideas.

- **Workshops**. The Office regularly engages with technical experts and nontechnical stakeholders in workshops, as well as in smaller meetings, to gather information on industry trends, emerging developments, and issues or concerns. The information gleaned from these engagements is used to inform the Office's research portfolio, often inspiring new avenues of research, making sure that the Office's portfolio is relevant and on target. A recent example is a series of six interagency workshops on siting issues focusing on potential use conflicts between wind energy and radar for weather, navigation, military training, and national security.

- **Professional fora**. The Office also encourages its staff, principal investigators, and researchers to publish papers based on funded research and speak at professional meetings on findings and results. This is helpful for professional development, team retention, and career progression, but also for external program evaluation, as the visible works receive scrutiny and constructive feedback from experts and professionals with relevant knowledge and insights.

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Appendix

Wind Test Facilities and Research Centers

Wind test facilities and research centers provide platforms for industry to access world-class and unique research capabilities. Such facilities are essential for the advancement of the technology but are too costly for most companies to support individually. They also provide the wind energy research and development (R&D) program the opportunity to curate public-private partnerships and advance novel or specialized R&D concepts. In general, these facilities offer a purpose-built technology space wherein public and private sector experts can approach technical problems that are not only significant in terms of scientific scope, but in physical size, such as stress-testing a 100-meter (m)-long wind turbine blade. The physical space, technical capabilities, and knowledge base of these centers enable partnerships as follows:

- **Wind Technology Testing Center (Charlestown, Massachusetts)**. Funded by the U.S. Department of Energy (DOE) and the commonwealth of Massachusetts in 2009, the center supports the testing and certification of wind turbine blades up to 120 m long. It enables U.S.-based ventures to meet international standards and be competitive. Public sector collaborators include the Massachusetts Clean Energy Center, the National Renewable Energy Laboratory (NREL), Sandia National Laboratories, the University of Massachusetts, Georgia Tech, and City College of New York. Private sector collaborators include General Electric (GE), Siemens-Gamesa, MHI Vestas, LM Windpower, and Blade Dynamics. The center was competitively selected to receive additional DOE funding for upgrades in 2019.

- **Energy Innovation Center (Charleston, South Carolina)**. Funded by DOE and Clemson University, the center offers world-class, large-scale wind turbine drivetrain and grid interface test facilities. Commissioned in 2014, it is now self-sustaining through commercial and research contracts. Private sector collaborators include GE testing a land-based 3+ megawatt (MW) drivetrain and MHI Vestas testing an offshore 9.5-MW drivetrain.

- **Scaled Wind Farm Technology (SWiFT) Facility (Lubbock, Texas).** SWiFT is the principal DOE facility for investigating wind turbine wakes as part of an integrated wind power plant operational experiment. It is operated in partnership with Texas Tech University's National Wind Institute and Group NIRE and avails itself of consistent wind conditions up to 200 m in height throughout the year. Planned activities include integrating SWiFT with Texas Tech's technology-to-market laboratory, which will expand future research into smart grid; cybersecurity; energy storage; microgrid; transmission and distribution and grid integration.

- **Lidar Buoy Loan Program**. DOE owns and makes available to industry two AXYS WindSentinel buoys that collect—while moored at sea—a comprehensive set of meteorological and oceanographic data to support resource characterization for offshore wind energy. The buoys support research to validate wind resource models, understand the wind profile behavior from surface to hub height, provide wave measurements for load modeling, and understand subsurface impacts of air-sea interactions. In partnership with the Bureau of Ocean Energy Management, one of the buoys is collecting data through 2021 in a planned offshore wind lease area off the coast of California.

- **Wind Energy R&D Capabilities Upgrade (NREL)**. Planned activities include the expansion and interconnection of several NREL research facilities that are expected to be heavily utilized by the Office over the next 5 years. In 2019, NREL took steps to integrate the High-Performance Computing environment, Flatirons Campus, and Energy Systems Integration Facility, and support the Advanced Research for Integrated Energy Systems initiative. This new upgrade will support integrated research at the greater-than-20-MW scale at the interface between the distribution and bulk power systems. In support of the Office's system integration objectives, this facility will enable the development of power electronics-based management and controls, hybridization of energy systems, and cyber control strategies. It will employ the capabilities of new technologies and control techniques, advanced sensing and data analytics, and more sophisticated models and validation techniques.

Ten years ago, these centers and facilities recognized technology gaps in the wind sector. They have been, and continue to be, successful in meeting their original design goals. As new technologies are developed, testing centers will need to adapt, evolve, and upgrade to meet future needs. To enable and facilitate continued innovation and U.S. competitiveness in wind energy, the Office plans to maintain relationships with the facilities and centers and assess their adequacy to meet ambitious R&D needs as wind technology moves toward greater economies of scale.

University Engagement Strategy

Universities are intellectual wellsprings of knowledge, creativity, practical engineering, and problem-solving. They are and will continue to be important contributors to wind energy science, research, and technology development.

The Office has a long history of supporting university-based research. Engagements are accomplished by a number of means, the more common of which are competitive solicitations, lab-university research partnerships, and subcontracts to primary awardees.

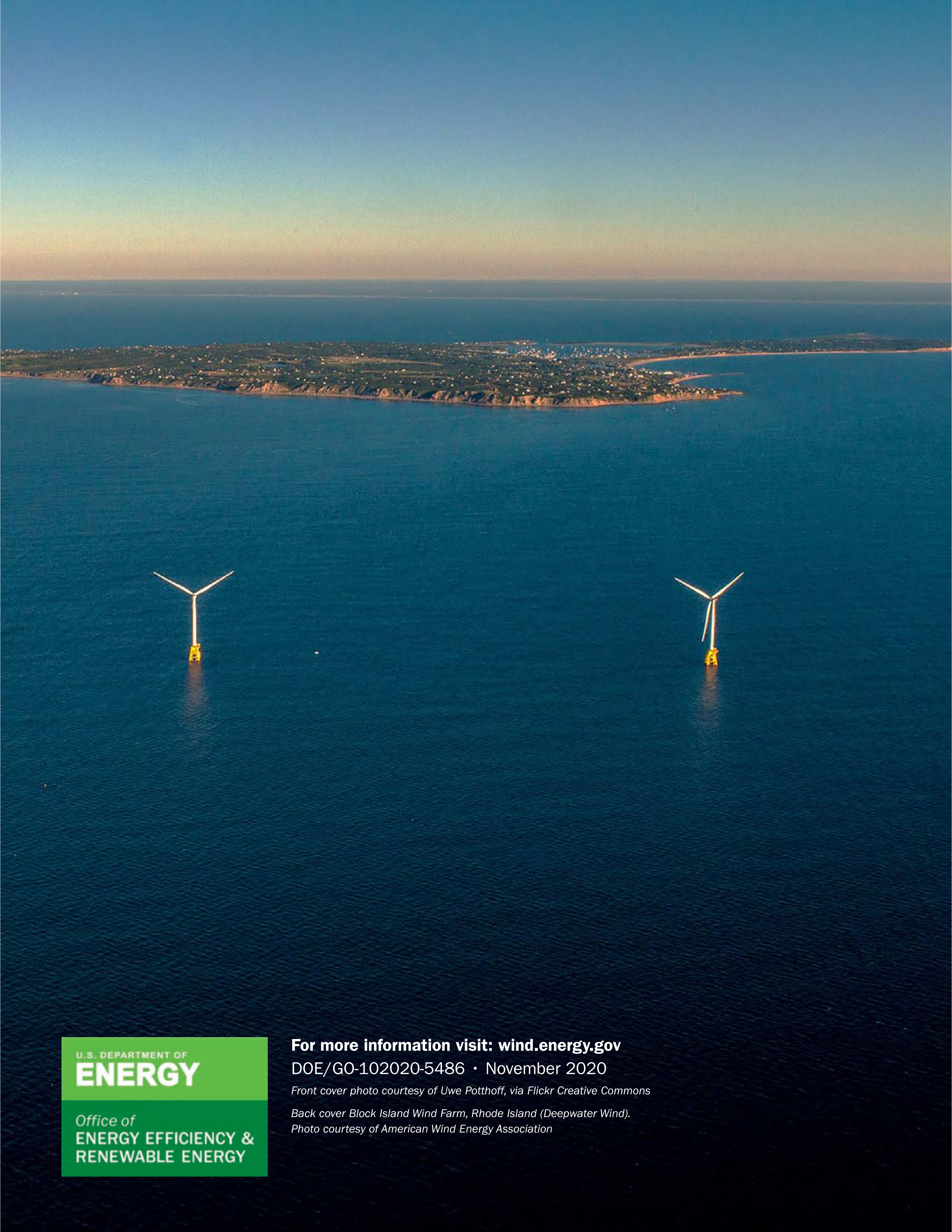
In 2020, the Office had active projects with more than 55 universities. Of these, many were multiyear awards. Topics include basic research, atmospheric sciences, materials design, high-performance computational modeling and tools, ultrasound bat deterrence techniques, fatigue testing of blades, carbon fiber strengthening, and novel designs for floating offshore wind platforms.

Over the next 5 years, the Office will aim to increase the breadth and depth of its university-based research by developing and implementing a multifaceted strategy of engagement. In general, the Office will identify areas where universities can add value to R&D priority areas, as identified in this MYPP. It will structure fair and open competitions in ways that encourage universities to apply and encourage nonuniversity applicants to include university expertise among its team of collaborators and partners. The Office will also continue to encourage DOE national laboratories to award subcontracts to universities, where appropriate.

Additionally, the Office will review and strengthen its science, technology, engineering, and mathematics (STEM) activities aimed at attracting, training, and re-training men and women for professional careers in the wind industry. Steady and sustained support of wind-focused academic institutions, curricula, and related activities at the university and postgraduate levels will ensure a healthy population of wind power professionals with a wide range of skills and expertise, including the sciences, engineering, law, business, and finance.

The Office's strategy will also include support for advanced-degree research (e.g., research assistants, academic fellowships) at the university level, as well as using national laboratory internships to introduce high-potential Ph.D. and master's degree students to the technical challenges facing wind energy. This work will build on or complement other existing Office-supported programs, including the Collegiate Wind Competition, North American Wind Energy Academy, and Wind for Schools program.

Through a sustained investment in university-based research, progress in wind energy science and technology innovation will be accelerated, and a robust pipeline of technical, scientific, and other skills needed for the future of wind energy in the United States can be assured.



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Back cover Block Island Wind Farm, Rhode Island (Deepwater Wind). Photo courtesy of American Wind Energy Association