April 2019

IEA Wind TCP

Results of IEA Wind TCP Workshop on a Grand Vision for Wind Energy Technology

Technical Report

Results of IEA Wind TCP Workshop on a Grand Vision for Wind Energy Technology

Prepared for the
International Energy Agency Wind Implementing Agreement

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April 2019

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy National Renewable Energy Laboratory Directed Research and Development (LDRD) Program. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Preface

The wind industry has realized substantial growth reaching over 500 gigawatts (0.5 terawatts) of installed capacity in 2017 (Global Wind Energy Council 2018) and producing about 5% of global electricity demand in 2016 (Wiser and Bolinger 2018). The levelized cost of energy (LCOE) for wind energy projects both on land and offshore has fallen as a result of substantial innovation over the last several decades. More specifically, equipment, installation, and operation costs have decreased while energy production per turbine has increased (Wiser et al. 2016).

At the same time as LCOE has been decreasing, integration challenges in the broader electric system have been successfully addressed in many markets, thereby enabling the level of wind energy generation to grow to more than 10% of electricity consumption in at least eight countries around the world and more than 30% in Portugal and Denmark (Wiser and Bolinger 2018).

What does the future of the wind industry hold?

Looking ahead, a variety of scenarios for future global wind deployment illustrate possibilities ranging from a plateau in deployment near current levels to a rapid growth in global installations. Based on analysis by DNV GL (2018), wind-generated electricity projected growth will provide over a third of global electricity demand and accordingly, wind technology could become a primary electricity generation technology.

However, there are challenges facing continued growth of wind energy deployments globally. Competitive technologies for electricity generation including solar photovoltaics and shale gas have seen rapidly declining costs in recent years (Haegel et al. 2017). In many countries, conditions also favor continued interest and investment in coal and nuclear power (International Energy Agency [IEA] 2018). Finally, many stakeholders still question the ability to maintain reliable and stable electric grid system operation as wind-generated electricity increases to levels of 10%, 20%, and 30% or more. In these future scenarios, wind power plants will not only provide energy resources, but also significant capacity value and reliability services to the grid (Ahlstrom et al. 2015).

Therefore, realizing the full potential of wind technology will require a paradigm shift in how wind turbines and power plants are designed, controlled, and operated. Notwithstanding the accomplishments of the wind industry to date in driving down costs and increasing performance, there is still an immense opportunity for innovation to enable continued expansion of wind power around the world.

The IEA Wind Topical Experts Meeting (TEM) #89 “Grand Vision for Wind Energy” workshop sought to bring together a group of experts to consider the question of how to enable a future in which wind energy supplies more than 50% of global electricity consumption. Over 70 experts representing 15 different countries attended the workshop and provided a diverse set of perspectives for the Grand Vision for Wind Energy. The experts participated in one or more meetings to develop the vision including: 1) the main IEA Wind TEM #89 held at the National Renewable Energy Laboratory in Golden, Colorado, on October 22−23, 2017, 2) a meeting at the Utility Variable Integration Group 2017 Fall Technical Workshop in Nashville, Tennessee, on October 12, 2017, and 3) the IEA Wind

Task 25 Fall 2017 Meeting held at the Instituto Nacional de Electricidad y Energías Limpias in Cuernacava, Mexico, on November 20, 2017. The list of participants from the workshop and follow-on meetings are provided in Appendix A.

Attendees were asked to create a vision for wind where the:

- Cost of energy for wind is less than that of natural gas fuel and solar electricity generation (i.e., serving as the cheapest global electricity resource)
- Wind power plants can operate in a manner commensurate with traditional thermal plants to provide reliability, flexibility, and resilience for the power system (i.e., wind energy can become a new backbone for the electricity system of the future).

The workshop was organized into four working sessions (see Appendix A for the core meeting agenda). The first was meant to solidify the context (e.g., grid architecture, markets) for the vision of wind energy supplying over 50% of global electricity demand. In the next two sessions, participants explored technology innovation opportunities for wind energy within this context. Specifically, the second session looked at driving the LCOE to make wind the least-expensive energy generation technology and thus spur the needed continuous expansion of wind energy deployment. The third session looked beyond LCOE to increasing the overall system value that wind energy provides to the grid in terms of reliability and resilience—resulting in significant capacity value, dependable ancillary services, and rapid response to system perturbations. The fourth and final session considered the research and development (R&D) challenges critical to realizing the wind energy LCOE and system value improvements identified in the prior two sessions. Workshop findings are broken out by the working group in the areas of 1) atmospheric science and forecasting, 2) turbine technology and design, 3) manufacturing and industrialization, 4) plant controls and operations, 5) grid integration, and 6) offshore-specific technologies. Outcomes of the workshop for each of the working group areas included:

- Identification and ranking of high-priority wind energy technology opportunities for significantly reducing LCOE and improving grid system value
- Identification and ranking of R&D challenges associated with the technology opportunities along with recommended actions to address those challenges.

The workshop focused on the economics of wind energy in the system and did not consider deployment concerns related to environmental and societal impacts. In addition, the workshop did not address policy concerns in terms of how they might shape the opportunity and requirements for wind energy looking forward.

Sections 1, 2, and 3 of this report provide the findings from the IEA Wind TEM #89 "Grand Vision for Wind Energy" workshop including the future landscape of the electricity system with over 50% of the electricity supply from wind energy, a review of key innovation pathways in different topic areas that will be embodied in the wind power plant of the future that supports the Grand Vision (including innovations that both reduce LCOE and increase system value of wind energy), and identification of the key R&D challenges that must be addressed to realize the wind power plant of the future and the Grand Vision.

Through the process of identifying key R&D challenges in each of the working group areas, cross-cutting themes emerged: data science and multiscale/multidisciplinary modeling capabilities. Section 4 of this report looks at synergies between wind energy science and enabling research advances in sensing technologies and measurement techniques, computer and computational sciences, multiscale and multidisciplinary modeling, digitalization, big data, and information science. The result of the effort led to an alignment between the key R&D challenges and scientific activities in data and modeling.

Overall, the integrative and coupled nature of wind energy physics across the full system led the authors to conclude that there is a need for overarching coordination efforts and frameworks to fully address the R&D challenges identified by the experts. Follow-on work will need to articulate a wind energy science discipline to address the grand challenges in wind energy R&D and realize the Grand Vision for wind energy as a foundation of the future electricity system.

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1 Historical Innovation, Status, and Challenges Ahead To Motivate a Grand Vision for Wind Energy

Wind energy has evolved over the last several decades from a niche technology to one that provides a significant share of electricity generation in grid systems across the world (Wiser and Bolinger 2018; Wingfield 2017; Kleckner 2017). A key factor in the success of wind energy to date is innovation that has increased energy production for a given project while simultaneously reducing overall wind turbine and power plant costs (Lantz et al. 2012). In other words, innovation has lowered the cost of energy for wind power plants. Looking ahead, the prospects for increased global wind energy deployment are compelling but significant competition is also anticipated from solar photovoltaics (PV) and other energy resources. Moreover, as the share of wind and other variable renewable energy sources—such as solar PV—grow within electric grid systems, there is an increased need for power system services that extend beyond cost-effective energy. With continued innovation, wind power is expected to be capable of providing both highly competitive energy supply (Dykes et al. 2017) and power system support services that are essential to the reliable and resilient operation of the grid (Ackermann et al. 2017).

Recognizing the need for continued innovation in wind energy to enable the full potential for wind power in the future electricity system, a group of more than 70 international experts came together to examine: 1) the current challenges to continued large-scale deployment of wind energy, 2) the opportunities for innovation to address those challenges, and 3) the necessary research and development (R&D) to realize those innovations. This report documents the overall findings of these experts. The report also highlights trends in science and technology that are expected to enable wind energy R&D as identified by the experts.

1.1 Historical Wind Energy Development

Global electricity generation from wind was estimated at approximately 5% of total electricity supply in 2017 (Wiser and Bolinger 2018). To arrive at this level, global installations have grown rapidly since the turn of the century (Figure 1). By the end of 2017, global installations of wind power capacity exceeded half a terawatt (Global Wind Energy Council [GWEC] 2018).

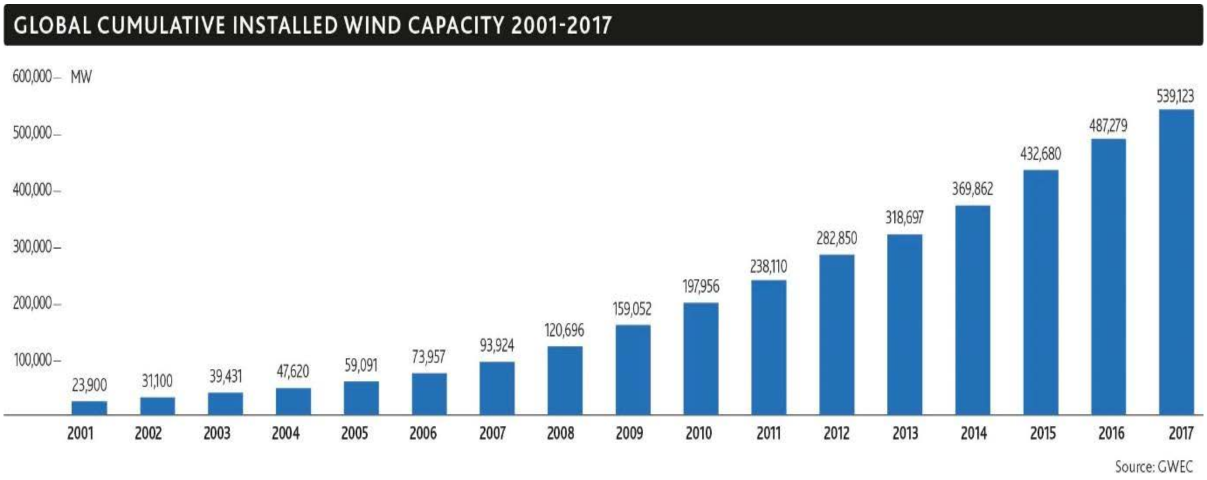

Figure 1. Global cumulative installed wind capacity from 2001 through 2017. Note that prior to 2001, a similar growth trend is present from the mid-1980s to today
(Source: GWEC 2018)

Growth in wind energy has been spurred by policy supports in different locations around the world. However, as global installations have grown, innovation driven by technology scaling, technology learning, and R&D investment have led to a corresponding drop in the levelized cost of energy (LCOE). Figure 2 illustrates how costs have generally fallen through time. As of 2016, a composite characterization of wind power costs among Northern Europe (e.g., Denmark, Germany, Ireland, Sweden, Norway, and the European Union) and the United States indicated an LCOE of approximately $50/megawatt-hour (MWh) for new installations.

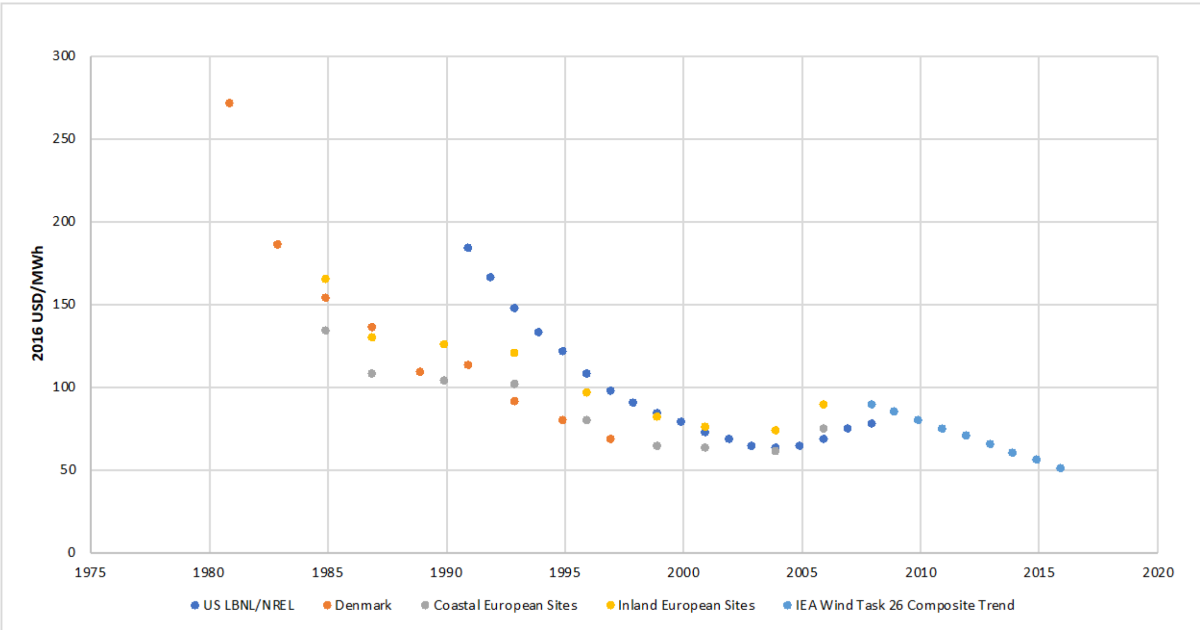

Figure 2. Wind energy LCOE from 1980 through 2016 (Source: IEA Wind Task 26 [Lantz et al. 2012; Wiser et al. 2016])

The main drivers for LCOE reduction have been technology scaling to larger wind turbines coupled with innovation in several areas of wind turbine and plant design, operations, and reliability (Wood Mackenzie 2018; Lantz et al. 2012, Wiser et al. 2016). In terms of scaling, turbines have grown in rotor diameter, power rating, and hub height consistently since commercial deployments first began in the 1980s. Rated power has increased by a factor of approximately 30-50 for land-based machines such that wind power plants today can produce far more energy with a much smaller number of machines. These size increases have led to significant turbine- and plant-level economies of scale. At the same time, rotor diameter and hub heights have also increased. These changes allow turbines to capture more energy at greater heights above ground level where the wind resource quality is better. As a result, the energy per turbine and per-unit cost has fallen—also contributing to lower LCOE.

Figure 3 illustrates how turbines have grown since the early 1980s. Although the basic platform configuration of the technology, three-bladed horizontal-axis upwind wind turbine on a monopole tower, has not changed, the size has increased 6−7 times in terms of hub height, 6−8 times in terms of rotor diameter, and 30−50 times in terms of power rating. The size of wind turbines today rivals large-scale monuments and buildings while withstanding dynamic and complex loading throughout the turbine's lifetime.

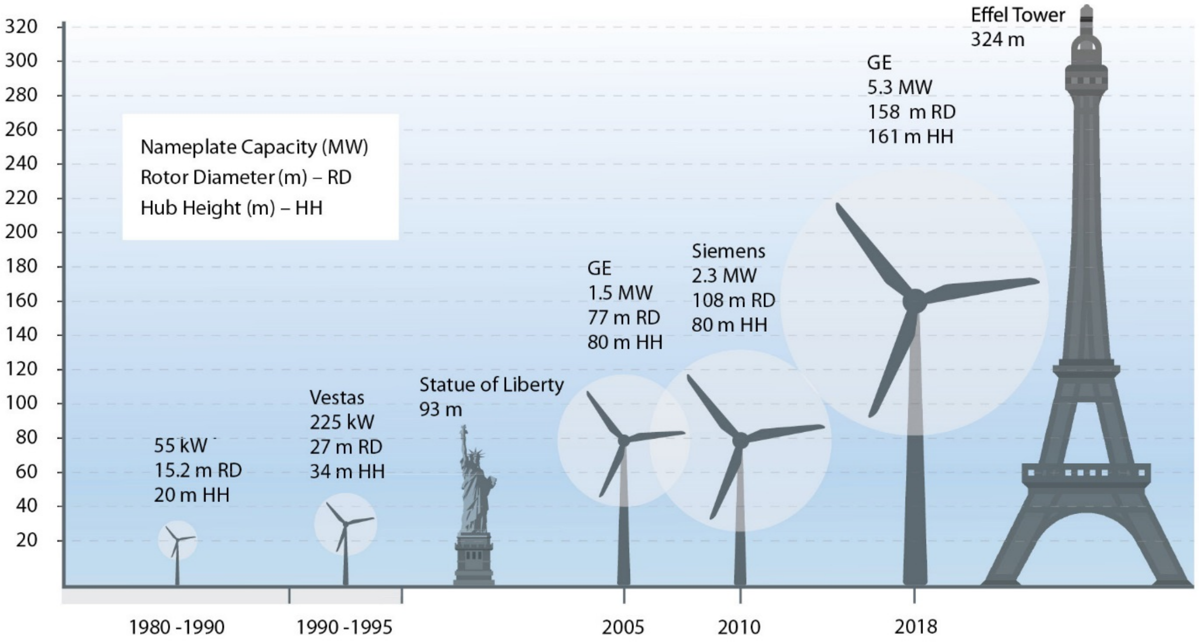

Figure 3. A small selection of turbines from a few global wind turbine manufacturers illustrate the growth in wind turbine sizes over time for land-based wind turbines in terms of hub height, rotor diameter, and power rating (in megawatts [MW])
(Source: National Renewable Energy Laboratory [NREL])

In addition to scaling and the associated performance improvements, the relative cost of wind power plant development and operations has also decreased. These reductions are, in part, a function of technology learning, R&D, and innovation but are facilitated by increases in turbine size, and in some locations, plant size, allowing for fewer moving parts overall and economies of scale with larger facilities. Combined, these trends have helped enable overall capital expenditures (CapEx) and operational expenditures (OpEx) per unit of energy to decrease over the decades (Wiser and Bolinger 2018; Lantz et al. 2012).

An important example of the innovation that has evolved in wind energy is evident in wind turbine blade designs—which are far more sophisticated in aerodynamic design, use of materials, manufacturing process, special features, and structure than ever before. Figure 4 shows a comparison of the design features for a state-of-the-art blade design in 2015 versus one of the early mass-produced blades of the 1980s. A selection of design features is shown, including custom airfoils that were developed specifically for wind energy applications; advances in aerodynamic design, such as optimization of the planform, solidity, and tip shape; and advances in reducing weight through load mitigation by coupled aerostructural design (e.g., passive twist bend coupling). Current blades also incorporate various add-ons that may improve aerodynamic performance, reduce structural loads, or mitigate aerodynamic noise produced by the turbines (e.g., trailing-edge serrations).

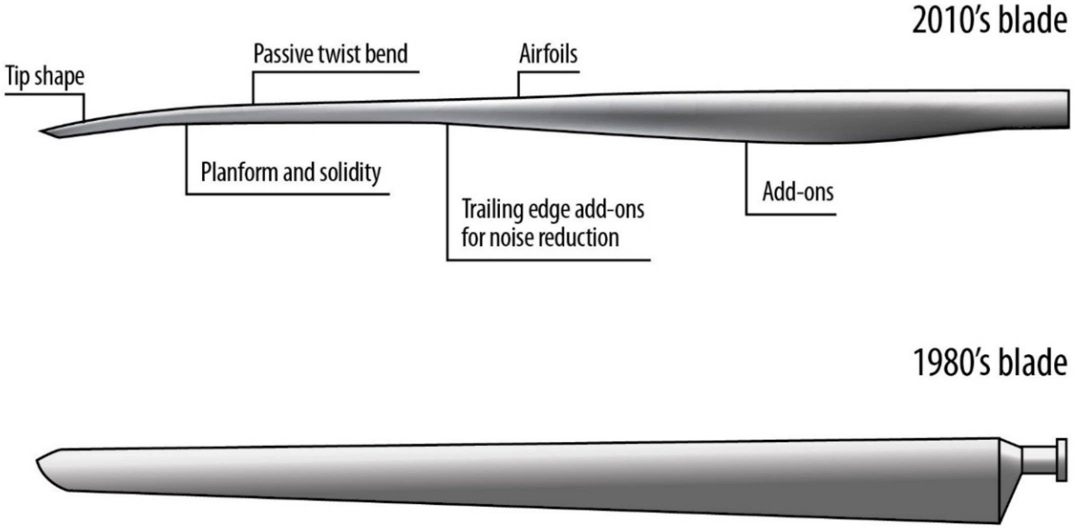

Figure 4. Innovation in blade design from the 1980s to present day—incorporating significant technological innovation in aerodynamics, structures, materials, controls, and manufacturing. (Source: NREL—based on graphic from Kenneth Thomsen, formerly Siemens Gamesa Renewable Energy)

Typical blades of the first generation of large-scale deployment turbines in the 1980s had a length of around 7.5 meters (m) (rotor diameter of 15 m) and weighed roughly 1 ton for a machine rating of 55−65 kilowatts (kW). Without innovation, scaling of these blades for current large-scale offshore machines of roughly 6 megawatts (MW) in power rating and 154 m rotor diameter (75-m blade) would result in blade weights of nearly 1,000 tons. However, with innovation, a blade of this size in 2015 weighed only 80 tons. Thus, the rotor weight scaled with rotor diameter by an exponent of closer to 2 rather than an exponent of 3, which would have been the case without technology improvement. The “square-cube law” is known in the wind community as the rule that as you scale the size of the rotor diameter, the power increases by a power of 2 (power is directly proportional to rotor area) but the mass of the blade would increase by a factor of 3 (proportional to the volume increase). Through innovation, the blades have become slenderer and less material intensive such that the industry has been able to “beat the square-cube law” as rotor sizes have increased. Innovation in blades as well as the rest of the system have resulted in substantial cost savings on a per-unit energy production basis.

Lower LCOE driven by these technological innovations has given rise to wind energy projects that are now competitive in a growing number of regions of the world (Wiser and Bolinger 2018; Lazard 2018). Depending on the resource quality, wind energy may be the most cost-effective new electricity generation resource available. According to Lazard's *Levelized Cost of Energy Analysis* (2018), which estimates unsubsidized energy costs for an array of electricity generation sources ranging from \$29−\$56 USD/MWh for wind energy can be compared to \$41−\$74 USD/MWh for combined-cycle natural gas generation, and \$36−\$44 USD/MWh for utility-scale solar PV energy (Lazard 2018). It is important to note that these LCOE comparisons do not consider system value and so cannot be used in isolation to assess competitiveness.

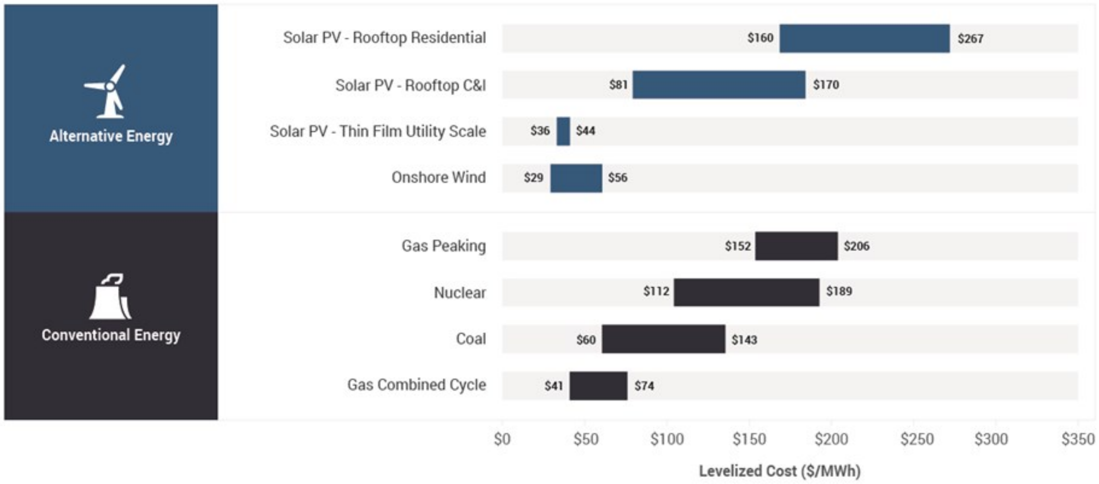

Figure 5. Analysis of cost of energy across different technologies as of 2018
(Source: Lazard 2018)

1.2 Challenges to Future Wind Energy Deployment

Continued growth of wind energy deployments may require continued technology innovation. Even as wind energy has become among the most competitive new sources of electricity generation, persistent challenges could limit continued growth of wind energy.

One of the most significant challenges to continued large-scale deployment of wind energy has and continues to be LCOE competition from other electricity generation technologies. In recent years, the cost of energy for natural gas and solar PV have dropped substantially (Haegel et al. 2017; International Energy Agency [IEA] 2018; Fu et al. 2018; Lazard 2018) and cost of energy for coal remains low as well. Although utility-scale wind power prices remained lower than for solar PV in 2018 for some projects (Lazard 2018), depending on the region of world and availability of respective wind or solar resources, LCOE for utility-scale solar PV can be lower than utility-scale wind energy. The relative forecasts of solar, wind, and natural gas prices have a significant impact on the expected future global electricity generation portfolio (Mai et al. 2017). Thus, for wind energy to remain competitive, further efforts to drive down LCOE through research and innovation will be needed.

At the same time as LCOE has been decreasing, integration challenges in the broader electric system have been successfully addressed in many markets, thereby enabling wind energy generation to grow to more than 10% of electricity consumption in at least eight countries and more than 30% in two: Portugal and Denmark (Wiser and Bolinger 2018). Moreover, subnational system-level instantaneous wind power share has frequently exceeded the 50% threshold in several U.S. systems (see, for example, Wingfield 2017; Kleckner 2017). Generation in Denmark has exceeded 100% of the entire national electricity demand on some days during and since 2015 (Nelson 2015).

However, wind energy deployment is still challenged on several fronts by concerns about the ability to integrate a variable resource into the electric grid system in a reliable, resilient, and sustainable way. Current market structures based on marginal operating costs respond to renewables with a "free" fuel source that supplies electricity at low marginal costs by lowering energy prices when large amounts of wind are available. This therefore reduces the available revenue for all electricity generation sources (including wind energy), and especially reduces the system value of wind energy as the share of wind energy generation increases (Hirth 2013; Helisto et al. 2017; Ahlstrom et al. 2015; Wiser et al. 2017; Zamani-Dehkordi et al. 2016). As more wind energy, near-zero marginal cost, and nondispatchable operation is deployed in a given energy system, energy prices and revenues to generation assets fall, leading to a negative feedback loop in which wind energy cannibalizes its own profit opportunities. Ensuring enough revenue for capital recovery and availability of critical reliability services may require a change in electricity market structures to explicitly consider additional elements of overall electricity system operation reliability—namely capacity and system service markets (Ahlstrom et al. 2015).

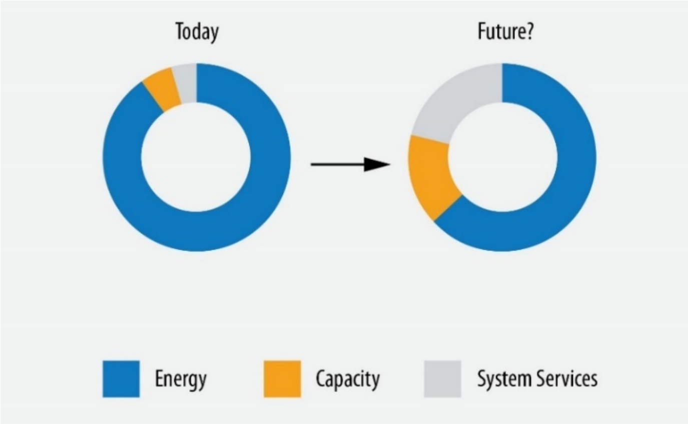

Figure 6. Potential shift in electricity market structure with increased renewables deployment. Renewables that take advantage of "free fuel" provide energy at near-zero marginal cost. When energy is free some of the time, the current paradigm in which energy markets make up the bulk of revenue for generation assets is unsustainable (Ahlstrom et al. 2015), unless scarcity pricing is allowed. New innovative uses of low-cost electricity could take much of the surplus energy (Helisto et al. 2017). New market designs that focus on real-time pricing and improving revenues from capacity and grid support (ancillary) service markets will pose challenges as well as opportunities to renewable and variable energy technologies, such as wind energy.

(Source: NREL based on Ahlstrom 2015)

For wind power plants to remain competitive as market structures and revenue streams evolve, there may be an increasing emphasis on the value of wind power plants in providing capacity value and other system services. To ensure profitability and become a primary source of electricity generation in the future grid system, wind power plants may need to seek value in forward capacity markets, provide "dispatchable" operation in peak energy pricing periods, and participate in ancillary service markets. Thus, innovations for wind energy may need to target not just reduced LCOE but also increased value to the electricity system. Wind plants that provide ancillary services will likely need to forgo some energy generation opportunities to deliver the service. For such an outcome to be financially feasible, either the market needs to compensate for that missed opportunity, or the capital cost of wind systems will need to be low enough that the missed energy revenue does not adversely impact energy cost.

Large-scale deployment of wind energy in the future will also need to address concerns related to nontechnical/nonmarket impacts. Social acceptance, transmission availability, and a variety of related system, social, and environmental factors are expected to influence physical design needs and constraints and ultimately the deployment of wind turbines and plants. Although these elements are also critical to the current deployment of wind energy, they extend beyond the scope of the current work. In addition, discussions around policy strategies that attempt to affect the evolution of the electricity system are beyond the scope of this effort. Instead, the focus of the current work is on research-based innovation that can affect the economics of wind energy from an LCOE and a system-value perspective to support wind energy deployment reaching shares of 50% or more in the global electricity system.

1.2 Description of Expert Meetings and the Grand Vision for Wind Energy Technology

For wind energy to achieve its full potential as an electricity generation resource for the future global energy system, further reducing LCOE and increasing system value is essential. To support and realize critical innovations, new R&D efforts and findings are expected to play a significant role. The IEA Wind Topical Experts Meeting (TEM) #89 "Grand Vision for Wind Energy" workshop sought to bring together a group of experts to consider the question of how to enable wind power to reach its potential. In this context, a future in which wind supplies more than 50% of the global electricity consumption was determined to be within the scope of wind energy's overall potential. Over 70 experts representing 15 different countries attended and provided a diverse set of perspectives for the Grand Vision for Wind Energy. The experts participated in one or more meetings including: 1) the main IEA Wind TEM #89 held at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, on Oct. 22−23, 2017 (see Appendix A for the meeting agenda), 2) a meeting at the Utility Variable Integration Group 2017 Fall Technical Workshop in Nashville, Tennessee, on October 12, 2017, and 3) the IEA Wind Task 25 Fall 2017 Meeting held at INEEL in Cuernacava, Mexico, on November 20, 2017. The list of participants from the workshop and follow-on meetings are provided in Appendix B.

Attendees were asked to identify innovations and research needs that would enable wind power to:

- Achieve a cost of energy that is less than that of all other electricity generation technologies (i.e., serving as the cheapest global electricity resource)
- Operate in a manner that provides reliability, flexibility, and resilience for the power system (i.e., to enable wind energy to supply as much as 50% of total electricity consumption and serve as a new backbone for the electricity system of the 21st century).

The workshop was organized into four working sessions (Appendix A). The first was meant to solidify the context (e.g., grid architecture, markets) for the potential of wind energy supplying over 50% of global electricity demand. In the next two sessions, participants explored technology innovation opportunities for wind energy within this context. The second session looked at driving down LCOE to allow for wind power to continue to be available as an abundant, low-cost, consumer-friendly energy resource. The third session looked beyond LCOE to increase the overall system value that wind energy provides to the grid in terms of reliability and resilience—specifically to provide capacity value, ancillary services, and rapid response to system perturbations. The fourth and final session considered the R&D challenges critical to realizing the wind energy LCOE and system-value improvements identified in the prior two sessions. Outcomes for the workshop included:

- Identification and ranking of high-priority wind energy technology opportunities for significantly reducing LCOE and improving grid system value
- Identification and ranking of R&D challenges associated with the technology opportunities.

This report provides the workshop findings including the future landscape of the electricity system with over 50% of the electricity supply from wind energy, a review of key innovation opportunities in different topic areas that will be embodied in the wind power plant of the future (including innovations that both reduce LCOE and increase system value of wind energy), and identification of the key R&D challenges that must be addressed to realize the wind power plant of the future and the potential for wind energy as a major supplier of electricity generation in the 21st century.

The report is structured as follows. Section 2 discusses the future context considered by the IEA Wind TEM. Section 3 describes the key findings related to innovation needs to reduce LCOE and increase system value and identifies challenges in wind energy to enable those innovations. Section 4 describes advances in related fields and enabling technologies that support the vision, and Section 5 summarizes the overall report findings.

2 The Future of Global Energy and Wind Energy Abundance

The IEA Wind TEM #89 "Grand Vision for Wind Energy" workshop identified trends of the energy system in the year 2050 to understand and subsequently define the future requirements for wind power plants operating in this hypothetical future. This approach helped determine the innovations and R&D efforts needed to realize the future potential for wind energy.

2.1 Context of the Grand Vision Including Global Megatrends

To characterize the effort, a wider context regarding global megatrends in terms of society and technology development was needed. Several analyses about global megatrends have been made in recent years to better understand how the world may look in 2050. Among these megatrends is continued population growth coupled with an increased standard of living for broad swaths of the global populace as well as increased mobility and electrification; continued sizable demands on the global agricultural and modern infrastructure systems are also anticipated (United Nations). Adding to these are trends in decarbonization of the electricity, heating, and transport sectors, as well as industrial use of energy and carbon. Moreover, climate change adaptation and mitigation are expected to support deployment of clean energy solutions, including wind power, in the decades to come (IEA 2018; DNV GL 2018).

Deployment and Social Acceptance of Wind Energy

Social acceptance and other aspects of large-scale deployment of wind energy were outside the scope of the workshop but are critical to the realization of the full potential of wind energy. As with all energy technologies, deployment of wind energy, especially at large scales, will have increasing impacts on society and the environment. In this vein, it is expected that social acceptance, transmission availability, and a variety of related system, social, and environmental factors will influence physical design needs and constraints for the technology, thereby ultimately affecting the deployment of wind turbines and power plants. We anticipate that with time and increasing wind power share around the globe, the ability to design and optimize wind turbines and plants to best integrate with the landscape, existing infrastructure, and local social and environmental considerations, as well as multiple land-use, ocean, and airspace needs, will become increasingly necessary.

Planning, policy, environmental, and broader social science research will help realize a 21st century society in which wind power contributes substantially to the global energy system. Although these additional factors and implications are an essential pillar in enabling the energy future envisioned by the participants in the IEA Wind TEM #89, a full elaboration of these social and environmental challenges and associated research needs is beyond the scope of this report. The authors suggest considering a similar comprehensive effort focused on these issues that complements the current effort, to address all the opportunities and challenges related to the future of wind energy.

2.2 The Future Electric Grid Sets New Requirements for Power Generation Sources, Including Wind

Continuing recent trends, increasing shares of solar and wind energy production are expected to be integrated into the world's energy and electrical systems. Many energy scenarios show wind power as becoming one of the main sources of electricity by midcentury. The IEA *World Energy Outlook 2018* forecasts that renewables, led by wind and solar PV, will make up two-thirds of new power plant investments through 2040, leading to a scenario in which they provide 40% of global electricity generation in that year (IEA 2018). Bloomberg New Energy Finance forecasts similar trends with renewables making up 72% of global electricity generation investments through 2040; wind and solar energy provide 34% of global electricity generation in that year (Bloomberg New Energy Finance [BNEF] 2017). Even if solar energy tends to dominate global investment and installed capacity of these scenarios, electricity generation is estimated to be dominated by wind energy in the northern hemisphere (Pursiheimo et al. 2018). Broadly, analyses predict a share of renewable electricity in the generation system of at least one-third globally by 2040 (Energy Information Administration [EIA] 2017; BP Energy Economics 2018; BNEF 2018; IEA 2018). An even higher wind energy generation scenario comes from the International Renewable Energy Agency (IRENA), which estimates over 60% of global electricity generation in 2050 from solar and wind energy alone (26% and 36%, respectively) (IRENA 2018).

A recent study from DNV GL, a global services corporation for the maritime, oil and gas, renewable energy, food, and healthcare sectors, found that their "central" case for the electricity generation portfolio in 2050 was comprised of more than two-thirds renewables, with approximately 29% coming from wind energy and 40% from solar PV (DNV GL 2018). Figure 7 shows the composition of the electricity generation mix forecast by DNV GL from 1980 through 2050. In 2050, the projected electricity generation from onshore, or land-based, and offshore wind combined is 29%. A key feature seen in future energy scenarios is that in addition to a renewable-energy-dominated electricity system, there is significant electrification of other energy sectors (e.g., transport, heating), such that electricity demand doubles and the role of renewable energy in larger energy systems is even more critical.

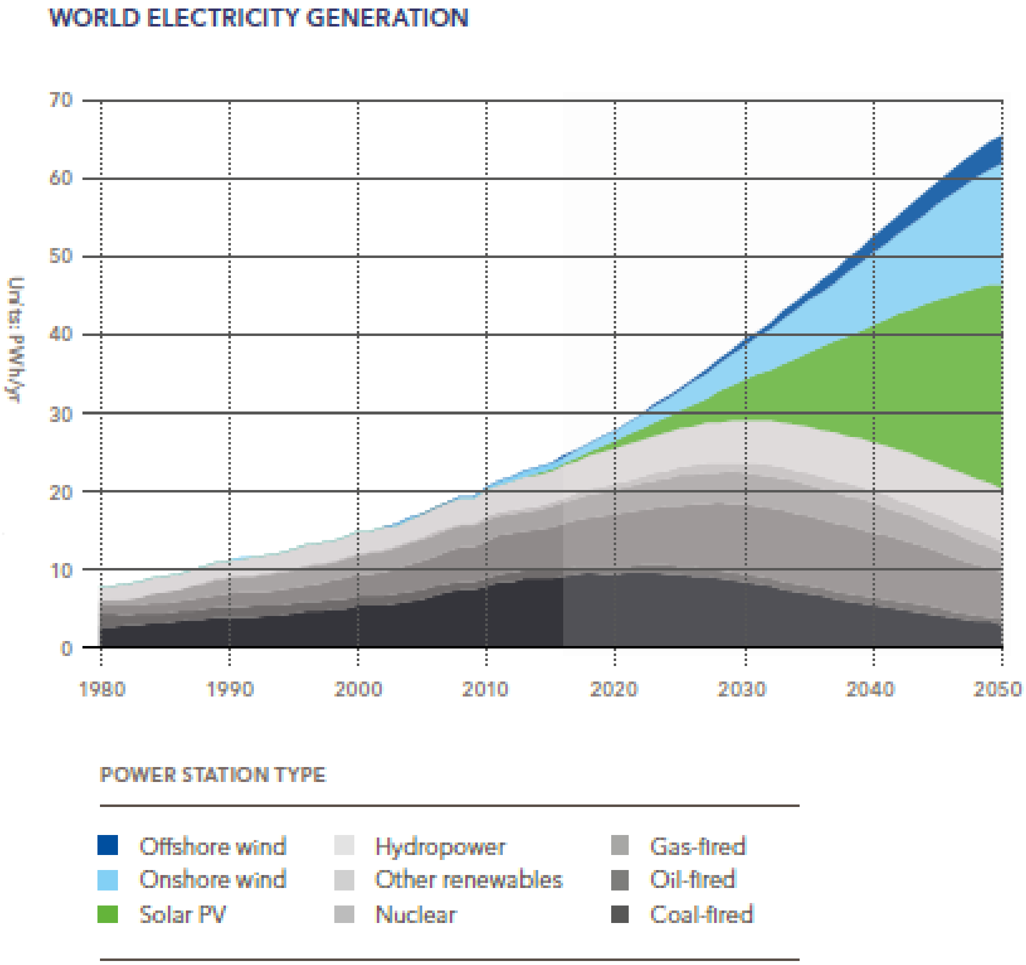

Figure 7. In 2050: 29% wind, 40% solar PV, and one-third everything else; "… a base or central case, … is the aim of this present exercise, which is a forecast, not a scenario," stated Remi Eriksen, Group President and chief executive officer of DNV GL (Source: DNV GL 2018)

Although the previously mentioned forecasts project substantial growth for wind energy over the next several decades, there is potential for wind power to provide an even larger share of future energy demand. The "Grand Vision of Wind Energy" workshop characterized a potential future in which wind energy is the "backbone" element of the future electricity and broader energy system. More specifically, the international experts from the workshop pondered a particularly aggressive scenario, with 80% of electricity generation coming from renewables in 2050. For wind energy specifically, the group identified a level of interest wherein wind provides more than 50% of global electricity generation by 2050 (versus the 29% observed from the DNV GL study). Although this target is aggressive, it helps provide a critical context for pushing beyond the boundaries of current thinking with respect to the innovation and R&D needed to realize the full potential for the future of wind energy. Table 1 summarizes the attributes that makeup the overall energy system that was the focal scenario articulated and considered by the participants, with full integration of bulk and distributed electricity systems into a single dynamic and holistic system.

Table 1. Summary of Global Energy System of Systems Attributes for the Grand Vision of Wind Energy (in 2050)

Global Energy System of Systems	2050 Future Scenario Attributes
Electricity Generation	• Renewables at 80% (wind energy provides > 50% of electricity supply) – instantaneous generation > 100% of demand in some regions • Retirement of thermal assets (few thermal assets in the electrical system) • Large amounts of generation in the distribution system
System Architecture	• Converter-based system (little to no physical inertia in the system) ○ Fast/transient stability challenges overcome ○ Wind and solar have converters that include "grid-forming capabilities" • Integrated generation, transmission, distribution, and customer systems into a single dynamic and holistic system ○ Distribution assets actively participate in all electricity markets ○ Many distributed systems/microgrids/customer assets/cellular networks building up the bulk system
Transmission Infrastructure	• Optimized use of existing assets/corridors—dynamic line/transformer ratings, upgrades, and reuse of transmission wherein thermal assets are retired • New technologies for AC and DC transmission and modular power flow control • Cost-competitive long-distance underground transmission is available
Storage Technologies	• Cost-effective storage may be widely available to balance diurnal and short-term fluctuations in variable resources • Power to X is cost effective/seasonal storage is widely available • Storage reacts to real-time price signals and gives grid support through fast response services
Electricity Consumption	• Massive electrification of the global energy system (e.g., heat, transport, buildings, industrial demand) ○ Significant growth in energy use in non-OECD countries ○ Increased energy efficiency for reductions in energy use in OECD countries • Assets responsive to real-time price signals or similar methods of demand response (highly elastic load profile) ○ Demand response provides grid support through fast response services
Market Design and Coordination	• Transformation of electricity markets (e.g., capacity, energy, ancillary (grid support) services) ○ Real-time retail pricing ○ Predominantly zero-marginal cost of energy with significant renewable share of electricity generation ○ All assets participate in capacity and grid-support-service markets ○ Increased coordination between neighboring markets
Institutional and Regulatory Context	• Larger balancing areas • Breakthrough institutional settings (including harmonization of regulation) • Local systems/markets capable of autonomy when needed

As mentioned, the future scenario resulting from the discussions includes a generation mix with 80% of annual demand being met by renewables, meaning regular periods where instantaneous generation from variable renewables exceeds 100% of load made up from variable renewables in some regions.

The shift toward an electricity system in which the main contributors are weather-driven and variable would likely require a paradigm shift in grid architecture. This paradigm shift is caused by a few key features that stem from proliferation of wind and solar energy in the system. First, the retirement of thermal/synchronous assets means the loss of mechanical inertia that has been key to supporting grid stability for more than a century (Bömer et al. 2010; EirGrid and SONI 2014). Figure 8 depicts the role of inertia in ensuring electric system stability where the lack of physical inertia from traditional synchronous machines creates a paradigm shift in ensuring electric system stability.

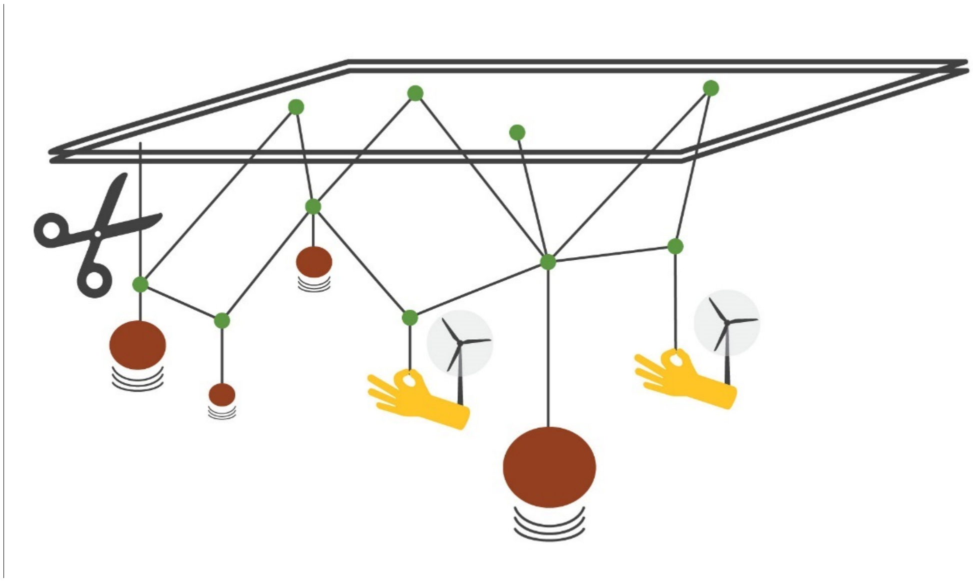

Figure 8. The challenge of stability in the converter-dominated electric grid system. The red circles represent traditional power plants. If there are many such masses or inertial elements in the system, losing one mass (by cutting the string) will shift to a new equilibrium quickly, with the other system masses dampening out the effects of the loss. However, as more and more wind turbines with low inertia, but considerable embedded intelligence, are added to the system, significant coordination and advanced control become necessary to ensure that the grid is resilient to perturbations.

(Source: NREL based on a figure created by Nick Miller, formerly GE Energy Services)

This new system must remain stable, which requires advances in the services wind power plants and other generators need to provide to the system of the future. In fact, wind power plants would need to provide grid-forming converters, which can set system frequency to support normal operation and are able to provide "black-start capability" to the grid in the event of a system outage (Halley et al. 2018).

The other significant shift for this electric system architecture has less to do with the incorporation of wind energy explicitly but is related to other trends in the broader electricity and energy system. Increased deployment of generation and storage assets on the distribution side of the system would lead to a new overall architecture for the grid system wherein the lines between generation, transmission, and distribution are increasingly blurred. Currently, there are trends toward stronger, more interconnected, and more closely coordinated bulk power systems and local, smart, bidirectional distribution systems and microgrids that are able to communicate with each other and the larger power system (McCalley et al. 2017; Bobinaite et al. 2018). In the scenario considered by the experts of the IEA Wind TEM #89, these trends are likely to continue and come to dominate the operation of the grid. Perhaps most notably, these smaller and more independent distribution systems/microgrids/cellular networks could operate autonomously when needed (Bobinaite et al. 2018; Hu et al. 2018). Subsystems in this larger, more integrated network would be like a web of cells capable of interacting with neighboring cells in partly autonomous operation alone or with any number of neighboring cells as needed, but otherwise providing smart resources for global system use (Kroposki et al. 2017). The operation of such a grid system could place additional requirements on wind power plants and other generators, such that they must provide grid-forming capabilities, control, and services both at the utility scale in the bulk system and as part of microgrids when operating autonomously (Persson 2017).

A more dynamic and optimized transmission system would also be required to support the future electric grid made up of many microgrids that provide their own generation and storage alongside bulk generation systems comprising large-scale generation and transmission assets. In this world, transmission improvements would likely need to optimize and maximize the use of existing assets and corridors. In many areas of the world, contractual mechanisms and lack of technology upgrades (i.e., dynamic line/transformer ratings) could limit further deployment and integration of wind energy in regions with transmission congestion (Bhattarai et al. 2018; Greenwood et al. 2014; Gentle et al. 2014, Estanquiero et al. 2018). At the same time, development of and investment in new transmission technologies (i.e., high-voltage alternating current [HVAC] and high-voltage direct current [HVDC] transmission, modular power flow control, and cost-competitive underground transmission) would enable a more robust, reliable, and accommodating transmission system for the 80% renewables electric system (European Technology and Innovation Platform on Wind Energy [ETIPWind] 2016). Some of these technologies (e.g., HVAC and HVDC transmission, modular flow control) could allow energy to be transmitted across greater distances more efficiently, thereby opening new resource areas and allowing for improved integration as a result of geographic diversity, whereas other technologies (e.g., dynamic ratings) will allow for improved utilization of existing assets and more reliable system operations. In order to realize many of the benefits of these new technologies, cooperation of multiple legislative, regulatory, and operational entities across broad geographical regions is required.

The other major changes in the future electric system as defined by the workshop are in the end use of electricity including storage, demand response, and electrification of other energy sectors. Using electric power for heat and transport will give new, potentially more flexible demand than the current electrical load. Heating loads have cost-efficient thermal storage options available today and vehicles are typically used much less than half of the hours in a year. Because of falling costs in utility-scale storage (predominantly batteries), there is likely to be an increasing amount of economic storage available in the grid system at both the bulk- and distributed-system levels. Storage would be an important technology for mitigating the challenges associated with the inherent variability of both wind and solar technologies at high penetrations. For many applications, there is a trend toward either colocated or virtual "hybrid power plants" with combined wind, solar, storage, and other generation assets. Storage technologies serve as electricity sinks during periods of overproduction from wind and solar assets relative to demand and to provide that energy as a source back to the grid during periods of low solar and wind generation. For many decades, systems with large hydropower resources through their reservoirs have served as energy storage systems and enabled large-scale deployment of wind energy in some markets, such as in Denmark and Portugal (Holttinen et al. 2016; Farahmand et al. 2013, 2015).

However, storage may also come in new forms. One significant new source of storage being investigated is "Power to X," in which electricity is used to produce various products, such as storable synthetic gases or liquids, that can be used in diverse industrial processes, heating, transportation, or other uses (Neo Carbon Energy 2017). Wind energy systems of the future may be able to provide significant "Power to X" resources either through the electric grid system or in off-grid applications (i.e., in remote regions or far offshore). Large and well-interconnected grids and "Power to X" will be available to shift power production from the grid to other systems across large geographic and temporal scales (even seasonally)—making the variability of wind energy generation less critical for large levels of wind energy deployment. An example application is steel fabrication, as demonstrated in the Finnish Hydrogen Breakthrough Ironmaking Technology project (HYBRIT 2018).

The electrification of other energy sectors (e.g., heat, transportation, buildings, industrial demand) would result in a substantial increase in overall electricity consumption in the years to come. However, overall energy usage in OECD countries is expected to stabilize or decline, whereas in non-OECD countries it is expected to substantially increase (like predictions from DNV GL and other forecasts suggest). With electrification and growth of overall electricity consumption globally, there would be a significant change in how that demand interacts with the overall electricity system. Some technologies, such as in the case of electric vehicles or "Power-to-X," would provide storage on various timescales. More generally, many assets will likely be responsive to real-time price signals or to similar methods that provide demand-side flexibility, such that the electricity demand profile of the future will be much more elastic than at present (Institute for Sustainable Development and International Relations 2015).

A final potential component of the future energy system pondered by the experts in the IEA Wind TEM is the need for (and value of) breakthroughs across the globe in institutional and regulatory contexts. If geographic and regulatory barriers can be broken down, utilities and system operators could take advantage of the potential of generation, transmission, storage, and demand assets that are geographically dispersed and can complement each other when integrated into larger balancing areas (McCalley et al. 2017). Several studies have shown that the geographically dispersed deployment of renewable energy resources within one technology area (i.e., wind) or across technology areas (i.e., solar and wind energy) can be beneficial to smoothing out the variability inherent with those resources. By spreading wind energy technologies across large geographic areas, there is significantly less variation in the expected generation from those assets over time—for example, from the north to south of Europe, or the north to south of the Atlantic Coast in the United States (Kempton et al. 2010; Grams et al. 2017; Olauson et al. 2015). In many areas of the world, solar and wind energy profiles are such that when combined, the variability of the combined resource is less than either technology by itself (Seel et al. 2018). Larger balancing areas and harmonized regulations would allow the electric system to take advantage of the complementarity of dispersed and diverse renewable generation assets; this could likely require increased transmission buildout in some locations as described earlier.

Benefits and Challenges of Wind Energy As the Electric System Backbone

The future electric system explored and pondered by the IEA Wind TEM #89 is one that departs from the electric system architecture and design that has been dominant since first introduced at the end of the 19th and beginning of the 20th century. The global electric system of the 21st century considered by the experts to inform future R&D needs would be a converter-dominated system largely made up of renewable energies, such as solar and wind. The system would be designed for increasing levels of interconnectivity across huge geographic areas coupled with a simultaneous increase in the level of autonomy for a given locale. The combination of autonomy and large-scale interconnectivity along with the proliferation of storage and demand response assets was determined to be capable of leading to a robust system with increased redundancy, distributed security, and resiliency, if the generation technologies can offer the required controllability.

As the electric system adapts, so do the requirements placed on the generation assets that provide its primary supply of electricity. For wind to serve as a potential backbone of this future electricity system, it will need to provide low-cost energy around the world, while at the same time supporting grid stability and reliability at all times, necessitating the innovation and research described in the remainder of this report.

3 Research Needs for Wind Energy at 50%

To assist in focusing and calibrating participant input, two opposing and extreme scenarios of the future energy system in year 2050 were created that would then guide objectives for wind power plant innovation discussions. In the first scenario, the grid would support large amounts of wind energy without significant burden being placed on wind technology itself. Large amounts of transmission, storage, changes in the distribution system, advanced power electronics, and other means would allow for high levels of wind in the system without requiring significant capacity and grid services from wind plants. Thus, the focus for wind energy innovation would be, as it has been historically, on **decreasing LCOE**. In the second scenario, however, constraints on all other aspects of the system described earlier would force wind to be "designed for curtailment" and provide significant capacity value and system services to the grid. In this case, wind power plants would have to be designed to provide **increased system value**. The two scenarios for LCOE and system value are shown in the Table 2.

Table 2. Scenarios for Wind Energy Grand Vision Breakout Sessions

Scenario 1: Objective of Lowest Possible Wind Power Plant LCOE	Scenario 2: Objective of Highest Possible Wind Power Plant Contributed System Value
Generation: • **Wind energy > 50% global electricity supply** • **Renewables > 90% global electricity supply** • **Global energy is predominantly electric (massive electrification of transportation, heating)**	
• **Transmission and storage are ubiquitous (seasonal storage available)**	• Transmission is constrained and storage is limited (no seasonal storage available
Distribution	
• **Large amounts of electric vehicles, demand response, solar; bulk and distributed systems are both significant**	• Limited amount of distribution-side capacity (e.g., electric vehicles, demand response, solar); mostly a bulk system
• **Load is highly elastic, large deployment of Power-to-X technologies**	• Load is highly inelastic, little deployment of Power-to-X technologies
Market/System Design	
• **Advanced energy, capacity, and service markets where wind participates (but energy is the dominant revenue stream)**	• Advanced energy, capacity, and service markets where wind participates (capacity and service payments are substantial)
Socio-economics	
• **Few constraints on siting (environmental, social) with increased deployment**	• More constraints on siting (environmental, social) with increased deployment
• Lowest cost of electricity prioritized	• Local economic development prioritized

The scenarios provided in Table 2 served as a guide for the Grand Vision for Wind Energy workshop to consider, in sequence, innovations to 1) reduce wind energy LCOE, and 2) increase the value of wind energy to electric grid system operation and reliability. These were considered separately because as Figure 9 demonstrates, innovations that reduce the cost of energy may actual decrease system value and vice versa. A combination of these innovations will lead to the realization of the wind power plant of the future capable of realizing an electric system future in which wind energy provides more than 50% of overall global electricity generation. Significant investment in wind energy research will be required to realize these innovations and create the Grand Vision for Wind Energy. The workshop also sought to identify R&D needs in wind energy to support the identified LCOE and system value innovations.

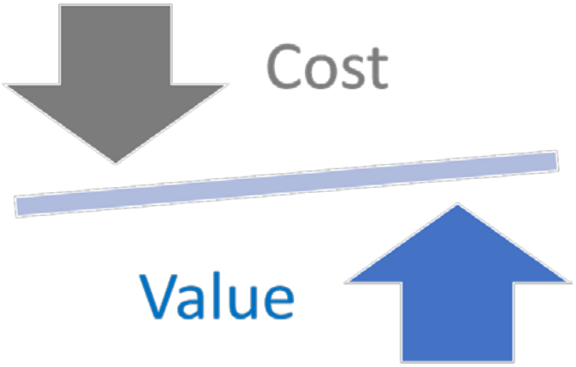

Figure 9. Future wind power plants will have to consider trade-offs in design and operation between LCOE and system value. Depending on the architecture and makeup of the grid, the relative importance of each objective will change. Thus, this workshop considered each objective separately and then sought to harmonize across them for an integrated Grand Vision for Wind Energy (Source: NREL based on graphic from Ryan Wiser, Lawrence Berkeley National Laboratory)

This section provides a high-level summary of the workshop findings broken out by the working group in the areas of 1) atmospheric science and forecasting, 2) turbine technology and design, 3) manufacturing and industrialization, and 4) plant controls and operations, 5) grid integration, and 6) offshore-specific technologies. What follows are the LCOE, system value, and R&D priorities identified by each breakout group. There is overlap across the categories as it is impossible to fully decouple a wind power plant system into distinct areas where innovations are isolated to single subsystems. In fact, many identified innovations and R&D challenges are common to several working group areas and this commonality is used in Section 4 to identify cross-cutting needs in wind energy research.

3.1 Breakout Group 1: Atmospheric Science and Forecasting

As the amount of wind energy increases to a considerable percentage of the world's energy supply, improving the knowledge base focused on the wind resource itself and its interaction with wind power plants is imperative.

Better understanding of the atmospheric environment is needed for three general timescales: short term for minutes, hours, and days ahead and medium-term energy and maintenance forecasting and long term for predictions of lifetime energy production and system loads and reliability. Short-term forecasting is becoming more important as the percentage of wind power on the grid increases (Marquis et al. 2011), the stability of the grid is more dependent on renewables, and the amount of ancillary services provided by wind energy increases (Shapiro et al. 2017). Modeling and prediction of the wind resource by numerical weather prediction (NWP), including various components of NWP, such as data assimilation, model physics, and parameterizations, and initial conditions from observations, are key to advancing knowledge in this area (Haupt et al. 2017). Forecasts will also require improved models for transformation of NWP predictions to quantities of power and energy including turbine performance in complex flows. Long-term energy estimates depend on many of the same physical processes that are important for short-term forecasting, but they are also influenced by longer-term sources of variability, such as the El Niño-Southern Oscillation, and those induced by future climate change (Pryor and Barthelmie 2010; Clifton and Lundquist 2012; Karnauskas et al. 2018). Longer-term forecasting also affects industry's ability to predict how and when there will be reliability issues with turbines and, thus, will support improved operation and maintenance strategies as well as better turbine and plant design in the future.

Uncertainty estimates for both timescales are important, and a deeper understanding and separation of compounding and canceling errors for different physical processes will be important for improving uncertainty quantification and reducing epistemic uncertainty in models across scales. Improved understanding of uncertainties in models as well as uncertainties in observations will help reduce the cost of energy with time (Pinson 2013). Better understanding of the resource and the uncertainties involved can help improve many aspects of wind energy systems, from turbine and plant layout design to optimal grid interaction and energy market structure.

The innovation pathways to address these issues include new approaches for multifidelity, multiscale simulations along with rigorous methods for uncertainty quantification. This involves coupling existing models in new ways as well as leveraging capabilities of new models as they are developed. Such models will be employed over a variety of timescales with forecasting time windows from less than a day to decades for wind resource and energy prediction. The models must be well-validated by researchers using large-scale data sets organized by innovative data science tools as well as high-resolution observations from advanced remote-sensing, unmanned aerial vehicle sensing systems, and other in situ technologies. Forecasting tools will not only predict the resources of wind energy and other renewable technologies, but the performance of energy storage technologies, the grid load, and grid behavior including transmission lines.

The benefits of the innovation pathways on LCOE include lower fixed charge rates from reduced uncertainty, higher annual energy production from better optimized wind power plants in both design and operation, and lower operating expenses from more optimally designed and operated wind plants. The system-value impacts include reduced uncertainty and variability in wind power plant energy production as well as an increased ability of wind power plants to provide services to the grid for reliability. Better forecasting tools in the wind energy space will also support optimization of the overall grid system with high levels of renewables to balance the use of wind energy with other generation assets as well as storage and distribution-side technologies such as electric vehicles and demand-response programs. The benefits of each of the innovation pathways is described in more detail in the following subsections.

The innovation pathways and their benefits will be realized through the undertaking of three research challenges in atmospheric science and forecasting. First, the scientific community must endeavor to fundamentally understand the wind resource as well as how wind plants change the resource (Fitch et al. 2012; Lundquist et al. 2019), and once the understanding is gained, the community must identify how to optimize the electricity system to work seamlessly with the resource. Second, the industry needs an improved model chain to accurately predict the varying energy resources provided by the atmosphere. Third, to ensure broad acceptance and long-term viability, atmospheric science can help inform industry to enable better decision-making regarding environmental and societal impacts from wind energy. For example, atmospheric scientists should determine the potential impact of wind farms on crop yield to mitigate potential negative consequences of large-scale deployments in the U.S. Midwest.

The innovation pathways, their impacts to LCOE, system-level benefits, and grand challenges to improve the fundamental understanding of the wind resource and its influence on wind power plants are described in more detail in the following sections.

Innovations To Reduce LCOE

Numerous pathways can reduce the cost of energy through the application of atmospheric science both for short-term forecasting and long-term energy estimation. As highlighted in Table 3, many of these benefits arise from enhanced models of the atmosphere that will improve the accuracy of forecasts at a range of timescales and, equally important, help quantify the uncertainty of energy estimates. These model improvements will require validation using new high-fidelity observational studies. Such observational studies will provide quantification of model skill in estimating and predicting physical processes that affect the wind resource. For instance, a recent 5-year public-private partnership project in the Pacific Northwest collected atmospheric measurements through all four seasons to measure the skill of weather forecasts in this area of very complex terrain. Changes were made to the underlying NWP models, particularly by revising the mixing length in the planetary boundary layer scheme, improved numerical methods for horizontal diffusion, and the introduction of small-scale gravity wave drag. (Shaw et al. forthcoming; Wilczak et al. forthcoming; Olson et al. forthcoming). Revisions to the model components were tested in retrospective model runs that were compared against the collected measurements. Revisions were made iteratively until optimized against the observations.

Table 3. Innovations in Atmospheric Science and Forecasting To Improve Wind Power Plant LCOE

Innovation Category	Innovation	LCOE Impact
Increase Accuracy of Long-Term Resource and Energy Estimates and Reduce Uncertainties	Development of multiscale, multifidelity modeling approaches—a spectrum ranging from numerical weather prediction to large eddy simulations to reduced-order models, with improved integration with observations; tools that will predict interactions between and among multiple turbines and wind plants	• Reductions in fixed charge rates through improved energy estimates
		• Increased annual energy production (AEP) through optimized micrositing, array design, and interplant effects
		• Lower OpEx through more optimized and efficient wind plant layouts for greater reliability and reduced interplant effects
	Improved tools with scientifically rigorous quantification of uncertainty for observational sensors and models; tools that more accurately predict P99/P50 uncertainty estimates	• Reductions in fixed charge rates through improved energy estimates with accurate uncertainty quantification
	Organized, connected, and distributed platforms for sharing open wind resource data or data "marketplace"	• Increased AEP through better plant siting
	Improved remote sensing across scales to observe wind plant inflow, wake effects, and regional impacts	• Reductions in fixed charge rates through improved energy estimates and uncertainty quantification
		• Improved AEP as a result of more optimized wind plant layouts and operation tuned to the observed resource
		• Lower OpEx as a result of more optimal operation of plant
	More accurate model tools to predict longer-term wind and other renewable resource trends including interannual variability and climate change at improved spatial and temporal resolutions	• Increased AEP through improved energy system planning and siting
		• Lower fixed charge rates through improved prediction of long-range variability

Multiscale, multifidelity models are key for developing more optimized wind plants in the future (Schreck et al. 2008). Such models are necessary to better understand the fundamental physical phenomena driving wind plant performance and wind plant interactions. Further research on the most relevant flow phenomena (Stevens and Meneveau 2017), such as wind turbine wakes (low energy bodies of flow in a plant created by upstream turbines extracting energy and imparting vortices into the flow), is expected to yield better tools for optimal siting of individual turbines within a given wind plant. Optimal siting strategies will decrease the negative impacts of turbulence on turbines that are downwind of others in the wind plant and maximize total energy production of that plant. Additionally, reduced wind power production at established wind plants has been identified after new wind plants have been developed many kilometers upwind (in the prevailing wind direction) of the established wind plants (Nygaard 2014), which can lead to power losses at the downwind wind farm of millions of dollars (Lundquist et al. 2019). Increased understanding of wind plant wakes on downstream wind resources is expected to lead to improved plant siting and optimized power production.

Wind energy project financing is dominated by prediction of risks (Schwabe et al. 2017). One of the largest and dominant risks is the preconstruction estimates of energy production over the lifetime of the wind plant. Developers currently use nonscientific approaches (Lee et al. 2018) primarily based on experience to estimate the risk from various sources of uncertainty (Clifton et al. 2016), often underestimating interannual variability (Bodini et al. 2016). A more rigorous, accurate method for predicting uncertainty in long-term energy estimates will lower the finance costs across all wind project development.

Long-term and short-term energy estimates of wind plants are heavily influenced by the observational data used to make predictions. For short-term forecasting, the initial conditions and data assimilation schemes using real-time observations can produce high sensitivities. Assimilated observational data includes observations from distributed meteorological towers, but also aircraft observations, and even wind turbine supervisory control and data acquisition (SCADA) data output. For long-term predictions, longer-term atmospheric observational records make significant impacts through the measure-correlate-predict process. New observational data sets could be similar to reanalysis data sets (e.g., Modern Era-Retrospective Analysis for Research and Applications [MERRA-2]; Gelaro et. al 2017), which are a combination of simulations and observation over a long period of time, but with higher fidelity and validated using more observational data. For example, NREL’s Wind Integration National Dataset Toolkit (Draxl et al. 2015) has a 2-km spatial resolution and could be extended for several decades and validated with many thousands of observational sites. These data should carefully catalogue any potential long-term variability from artifacts including sensor replacement or calibration and even local environmental changes, such as changing surface roughness (Vautard et al. 2014). As such, more advanced publicly available resource data sets will improve overall predictions across timescales. Data should include detailed metadata and taxonomies for making catalogues and finding atmospheric details. An example of taxonomy would be a catalogue of vegetation immediately within and surrounding a wind farm site, which may change with seasons or longer time periods.

As turbine heights continue to increase (Wiser and Bolinger 2018), tower-based measurement systems need to be augmented with advanced remote-sensing devices to measure atmospheric conditions over a wide range of heights and spatial distributions across potential wind power plants over the long time periods (multiple years) required for wind resource assessment. These advanced observations will serve to help validate new wind resource models and can also be assimilated into shorter-term predictions of the resource in the operational environment. Data assimilation of remote-sensing devices has been shown to increase accuracy of short-term forecasts (Wilczak et al. 2015). High-resolution Doppler lidar instruments can observe the wakes of individual wind turbines (Aitken et al. 2014), providing valuable data for wind plant model validation and real-time operational control.

The impacts of naturally occurring, large-scale climate drivers, such as the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, on wind resources will vary by location. This important phenomenon is often not acknowledged in terms of how critical it is to the impact of the overall wind resource for both intra and interannual variation. As a result, these climate oscillation impacts are not well-understood and thus difficult to predict in both the short and long term (DNV GL 2016). Similarly, the likely impacts of various climate-change scenarios on wind resources (Karnauskas et al. [2018] and references cited therein) also exhibit high uncertainty and will vary by location. Further research to understand how both natural climate variability and human-caused climate change will affect wind resources is needed to reduce risk to the financial investments made to deploy wind plants based on resource assessments. Given the increasing deployments of wind plants in locations vulnerable to extreme events like hurricanes (Hallowell et al. 2018) that will be affected by climate variability, assessments of the impacts of these extreme events on turbine-relevant atmospheric parameters (Worsnop et al. 2017) will become more important.

Innovations To Increase System Value

Beyond reductions in the cost of wind energy, improved understanding of atmospheric science has other benefits to society including 1) improved short-term forecasting of wind power plant output for participation in merchant markets, and 2) improved understanding and design of interactions of wind energy with the grid and its subcomponents. Each of these values is described further in Table 4.

Table 4. Innovations in Atmospheric Science and Forecasting To Improve Wind Power Plant System Value

Innovation Category	Innovation	System Value Impact
Short-Term Operational Forecasting - Postconstruction	Short-term wind inflow forecast adoption to improve bidding to merchant markets	• Reduced variability/uncertainty of supply • Ancillary service support • Increased energy value • Reduced curtailment impacts
	Forecasting wind turbine and plant performance in a wide range of operating environments	• Reduced variability/uncertainty of supply • Ancillary service support
Grid Interaction Improvements	Multigeneration type forecasts (e.g., wind, solar, and storage) to optimize production, storage, markets, and so on	• Reduced variability/uncertainty of supply • Ancillary service support • Increased capacity value • Increased energy value • Electrification support • Reduced curtailment impacts
	Forecast power line temperatures for estimating transmission "dynamic line rating"	• Reduced variability/uncertainty of supply • More efficient transmission use
	Coupled forecasting of wind and electricity load and grid state together	• Reduced variability/uncertainty of supply • Ancillary service support
	Smoothing power (diurnal)	• Reduced variability/uncertainty of supply
	Seasonal storage	• Reduced variability/uncertainty of supply over medium-term operations (seasonally)
	Shared platforms providing forecasting that supports demand response, time-of-use pricing, decision support; weather reports of day-before and day-ahead wind energy production	• More efficient demand management if energy forecasts are accessible by the public

As the amount of wind energy penetration increases, so does the value of energy forecasting—particularly in fast-acting merchant markets, where resources are more quickly dispatchable (Soman et al. 2010).

Improved physical understanding of processes that influence wind plants can lead to better optimized wind plant layouts and operational strategies. For example, understanding how turbine wakes interact with each other throughout a wind plant, in various kinds of terrain, on land or offshore, opens up strategies for optimal siting of individual turbines and for steering wakes to optimize power production (Fleming et al. 2016a).

For such improvements to take place, there is a need to develop a full understanding of site-specific atmospheric phenomena including but not limited to frontal systems, flows in complex terrain, sea breezes, cold pool erosion, the turbulent daytime and nocturnal stable atmospheric boundary layer, low-level jets, canopy effects, coherent structures, and turbulent wind gusts. Episodic field campaigns such as the Perdigão experiment (Fernando et al. 2018) can provide useful insights into the effects of atmospheric stability on wind turbine wakes (Wildmann et al. 2018) and terrain-driven recirculation on turbine-height winds (Menke et al. 2019). Through multiple, large, public-private partnerships, some improvements in understanding of atmospheric processes that affect winds at the height of wind turbines have been made and incorporated into operational weather forecast models.

In a recent project, the models used to predict temperature and timing of mix-outs of cold pools, among other processes in the Pacific Northwest (mentioned earlier), have been improved through revised planetary boundary layer mixing and horizontal diffusion schemes and introduction of small-scale gravity wave drag (Shaw et al. forthcoming; Wilczak et al. forthcoming; Olson et al. forthcoming). The private sector has made decision support tools to utilize such advances (Grimit et al. forthcoming). Such forecast accuracy advances support more efficient bidding into energy markets and wind plant controls. The latter facilitates site-specific designs for lower operation and maintenance (O&M) costs.

Improved and/or integrated forecasts of wind, solar, and water (for hydropower and pumped storage) support decision-making and optimization of power generation and storage (charging and discharging), as well as energy market operations (Hodge et al. 2018). Improved forecasting of temperature, irradiance, and wind speed and direction can support dynamic transmission line rating. Dynamic line rating can allow greater use of existing (and new) transmission lines because static line ratings, which do not change throughout the year or change only once or twice annually, limit the maximum current that a conductor can continuously carry without exceeding its temperature rating. Increased use of transmission lines is particularly helpful to renewable energy sources because they are spatially sparse (diffuse) compared to conventional energy sources (Bhattarai et al. 2018). Ultimately, this dynamic use of transmission lines would lead to a more dispatchable energy supply (Estanqueiro et al. 2018).

Coupled forecasting of the resource, load, and grid state, including transmission line capacity, can help regulators more accurately balance grid operation, leading to more grid stability and lower supply uncertainty (Bhattarai et al. 2018; Grams et al. 2017; Holttinen 2018).

Forecasts on a seasonal and longer-term basis could be used to optimally design, locate, and operate seasonal storage opportunities to ensure greater supply reliability. They can also be used to manage the storage devices themselves (e.g., pumped hydropower that will be influenced by rainfall and evaporation rate into the atmosphere (Wang et al. 2016).

Finally, through greater publicity of energy resource forecasts on a regular basis along with public education efforts, further demand management may be possible. If the forecasts can also be connected to publicized costs that vary daily and along with smart appliances, more optimal and reliable grid operation is also possible (e.g., Dietrich et al. 2012, Nistor et al. 2015).

R&D Challenges To Realize Innovations

The grand science and engineering challenges to realize innovations include 1) a fundamental understanding of the wind resource and how it will be modified, locally and regionally, by large-scale deployment of wind, and 2) an improved model chain to accurately predict the varying energy resources provided by the atmosphere.

A fundamental understanding of the wind resource and how it will be modified, locally and regionally, by large-scale deployment of wind energy is key to many of the innovations identified across the various breakout sessions. Atmospheric science has developed over the years, focusing on length and timescales most relevant for weather forecasting and climate prediction. Wind energy requires information about the wind resource and its availability at different levels of spatial and temporal resolutions (e.g., wind speed statistics at hub height and corresponding scales in between surface layer and regional-scale phenomena). This in-between region between micro and mesoscale meteorology has not been modeled well in the past because weather models focus on near-surface precipitation and temperature. In the vertical direction, model accuracy can be improved with increased model resolution and also improved surface layer parameterizations. In the horizontal direction, this region has already been termed “terra incognita” in the context of atmospheric turbulence modeling by Wyngaard (2004), a still-relevant description of the continuing insufficient knowledge of the relevant phenomena and underlying principles, although model improvements are currently being tested.

An improved model chain to predict accurately the varying energy resources provided by the atmosphere will support the ability to estimate the long-term resource, design wind turbines and power plants, as well as forecast energy production in the short term. At present, most of the modeling studies of wind energy systems are focused on a small range of scales. As a result, they may claim accuracy in a limited range of scales, but it remains a challenge to provide accurate and efficient predictions while capturing the relevant phenomena that range over many orders of magnitude of length and timescales, from micrometers to hundreds of kilometers, and from milliseconds to years. Although active work in this area is underway (Haupt et al. forthcoming), new advances in modeling coupling, such as cell perturbation methods (Muñoz-Esparza et al. 2014a, 2014b), will need development and refinement. Each of these research challenges requires addressing more specialized subchallenges, which are described in Table 5.

Table 5. Atmospheric Science and Forecasting R&D Challenges

Grand Challenge	Science and Engineering Challenge
Grand Challenge #1 – Fully Understand the Wind Resource and How It Interacts with Wind Power Plants	Understand, model, predict, and forecast the atmosphere and its impact on wind energy systems to develop a renewable energy system that "dances with the wind"
	Develop more accurate and higher-fidelity representations of the atmosphere using remote sensing, turbines, unmanned aerial vehicle sensing systems, and wind plant systems as sensors.
	Develop novel means for uncertainty quantification of the resource.
	Build mathematical theory for improved descriptions of a multipoint, time-evolving structure of highly non-Gaussian fields.
	Identify canonical cases that cover a wide range of operating behavior. Provide individual turbine inflow prediction and interface with control.
	Optimization of siting, layout design, and operation of wind plants, including possible effects of interfarm wakes and climate change influence
	Atmospheric science studies require access to industry data for comparison to meteorological measurements. Aligning meteorological phenomena with turbine performance and power production is necessary for ensuring relevance of atmospheric science results.
Grand Challenge #2 - Improved Model Chain To Better Predict Renewable Energy Resources	Complete model chain of atmosphere/wind plant interactions that seamlessly bridges scales
	Machine-learning-based forecasts
	Information and data science for information retrieval, data analytics, and machine learning; large, well-organized open-access data archives to enable accurate machine-learning techniques
	Probabilistic forecasting interfaced with deterministic forecasting
	Advanced, high-performance computing hardware and software architecture to exploit next-generation computing hardware; common model software architecture framework for software development
	High-fidelity model validation experiments

Knowledge must bridge scales that are important for turbine operation and reliability, with scales ranging from the large mesoscale to individual turbine wakes (Schreck et al. 2008). Improved multiscale models that capture the important physical processes across a variety of atmospheric and topographic environments will improve understanding of wind power plant performance, not only at the large plant level, but at each individual turbine location over the entire lifetime of a given wind power plant (Petersen and Troen 2012). As wind plants continue to be built worldwide, the interactions among plants at the largest scales (Nygaard 2014) will become more important: offshore wakes are already observed to extend 50 km in some circumstances (Platis et al. 2018). The occurrences, behavior, and predictability of these wakes require further examination (Siedersleben et al. 2018a, b). New models to simulate wind plant interactions with the atmosphere (Fitch et al. 2012) as well as new methods to access and share data on existing operational wind plants will be necessary. To advance R&D, researchers must have expanded and open access to meteorological and plant operational data.

The first research challenge is achieving a full fundamental understanding of the wind resource and how it will be modified, locally and regionally, by large-scale deployment of wind power, such that the industry can predict wind power output within 1% of reality 99% of the time. Addressing this grand challenge will require field campaigns with deployment of instruments to collect observations for model verification as well as permanent deployment of instrument networks to collect observations for assimilation into weather models to yield improved data for defining initial conditions for atmospheric simulations. In addition to anemometers that are already routinely mounted on towers and turbine nacelles, other instruments, such as lidars, can be mounted on turbines to provide situational awareness of the wind resource within and around wind plants.

Understanding the relationship of measured and modeled atmospheric phenomena to wind power production, at the level of individual turbines and wind plants, requires access to temporally and spatially matched data of wind power generation. At present, industry companies sign nondisclosure agreements with individual research teams for defined periods and locations; however, a national or international framework whereby companies could share power production data without compromising proprietary information would advance atmospheric science research for the industry. Additionally, the physical effects of turbines on the local environment can be modeled at various levels of fidelity, such as actuator disk and actuator line models in large-eddy simulations (Calaf et al. 2010; Martínez-Tossas et al. 2015; Vanderwende et al. 2016), and local momentum and kinetic energy sources included into weather models (Fitch et al. 2012). These methods have experienced limited testing than turbine power production data (Lee and Lundquist 2017). Moreover, ensemble forecasts can be generated by multiple methods (Lee et al. 2012). One or more models with different physics can be combined into an ensemble, different initial conditions can be used with the same model to yield an ensemble, and various components of a model can be stochastically perturbed to yield an ensemble (Ollinaho et al. 2017). The goal with any approach to ensembles is to yield a spread of forecasts that accurately represents the uncertainty in the forecast. Quantifying uncertainty in forecasts can support improved decision-making by power systems operations and markets.

The second grand challenge is the development of an improved model chain that seamlessly bridges scales to better predict renewable energy resources that are currently modeled separately. New multiscale atmospheric models developed must allow investigation into advanced understanding of the physics and also inform development of computational efficient models used by industry. A new set of tools across scales and with multifidelity will allow for prediction of fully coupled physics that drive performance and reliability of wind energy systems (Sanz Rodrigo et al. 2017). Such models may begin by coupling existing models across the mesoscale and microscale for which new numerical and physical methods for coupling must be developed and implemented (Muñoz-Esparza et al. 2014). These models must be sufficiently validated with new high-fidelity observations of wind plants over long time periods (Petersen 2017). These models will include the dominant physical processes required for prediction of the energy resources on different timescales and reduced-order models will take advantage of machine-learning techniques tuned to observed and simulated data for more time-efficient calculations.

To support this next generation of models, new computing architectures at the exascale or larger (Hammond et al. 2015) are needed in addition to software frameworks that support the next generation of hardware (Sprague et al. 2015). New "big data" tools, such as open numerical laboratories (Kanov et al. 2015; Meneveau and Marusic 2016) should be deployed to more openly share results from exascale numerical wind power plant simulations. Inclusion of data assimilation and machine-learning techniques will require stronger interactions with the growing data science community. Models of all fidelity must be validated to acceptable levels of accuracy to ensure acceptance by the wind energy community. New observational data sets will be needed that will be obtained through large-scale field campaigns to better understand the coupled physical processes and provide this validation data (Petersen 2017). Large, well-organized open-access data archives of meteorological and wind power plant operational data will also be useful for helping improve simulation accuracy. Because of sensitivities around intellectual property and other reasons, industry has historically been hesitant to share data. Discussion around more open access to data will be discussed further in Section 4 as a cross-cutting research need.

3.2 Breakout Group 2: Turbine Technology and Design

Turbine technology and design will continue to play a critical role in the deployment of wind energy, both in terms of reducing LCOE and offering greater value to the electrical grid. It is expected that turbine size will continue to grow, resulting in a trade-off between higher power ratings and higher capacity factors. This growth will require greater sophistication in rotor design to remove weight while controlling loads and deflections, and drivetrains that can reliably convert higher torques. Advanced sensing and control methodologies are critical to achieving these larger machines, as are new manufacturing and assembly methods to overcome logistics challenges. A deeper and more detailed understanding of the atmosphere discussed in other groups is also expected to lead to an enhanced ability to design for targeted conditions, extending design lifetime, reducing excessive safety factors, increasing energy capture, and enhancing grid support where needed.

One important note is that the breakout group focused on conventional technology for wind turbines (horizontal-axis turbines) and did not consider in any detail other architectures, such as airborne wind turbines or vertical-axis turbines. While there is room for innovation with novel architectures, the group focused more on opportunities that still exist for significant innovation on horizontal-axis turbines and identified many opportunities as discussed in the next section.

Innovations To Reduce LCOE

The greatest opportunities to reduce LCOE are found in the design and manufacturing of larger rotors, reduction of the impact of wakes, and improvement in major component reliability. Additionally, improved design standards and methods will allow for further optimization of turbine design.

Table 6. Innovations in Turbine Technology To Reduce LCOE

Innovation Category	Innovation	Innovation LCOE Impact
Larger Rotors	Blades optimized for structure and manufacturing over aerodynamic performance, where aerodynamic add-ons are installed after the fact to regain lost performance	• Decreased CapEx through lower manufacturing costs • Decreased OpEx through higher manufacturing quality and reliability
	Low specific power, high capacity factor rotors	• Increased AEP through higher energy capture in low and moderate winds
	Ultraflexible rotors with active aerocontrol	• Decreased CapEx through loads reduction on the rest of the machine
	Larger wind turbines	• Decreased CapEx through economies of scale
	Airfoil design for high Reynolds numbers	• Greater AEP through increased efficiency
	Turbine- and plant-level flow sensing and design impacts (wind awareness)	• Decreased OpEx through increased reliability
	Innovative materials (low-cost carbon) with highly tailored properties	• Decreased CapEx through loads reduction on the rest of the machine
	High-torque drivetrains	• Decreased OpEx through higher reliability
	Modular hybrid and taller towers	• Increased AEP through higher wind resource
	Extreme load mitigation	• Decreased CapEx through loads reduction
	Distributed and redundant sensing and controls	• Decreased OpEx by anticipating need for maintenance
Wake Management	Turbine rotor designed for wake dissipation/reenergization	• Decreased OpEx through increased reliability • Increased AEP
	Turbine rotor designed to extract energy from upper atmosphere	• Increased AEP through increased energy flow into plant
	Turbine designed to steer wakes away from downwind turbines	• Increased AEP through lower performance losses
Turbines with Higher Reliability	Implement turbine (redundant) load sensing and health monitoring for rotors, towers, and other components	• Decreased OpEx through increased reliability
	Adopting aerospace approaches that include inspection and damage assessment	• Decreased OpEx through more predictable failures
	Improved materials for metallic bearing surfaces	• Decreased OpEx through increased reliability

Innovation Category	Innovation	Innovation LCOE Impact
Improved Design Methods and Standards	Improved test methods for turbine components that more accurately simulate operational loading	• Decreased CapEx through optimized design • Decreased OpEx through increased reliability
	Probabilistic design (integrated into standards also) and increased understanding of uncertainties (for reduced safety factors)	• Decreased OpEx through increased reliability • Decreased CapEx through optimized design
	Improved aeroelastic and component models with lower uncertainty in loads and materials/manufacturing variability	• Decreased CapEx and OpEx through optimized, reliable designs
	Turbines designed and operated for 50-year lifetimes	• Decreased finance costs through longer turbine lifetimes
	Innovative turbine design approaches with unique site-specific criteria	• Increased AEP through site-specific optimized design • Decreased CapEx through site-optimized designs • Decreased OpEx through more accurate site-suitability assessment

The industry trend over the past few decades has been toward larger rotors (Wiser and Bolinger 2018). As described in Section 1, there are many reasons for the upscaling. Generally, an increase in blade length has a squared-factor effect in the power that can be captured from a given wind turbine (available power is a function of the rotor swept area), thereby increasing the annual energy production (AEP) produced by a turbine (Manwell et al. 2010). In addition, larger rotors and towers reach higher heights with better wind resources, and because power of the wind is related to the cube of the wind speed, this results in substantial increases in energy production at a given location.

In addition, as deployment of wind energy across the world becomes more substantial, the availability of the most desirable sites is becoming more limited. It is therefore necessary to deploy wind turbines in areas with lower wind speeds. Further, increasing the size of the rotor relative to the power rating increases the power capture at lower wind speeds. Turbines with larger rotors can capture more energy and make lower wind speed sites more economically attractive. Large rotor turbines with a lower specific power (rated power divided by swept area) also offer a higher capacity factor that not only increases AEP, but also increases the capacity value that the plant has to the electric grid.

One of the challenges associated with larger blades is the acoustic emissions. However, for offshore applications, acoustic noise from blades may not be an issue. For large-scale, land-based machines, it is often an active design constraint that limits the maximum allowable blade tip speed. Acoustic emissions scale with tip speed to the fifth power, so even a small increase in tip speed has a large impact on acoustic emissions from the blade (Moriarty and Migliore 2003). To keep acoustic emissions within acceptable levels, it is typically necessary to operate the rotor at a suboptimal rotational speed. Doing so increases the torque in the drivetrain, which then drives up drivetrain mass. Therefore, innovations in medium- and low-speed drivetrains will offer concurrent design options to limit system weight and capital cost. If tip speed could increase, this would imply an increase in the Reynolds number for the airfoils. There are limited data on the aerodynamic performance of wind turbine airfoils at higher Reynolds numbers, yet the data that are available suggest an improvement in overall aerodynamic performance (Pires et al. 2016). Still, more research in this area is needed.

So far wind turbine blades have avoided the square/cubed law that governs blade volume and consequently mass as blade length increases. Current control technology, materials engineering, and manufacturing have enabled blades to grow in length with much less than a cubic increase in mass, thereby overcoming the square/cube law to the point where it is still economical to increase the length of the blade to reap the benefits of increased power produced (Fonseca 2017). Advances in turbine control, active aerodynamic control (Barlas et al. 2016), and remote sensing of the wind power plant flow environment may enable future blades to be even longer, lighter, and reliable while still adhering to the safety standards required by industry. In response to larger rotors, taller towers will also become necessary (Dykes et al. 2018). Research is needed in this area to enable tall towers that conform to transportation and other logistical constraints as will be discussed in Section 3.3. Increasing the overall power rating of these machines will also take advantage of economies of scale, using fewer individual machines for a desired total power plant output. There are significant balance-of-system savings and potential O&M reductions in a plant with fewer turbines, such as the reduction in the number of foundations, material usage for cables and roads, and more.

A key consideration for turbine design is how individual turbine properties can be tailored such that the interactions with each other within a plant will result in optimum net energy production for the site (after the losses from interturbine interaction are considered). By coordinating and designing turbines based on their operation within a plant, future wind power plants will generate the maximum possible power for a given inflow condition at the plant and not at the individual turbine level. This approach will likely affect how each turbine within a plant is designed. For example, it may be beneficial to the overall wind power plant system value to not extract the maximum available wind power for every individual turbine, but instead for the upwind turbines to allow some wind energy to pass through to the downwind turbines (Bossanyi 2018). This strategy may result in design of a low induction rotor that maximizes power generation for the wind plant. Another strategy may be to design turbines with a rotor tilt in such a way that allows for entrainment of flow from above the turbines (Annoni et al. 2017). This would reduce the effective swept area of the tilted turbine, but it would encourage mixing of more energetic flow from above the wind power plant that would expedite reenergization of the wake deficit and thereby have a beneficial effect at the wind plant level. Future designs of wind turbine technology wherein the actual machine design is optimized for the full plant performance and cost will continue to drive down LCOE.

Turbine reliability remains a high-priority research area as more turbines are installed, and operational expenses will continue to be a driver for LCOE (U.S. Department of Energy 2015). For example, drivetrain bearings have been plagued by early failures because of axial cracking. This phenomenon is caused by a material failure, known as white etching area cracking, driven by a damage process that is not currently included in the design specification of wind turbines. This area requires further fundamental research to both uncover the fundamental process, design to mitigate against it, and change the design criteria to make the failure mode rare. This is just one example of the continuous need to define, research, and solve issues that cause endemic reliability problems as they emerge so that super-reliable systems can be designed, manufactured, and deployed.

Another opportunity to improve reliability is a novel approach to the monitoring of critical components based on using a larger number of sensors and transducers—a classical approach in the monitoring of conventional power plants, and not typical in the wind sector. As methods for big data analysis and condition monitoring (Márquez et al. 2012) mature, they will have a dramatic impact on turbine monitoring and may lead to lower uncertainty in the operational environment, thus allowing for more efficient and robust designs. The fusion of the existing massive data sets, which are not accessible on a real-time basis, offers some near-term opportunities for enhancing both performance and reliability. Condition monitoring within the turbines and inflow sensors around the plant, used in conjunction with advanced data assimilation and machine-learning innovations, can open the door to significant improvements in plant operations that increase revenue and reduce costs.

Design methodologies and standards must evolve to keep pace with changing regulatory and operational environments. Deterministic design approaches have been very successful in developing current multimegawatt wind turbines, but as power purchase markets evolve and industry subsidies expire, more emphasis will be placed on developing the most reliable and cost-effective technology available. As such, understanding uncertainties in the design process and moving toward a probabilistic design philosophy (Sørensen and Toft 2010) will be critical to developing the most efficient and reliable wind turbines of the future. By understanding these uncertainties, designers can safely move away from padding designs with safety factors that may add unnecessary mass, and therefore, cost to the system. This shift in design approach represents a fundamental alternative to the classic approaches to structural design embedded in the current design standard. New standards based on this approach will need to be developed.

A key caveat to much of the discussion is that there is often a trade-off between many of the design objectives that make up LCOE including the energy production, balance-of-system costs, and operational expenditures. For instance, an upstream design innovation that reduces capital expenditures may lower energy production and increase operational expenditures or vice versa. For instance, blade segmentation that allows the transportation of larger blades to a given site may allow for increased energy production, but the segment itself will introduce additional costs in terms of materials and manufacturing, on-site assembly of the jointed blade, and potential long-term issues for reliability and maintenance costs. A full system design perspective is necessary to evaluate technologies to appropriately assess their impacts on the LCOE (Dykes et al. 2011).

Innovations To Increase System Value

As the share of wind and solar into the electrical grid increases, there will be greater need for wind turbines to replace the grid services currently offered by synchronous, dispatchable conventional power plants. Wind power plants have the potential to contribute greatly to grid reliability through the design of machines with a higher capacity factor, turbines designed to allow for advanced grid service controllers, and improved operational strategies. Additionally, advances in turbine design that allow for deployment in a more diverse set of environmental and geophysical conditions will allow for more flexibility in plant location, reducing grid congestion and overall output variability. Finally, an opportunity exists for power plants to produce fuel and other outputs (Power to X), which would enable storage or use of energy for other applications such as transportation.

Table 7. Innovations in Turbine Technology To Increase System Value

Innovation Category	Innovation	System Value Impact
Higher Capacity Factor	Longer rotor blades for given rated power	• Increased capacity value • Increased energy value • Ancillary service support • Reduced variability/ uncertainty of supply
Low-Wind-Speed Turbines	Turbines that are deployable across larger geographic regions for reduced variability/uncertainty and ability to produce power at lower wind speeds	• Reduced variability/ uncertainty of supply
Optimized Operational Strategy	Develop detailed understanding of real-time turbine operational cost and revenue production	• Reduced variability/ uncertainty of supply
Design for Grid Services	Integrate wind turbine with energy storage	• Ancillary service support • Increased capacity value • Increased energy value • Reduced variability/ uncertainty of supply
	Controls for active and reactive power	• Ancillary service support
	Synthetic inertia	• Ancillary service support
Alternative Plant-Side Energy Usage	Fuel production	• Electrification support
	Water pumping/desalinization	• Reduced curtailment impacts

Higher-capacity-factor wind turbines and wind power plants offer several advantages, and there has been a clear industry trend toward such machines over the past decade (Wiser and Bolinger 2018). Larger rotors relative to rated power are the main avenue to achieving high-capacity-factor wind turbines. These machines are ideal for lower-wind-class sites to allow for operation at rated more of the time, but there are also advantages to the overall grid system when there is less variability in power production for large wind plants. A reduction in power production uncertainty will also reduce the cost of project financing. Further, turbines designed for low-wind-speed sites (often with larger rotors) will allow for wind plants to be better distributed geographically, which generates lower variability in overall power production and reduces congestion on power lines.

For every unit of energy produced by wind turbines, there is an implicit trade-off of the revenue from that unit of energy and the cost of operating the turbine (largely in the loading and damage accumulation to the machine over time). Optimizing long-term operational strategies of wind turbines will allow for balancing turbine revenue and cost in the most profitable way possible. In turn, this optimization will require a detailed understanding of the turbine operation over its lifetime and accurate predictions of the health of various components and ability to accurately predict when failures may occur.

As more and more renewable energy services are integrated into the grid, wind turbines and power plants can provide services for reliability and stability to the grid. Wind turbines have physical inertia in the spinning rotor. The energy stored in this rotor inertia is accessible almost instantaneously to support a sudden grid fault, such as a major substation trip or loss of generation. If the wind power plant is coordinated to control all its rotational inertia assets, it can act in rapid response to feed the front end of a critical fault until other, slower assets can be brought on line to stabilize the grid. Generally, wind turbines with type 3 or type 4 drivetrains (those with power converters) can provide several services to the grid including inertia, active and reactive power control, and fault ride-through capability (Kroposki et al. 2017).

Finally, wind plants can use energy on-site or at strategically located points on the transmission system for other purposes, such as fuel production and water processing, thus avoiding complete shutdown during curtailment periods. Additionally, wind plants in some areas can be used for water pumping and desalination.

R&D Challenges To Realize Innovations

For wind energy to continue to be a viable source of electricity at the scales envisioned, two grand R&D challenges have been identified as critical to unlocking the potential innovations highlighted in this document.

Table 8. Turbine Technology R&D Grand Challenges

R&D Grand Challenges	Specific R&D Activities
Grand Challenge 1: Complete Understanding of Physics for Design and Operation of Very Large-Scale Machines	Validation and verification of the simulation and design tools including new instrumentation, open data access to the research community, and “big science” grand challenges
	Assess the inflow characteristics across very large rotor diameters, such as, veer, shear, three-dimensional distribution turbulence, and wake inflow coupling
Grand Challenge 2: Physical Understanding of the Boundary Layer Physics - Multiscale Characterization Driving Turbine Performance and Loads	Assess impacts and potential for two-way coupling of physics from the turbine and the flow and effects on the boundary layer inflow
	Assess wake dynamics (generation, meandering, dissipation) and subsequent array interaction effects

The first grand challenge is to improve the accuracy and reduce the uncertainty of the current design tools, as well as inflow characterization. This has a lot of complementarity with the challenges as discovered in the atmospheric science and forecasting breakout group as will be discussed in Section 3.2. There are still significant gaps in our knowledge around wind turbine and plant physics—especially as we go to larger machines and applications in complex terrain or offshore (Hills et al. 2015; Womble et al. 2015; Damiani 2018). Aeroelastic tools based on blade element momentum (BEM) theory have been used to design almost every turbine in the commercial market to date, including very large wind turbines; however, there are limitations to the accuracy of BEM theory. For example, highly flexible blades have large deflections out of the plane of rotation, which breaks some of the fundamental assumptions of the method. Floating offshore systems with moving substructures will produce motions of the rotor that are not easily modeled in BEM theory. Momentum balance methods are also unable to directly resolve highly three-dimensional (3D) flows near the hub, which are increasingly important in understanding the wakes that impinge on downstream turbines. These issues will become increasingly more pronounced as the size of rotors continues to grow larger. Enhanced modeling techniques that resolve the actual geometry of the blades in a flow-field computation will be needed to compute and understand the behavior of these flexible, moving systems and their overall dynamics. Design tools that accurately capture the resulting loads at all times (and under all relevant atmospheric conditions) will also need to be derived from high-fidelity models to assess the adequacy of advanced, enlarged rotors for extreme loads and operating fatigue.

A common practice to handle these limitations is to design blades and other components with greater-than-optimal factors of safety and to avoid design alternatives that are too far from the current configurations wherein there is institutional knowledge of what works and what does not. This approach leads to components that are costlier and heavier, leading to overall adverse system impacts, as well as stifled innovation. To improve the design process, it is necessary to fully validate and verify the simulation and design tools and understand the uncertainties associated with each model. A robust validation and verification process would require investment in new instruments capable of producing high-resolution experimental data (Hills et al. 2015). This challenge is so big that no institution can solve it on their own and will require a high degree of transparency and knowledge sharing among stakeholders. The use of open-source tools should be encouraged as it will facilitate the process.

A second and somewhat related grand challenge focuses more specifically on the interaction of wind turbines and wind plants with environmental conditions. Researchers have developed mesoscale models capable of describing atmospheric phenomena on a large spatial and temporal domain, and microscale models capable of describing atmospheric phenomena on a smaller spatial and temporal scale. Currently, there is a lack of understanding and modeling capability to accurately represent the interactions between these two modeling techniques. Developing an understanding of how these models interact with each other is important to reducing uncertainty in the physical processes driving turbine performance in the local environment. Computational models that bring the characteristics of the mesoscale flows down to the scale of the wind plant and compute the impact of local flow features on the wind plant operating production and turbine loads will have to be created (Womble et al. 2015). The needed detail resolution of the flow field and its impact on design criteria can only be observed from computational models. Measurement systems are still inadequate for observing the fine scale of turbulence, wakes, and other local effects important in generating the loads on these highly dynamic flexible machines. An especially important process to understand is that of wake generation and evolution through the wind plant. This cannot be modeled with a high degree of accuracy and low degree of uncertainty without this approach.

Solving this grand challenge will give engineers the appropriate tools to design optimal wind turbines and wind plants in the future and will allow for more efficient and reliable operation of wind plants. The topic of understanding the physics and creating validated modeling capability across all relevant spatial and temporal scales is a key focus of breakout group 3 and will be discussed in even more detail in the following subsection on atmospheric science and forecasting.

3.3 Breakout Group 3: Manufacturing and Industrialization

As discussed, increasing turbine sizes over the last several decades has resulted in significant economies of scale and lower cost of energy for wind power plants. The sizes of land-based machines that are the state of the art today have blades exceeding 70 m, with hub heights reaching toward 200 m, for total tip heights of 250 m or more, and have generator ratings of 4 MW or greater (and offshore wind turbines are becoming even larger). The sheer size of major components for these machines presents new challenges for their manufacture, transport, and installation on-site. For the last few decades, the technologies and processes for manufacturing the largest components, such as wind turbine blades and towers, have remained relatively unchanged—utilizing low-cost manufacturing processes and materials, as well as manual labor practices. In addition, advances in component design and manufacturing have been constrained significantly by transportation limits. For example, 4.3 m is a common maximum allowable chord dimension for traditional transport of a land-based turbine to avoid overhead obstructions on roads. The maximum allowable blade root diameter is only slightly above that value. The maximum diameter of most commercial wind turbine towers for land-based wind turbines, as well as the maximum chord of their blades, are still constrained by transportation limits on roads and rail (Cotrell et al. 2014). In addition, as land-based turbines reach higher heights and components are increasingly heavier, the industry will no longer be able to use traditional installation practices that have relied on cranes commonly available for other industrial applications. For offshore wind energy, specialized installation vessels and equipment have been introduced and their availability is one factor that has contributed to significant reductions in LCOE for offshore applications in Europe (Musial et al. 2017).

Conventional manufacturing, transportation, and installation approaches have worked well enough over the past 20 years to support the overall system reductions in LCOE. However, with the continued need for even lower LCOE as well as the desire to expand into new markets where turbines must reach even higher heights to access good wind resources, the demand for ever-larger wind turbine components is causing a rethinking of these approaches. This dynamic creates an opportunity to revisit the product development cycle with a focus on how investment in manufacturing, industrialization, and transportation and logistics innovations can enable future reductions in LCOE.

The recent emergence of the fourth industrial revolution, or “Industry 4.0” (Cotteleer and Sniderman 2017), may promise technologies that can realize new levels of efficiency and cost reduction in manufacturing. These technologies may include advances in areas such as additive manufacturing, advanced materials, advanced sensors, advanced automation, digitalization and digital twins, artificial intelligence, and high-performance computing. Combining extreme-scale sizes of wind turbine components with advances in the areas mentioned earlier positions the global wind industry to innovate on the product development cycle and exploit R&D pathways in manufacturing and industrialization on its quest to continuing to lower LCOE.

Innovations To Reduce LCOE

For land-based wind turbine components, one pathway that might relax the design constraints imposed by transportation size limits is manufacturing of large components at the sites where wind power plants will be installed. In addition, potential innovation in the areas of advanced materials, additive manufacturing, standardization, and quality control have been identified that may enable the production of very large components including wind turbine blades in both traditional and on-site production facilities. These innovations are presented in Table 9 and discussed in more depth in the text that follows.

Table 9. Innovations in Manufacturing and Industrialization To Reduce LCOE

Innovation Category	Innovation	LCOE Impact
Additive Manufacturing	Three-dimensional (3D) printed molds and tooling for blades, nacelles, and other components	• Reduces CapEx through lower-cost molds and tooling • Reduces time to market through rapid printing of molds and tooling
	3D-printed components (i.e., blades, towers, hubs, nacelle canopy, generators, and other drivetrain components) including power electronics	• Reduces CapEx by eliminating molds and tools • Increases AEP through advanced wind blade geometries and better drivetrain efficiencies • Reduces CapEx through lighter weight and subsequent reduction in structure
Manufacturing Automation	Wind turbine blade molding automation	• Improves blade quality, which increases field reliability, thus decreasing downtime and maintenance cost —leading to overall reduction in AEP
	Wind turbine blade finishing automation	• Reduces labor costs for blade manufacturing • Decreases overall required floor space, thereby decreasing CapEx
	Wind turbine tower automation	• Decreases labor costs for tower manufacturing
Advanced Materials	Low-cost carbon fiber and other advanced materials for wind turbine blades	• Reduces CapEx and OpEx with system-level improvements • Increases AEP via longer, lighter weight blades
	Advanced, 3D-printed and manufacturable materials for other wind turbine components	• Reduces CapEx and OpEx with system-level improvements • Increases recyclability
Machine Learning/Advanced Modeling	Advanced design optimization using high-performance computing, advanced	• Reduces CapEx and OpEx with system-level improvements • Increases recyclability

Innovation Category	Innovation	LCOE Impact
	algorithms, design for advanced manufacturing, and artificial intelligence	• Increases overall AEP
Industrialization and Standardization	Standardized or commercial off-the-shelf support structure solutions for offshore wind	• Reduces CapEx • Increases reliability of components
	Standardization of supply chain	• Reduces CapEx
Quality Control and Improvement	Reduction in scaling-related defects and nonconformance	• Reduces OpEx through less nonconformance and greater reliability
On-Site Manufacturing and/or Assembly	Segmented blades	• Increases AEP by enabling larger rotors • Decreases transportation costs
	Thermoplastic composite blade structures with thermally welded joints (also applies to advanced materials)	• Increases AEP by enabling larger rotors • Decreases OpEx through reduced repair and replacement costs
	On-site manufacture of large components (potentially including 3D printing, automation, and robotics)	• Increases AEP by enabling larger rotors • Decreases transportation costs
	Technologies to enable land-based turbines of 10 MW or greater	• Increases AEP by enabling larger rotors and power ratings

Wind Turbine Blades

One of the emerging areas of innovation that could be deployed in the manufacturing of wind turbine blades is additive manufacturing. This technology could be utilized in two disparate areas: the production of tooling and the manufacturing of actual wind turbine blades and their subcomponents. As discussed in Section 1, innovation in blade design has been a key driver of performance improvement and cost reduction for the overall system. Still, manufacturing for blades has not realized revolutionary changes in process and equipment in the last few decades. On the equipment side, blade tooling, including molds and fixtures for wind turbine blade components such as high-pressure and low-pressure skins, root inserts, spar caps, trailing-edge stiffeners, and shear webs, is currently developed and produced using traditional manufacturing methods once a blade geometry is defined and before production begins. Future wind turbine mold production may be accomplished using additive manufacturing, or 3D printing (Post et al. 2017b). This advancement could reduce the time and overall cost of tool production and increase the efficiency of tool operation. Traditionally, tooling development and production consumes a large amount of time, often from 6 months to a year, and limits the speed to which new products can be introduced to market. To commercialize new turbine models in a timelier fashion, advances in the speed of 3D printing could be used to shorten the time to print tooling.

Additive manufacturing could also enable new tooling features specially adapted to the needs of very large blade production (Post et al. 2017a). For example, current fiberglass/carbon-fiber epoxy blades require heated molds to cure the resin and adhesive systems once the blade components have been infused and assembled. The common mold heating approach of built-in resistive heating elements, which are typically high in cost and take a long time to construct, could be replaced with discrete and distributed built-in heating and cooling cavities. An early development of additive manufacturing for wind turbine blade tooling has been achieved through 3D printing of a blade mold (Post el al. 2017b). Future innovation in 3D printing could also lead to the direct use of additive manufacturing to produce actual wind blade components—or even full wind turbine blades—thus eliminating the need for blade tooling entirely.

Targeted automation is another area of manufacturing innovation for both on-site and traditional factories. Particularly for wind turbine blades, their production has long been a labor-intensive process. Although there have been a few successes, such as in-root cutting, facing, and drilling, most attempts to automate labor steps have been unsuccessful. Opportunities to reduce costs must be identified in terms of understanding cost drivers in blade production as well as the potential for advanced manufacturing solutions, including automation, to reduce these costs. Examples of research that target use of automation in manufacturing include new methods of placing core material and other composite materials in an automated setting as well as automation of thermal welding processes to bond the wind turbine blade components together without adhesives.

Another area of innovation for manufacturing and industrialization is the development and deployment of advanced materials in wind turbine components. While the discussion in the following paragraph emphasizes materials used in blade manufacturing, innovative materials in several areas would also benefit the design and manufacture of other major components, such as towers and generators.

For transforming wind turbine blade production, two advanced material systems have been identified. The first of these materials is low-cost carbon fiber, including the potential use of low-cost textile-based carbon fiber (Oak Ridge National Laboratory 2010). Carbon fiber has long been utilized selectively in the design and production of wind turbine blades as they have increased in length over the past 20 years. However, by lowering the raw material cost of this high-strength/stiffness-to-weight ratio material, low-cost carbon fiber could be more broadly deployed in the design and manufacturing of wind turbine blades up to and beyond 100 m in length. Whether used in pultruded (fabrication of a composite by drawing resin-coated glass fibers through a heated die) spar caps, infused trailing-edge stiffeners, or other highly structural components of wind turbine blades, low-cost carbon fiber could further reduce LCOE. This larger tow, lower-cost carbon fiber has the potential to be optimized for performance in carrying the loads specifically related to the durability and survival of wind turbine blades. If successful, the development of this advanced material will transform how wind turbine blades are designed and produced.

A second material that could revolutionize the way that wind turbine blades are manufactured is a specialized in-situ polymerized thermoplastic resin system. Currently, almost all megawatt-scale wind turbine blades are manufactured using traditional thermoset resin systems, such as epoxy, polyester, or vinyl ester resins. Although traditional thermoplastic resin systems have been evaluated in the past for use in wind turbine blade production, such drawbacks as very high temperature exotherm and elevated moisture sensitivity have prevented the adoption of thermoplastics in blade manufacturing. With the recent development of a two-part acrylic-based reactive thermoplastic resin system, including the successful demonstration of manufacturing a 9-m thermoplastic blade (Murray et al. 2017), thermoplastic resins have been gaining interest as a replacement for thermosets in wind turbine blades because of their room temperature cure, recyclability (Cousins et al. 2018), and decreased cycle times, which could lead to lower manufacturing costs (Bersee and Noi 2016; Murray et al. 2018; Wiser and Bolinger 2016).

Thermoplastics typically do not require a heated mold for cure and do not require a separate step in an oven for postcure, which would eliminate the need for some plant tooling and save substantial factory floor space. In addition, they could eliminate adhesives used to bond blade subcomponents. These adhesive joints, which are often the area of wind turbine blades that fail prematurely, could be replaced by a form of thermal welding (Stavrov and Bersee 2005). This fusing of thermoplastic components together, either in a traditional factory or in the field, may result in more robust and reliable wind turbine blade joints.

Thermoplastic resin systems create the possibility of blades being widely recycled at the end of their lifetime (Cousins et al. 2018). The inability of current thermoset resin systems to be efficiently broken down and reused leads to most blades being disposed of in landfills after their useful life on a wind turbine (Larsen 2009; Ramirez-Tejeda et al. 2017). Thermoplastics, however, can be reheated, recycled, and reused in future composite structures, whether for wind turbine blades or other industrial parts. The ability to recycle wind turbine blades will become more important as the rate of decommissioning and replacement of wind turbines increases. With increasing deployment of wind energy, the resulting composite waste from wind turbine blades alone could reach millions of metric tons per year by 2050 (Liu and Barlow 2017) unless recycled as in-fill, inert material, or other secondary uses of decommissioned blades. For those blades that are not recycled into secondary products, the adoption of thermoplastic resin systems in the design and production of wind turbine blades could transform the way that blades are recycled and avoid the deposition of millions of tons of composite waste in landfills.

Workshop attendees also identified on-site manufacturing as a leading enabler of the larger rotors needed to reduce LCOE as it avoids the transportation barriers altogether. Currently, transportation barriers are limiting the design dimensions of critical elements, such as blade chords and tower bases, resulting in suboptimal component designs and weights that are much greater than they would be with on-site manufactured dimensioning. The manufacturing capabilities that would allow production of wind turbine blades, towers, and other components directly at the location of planned wind power plants is still a research topic. However, to be economically viable, on-site manufacturing would require innovation in many of the technologies already mentioned earlier, such as 3D-printed tooling and advanced thermoplastic resin systems. For example, the ability to quickly and economically print blade tooling and molds on-site will eliminate the requirement to produce tooling at a separate factory and then ship these tools in segments to the on-site location. This ability will provide significant savings in the cost of the tooling and will also decrease the time required to build tooling. The use of thermoplastic resin systems in an on-site manufacturing environment can also have a positive impact on production by eliminating the need of heated tooling and postcure ovens. An in-situ thermoplastic resin system could also decrease the cycle time through the fast infusion of thick composite laminate resulting from the relatively low viscosity of that resin. The ultimate success of wind turbine blades and towers manufactured on-site will stem from an entire rethinking of both the design and manufacturing of these large composite (blades) and metallic (tower) structures. On-site manufacturing will be successful if a newly designed blade or tower, free from the constraints of transportation limitations, can save enough weight through the reduction in the overall bill of material, reduce turbine system loads with this decreased weight, and decrease overall labor and cycle times as mentioned earlier.

Finally, the reduction of LCOE through innovation in wind turbine blade, tower, and other component production requires the use of advanced nondestructive evaluation methods implemented upstream in the fabrication process to produce defect-free components with increased lifetime reliability in the field (Sutherland et al. 1994; Adams et al. 2011; Zwink 2012). Most often in current wind turbine blade production, nondestructive evaluation is used to inspect, validate, and, if required, define repairs to already manufactured blades before they leave the factory. An example of this is the use of ultrasonic nondestructive evaluation systems to inspect internal blade adhesive joints. However, innovation in nondestructive evaluation technology and deployment earlier in the manufacturing process will enable the production of better-quality component structures.

Hub, Drivetrain, and Other Nacelle Components

As wind turbines get larger, innovations in rotor designs, drivetrain components, towers, and substructures are equally critical as they have cascading effects. As weight and size are key cost drivers, turbine subsystem costs including materials and manufacturing for nacelle and drivetrain power systems can significantly add to the CapEx. Given the level of upscaling anticipated in the coming years and recent advances in metal additive manufacturing, the design and manufacturing processes for critical components such as the hub, nacelle, and drivetrain components may undergo a radical shift as there exists a great opportunity through better, low-cost materials and high-volume production, while ensuring the reliability is maintained. As much as being a great enabler for large-scale components, considering the costs, additive manufacturing is expected to bring in greater value for creating highly complex drivetrain components with added functionality.

Additive manufacturing technologies have already entered the powertrain chain in the automobile industry for driveline components (Du 2019) and sealing and thermal management (Giffi et al. 2014). However, decisions about its transferability to wind power conversion is highly dependent on scalability in manufacturing, materials, costs, and the ability to address key performance drivers, such as weight reduction, added functionality, and increased strength. A variety of metals and alloys including titanium, aluminum, and steel are printable both directly and indirectly. In terms of direct metal printing, both electron beam melting and direct metal laser sintering/melting techniques are popular, use a powder bed, and are trending toward large-scale metal printing with a customizable and scalable build volume designed for use with multiple materials, including nonreactive and reactive. Several iron-based alloys are currently available on the market with well-developed process parameters and postprocessing solutions, including steel.

Along with optimum processing parameters and posttreatment, the resulting additive manufacturing material mechanical properties are comparable or even better than the conventional production methods. However, additive manufacturing processes with various type of machines are presently far from being completely developed to manufacture the controlled-microstructure materials for some metals. It is safe to assume that direct metal printing has limitations in terms of usable materials and manufacturing precision in strict tolerance design situations. At the same time, the mechanical properties, stability, and fatigue performance of printed parts remain to be established as the components become bigger. Because of these challenges, few companies are considering indirect additive manufacturing as a feasible option to produce large, complicated geometries. Methods have advanced to make structural steel joints that will significantly reduce the time and cost needed to make complex nodes in tensile structures (Niche 2017). More recently, printing sand molds for use in a traditional metal casting process is gaining popularity. Build volumes of up to 4.0 m by 2.0 m by1.0 m are now possible commercially (Voxeljet website). Using a printed sand mold, metal nodes can be produced as any other metal cast as a certified material. To be able to fully explore these opportunities, considering the complexity of metal additive manufacturing, all optimization domains should be integrated during the early design phase. This involves accurate materials selection, technology parameters optimization, 3D modeling, and finally part postprocessing. Yet, it is believed that layered technology has not proven to produce parts that can take a lot of torque or tension, but as advanced metal additive processes are being developed very quickly, the potential to disrupt the normal flow of gear manufacturing is a possibility (American Gear Manufacturers Association 2019), although key challenges remain in demonstrating the requirements of material hardness, fatigue strength, surface finishes, and tolerances for components that are subjected to in-service wear and complex failure mechanisms.

Three opportunities with metal additive manufacturing are already being considered in the wind industry with regards to drivetrain subsystems reliability and efficiency: integrating printed internal channels in gears for condition monitoring the structural health of gears, making lightweight structures (Dodd 2017), and producing power electronics. NREL is leading the first research investigations on structural light weighting opportunities for large direct-drive generators and the potential for indirect metal additive manufacturing in realizing large-scale geometries (Hayes et al. 2018). The research identifies new opportunities to realize significant power densities and achieve savings in top-head mass. Three-dimensional-printing nacelle assembly (Post et al. 2017a) can provide new and improved design geometries with higher complexity and thermal management. Wide bandgap electrical components and additive manufacturing are already being used to redesign and develop higher efficiency power electronic converter systems. Additive-manufacturing-part-enabled converters have the potential to achieve up to 98% system efficiency, higher power densities, and specific power ratings. Considering the present costs of metal additive manufacturing and printed materials, the feasibility for LCOE reduction would be more pronounced by implementing design for additive manufacturing methods and tools that can better exploit and efficiently tap into the advantages including geometric complexity, component integration, and light weighting.

Beyond additive manufacturing, advanced materials in electromagnetic and power electronic components also have the potential to improve performance and reduce system costs (Bahmani 2016). Power electronics and generator research has been driven by the need to maximize efficiency at high power levels, incurring the greatest losses and need for heat transfer. Further, at low power levels, when the winds are low, it is vital that the system have the highest efficiency possible. In addition, weight of the electrical components is more critical for wind applications because weight reductions also have a multiplied impact on the cost of the supporting structural components of the turbine. Generators using DC-DC converters with high-frequency transformers will gain weight reduction in the range of 90% compared to the standard transformer (Max 2009). For offshore applications, it is even more important to reduce volume and weight, as it can reduce the size of the offshore substation platforms or even eliminate them (Chatterjee et al. 2016).

Towers

For any type of on-site manufacturing, factory mobilization and total cost, time to deployment and operation, risk of project delays, required cycle times to meet other scopes of work on the wind farm, and intrawind farm logistics and transportation must be considered. Locating and acquiring usable land for a factory, civil works and foundations required for factory equipment, availability of utility energy for process requirements or self-generation, and reclamation are all considerations that may constrain the application of various on-site manufacturing approaches. Components must also be sized for intrawind farm transport and handling by cranes or trailers. Transporting 100-m-long blades (or longer) and complete towers is possible but terrain complexity and the cost implications of constructing site roads able to handle specialized loads must be considered.

Towers for modern and near-future wind turbines are designed with transportability as one of the key drivers (Dykes et al. 2018). Increased energy production has been realized with higher hub heights that place turbines into higher-quality resource regimes as well as larger rotors that enable more of the wind passing by the turbine to be converted into electricity. Basic science R&D coupled with industry innovations have allowed hub heights and turbine rotors to grow and increase energy capture while simultaneously eliminating excess material, improving production processes, and maintaining reliability, thereby enabling this increased energy to be achieved at a negligible cost penalty. Specifically, advancements in turbine controls have significantly reduced these cost and mass penalties as turbines and hub heights increase in size.

However, as turbines continue to grow, the forces generated by the turbine have also increased. This requires more material to be used for a constrained geometry, or alternatively, changing the geometry of the tower. The constraints introduced by transportation are allowing many alternative tower technologies to be explored and deployed to exploit the ability to change the geometry outside of the transportability envelope. On-site manufacturing of steel and concrete towers is becoming more common to allow for the use of new tower geometries.

The most common approach for on-site manufacturing of tall towers is a hybrid tower composed of tubular steel sections and cast on site concrete lower tower sections (Lantz et al. 2017). Max Bogl has successfully deployed and produced concrete tower sections on-site with their mobile factory approach. Steel towers can be manufactured on-site as well. It is common practice in pipeline construction to construct tubular cylindrical steel sections using flay steel plate and rolling and welding the material on-site. Keystone Tower Systems has several patents and has demonstrated a similar technology but with the benefit of adding the capability to roll tapered conical towers, which dramatically improves the mass intensity of the tower compared to cylindrical towers. Lattice towers have a very low material cost, but much higher labor costs compared to tubular steel or concrete towers. GE recently demonstrated a lattice tower but has not made any commercial offerings to date. Other tower technologies, such as the Vestas Large Diameter Steel Tower and Siemens bolted shell are somewhere between a lattice structure and a conventional tubular steel tower. See Lantz et al. (2017) for a review of different tall tower technology options.

The opportunity space for towers is constantly changing as advances in turbine controls are reducing cost penalties to conventional tower technologies. Automation of on-site manufacturing of steel or concrete may hold promise but the primary barriers that still exist are time to production, mobilization cost, and land availability. A system optimization model considering the temporal aspect of farm construction is critical to understanding the feasibility of these on-site manufacturing technologies.

R&D Challenges To Realize Innovations

Given the manufacturing-focused pathways to LCOE reductions described in the previous section, the three most important grand R&D challenges to realizing these innovations are advanced materials for wind turbine design and manufacturing, automation of wind turbine component manufacturing, and enabling on-site manufacturing of major turbine components. Table 10 summarizes these challenges and more detailed discussion follows.

Table 10. Manufacturing and Industrialization R&D Grand Challenges

R&D Grand Challenges	Specific R&D Activities
Grand Challenge 1: Advanced Materials	Research new materials for the “circular economy” for energy materials, allowing for the design, substitution, reuse, recycle, and remanufacturing of critical materials in the production of wind turbine components, including blades and towers
	Continue to develop and implement low-cost carbon fiber for use in wind turbine blades, including use in pultruded carbon-fiber spar caps and preformed carbon-fiber trailing-edge and leading-edge stiffeners
	Research the design and production of advanced core materials, including the use of additively manufactured core materials
	Develop ideal material characteristics to enable advanced design and manufacture of wind turbine components

R&D Grand Challenges	Specific R&D Activities
	Research advanced erosion-resistant composite materials for use on the leading edge of wind turbine blades
	Research, development, and scale-up of thermoplastic resin systems to reduce wind turbine blade manufacturing cycle times, reduce blade costs, enable thermal welding of bond lines, increase recyclability, and enable advanced in-field blade repair techniques
	Research advanced thermoset materials that can be recovered and reused
	Research metals and other noncomposite materials for development of lightweight, high-strength, and high-stiffness turbine components
Grand Challenge 2: Automation	Develop comprehensive techno-economic models for automation and a virtual factory (or digital twin of a factory) to understand advantages and disadvantages of targeted automation for both wind turbine blade molding and finishing operations
	Identify and quantify all cost inputs for wind turbine component manufacturing (e.g., blades, towers) to identify production steps that would benefit from automation
	Develop automated production methods for the continuous manufacturing of one-piece wind turbine towers for on-site manufacturing
	Develop advanced design tools to optimize blade and tower design with respect to manufacturing with automation
	Research and develop automation technology able to locate complex wind turbine blade geometry in space to allow for effective automated finishing operations, such as sanding, drilling, and cutting
	Develop methods to automate the delivery, placement, and inspection of core material into blade skin molds during the composite laminate skin lay-up
	Integrate real-time inspection and quality control into automated production steps for wind turbine blades, towers, and other components
	Develop large-scale, low-cost, high-throughput, high-performance automated additive manufacturing technologies (e.g., 3D printing, automated fiber placement and tape layup, filament winding) for the production of towers, blade skins, blade spars, and other turbine components
	Develop embedded metrology and out-of-mold indexing technologies
Grand Challenge 3: On-Site Manufacturing	Develop robust composite materials for use in broad on-site environmental conditions
	Research the chemistry and processing of in-situ thermoplastic resin systems to enable thermally welded joints in an on-site manufacturing environment
	Develop targeted wind turbine blade finishing automation techniques designed to reduce the overall footprint of on-site finishing operations and minimize production facility floor space
	Research additive manufacturing to print wind turbine blade molds and tooling at on-site manufacturing locations

R&D Grand Challenges	Specific R&D Activities
	Develop optimized factory designs and manufacturing techno-economic models to identify key areas for cost savings in an on-site manufacturing facility
	Research and develop "digital twins" for the structures produced in an on-site manufacturing facility to enhance structural health monitoring in the field and to increase reliability of structures
	Research optimized blade and tower designs for on-site manufacturing without the constraints imposed by typical transportation logistics
	Research advanced nondestructive evaluation methods to be implemented upstream in the production environment in on-site manufacturing facilities to ensure robust manufacturing methods
	Develop manufacturing techniques to co-infuse precured components (such as pultruded carbon-fiber spar caps) into blade skins in an on-site manufacturing environment
	Research innovative manufacturing methods to produce single-piece tall wind turbine towers on-site

The first grand challenge is the development of the advanced materials needed to support future wind turbine technologies, including lightweight, long wind turbine blades. Although glass-fiber-reinforced plastics, steel, and cast iron are all low-cost constituents used in the manufacture of modern-day wind turbine components, they have shortcomings when considering scaling effects and the large blades, hubs, bedplates, and towers that will be needed to further reduce LCOE. Material innovation will be needed in the areas of low-cost carbon-fiber technologies, recyclability, thermoplastic composites, high stiffness to weight laminate and core materials, and advanced 3D printable thermosets, thermoplastics, and metallics. In addition, materials for electronic components including the generators, transformers, and power electronics will also enable improved performance and cost reductions of those components. Along with these developments, new tools and techniques for material characterization, as well as material durability analysis techniques, such as advanced crack propagation tools, will need to be developed.

The second grand challenge is in the development of cost-effective automation. For wind turbine blades, manufacturing involves significant amounts of manual labor that will need to be automated in the future to reduce LCOE. The automotive and aerospace industries have already implemented automation in their manufacturing processes to reduce costs. However, these industries have different price points driving cost, cycle times, scale, materials, and manufacturing processes that have allowed for this development. Research is needed in the field of automation and robotics regarding blade manufacturing, specifically, automation that can prepare tooling, lay down fabric and core material, assist in infusion, apply adhesive, trim, cut, drill, sand, paint, balance, and inspect a typical 100-plus-m and 20,000-plus-kg blade in a more efficient manner than human labor. There also needs to be research in advanced positioning and metrology tools such that the blade can be located at every step of the manufacturing process. All of this must be implemented at a cost consistent with a price point of approximately \$9/kg for finished composite wind turbine blades as they leave the factory—orders of magnitude less than the aerospace industry.

The third and final grand challenge is the development of the science and technology to enable on-site manufacturing of large wind turbine components. An example of this for on-site manufacture and assembly is for blades that will have to compete with the cost of advanced logistics solutions as well as potential segmented blade costs, a detailed techno-economic model will be needed to assess the costs and viability of competing production approaches. These costs, coupled with required blade cycle times and quality, will drive the innovation needed in automation, material science, additive manufacturing, smart factory design, and advanced manufacturing design tools to support on-site blade manufacturing. The challenge will be in aligning and leveraging these innovations in a creative fashion to formulate the on-site factory of the future.

3.4 Breakout Group 4: Plant Controls and Operations

In recent years, there has been a fundamental shift in research thinking from a turbine-centric view of wind energy to a plant-centric view. Rather than each turbine being controlled and operated in isolation, the overall plant is operated collectively to manage flow within the plant and overall energy production. This approach provides new opportunities to reducing future wind plant costs and enabling grid operation of the future.

Innovations To Reduce LCOE

Research into improved wind power plant controls and operations provides several avenues to reduce LCOE, which are summarized in Table 11. Methods that most directly reduce LCOE raise the total output power production, either through coordinated plant control or improvements to electrical infrastructure reducing losses. LCOE can also be reduced through mitigating costs—for example, by reducing loads and thereby O&M costs or reducing O&M through modern inspection and fault detection techniques, or reduced capital costs through inclusion of wind plant control benefits at the point of design through methods such as co-design (integrated design of turbine and plant hardware with software controls). Wind power plant design can lead to LCOE reductions as well, in terms of better optimizing the choice of wind turbine sizes, wind power plant layout, and so on. While some aspects of wind plant design are indicated in the tables and discussion, wind plant design was not a focus of this breakout group in the workshop and hence the upcoming discussion from the wind plant design perspective is cursory.

Table 11. Innovations in Plant Control and Operations To Improve Wind Power Plant LCOE

Innovation Category	Innovation	Innovation LCOE Impact
Wind Power Plant Control and Flow Control	Wind power plant controls for power maximization	• Improved AEP
	Wind power plant controls for loads reduction	• Reduced OpEx through increased reliability and longer component/turbine lifetime
	Understanding inflow conditions and acting on information	• Improved AEP • Reduced OpEx through advanced knowledge of loading conditions
Design for Control and Co-Design	Design for control and co-design, wind plant design (e.g., class 3 machines on class 1 sites)	• Improved AEP while keeping OpEx approximately the same
Deployment of Sensors for Measuring and Providing Real-Time Full-Field Flow Estimates	Increasing the sensing of the flow and developing estimation algorithms to provide real-time full-field flow estimates are expected to drastically improve wind plant control; they will also provide big data for structural health monitoring machine learning and optimization	• Improved AEP • Reduced OpEx through advanced knowledge of loading conditions
Big Data, Algorithms, and Deployments of Robots	Big data for structural health monitoring, machine learning, optimization, and predictive failure	• Reduced OpEx through increased reliability
	Real-time machine learning, adapting controls	• Reduced OpEx through better prediction of component health • Increased AEP by supporting a plant-level control strategy
	Drones/robotic O&M innovation (e.g., drones, vessels, access, and virtual reality) in-field repair	• Reduced OpEx through increased reliability and longer component/turbine lifetime

Wind power plant controls is a field of research in which the control actions of individual turbines are coordinated to improve the global wind power plant performance (Knudson et al. 2015; Boersma et al. 2017). Any level of coordinated control at the wind power plant level will require that information to be shared among turbines. Such information sharing and coordinated control can then be used to improve performance, or turbines can take control actions expecting to benefit other turbines.

One example of wind power plant control is wake steering, in which upwind turbines—that are waking downstream turbines—implement an offset angle to the wind to cause a redirection of their wake to improve the power capture downstream (Bastankah and Porte-Agel 2016; Gebraad et al. 2014; Dar et al. 2016; van Dijk et al. 2017; Fleming et al. 2014, 2016; Campagnolo et al. 2016; Howland et al. 2016). This method can improve overall power capture of existing wind power plants as well as to-be-installed farms. Other forms of wind power plant control include stationary and dynamic induction control (Munters and Meyers 2018; Annoni et al. 2015). In the former case, upstream turbines are derated so that less power is extracted from the flow, to the potential benefit of downstream machines. In the latter strategy, the induction is varied in a manner that promotes a faster recovery of the wake, which again can benefit the power capture of downstream machines.

To date, wind power plant controls research has involved open-loop set-point control, wherein the (e.g., yaw) set points for the individual turbines are determined at the wind power plant level, based on prevailing persistent wind conditions on the wind power plant. Demonstrations of these technologies in practice have been and are currently being explored in field trials (Fleming et al. 2017a, 2017b). Initial closed-loop (e.g., wake steering) control methods at the wind turbine level are currently being developed that will ultimately support closed-loop wind power plant control, and preliminary investigations of closed-loop wind power plant control have begun (Annoni et al. 2018; Raach et al. 2016, 2018; Campagnolo et al. 2016). In this case, there is feedback from a set of turbine data across the plant to improve the control in real time. Many avenues of research are still needed to bring the full vision of closed-loop wind power plant control to reality, including novel methods for sensing and estimating wind speeds across wind power plants.

For wind power plant control to realize its full potential, it is necessary to sufficiently sense the flow field on a wind power plant so that real-time estimates of the full wind power plant flow field can be computed. These estimates will allow advanced wind power plant controllers (such as model-predictive controllers) to optimize wind power plant performance metrics while ensuring that actuator and state constraints are upheld. Additional flow field measurements and estimates will also contribute to big data and machine-learning algorithms in better predicting maintenance issues.

Co-design methods attempt to capture the benefits of controls more completely, by synchronously designing turbines and plants along with their control algorithms. This bidirectional optimization can allow the benefits of control to be most effectively exploited. For example, the layout of a farm can be optimized by planning at the layout design phase to utilize wake steering (Fleming et al. 2016a). Instead of simply increasing power production, this allows wake steering to be used to enable higher power density and more cost-effective plant designs, potentially impacting LCOE in a more significant way.

As more data become available regarding wind plant operation under various atmospheric conditions and in different turbine operational regimes, machine-learning methods can be used to better predict performance and maintenance issues. Predicted problematic issues can then be addressed in a preventative manner, which can mitigate costs compared to addressing the issues after problems occur. Moreover, issues that might otherwise go unnoticed, including degradations in performance, such as yaw alignment errors or blade fowling, can be discovered.

Innovations To Increase System Value

Improved controls and operations also have critical opportunities to boost the system value of wind. This will be increasingly important as variable sources of generation come to make up a growing share of the energy production mix. Enhanced plant controls can be deployed to greatly improve the value of wind energy. Wind energy power output, within the limits of the power available in the wind, can respond to grid needs across time frames. Although wind energy today already participates in providing grid regulation services, there are numerous opportunities to raise the value of wind to the grid, and these are summarized in Table 12.

Table 12. Innovations in Plant Control and Operations To Improve Wind Power Plant System Value

Innovation Category	Innovation	System Value Impact
Provision of Ancillary Services (Not Including Storage)	Coupling of weather forecast to plant ancillary services	• Provide ancillary service support
	Wind turbines provide inertial response	
	Standardize 0-30-second wind turbine frequency reserves market structure	
	Provide probabilistic forecasts and implement them in grid operation	
	Respond to interarea oscillations	
	Black-start capabilities	
	Islanded operations	
Geographic Diversity	Global information retrieval system to enable coordinated planning across large geographic areas	• Reduced variability/uncertainty of supply
	Full wind fleet data assimilation	• Reduced variability/uncertainty of supply
Hybrid Wind System Services	Demonstrate integration of electric vehicle/wind system where significant levels of each are present	• Reduced variability/uncertainty of supply • Ancillary service support • Increased capacity value • Reduced curtailment impacts
	Coupling of electric vehicle charging and water heating, thermal storage with wind energy production	
	Integrate wind plant with solar and storage	
	Playing into smart grid	
Regional Control of Wind Plants	Regional controls for wind-intensive areas	• Reduced variability/uncertainty of supply • Ancillary service support • Increased capacity value
	Centralized control of multiple plants	

Innovation Category	Innovation	System Value Impact
	Take away individual plant ramp rate limits and base on aggregate	- Reduced curtailment impacts
	Transmission-based control	
	Aggregated distributed winds	
	All wind power plants connected via high-voltage DC lines	
	Aggregation of wind and solar PV for use of resource complementarity and optimization of electric infrastructure	

In terms of ancillary services, wind energy already provides various services to power grids, depending on regulations and markets. However, improvements in controls and especially wind power plant coordinated controls, can enable higher-quality provision of services (Fleming et al. 2016b; van Wingerden et al. 2017; Shapiro et al. 2017; Petrovic et al. 2018; Vali et al. 2018a, 2018b, 2018c). By coordinating turbine controls, the total power output of the wind power plant can be controlled very accurately. As a result, wind energy can already be shown to be an effective source of inertial and primary type responses.

One very important subject of research is the estimation of available power in the wind, now and in the future. This is a difficult quantity to estimate, because wakes make the power dependent both on the nonhomogenous wind speed and direction. However, continual improvements in monitoring and estimation enable this quantity to be more and more accurately predicted. With this improved accuracy, wind energy can effectively contribute to longer timescale grid services including automatic generation control and power reserve. The ability of wind to increase value to the grid will enable higher penetrations, as it provides its own regulation services.

Hybrid wind power plant control further increases the value of wind by coupling wind turbines in a farm with additional generators, such as solar panels, or possibly with storage, such as batteries. This coupling enhances value by allowing power to be generated when the wind is not blowing and allowing for a higher-quality power output to be produced. Research into this area, and the control of hybrid plants, can yield optimal combinations of wind, solar, and storage to maximize the complementary benefits of the individual subcomponents.

Regional power control provides the ability to coordinate wind power plants in a given geographical region. Ancillary service provision is then commanded and evaluated at this regional level. An important benefit is that regional variation in wind will reduce the impact on total power output from variations in wind in specific localities. Beyond regional control, coordinating wind power plant monitoring, forecasting, and control activities at a larger geographic, grid-wide scale can enable further benefits, including the ability to increase the predictability and controllability of wind energy, and therefore value, from the grid perspective.

R&D Challenges To Realize Innovations

During the workshop, important R&D challenges identified for wind power plant control and operations included 1) a full end-to-end accurate modeling capability from the atmosphere to the grid, 2) accurate power system models with large amounts of wind power, storage, solar energy, and flexible loads, 3) implementation of wind power plant controllers and integration with turbine controllers, 4) field trials of wind power plant controllers and conclusive studies of performance, 5) and development and release of open data sets for public research. These challenges are outlined in greater detail in Table 13.

Table 13. Plant Control and Operations R&D Grand Challenges

R&D Grand Challenges	Specific R&D Activities
Grand Challenge 1: Full End-to-End Model from the Atmosphere to the Grid	Validate model of control-flow interaction (bidirectional)
	Establish hierarchy of models for solving a variety of problems wherein the flow, grid, lifetime, and controls interconnect
	Model of interaction of turbine control and flow
	Multiscale modeling; spatial or temporal
	Engineering-level models of wind power plant control
	Models of progression from flow to structure to loads to electrical performance and vice versa
Grand Challenge 2: Power System Model with Large Amount of Wind Power, Storage, Solar, Flexible Loads	Multiscale modeling; spatial or temporal
	Simple enough, good enough, validated model
	Examine how wind interacts with storage, location of storage, and what best serves the system
	Models with wind, flow, storage, grid, and solar
Grand Challenge 3: Implementation of Wind Power Plant Controllers and Integration With Turbine Controllers **(Including Field Trials and Validation)**	Determine how to best implement control strategies, such as wake steering and power reserve
	Investigate how to best estimate current conditions (e.g., speed, direction, atmospheric stability, available power, turbine issues)
	Study how to implement controls of hybrid plants (+ solar, + storage)
	Determine what sensing is required to implement various types of wind power plant control as well as what would be the value of new advanced sensing to control, such as from direct measurement of the atmosphere through remote-sensing technologies like lidar and radar

R&D Grand Challenges	Specific R&D Activities
	Conduct repeated and public trials of wind power plant controls concepts to build confidence and validate benefits
	Perform coordinated trials with utilities to demonstrate new grid support functionality
Grand Challenge 4: Creation of Open Data Sets for Use in Open Research	Establish the institutes, facilities collaborations, and database architecture necessary for collecting, storing, and distributing large open data sets for research purposes

To realize the innovations described earlier, it is critical to have the ability to fully model wind power plant operation from atmospheric flow that provides the input to wind power plants and determines how the flow interacts with wind turbines throughout a plant. It is also critical to understand how the power produced by a wind power plant is injected into and distributed throughout the grid. Further, how wind power plants impact the atmospheric flow and how nearby wind power plants interact (especially at the electric grid level), are important areas of research. Similarly, power grid effects can influence the power demanded by transmission system operators on wind power plants. A comprehensive modeling tool that incorporates all of these capabilities will help all parties fully understand how changes in one part of the system can affect other portions, and only such a model can enable full system co-design and optimization. A full "end-to-end" model enables comparable research and detailed analysis of the impacts of advances in wind energy control on the power system.

Design of wind power plant controls and the methods by which they are integrated both with wind turbine and grid control activities, is an important topic of research. Although there has already been a large number of studies to look at various aspects of wind power plant control (including wake steering, induction control, and controls for grid services), there is still a long way to go to fully realizing the potential of these innovations. As the understanding of the physics and the ability to model the full end-to-end system advances, research into and the development of novel control strategies will be needed. In addition, field trials of wind power plant controls, with conclusive analysis, will be necessary to validate models and demonstrate that these technologies 1) will deliver the promised benefits, and 2) will do so without unacceptable risk in terms of adverse impacts to plant performance, reliability, and cost.

Further, there is a need to develop more publicly available data resources for wind power plants that can be used by the wind research community to validate models and test hypotheses. Comprehensive, high-quality, fully open data sets can provide a dramatic acceleration to R&D efforts and to achieving a basic scientific understanding.

Other examples of R&D challenges not included as grand challenges include a mapping/coupling of the effect of wind provision of grid services to the lifetime of turbines, which could be used in cost-benefit analysis. Additionally, a financial analysis of the benefit (beyond LCOE-only analysis) would be helpful in determining what should become best practice.

Research into how controls might be used to extend the lifetime of turbines (for example, to 40 years), could have a substantial impact on LCOE. Also, there is value in research that assesses the relative merits of long-life design for turbines, versus expected repowering as turbine technology advances and the role that controls can play in both cases. Finally, research into advanced electrical components for wind can yield benefits in cost, reliability, and robustness.

3.5 Breakout Group 5: Grid Integration

The perspective of grid integration is critical to the future scenario in which renewable energy sources provide 80% or more of the global electricity generation, with wind energy providing at least 50%. Although innovations to reduce LCOE are still needed to maintain and increase competitiveness of wind energy with other electricity generation technologies, the value to the electric system from wind energy is critical to realizing the Grand Vision. Within the grid integration breakout group, the participants looked at the innovations that would be necessary both from wind turbines and plants but also other key features of the electricity system that would be needed to realize the Grand Vision. The group then identified key R&D challenges that would need to be addressed to support the development of the needed innovations.

Innovations To Increase System Value

The grid integration perspective focused on operation of an electricity system with over 50% electricity generation coming from wind energy at different timescales. Many of the identified innovations focused on support of electricity system reliability through the ability to provide short-term services to the grid. Others focused on power system operations for providing low-cost and reliable energy to match supply and demand over the course of the day, and throughout the weeks, months, and years. Table 14 summarizes the innovations identified by the breakout group to improve overall system value from wind energy to the electric system.

Table 14. Innovations in Grid Integration To Improve Wind Power Plant System Value

Innovation Category	Innovation	System Value Impact
Wind Turbines and Power Plants	Power electronics adapted to provide grid-forming converter capabilities (including black start) and controls for islanded/weak grid operation	• Support for ancillary services and stability
	High capacity factor/oversized wind turbines with lower specific power wind turbines, overplanting/overbuilding (number of turbines)	• Increased capacity value • Increased energy value • Reduced variability/ uncertainty of supply • Reduced need for grid infrastructure (more energy per unit of transmission capacity)
	Provide ancillary services, such as regulation, primary frequency response, inertia support (at plant level), and improved fault-ride-through capabilities	• Grid support through ancillary services provision • Reduced amount of “must run” thermal units

Innovation Category	Innovation	System Value Impact
	Turbine and plant state estimation/accurate estimation of capacity for providing services (e.g., available power) over different time periods (e.g., minutes, hours) (e.g., data, sensors)	• Support for ancillary services • Reduced variability/ uncertainty of supply
	Geographically disperse plant locations	• Reduced variability/ uncertainty of supply • Increased capacity value • Increased energy value
	Plant-level optimization and control	• Support for ancillary services • Reduced variability/ uncertainty of supply
	Optimal use of storage in wind power plants/hybrid power plants	• Support for ancillary services • Reduced variability/ uncertainty of supply • Increased capacity value • Increased energy value
Converter-Dominated System and Power Electronics	Control interactions between converters	• Reduced curtailment impacts • Support for ancillary services
	Improve efficiency converters	• Reduced system losses
	Accurate measurement and control of harmonics	• Reduced system losses • Improved system reliability
	Control of electrical resonances/small-signal oscillations	• Improved system stability
	Improve reliability of power electronics	• Improve system availability
	High-voltage DC (HVDC) transmission and control of HVDC systems also with DC/DC converters	• Increase transmission efficiency and system economics
	DC grid for collection grid with DC/DC converters	• Increase local transmission efficiency
Transmission	High-temperature conductors	• Improved utilization of transmission assets • Improved siting ability • Reduced cost of transmission
	Flow control through flexible AC transmission systems	
	Low-cost, high-capacity underground transmission	
Storage on Multiple Time Frames	Short-term storage for frequency control (seconds)	• Reduced variability/ uncertainty of supply • Support for ancillary services • Increased capacity value • Increased energy value • Reduced curtailment impacts • Reduction in need for thermal units on line • Reduced emissions from fossil fuels • Dispatchable wind power
	Hours of storage	
	Smoothing power (diurnal)	
	Seasonal storage	

Wind Power Plant Innovations

Reducing variability and uncertainty of supply can be accomplished through improved forecasting and wind turbine/plant state estimation (see Section 3.1 on atmospheric science and forecasting for more in-depth discussion of this topic). Reduced variability and uncertainty of energy supply is important for system operation at timescales of seconds, to minutes and days, or longer. Advances in turbine state estimation (accurate estimation of capacity for providing services) will be critical for wind power plants to provide ancillary services and grid-forming capability in the converter-dominated system. Accurate estimation of overall wind power plant availability and expected output will be made possible through advances in forecasting, wind plant controls, and operation and maintenance technologies and strategies (see previous sections for discussions of these different technology areas).

Perhaps the most critical capability required for wind power plants to become the backbone of the electricity grid is the ability to provide grid-forming services. Though wind power plants already supply grid services of various types in many markets, they typically use information from the electric grid (i.e., measurements of grid voltage and frequency) as input to their control systems. Synchronous generation, from thermal, nuclear, or hydropower plants, provide the services that “form” the electric grid in terms of its voltage and frequency characteristics. This capability for synchronous machines is tied closely to their physical inertia (being massive rotating mechanical machines) and a controllable voltage behind a reactance which together provide a voltage magnitude and frequency reference for the entire interconnected system. Wind power plants do not have physical inertia in the same sense that traditional power plants do, but with the power electronic control inherent in many turbines (those with doubly-fed induction generators or fully rated converter systems), the wind plants are able to provide “synthetic inertia” and act as “virtual synchronous generators” in the system (Ackermann et al. 2017). In this paradigm, wind power plants of the future are expected to provide grid-forming capabilities and provide a voltage and frequency reference for the remainder of the system.

By developing wind power plants with further grid support functionalities (e.g., grid forming) they will be able to serve as the backbone of the future converter-dominated electricity system on a large scale and provide support for weak grids (with low amounts of synchronous generation), smaller grid systems, cells, or microgrids in normal and islanded (with the loss of the support from a larger grid system) operation.

Closely tied to innovation around the grid-forming capability of wind farm and plant power electronics is the improved capability to provide a large range of ancillary services to the system operator to support overall system reliability. These services include reactive power control and voltage regulation, active power control and various forms of frequency control, as well as the ability to ride through various faults on the larger electric system (Ackermann et al. 2017; Kroposki et al. 2017) and black-start capability. Although wind power plants are already able to provide some of these services today, more development is needed to advance and improve the capabilities. While wind power plants may not need to provide all of these services in the future grid system, were they able to do so (and do so economically), this would certainly encourage more global deployment of wind energy.

Beyond innovations related to the wind turbine and plant power electronics and their control are innovations related to the physical design of the turbines and plants. There is a need to reduce the variability and uncertainty associated with the supply of electricity from wind power plants at any given time. One mechanism to reduce the variability and uncertainty is to oversize the turbines or the overall wind power plant. In the former case, shifting to low-specific-power machines essentially shifts the power curve of wind turbines to the left (to lower wind speeds) so that wind turbines are producing more energy for a higher percentage of the time for a given site and wind resource, which leads to a higher overall capacity factor for the site and potentially higher capacity value (Wiser and Bolinger 2018).

In the latter case, "overplanting" is where the rated power of the plant is less than the sum of the rated power of all the turbines in the plant, or the transmission limit to the site. This is analogous to having higher inverter loading ratios in solar PV plants where the DC/AC ratio is much larger than 1. This will increase the usage of existing transmission, provide more megawatt-hours from wind power plants for each megawatt of transmission available, and thus reduce build-out and cost of transmission. Coupling either of these approaches with plant-level optimization and control would allow turbines to provide more reliable and on-demand electricity because some or many of the turbines in the plant could be operated in a "derated" state (i.e., at less than their rated power). Through coordination of turbine power output at the full plant level, wind power plants are also able to provide the various ancillary services as previously described—voltage regulation and frequency control as well (Kroposki et al. 2017; Milligan et al. 2015). The future wind power plant contains a collection of highly controllable turbines for coordinated control of energy supply and ancillary services at all timescales of interest (Kroposki et al. 2017; Milligan et al. 2015).

Moving beyond individual plants, various studies have shown how geographic diversity in location of wind power plants can smooth out variability associated with wind electricity production in a bulk electricity system (Kempton et al. 2010; Grams et al. 2017). Spreading out wind power plants may not be optimal from an individual operator's perspective—in which one tends to seek the highest wind resource sites for maximum energy production; however, from a system operator's perspective, locating plants in geographically distinct wind regimes provides more reliable overall generation both from land-based systems (for example, spreading plants north and south in Europe (Grams et al. 2017) or across the continent east to west in the United States) and from offshore systems (for example, spreading plants along the full eastern or western seaboard of the United States [Kempton et al. 2010]).

Another mechanism for reducing wind power plant variability and uncertainty of energy supply, increasing capacity value, and increasing their capability for providing ancillary services is through the development of hybrid power plants including wind, storage, and other technologies (i.e., solar PV). On the one hand, wind and solar in many locations have inversely correlated diurnal cycles (i.e., in many locations wind is typically strongest at night and solar only operates during the day, so that having more wind energy and solar together can complement and smooth out their variability [Seel et al. 2018]). On the other hand, cost of storage technology is rapidly falling and can assist both wind and solar in mitigating the variability and uncertainty of those assets (IRENA 2017a). By combining generation assets together, including storage, solar, and wind, into "hybrid power plants," an individual plant owner can 1) develop economies of scale in terms of land usage, electrical and physical infrastructure, and operational expenditures, and 2) increase their system value to capitalize on revenue streams available through forward capacity markets (where present), "dispatchable" operation in peak energy pricing periods, and ancillary service markets (where present). However, hybrid power plants might also have higher costs and their overall profitability must be considered with the various revenue stream opportunities balancing those additional costs.

Power Electronics, Transmission, and Storage Innovations

Traditional AC overhead lines with high voltages, typical 400-500 kilovolts, are used for bulk power transmission on land. For subsea connections and certain land-based applications, DC systems are used because of the reactive power limitations associated with using AC cables for long-distance power transmission. The AC cables produce reactive power themselves and thus reduce their capacity to transmit useful active power. In the past, interfacing DC systems with the bulk AC system relied on older technology (e.g., thyristor converters for transforming AC to DC current) and required connection to a strong AC grid for proper control. Newer converter technology uses transistors and can provide grid-forming functionality. The losses of these systems have also been reduced and there are still possibilities to reduce them further. With the achievements in power electronic development and the control of power flow, it is possible to have a future converter-dominated electric system. These innovations in technologies beyond the wind power plants themselves are important for a power system with a large share of renewable generation.

In a converter-based system, the power flow is controlled by the converters. Extensive simulations and good models are essential components in avoiding control interactions between converters and achieving stable operation of the system (Yunus 2017; Max 2009). The converters in a wind turbine as well as in a DC transmission system have to be designed to withstand the electric constraints and the control has to be tuned in a way to avoid instabilities/resonances between the wind converters and the power system. One example of this is the instability caused by subsynchronous resonance conditions in large wind power plants connected to series-compensated transmission lines (Chernet 2018). Power electronics enable the accurate control of the torque in the drivetrain and variable-speed operation of the turbine, while also damping mechanical oscillations to avoid resonances in the drivetrain and with the grid. Power electronics also enable the low loss and fast control advantages of DC technology.

In offshore wind, as well as some instances of land-based wind, the power produced by wind power plants must be transmitted over long distances to a suitable grid connection point. Cables quickly become the preferred option for transporting the energy from wind installations to suitable main grid infeed points. The use of HVDC transmission facilitates the connection of the wind power plant to weak grids. DC is already used to transport power from remote wind power plants in the North Sea to grid systems in Northern Europe, and the next natural step is to introduce DC in wind power plant collection grids as well as to a bulk DC transmission system.

A major question that must be addressed in designing DC-DC converters for offshore DC grids is to determine the optimal layout of future grids in terms of using radial connections, meshed grids, or hybrid grids based on the different converter technologies, considering the components and corresponding functionalities that are needed for proper and secure operation and control of the offshore grid. In addition, the use of energy storage systems should be better coordinated with the introduction of DC technology. This can be important when integrating wind power in very weak grids (as is currently the case in many projects in China), but also to provide black-start capabilities to the wind power plant. Today, a wind power plant typically relies on its connection to the larger system for start-up and aligning its active and reactive power output.

The losses in the transmission system decrease with higher voltage for a given power transmission level, and correspondingly, the current decreases. The development of ultrahigh-voltage transmission for long-distance bulk power transportation is of great interest but the challenges for realizing such technology are in the insulation systems. Because of the environmental impact of the overhead transmission power lines, it is preferable to create a low-cost, high-capacity, underground transmission system. Especially with the future development of the DC transmission system, this is a realistic development. A future collection and transmission grid of wind power plants would likely include a meshed DC grid for connection of wind power plants as well as for the transmission between different parts of a large AC system or between different synchronous AC systems.

Finally, the ability to store wind power over both short and long time frames will enable wind to be a fully dispatchable power source. Innovation in storage technology, especially for short-term applications, has accelerated in recent years and created a new dialogue around the potential for a renewables-dominated electricity system. Energy storage is a topic with a large scope and deserving of its own visioning study, so it will not be discussed in depth here. Lazard's 2017 study on the levelized cost of various storage technologies provides a more complete overview of storage potential and costs for different time frames of interest (from very short-term grid services to seasonal storage to support of long-term variability in wind and/or solar assets) (Lazard 2017). In particular, seasonal storage is important to very large shares of wind energy in the system and this is an area where significant research breakthroughs are still needed.

R&D Challenges To Realize Innovations

Most of the identified R&D challenges for grid integration of wind power plants involve providing more support to the grid and supporting the paradigm shift to the converter-dominated electric grid with very low levels of traditional synchronous generation and high levels of variable generation including wind and solar energy. Grand challenges for grid integration of wind energy include the need to develop the fundamentals for the converter-dominated electric system, the controls capability for the converters themselves, the ability to accurately model the converter-dominated grid system across all relevant spatial and temporal scales, and integration of data and physical models for intelligent wind power plant operation in converter-dominated systems. Table 15 summarizes these challenges.

Table 15. Grid Integration R&D Grand Challenges

R&D Grand Challenges	Specific R&D Activities
Grand Challenge 1: Develop Fundamentals and Paradigm Design of a Converter-Dominated System	Develop a new generation of power system analysis and design tools Develop accurate models of the grid-forming converters for all operating conditions
Grand Challenge 2: Control of Converters with Grid-Forming Capability in a Converter-Dominated System	Coordinate and control multiple grid-forming wind turbine converters in a single plant
	Coordinate and control multiple grid-forming wind plants
	Establish protection aspects of converter-dominated systems
Grand Challenge 3: Multiscale Modeling Across an Entire Grid System with Accurate Modeling of Converters in a Converter-Dominated System	Model the new grid, including multiple wind plants with grid-forming converters embedded in AC systems (bridge scales of slow AC and fast dynamic systems)
Grand Challenge 4: Intelligent Wind Power Plant with Integrated Data and Modeling for Active Power System Operation and Support	Combine data and modeling approaches for state estimation and accurate performance prediction (flow and electrical)

The first challenge around fundamentals and design of converter-dominated systems involves developing accurate models for converters under all operating conditions at all timescales. Models and simulations of power system operation under the new paradigm of the converter-dominated system are needed to confidence to system operators that system reliability can be maintained under all future operating conditions.

The second R&D challenge is related to the converter capabilities themselves to ensure that they can provide the services required to support the electric system stability and reliability. Kroposki et al. (2017) speaks to the potential of wind power plants to provide support for system inertia, active power control, reactive power/voltage control, and fault ride-through. Although existing wind power plants are already capable of providing these services, there is a significant amount of work required to fully develop the power electronics and controls. In the future, the converters must provide the full grid-forming capability while simultaneously providing the full range of ancillary services to attain the necessary system stability and reliability. This is especially true at the full wind power plant level.

Having developed the needed hardware, controls, and associated converter models, significant work still needs to be done to integrate all the relevant models together for a complete and accurate multiscale model of the converter-dominated electric grid. This work will involve bringing models of wind power plants capable of accurately modeling the flow and electric performance of the power plant at a wide range of time intervals and all of the services provided not just at a single power plant level but across many plants for full system operation and analysis. In many ways, this R&D effort is the culmination of research conducted across a number of domains in wind energy for developing validated models of wind turbines, their components (especially power electronics), plant level flow and control, and grid interaction and system operation—thus building on R&D challenges identified in the preceding breakout sessions.

Finally, future R&D in grid integration of wind energy will, like other wind R&D areas, start to incorporate more data science and integrated data and modeling approaches to create more intelligent wind power plants and electric power systems of the future. The significant complexity of wind energy systems and the larger electric systems with the range of spatial and temporal scales means that modeling the system purely with physics-based models will be challenging. As with the weather itself, there will always be aleatoric uncertainty affecting the system behavior and epistemic uncertainty relating to model validity. On the data side, again because of the sheer size and range of spatial and temporal scales involved, it is unlikely that a pure data approach will ever be capable of accurately representing either wind power plants or the larger electric system. Going forward, combined approaches leveraging data and modeling (e.g., as currently done in wind power plant forecasting applications) will be used to enable intelligent wind power plants of the future providing support at all necessary timescales to the converter-dominated grid.

Beyond the grand challenges identified by the group, several other challenges exist including the need for advancing optimization research for large-scale problems involving system topology and infrastructure both for system design as well as control and operations. Optimizing the design and operation of the electric grid system of the future will push beyond our current capabilities in terms of methodologies and computing resources and will be critical for supporting the R&D described earlier. Significant research for optimization of power system design and operation is available for current systems (Zheng et al. 2015; Molzhan et al. 2017; Cole et al. 2017; IRENA 2017b; Pietzcker 2017; Holttinen 2018; IEA Wind 2018; Helistö et al. forthcoming,) but will need to be adapted for the future electric system. Another area of interest for future R&D includes the development of advanced materials for power electronics applications.

Market Design as a Techno-Economic Grand Challenge

One additional area that represents a grand challenge that goes beyond the purely technical is the market design of renewable energy and converter-dominated electric systems. Up to the present day, most electricity markets focused on energy as the main stream of revenue for generation assets with secondary opportunities associated with capacity value and system services. As mentioned in the discussion of the future electricity system, with more and more renewable energy resources on the grid, we are already seeing downward pressure on electricity prices and a need to develop and expand the markets for capacity value and system services to ensure grid reliability over all timescales (Ahlstrom et al. 2015). The market design has a direct influence on system operation. Therefore, research on modeling and analysis of the design, control, and operation of future wind power plants and the converter-dominated system must go together with research on market design that will involve additional dimensions of economics and policy research.

3.6 Breakout Group 6: Offshore-Specific Technologies

Offshore wind energy has experienced remarkable growth over the last two decades, with 16.3 gigawatts installed capacity in 2017, but there is reason to anticipate substantial advancement over the next several decades as well (WindEurope 2017; Beiter et al. 2017b). Some of this advancement will be in the form of evolutionary refinement of existing technology (InnoEnergy 2017). In other cases, there are some grand challenges that will require significant innovation and associated R&D efforts (ETIP Wind 2016; van Kuik et al. 2016). To provide some context for considering these challenges, we first provide a summary of current offshore wind energy technology.

Offshore wind turbines are conceptually divided into two main subsystems: the rotor nacelle assembly (RNA) and the support structure. The RNA incorporates the blades, hub, rotating machinery, and most of the ancillary equipment. The support structure includes the tower, substructure, and (for fixed-bottom turbines) foundation. For floating offshore wind turbines, a floating substructure is used and held in place by a station-keeping system consisting of mooring lines or tendons and anchors. Fixed-bottom turbines are normally located in water depths of less than 60 m, whereas emerging floating offshore turbines are located in waters deeper than this. Currently, there are some technical challenges in mooring floating offshore in shallow waters (e.g., 60 m–90 m) but technology solutions are expected as the designs mature, and it is likely that future floating turbines will be able to access shallower waters without significant additional cost. Through this type of continued innovation, the cost of floating wind is anticipated to reach levels on par with (or lower than) fixed-bottom systems.

In principle, the concept of offshore wind is simple: take existing wind turbines, designed for use on land, and place them on support structures in the ocean and connect them electrically via submarine cables to a suitable land-based electrical grid. However, the situation is more complicated for a number of reasons. First, offshore wind support structures are massive and more complex than land-based towers and foundations; they have more in common with structures used by the offshore oil and gas industry than they do with land-based systems. Second, the marine infrastructure required to install, deliver power from, and operate offshore wind turbines and plants is expensive—as lifting capacities and port facilities need to be adapted for offshore wind energy applications. Because of the cost of deploying and operating offshore wind turbines are high, benefits of increased scale are greater. Through increased turbine and power plant size, the offshore wind industry has been able to make significant reductions in cost of energy, and this trend is likely to continue.

The expectation for continued scaling of offshore wind turbines, together with the need to improve design, manufacturing, and operation for harsh environmental conditions offshore, form the basis of the innovation and research challenges that must be overcome (Jamieson 2011). Although much of the experience with land-based wind energy is applicable offshore, there are significant differences as well.

Innovations To Reduce LCOE

Although LCOE for offshore wind energy has fallen significantly in the last several years, there is still potential for further cost reductions in the future. Some of the innovations that will create those reductions will be applicable to all offshore systems, including both fixed-bottom and floating designs; however, other reductions will be specific to certain design types.

For both fixed-bottom and floating technology, innovations in turbine and plant controls as well as operational strategies are expected. In addition, improved design criteria for site-specific environmental conditions will lead to offshore wind energy cost reductions. Finally, integrated design approaches that couple the turbine and support structure to full plant design will likely benefit both floating and fixed-bottom technologies (but will likely benefit floating wind systems more).

Floating wind systems are presently costlier than fixed-bottom designs and have some specific focus areas that could improve LCOE. These areas include the industrialization of floating wind energy technology, use of novel materials, component innovations, novel support structure designs, and completely new technology configurations that could lead to step changes in offshore wind LCOE. Table 16 provides a review of major innovation categories that will reduce offshore wind energy LCOE as well as specific innovations and their LCOE impacts.

Table 16. Innovations in Offshore Wind Energy Technology To Improve Wind Power Plant LCOE

Innovation Category	Innovation	LCOE Impact
Improvement of Manufacturing and Installation Process	Floating substructures manufactured with standardized, modular components	• Reduced CapEx through economies of scale • Reduced OpEx through increased reliability
	Large-scale manufacturing for technology learning offshore	• Reduced CapEx through learning
	Systems that can be installed with limited labor at sea (self-erecting)	• Reduced CapEx through less costly installation
	Alternative installation techniques for fixed-bottom systems	• Reduced CapEx through less costly design
Innovative Technology Development	Novel turbine concepts (downwind, two-bladed, vertical-axis wind turbine, airborne, superconducting, direct drive)	• Various impacts in AEP, CapEx, and OpEx depending on technology
	Support structure design innovations that capitalize on rapid evolution of supply chains	• Reductions in CapEx
	Novel tower designs (including lightweight, soft designs)	• Reductions in CapEx
	Novel materials for support structure (e.g., to limit corrosion, increased local content, use of composites)	• Reductions in OpEx through increased reliability • Reduced CapEx
	Novel mooring designs and materials (including shared moorings)	• Reductions in CapEx
	Hurricane-resilient turbines to open new markets	• Reductions in OpEx through increased reliability

Innovation Category	Innovation	LCOE Impact
Novel Design Approaches	Systems engineering design and optimization (full plant components including lifecycle costs, system-level costs, environmental impact)	- Reduced CapEx in all major components - Reduced OpEx through optimized maintenance
Improved Design Criteria Including Site Suitability	Class-based designs with site-suitability assessment (including higher-strength designs for tropical storms)	- Reduced OpEx through increased reliability - Reduced CapEx through mass production
	Probabilistic (reliability-based) design to reduce conservative design assumptions (e.g., safety factors)	- Reduced CapEx through optimized designs - Reduced OpEx by derisking
	Better wind characterization to enable hurricane-resilient design (needed in some locations, but not others)	- Reduced OpEx through increased reliability - Reduced CapEx through designs optimized for location
	Better assessment and modeling of soil/foundation interaction	- Reduced CapEx through better optimized designs
Smart O&M Practices	Increased reliability and smarter, more predictive O&M practices (condition monitoring, life extension, robots for inspection, access, ability to do quayside maintenance)	- Reduced OpEx through increased reliability and longer component/turbine lifetime
Advanced Control Strategies to Lower Loads and Increase Performance	Advanced control strategies (e.g., for floating wind systems) at the turbine and farm level (including new actuators)	- Increased AEP and reduced OpEx

Floating systems are in a precommercial stage but have the potential to be more cost effective than fixed-bottom systems in the long term (Beiter et al. 2017a; James and Ros 2015). To achieve this, the manufacturing and installation process for floating wind systems needs to be industrialized (i.e., developments are needed to enable, streamline, and standardize manufacturing of floating units and provide efficient installation protocols). For tension leg platforms and spars especially, the substructure cost is typically smaller than a fixed-bottom substructure in very deep water, and finding cost-effective installation and O&M strategies will be key to making these design approaches commercially viable. Costs could be further reduced by using commercially available components, which benefit from high-volume manufacturing. Ultimately, it may be possible to mass produce floating turbines for multiple farms and use simple tow-out procedures for both installation and maintenance, requiring minimal expensive effort spent on at-sea work (e.g., expensive offshore cranes). Fixed-bottom offshore wind turbines are already commercialized, but there is still opportunity for reducing their cost. In particular, the installation phase is an area of ongoing innovation (Sarker and Faiz 2017), with a focus on new piling and alternative installation technologies that avoid transition-piece-related reliability issues, while at the same time reducing environmental impact.

Currently, offshore wind turbines resemble land-based turbines in that they typically use horizontal-axis, three-bladed, upwind rotors on tubular towers, but have generally addressed the added necessity for corrosion resistance. Further, many have implemented more robust methods of remote health monitoring. Two of the most significant trends that differentiate offshore turbines from land-based wind turbines are their larger size and drivetrain architectures that deviate from conventional modular gearbox designs. Offshore turbines do not have the same transportation- and installation-driven size limitations as land-based wind turbines. Hence, the offshore nameplate rating has grown beyond 8 MW, with rotors as big as 164 m in diameter—more than twice the size of most land-based turbines. They also differ from land-based turbines in their drivetrain configurations, especially the use of direct-drive generators or single-stage geared drivetrains with medium-speed generators. These drivetrain configurations have fewer moving parts and promise lower maintenance costs, with the drawback of generally being slightly heavier upfront than traditional modular gearboxes.

One exception to the conventional upwind turbine is Hitachi’s 2-MW and 5-MW downwind turbine series, deployed successfully on proof-of-concept floating offshore projects in Japan. Developing downwind turbines at the same scale as upwind machines for offshore applications is a technology improvement that could lower cost and reduce turbine weight by relaxing the blade stiffness required to avoid tower strikes, allow for wake steering options at the plant level, and reduce demand on yaw drives (Ning and Petch 2016; Loth et al. 2017). Especially for floating offshore wind turbines, reducing top weight can have significant potential for reducing cost due to the lower buoyancy/size requirement. For this reason, two-bladed wind turbines could have an advantage in an offshore market. In addition, a two-bladed rotor would operate at higher tip speeds with lower solidity, which would reduce exposure to extreme wind loading and lower drivetrain torque, and therefore drivetrain mass.

Much of the nacelle weight in offshore wind turbines can be attributed to the drivetrain. Although it may be possible to substitute some of the static components with lightweight (e.g., composite) materials, the heavy direct-drive generator may be a greater challenge. New technologies, such as superconducting permanent magnets or pseudo-direct-drive generators (Liu et al. 2017) are being considered as a possible weight-reduction pathway for direct-drive generators.

For the towers, alternative configurations may be sought in the future, including lattice towers, prestressed concrete towers (e.g., steel and fiber reinforced), and composite towers to reduce mass and facilitate fabrication, both above and below the waterline. More expensive glass-fiber-reinforced polymer towers have also been proposed, as they promise lighter system weights with net positive advantages for overall cost (Young 2017).

As floating wind designs increase in size, the mooring lines and layouts will also need to increase in size. For catenary approaches, the increased diameter chains run the risk of exceeding market availability, and also the capabilities of anchor-handling vessels, whereas the larger layouts may lead to increased environmental impact. For these reasons, synthetic moorings are being investigated, in conjunction with semitaut configurations. Finally, substructure designs that consider the ability to achieve mass production and installation will be key components in driving down the costs of the entire floating wind system. Hybrid approaches, such as gravity anchors or components that can change ballasting levels between tow-out and installation, are some ideas that can lower substructure weight and cost while reducing expensive labor at sea. As turbine size increases, there will also be a need to limit the size of the substructure to enable manufacturing in a wide variety of ports, as well as the ability to store completed components prior to installation.

An integrated, system-level “cradle to grave” design and optimization approach will be needed, which will consider all aspects of the plant, from environmental impact through manufacturing, deployment, and operation, to repowering and then recycling or disposing of those items that have been replaced. Through the application of the developed systems engineering tools, innovative design concepts can be evaluated and optimized to identify the most cost-optimal design solutions. Because of the coupled nature of floating systems, optimal solutions will require a combination of innovative components that best work together to achieve system-level cost reduction. As noted earlier, this could include novel turbine concepts, such as downwind and two-bladed rotors, as well as the use of novel materials that will lower system weight, that may have unique advantages offshore. Advanced control approaches will also be critical for reducing loading and optimizing power production for large, flexible, and floating systems, both at the turbine and farm level. And increased reliability and advanced O&M practices are needed to reduce costly work at sea. Improved understanding of wind conditions at the rotor height and the associated design criteria will be needed to address unique conditions in offshore regions, including hurricanes or other extreme events.

Reducing uncertainties is expected to lead to significant cost reductions when combined with a probabilistic, reliability-based design of support structures (Jiang et al. 2017). Computer-aided structural optimization can facilitate support structure design (Chew 2016; Oest 2016), but is still at the precommercial stage. For floating systems, a class-based approach similar to the methodology used for land-based turbines might enable cost reductions through high-volume production. Classes could be based not only on the wind characteristics but include wave conditions as well. Site-suitability assessment would still need to be performed but could lead to the development of classed designs that are applicable to many regions. Hurricane-prone regions will need to be addressed, perhaps even through a special class, if the conditions fall outside the developed classes considering that the mean wind speed, 3-second gusts, gust factors, and shifts in wind direction can exceed the current design criteria for International Electrotechnical Commission (IEC) 61400-1 (2005) standard Class IA wind turbines. A new IEC Class T (typhoon) has been proposed that calls for a higher reference wind speed. Although this criterion may suffice to render turbines “hurricane reliable,” it is not clear whether the reliability level achieved would suffice for all hurricane categories, whether the wind conditions are representative of the actual physics, and whether this is harmonized with the level achieved by American-Petroleum-Institute-derived methods for the substructures. Work is needed to delineate the offshore regions of the United States where present standards are applicable and new approaches are needed. Additional topics are important for derisking fixed-bottom wind turbines, including achieving a better understanding of extreme loads and with the uncertainties in soil properties and foundation behavior under long-term cyclic loading (Kallehave et al. 2015), including changes in the properties during its lifetime (e.g., erosion, farm-level sand waves, and liquefaction).

Important for both fixed and floating systems is the development of O&M procedures that are smarter, requiring less work at sea, and the development of designs that better facilitate cost-cutting O&M strategies. This includes feedback from optimizing maintenance and inspection regimes into the design process to achieve material savings while guaranteeing the structural reliability over the wind farm lifetime (Ambühl and Sørensen 2017). Some substructure concepts allow for disconnecting the platform from its moorings and towing it back to a harbor, which may be a safer and cheaper alternative for major component replacement. Alternatively, vessel arrangements suitable for main component replacement that minimize the relative movements of the turbine, vessel, and crane must be devised. This is an example of incorporating innovative O&M strategies into the engineering design of the turbine.

On the operational side, advanced wind turbine control methods are being developed to reduce wake effects on neighboring turbines, thereby increasing the total energy yield of the whole wind power plant, in addition to reducing turbine loads. Fleming et al. (2016a) showed that wake steering could be used to achieve tighter turbine density without sacrificing plant AEP, than would otherwise have been possible for fixed-bottom turbines. The ability to control the yaw or tilt of a turbine, thereby steering the wake away from downstream turbines, can be leveraged for intelligent control of the entire plant. In fact, wake-steering and plant-level control strategies can improve plant AEP by as much as 7.6% (Fleming et al. 2016b). This finding has not yet been verified for floating systems. In a floating turbine, there is an extra degree of freedom that allows passive platform yaw motion that is not under the surveillance of the active yaw system. Therefore, new yaw control strategies may be needed. Wake steering may have possible applications in floating systems, but the implementation and benefits may not be the same.

Innovations To Increase System Value

Cost reduction provides an intrinsic impetus to having large offshore wind plants. Accordingly, the relatively large electrical output needs to be brought ashore with a minimal number of high-capacity submarine cables and connected to the grid at a point with enough transmission capacity to accept that power. As more offshore wind plants are constructed, the integration of these plants into the overall energy system becomes progressively more difficult. As renewable energy achieves larger and larger shares of overall electricity generation, offshore wind plants will also need to supply services to the grid on par with conventional power plants (Hennig et al. 2014; Kakorin et al. 2014). Table 17 points to some key innovations that will allow offshore wind energy to provide better support to the future electricity system.

Table 17. Innovations in Offshore Wind Energy Technology To Improve Wind Power Plant System Value

Innovation Category	Innovation	System Value Impact
Offshore Electrical Infrastructure	Offshore electrical infrastructure innovations (superconducting, HVDC, super subsea grids)	• Increased capacity value • Increased reliability
Storage and Grid Services	Power to X: energy storage (compressed air) or fuel production (hydrogen, ammonia) and how to address wind-powered desalination	• Support for electrification • Reduced variability/uncertainty of supply • Support for ancillary services • Increased capacity value
	Large-scale coordinated control (interfarm control for storage and grid services)	• Reduced variability/uncertainty of supply • Support for ancillary services • Increased capacity value
Novel Approaches To Extract Energy Beyond Traditional Paradigm	Ability to move to where resource is optimal (floating and/or airborne)	• Reduced variability/uncertainty of supply • Support for ancillary services • Increased capacity value • Storm avoidance
	Dynamically moored systems and turbine control actuation to move systems (not just flow) to control plant power output	• Reduced variability/uncertainty of supply
Wind Forecasting	Better methods for predicting hourly and diurnal energy production through better understanding of meteorological-ocean conditions	• Reduced variability/uncertainty of supply • Realized synergies with other variable sources • Reduced uncertainty in system design and optimized reserve strength • Increased capacity value

Integrating wind plant and power system designs, previously decoupled in most land-based wind systems, can provide new cost savings and more efficient and reliable power system operation. Offshore wind is anticipated to require new transmission infrastructure development and therefore the opportunity to take advantage of recent innovations in power systems including recent advances in power electronics, active power control for wind turbines, energy storage integration, and HVDC or superconducting transmission systems. In addition, new infrastructure means the possibility of synergizing with other applications with similar needs to share in the cost. Industries, such as oil and gas, fishing, or even transportation, could better enable offshore wind commercialization while adding positive regional economic value. Finally, one of the motivating factors for offshore wind is the proximity of the resource to high-load regions. Understanding within the grid infrastructure how to best take advantage of colocation can also be important to maximizing the value of offshore wind.

Additional avenues beyond bringing electricity back to shore could be explored to add value to offshore wind energy extraction. One possible approach would be to generate fuel at sea rather than extract and transmit electricity (Wiersema et al. 2016; World Energy Council Netherlands 2017) and there exist other proposals to integrate energy storage with wind generation also on shorter timescales (Garvey 2015). The energy extracted from the offshore wind turbine could be used to produce hydrogen or ammonia, which would be stored locally until tanker vessels could bring it to shore. Or, fuel could be used more directly in its remote location to power fishing or transport vessels.

Another means of providing energy for storage and services to the grid could be achieved through wind power plant control. For offshore wind energy wherein smooth sea surfaces allow wakes of whole wind farms to propagate very long distances, wind farms affect the energy capture of other wind farms that are nearby. Optimizing and controlling power output not just across full wind plants but across collections of power plants will allow offshore wind energy to provide services to the grid and have more predictable and dispatchable energy production.

Floating wind turbines have an advantage over land-based and fixed-bottom systems in that they are not constrained to one position. Moving turbines inside a wind power plant could allow for decreasing wake effects and reducing loads. But, to gain even more energy extraction and reduce costs, floating wind turbines could be unmoored in deep open-ocean waters, allowing them to roam to where the wind resource is best while also avoiding extreme conditions such as tropical storms. This could also be used to move turbines closer to load centers in times of increased electricity need (e.g., during disaster relief or grid congestion).

Finally, improved understanding of meteorological ocean (metocean) conditions over various timescales will enable the introduction of better wind energy forecasting capabilities for offshore wind. As discussed in detail in Section 3.1, many innovations are expected to enhance forecasting capabilities for wind energy in general, but for offshore wind energy, there will be additional opportunities for improved forecasting through better understanding of the coupled metocean physics and systems.

R&D Challenges To Realize Innovations

Fundamental research is needed to address the challenges for offshore wind and begin to realize the innovations needed to bring down costs. Four grand R&D challenges are identified in Table 18 as important areas to tackle in this regard.

Table 18. Offshore Wind Energy Technology R&D Grand Challenges To Realize LCOE and System Value Potential

R&D Grand Challenges	Specific R&D Activities
Grand Challenge 1: Development and Validation of Multidisciplinary, Multiscale, Multifidelity, System Modeling Tools To Optimize Floating Wind Designs	Ensure modeling tools can adequately handle complexity—different scales, coupled phenomena, large machines, downwind (e.g., highly flexible, lead/lag behavior)
	Develop improved, validated farm-level design tools (e.g., wake modeling offshore, large turbines)
	Create a plant-level holistic design optimization process for floating wind systems and identifying concepts from this approach
Grand Challenge 2: Industrialization for Offshore: Manufacturing, Ports, Vessels, Deployment, Installation, O&M	Develop lower-cost methods to manufacture, install, and operate offshore wind systems (i.e., automated and/or improved welding) Employ specialized access/installation vessels
Grand Challenge 3: Wind Turbine RNA Designs Specifically for Offshore	Research innovative drivetrain and generator concepts that improve LCOE for offshore systems (e.g., hydraulic systems, direct drive, superconducting, high-voltage DC generator)
	Develop innovative rotor concepts (e.g., downwind and two-bladed)
Grand Challenge 4: Develop Full Understanding of Offshore Environmental Conditions	Achieve a full understanding of offshore environmental conditions including different turbulence levels, hurricane/typhoon risk, extreme waves, atmospheric stability, and resource assessment in the context of uncertainties and potential climate change/neighboring wind power plants

The first grand challenge is the development and validation of the modeling tools and procedures needed to find cost-optimal design solutions. To produce transformational cost reductions, multiple advancements are needed over the entire system: the turbine, tower, floating platform, moorings, anchors, construction, and logistics. As mentioned previously, this will require the development of tools that consider cradle-to-the-grave costs throughout the entire wind power plant through the implementation of a multidisciplinary, multiscale, multifidelity system design and analysis approach. The tools will need to be developed and validated to ensure they are capable of adequately representing both the design approaches used today and the innovative concepts being proposed for tomorrow. A lifetime, systems-engineering approach includes design choices that influence manufacturing and deployment processes and their associated costs. Executing this proposed approach in a closed-loop optimization framework is critical to achieving superior cost and performance gains over what is possible with today's "open-loop" or stovepipe approach.

To find optimized designs, the system-level optimization tool must accurately represent the costs and physics of offshore wind systems. This includes representing the physics of offshore wind turbines at the different scales needed, validating these models, and quantifying the uncertainties present. Future offshore turbines will operate at much larger heights in the atmospheric boundary layer than current designs, and the increasing size of the rotor means that turbulent fluctuations and atmospheric layering will have a greater impact on rotor design, performance, and reliability and need to be understood much better. The larger turbines will also have more flexible members and perhaps the addition of flow control devices. Floating systems also bring new modeling challenges including the representation of the hydrodynamic loading on the structure, aerodynamic loading under large motions, and the coupling between the two. This might also imply new aeroelastic stability issues, and the excitation of low-damped modes, which may lead to vibrations and increased fatigue loading. On the metocean side, challenges also exist regarding accurately modeling extreme conditions, such as breaking or steep waves, atmospheric stability, and tropical storms, such as hurricanes.

Ensuring that accurate models are used to represent the physics at the plant level is important as well. Central to this is an adequate representation of the wake propagation through a farm and its influence both on power performance and structural loads. Plant-level control strategies can have a significant influence on the impact of the wakes. And, the behavior of floating systems will be very different from fixed-bottom systems requiring different design approaches for plant layout and control. As mentioned previously, the ability to move the turbines either through pitch and yaw control or a more active repositioning approach could yield significant advantages for floating system performance and loads at the farm level. Integrating and reducing the physics-based models to a manageable complexity to fit within a system-level optimization framework is a significant engineering challenge and will rely on a multifidelity process through which lower-fidelity models will be utilized upfront, with checks using higher-fidelity models.

The second grand challenge is the industrialization of the offshore wind industry. Though this is not purely a technical challenge, as it also involves supply chain development, there are underlying challenges in advanced manufacturing and automation. Although the cost for fixed-bottom wind has dropped significantly and is reaching cost competitiveness, prices will need to drop even more. Some of the ways this can be achieved is through improving the processes used in manufacturing and installation. For floating wind, less dependence of the design on site-specific seabed conditions and water depth will enable mass manufacturing. A class-based system for floating wind system design, considering metocean conditions of a site but not requiring *a priori* knowledge, similar to RNA design, could be used to enable high-volume production to reduce costs further. Developing designs that use readily available components could also support a mass-manufacturing approach. Engineering challenges arise in the context of improving manufacturing technology (e.g., robotic welding of nontrivial joints). The development of purpose-built boats for the transport and installation of offshore turbines will also be needed. Considering the transportation and installation needs in the design process, as is done within a systems engineering approach, will help to find cost-optimal solutions. Other scientific challenges relate to the optimization of supply chain management.

The third grand challenge focuses on designing wind turbines (specifically the RNA) that are optimized for their offshore wind application—especially for floating wind energy. While an off-the-shelf turbine can be placed on an offshore wind support structure (after suitable "marinization," [e.g., sealing and corrosion protection]), cost advantages can be realized if the turbine could be better designed to suit the offshore environment. This goes back to the goal of designing the offshore wind system holistically—turbine and support structure—rather than separately, while considering transportation, installation, and O&M costs. For fixed-bottom offshore wind systems, research can focus on increasing size, due to limited issues in regard to transportation and installation as compared to land-based wind turbines, which can contribute to major cost reductions in the balance of system. Fixed-bottom offshore wind turbines can also benefit from research on new generator technologies with fewer moving parts, such as direct-drive generators or single-stage geared drivetrains with medium-speed generators. A contrasting need is for a lighter generator, to decrease the requirements on the support structure, especially for floating systems; thus, weight reduction options on floating drivetrains may inspire innovation to fixed-bottom configurations, especially as the ratings grow beyond 10 MW. New technologies, such as composites, higher-flux magnets, material optimization, and superconducting or pseudo-direct-drive generators, promise weight reductions in direct-drive generators that could reduce the weight penalties for floating applications. Other design requirements are more readily apparent for a floating wind turbine, in which the compliant nature of the support structure allows for larger motion of the system. Rotor concepts that are better adapted to this motion could increase power capture. Another focus area for research is on the turbine-level controls, which can provide improvements to load management for both fixed-bottom and floating systems. By integrating the control design upfront in the system-level offshore wind system design, better synergy and cost reduction pathways for the entire offshore system can be realized.

The fourth grand challenge involves developing a complete understanding of offshore environmental conditions to accurately characterize the metocean conditions (including bathymetry) at offshore locations for site assessment, system design, and model validation. This includes understanding different turbulence levels, hurricane or typhoon risk, extreme waves, atmospheric stability, wind shear profiles under differing atmospheric conditions, resource assessment in the context of uncertainties over various timescales (diurnal, seasonal and annual), potential climate change, and neighboring wind power plants. In addition, there is much to be learned about joint occurrences of wind speeds, wind turbulence, wind shear (and more), wave height, wave period, and wave direction. All of these are of direct relevance to wind turbine design, especially as we move into more sophisticated application of reliability-based design for offshore, because we neither want to overdesign (unnecessarily costly) or underdesign the turbines (excessive failure rates). To do this, we need to have a better fundamental understanding of the offshore environment, presumably involving sophisticated measurement and analysis, but then would like to reduce the site-specific measurements and analysis required for specific projects. There is also much more to be done in the development/improvement of metocean instrumentation. Lidar technology is getting a lot of attention these days, but it has limitations, especially regarding turbulence and, to some extent, extreme winds; also, performing simultaneous measurement of wind speeds well above the sea surface and waves is still a challenge, especially during storms. Long-term, high-quality data measurements are a necessity for better understanding offshore conditions in the United States, including the diurnal and seasonal variations. Accurate metocean condition measurements are needed for resource assessment, and also to inform site-suitability studies for projects at a specific site.

There are other research challenges to be addressed beyond the ones identified in Table 17. One important topic not mentioned thus far is the development of a relevant design standard for floating offshore wind systems. IEC has some material in its 61400-3 standard (IEC 2009) relevant for offshore systems, but this is really focused on fixed-bottom designs. The last edition IEC 61400-3-1, still in draft form (IEC 2017a), is explicitly concerned only with fixed-bottom turbines, and so it is only partially relevant to floating turbines. The draft IEC 61400-3-2 guideline (IEC 2017b) begins to discuss some of the additional needs for floating systems, but no formal design process has yet been established. Research is needed to define the appropriate load cases, including, for example, an understanding of simulation time, wind/wave directionality requirements, and how to adequately address tropical storms (hurricanes) for U.S. installations and other locations subject to tropical cyclones. As mentioned previously, also moving toward a reliability-based approach might enable a design with less uncertainty.

Research is also needed to better understand fatigue behavior of both moorings and power cables, and the influence of marine growth on their health and performance. To commercialize floating wind, some of the initial designs may need to be developed in shallow water, where an economic mooring design approach has yet to be established. Research is needed on new materials and/or alternative configurations to enable floating substructure designs at shallow sites without adding cost. As turbine size grows, the use of catenary mooring configurations may become more difficult, both because of the large amount of space it will use on the seafloor, and the ability to transport the large chain. Research is needed on new mooring materials and configuration also for deep-water sites. Finally, additional research could focus on the use of shared mooring and/or anchoring approaches to reduce costs.

A final research topic could focus on environmental impact, including, for example, a better understanding of marine growth on offshore turbines, noise development and noise propagation during installation, and the electromagnetic shielding effect of offshore wind power plants. Engineering challenges are to develop novel, more environmentally friendly installation techniques and better corrosion protection systems (e.g., novel coatings) and to engineer efficient multiuse platforms.

4 Cross-Cutting Needs for Data Science and Multiscale, Multidisciplinary Modeling

The previous sections set out the steps and associated grand R&D challenges that will be necessary to enable and support very high levels of wind energy shares in the global electricity system by 2050 while still maintaining low-cost energy, grid reliability, stability, and security over time. Data science and multiscale/multidisciplinary modeling capabilities surfaced as common themes across the breakout groups and led to a discussion around providing a cross-cutting look at these topics.

Collected together, the range of temporal and geospatial scales along with the variety of disciplines involved makes wind energy one of the most complex technical systems in the world. The complexity and scale of wind power plant systems and their interaction with the electric grid challenge state-of-the-art research in data science, high-fidelity modeling, high-performance computing, and related fields, and motivates the need for coordinated research efforts. Figure 10 showcases the vast range in geospatial scales associated with the system from the climate to the wind power plant coupled to the electrical grid system. Though not illustrated, the range in temporal scales—from fast-reaction grid stability requirements to long-term accurate predictions of plant lifetime energy production—are just as vast.

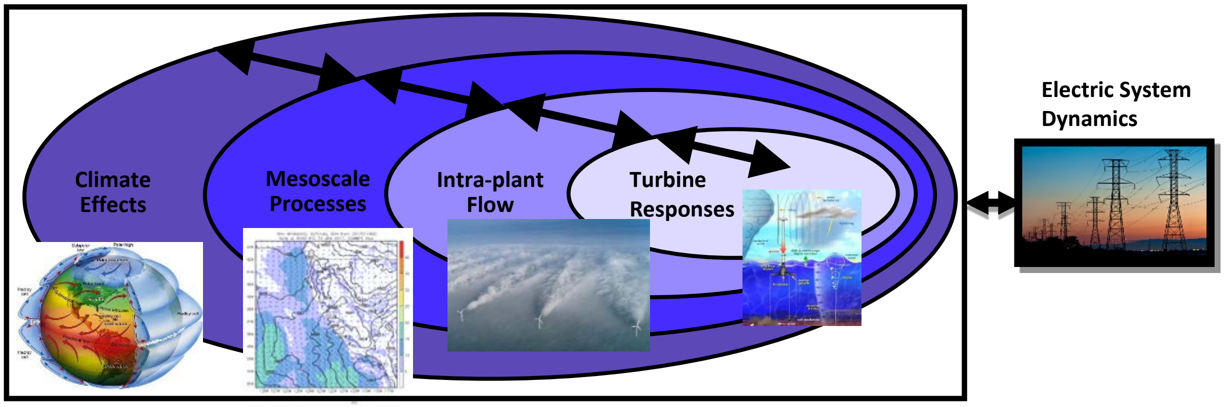

Figure 10. Wind power plants at every scale—from large-scale atmospheric effects to local climatology and topography to inter and intraplant flows and turbines responses to dynamic interaction with the electric grid system (Source: NREL)

Understanding and optimizing the wind energy system of the future will require collaboration between many different stakeholders, each working on separate aspects of common goals. In turn, this will be enabled by a combination of multidisciplinary and multisector data gathering, data science, and advanced modeling capability development that resolve the many different temporal and geospatial scales. Wind energy science will advance through coordination and collaboration across many academic disciplines while leveraging advances in several enabling technologies and research fields. Figure 11 provides a perspective of wind energy at the center of integrated research that leverages advances in 1) sensing and measurement technology, 2) computer and computation science, 3) big data, data science, and digitalization, and 4) multiscale and multidisciplinary modeling.

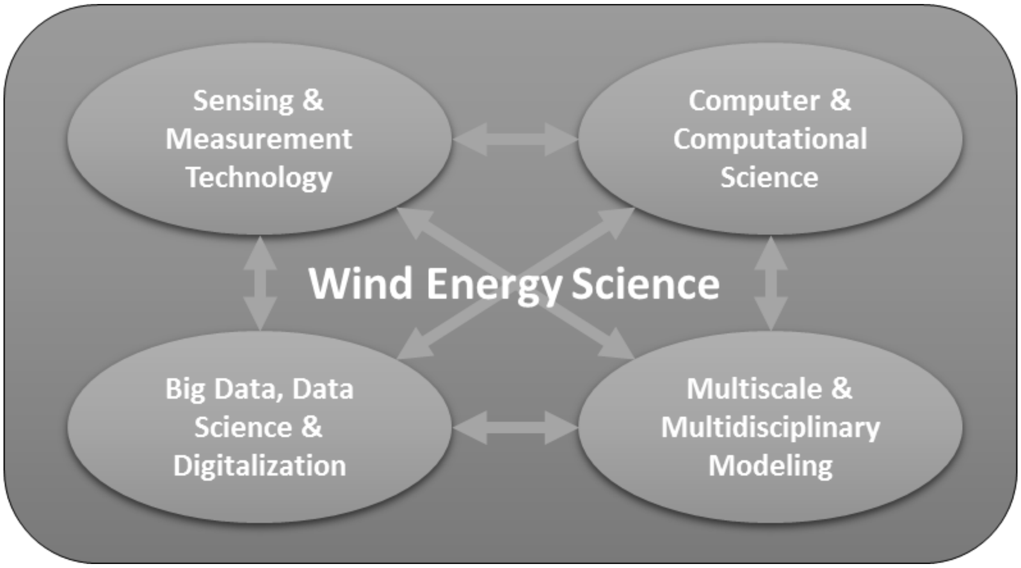

Figure 11. Enabling technologies/research for advancing wind energy science

Through coordinated research that leverages and integrates work within and across these areas, the wind energy community will develop the understanding and tools to drive innovation that will help realize the wind power plant of the future. This section will provide background in each of the areas mentioned earlier, with emphasis on their potential to impact and accelerate wind energy research. The discussion will then tie back to the grand challenges to illustrate how coordinated research within and across these areas will help address and overcome specific challenges.

4.1 Novel Sensing Technologies and Measurement Techniques

First, it is essential to recognize the critical role of recent and expected advancements in sensing technologies and measurement techniques. Current wind power plants contain many sensors associated with each individual turbine, meteorological equipment on-site, and the electrical infrastructure of the plant up to the point of interconnection. As an example, a typical commercial wind turbine will continuously provide 40−50 sensor channels of data that can be sampled at various time intervals (Yang et al. 2013) within its SCADA system. Assuming storage of data at a 1-hertz rate, this would yield over 30 million separate data points per turbine per week. For the global fleet of wind power plant assets in 2017, one estimate suggested daily data generation rates of 25 trillion bytes (Bouqata 2017). Although this may seem like a considerable number of sensors generating huge amounts of data for an all-encompassing view of wind power plant behavior, there are still significant gaps in our ability to measure the complex inflow conditions to wind power plants, the intraplant flow, and the responses and loading of the turbines to that flow within a wind plant.

Understanding and predicting the behavior of wind turbines, wind power plants, and the electric grid will require advancing sensing technologies and measurement techniques to create a more complete picture of the overall flow into and through a wind power plant and the responses, electrical performance, and loading of all the turbines interacting with that flow (down to the component level).

Measuring Weather Variables Including Large-Scale Weather Phenomena and Wind Power Plant Flow and Intraplant Flow

The weather is of paramount importance for wind energy systems in that it provides the fuel for a wind power plant but also impacts the transmission, distribution, and consumption of energy. A few key technologies and research directions offer opportunities that are important to the design, control, and operation of a future electric power system with large shares of wind energy generation. For a detailed overview of recent advances in weather measurement technologies, see Peña Diaz et al. (2015) and Lundquist et al. (2019).

Remote Sensing of Wind by Sodar, Lidar, and Radar

Measurement systems in wind power plants have traditionally measured quantities of interest directly at the place they are required. For example, wind speed was measured by cup anemometers mounted on towers, wind direction through vanes on the same towers, and so on. These instruments were often mounted on a few meteorological (met) towers that were put up before plant construction and provided local point-wise information on wind speed and direction, temperature, and pressure (see, e.g., Brower 2012 and Clifton, Smith, and Fields 2016). Met towers are still in common use today but are limited in their spatial coverage and the height they can reach (often met towers are less than 100 m tall, whereas turbine blade tip heights may reach 200 m or more).

Remote-sensing devices, on the other hand, can measure the wind at some distance away from their physical location. The most commonly used variants of this technology are sodar, lidar, and radar, which respectively use sound, light, and radio emissions to actively measure the wind. Sodar has been popular for use in resource assessment campaigns (Peña Diaz et al. 2015). Radar has been used for a few specialized commercial applications (Nygaard and Newcombe 2018). At this time, lidar appears to be the most-frequently used remote-sensing device for wind energy applications (Emeis et al. 2007).

Commercial wind lidars were introduced in the 2000s to measure general weather conditions and later in the mid-2000s for specific wind energy applications. The devices provide data across large volumes, potentially throughout an entire gigawatt-scale wind plant. Since their first introduction, commercial wind lidars have reduced in cost to the point that they are now competitive with traditional met masts and are often used for wind resource assessment and power performance testing. Given the gradual reduction in costs of electronics in wind lidar and economies of scale associated with more manufacturing, it is likely that unit costs will further decrease.

Inexpensive, reliable wind lidars can improve operations ranging from the micro to the macroscale. For example, they could be used for wind resource assessment, wind monitoring, and power performance testing. Or, they can be integrated into wind turbines for feed-forward controls or integrated into a plant for wind-plant-level control for plant optimization or power dispatch. They can also be used to increase the accuracy of data from model chains from large to local scale to support validation of wind plant flow models. It should be noted, however, that present-day lidars are not able to accurately measure turbulence intensity and gusts, so they cannot present a complete picture of the meteorological conditions that are relevant to the design of wind turbines. As a result, further work needs to be done in this area.

Another remote-sensing technology that has the potential to improve measurement of wind plant flow is radar. Radar is also used for wind resource monitoring and research studies and has the potential capability to produce an even more refined and complete set of data over the entire flow into and through the plant at various heights and spatial resolutions (Hirth et al. 2012). Airborne- or satellite-based synthetic aperture radar have proven useful for large-scale measurements on complex flows in the offshore environment (Hasager et al. 2008). However, radar systems are still very expensive, which limits their use for commercial application.

Other Sensing Technologies for Weather

New opportunities based on innovative technologies, such as acoustic tomography (Arnold et al. 1999) and sensors placed on unmanned aerial vehicles (Giebel et al. 2010) among others may someday prove useful. While still early in development, ongoing research in several areas of weather sensing technology reveals that there is still an opportunity to improve the ability to measure weather data and increase the resolution, accuracy, and amount of data around wind plant inflow and intraplant flow conditions.

As well as benefitting from improved weather forecasts, the wind energy industry may see new approaches based around data fusion (i.e., the use of many different data sources of varying quality to achieve a picture of the whole). This approach is in its infancy but is often used by the automotive industry, particularly for self-driving vehicles. New vehicles increasingly contain sensors that monitor vehicle conditions, air temperature, visibility, road surface conditions, and other factors that impact vehicle safety and traffic. These data can be used by the vehicle itself to support autonomous decision-making (for example in self-driving vehicle applications). Data from vehicles and other sources (e.g., cell phones and potentially a vast array of distributed devices) may be harnessed in the future to improve forecasts of weather conditions, which in turn will improve the predictability of wind energy.

Wind Turbine Response and Loading

It is necessary to collect data from the wind turbine itself to inform turbine models and predict its performance or maintenance requirements. Such models require information about the state of the wind turbine, particularly the load-bearing structures, drivetrain, and actuators. As mentioned, there are currently upward of 50 sensors in a wind turbine SCADA system that monitor different components, with over half to three-fourths of the sensors focused on monitoring the turbine performance in terms of power output and related electrical performance (Yang et al. 2013). If a turbine is being used for testing, certification and/or research, there may be the addition of other sensors to monitor performance and loads throughout the turbine (Santos and van Dam 2015), but these sensors are not common in commercial applications to date. For commercial applications, in addition to typical SCADA channels, here may also be some sensors on the turbine primarily targeted to condition monitoring of the drivetrain and loading on the tower or support structure; rarely are there sensors that provide detailed loads measurements of the turbine during commercial operation. For the evaluation of the turbine component health over its lifetime, ideally more detailed measurement of blades, tower, and other component loads (i.e., the main shaft and bearings, gearbox, coupling, generator, and yaw system) would be available. As load measurement sensor technology advances and costs decrease, this will enable fleetwide instrumentation and turbine state estimation over the turbine and plant lifetime.

Several companies have recently demonstrated fiber-optic based sensors that can measure loads, strains, vibrations, electric fields, and temperature within wind turbines (Schröder et al. 2006). These systems are characterized by lower prices, higher reliability, easier installation, and improved safety compared to traditional sensors and may enable more effective turbine observations than currently possible. Cheaper and ubiquitous sensing of the turbine offers the potential to use these data to make wind turbine control decisions that are simply not possible now. These steps could result in higher reliability and more predictable energy compared to current wind turbines.

Wind Plant State and Beyond the Plant

Measurement and aggregation of turbine state information at the full wind power plant level will be increasingly important as future wind power plants provide more and more services to the grid system including ancillary services and grid-forming capabilities. Thus, sensing technologies and measurement techniques at and beyond the wind power plant/electric grid interconnection point will be critical. State estimation of the larger electric grid system is a massive research topic beyond the scope of this report. For some background on the topic, see Kroposki et al. (2017) and similar studies that look at state estimation, power flow analysis, and operation of future converter-dominated electric grid systems.

4.2 Computer and Computational Sciences

Advances in computer science and scientific computing are being leveraged to support large-scale computational needs imposed by wind energy science both for management and analysis of huge amounts of data as well as in the ability to successfully model the wind energy system across physical disciplines and scales.

In the last decade, there has been a revolution in computing power through advances in hardware for processing power, parallelization, memory, and other features as well as in software in terms of algorithm development and architectures for handling computing at petascale and moving toward exascales (Sprague et al. 2017). The growth in computing capabilities has been applied to a large range of systems from very small devices that are mass produced (i.e., mobile phones) to large-scale supercomputers that continue to grow in size every year (i.e., the largest supercomputer in 2018, the Summit, has maximum performance potential of 122 petaflops (https://www.top500.org)). The growth in computing power at both very small and very large device scales has led to a proliferation of major computing architectures. There are many ways to classify computing architectures and a lack of agreement persists amongst experts in the field. The following provides one high-level classification of computing architectures from a wind energy science perspective:

- **High-performance, or high-throughput, computing**. Associated with supercomputing and supercomputers in which there is significant vertical scalability with a single application run across numerous computing nodes. Many large-scale meteorological, wind power plant flow, and grid operation models leverage this type of computing (Sprague et al. 2017; Womble et al. 2015; Haupt et al. 2015, 2017).

- **Cloud computing**. Associated with the use of many remote computing systems to target “embarrassingly parallel problems” that can be separated out easily into many parallel computational tasks with little-to-no dependency between them (and thus achieve horizontal scalability). These types of systems can be and are used for processing large amounts of data that can be processed separately (e.g., wind turbine and plant SCADA data).
- **Grid, or distributed, computing**. A heterogenous and geographically dispersed set of devices/computer resources that coordinate together on a common computational goal. There is ambiguity in terms of the difference between cloud and grid computing, with a key distinction being the level or role of the distributed devices in terms of executing computation as part of the larger application goal. An example from a wind energy perspective would be an advanced wind power plant control system in which each turbine controller processes and analyzes internal data that are used in a coordinated plantwide control scheme (Annoni et al. 2018; Bay et al. 2018).

These developments in computing underly the ability of the wind energy research community to coordinate the acquisition and management of large amounts of data, to develop both data-driven and physics-based models that can scale across all relevant temporal and geospatial scales, and directly support the implementation of the control and operation of wind power plants of the future.

4.3 Multiscale and Multidisciplinary Computational Models

Integrated models of wind turbines, wind plants, the grid, and consumer behavior allow stakeholders to test the performance of current wind turbine designs and the grid for working conditions and extreme cases. Similarly, models of new turbines and future grid designs allow new solutions to be investigated. Accurate models of the full end-to-end system are imperative to understand how to operate and stabilize the future electricity grid dominated by renewable energy with wind energy contributing 50% or more of the overall generation.

Wind Turbine and Plant Design and Analysis Tools Driven by Flow Models

A large majority of the wind power plants in operation were designed using flow models and engineering design tools developed in the late 1980s, notably after the publication of the European Wind Atlas (Troen and Petersen 1989). At the time, limitations in computing power required drastic simplifications in the development of engineering models. Flow models were simplified by different assumptions. These conditions were used to simulate the mean flow under stationary conditions that would be justified in a climatological sense, relevant for wind resource assessment, when wind conditions are averaged over long-term periods of years to decades.

Turbulence modeling in wind turbine design standards also assume stationarity and surface-layer similarity to characterize a wind spectrum that is decoupled from the large-scale variations of weather processes (Kaimal et al. 1972; Veers, 1988; Mann 1994). This separation between microscale and mesoscale effects on the turbulence structure has been historically attributed to the “spectral gap” described by Van der Hoven in 1956 (Van der

Hoven 1956; Larsen et al. 2016, 2018), as opposed to a more generalized spectrum in this so-called “terra incognita,” wherein turbulence progressively cascades from mesoscale to microscale (Wyngaard 2004). Similarly, wind power plant wake models have also required strong approximations, such as axisymmetric similarity and terrain-wake decoupling, together with calibration against wake measurements to build engineering models that can be effectively used in the wind power plant design and optimization process (Sanz Rodrigo et al. 2017). Turbine design relies on industry standards in which wind conditions are defined in terms of canonical classes that can be representative of generalized wind resource and turbulence characteristics.

These and other approximations have also facilitated the separation of modeling communities that would develop their models with little interaction between them. Historically, four flow modeling silos would develop, each one dealing with a specific range of scales from the perspective of different individuals with specialized scientific backgrounds: 1) a meteorologist, dealing with climate and large-scale weather effects, for whom a wind power plant is just another type of land use, 2) a wind turbine siting engineer, dealing with the flow at microscale affected by local topographic and wind power plant wake effects, for whom the wind turbine reduces to an actuator disk driven by a power law, 3) an aerodynamicist, specializing in rotor design aspects, for whom the inflow wind profile can be characterized with a simple log law in free-stream conditions (Shaw et al. 2009), and 4) a wind turbine structural designer, concerned with the ability of the entire structure to withstand the effects, both fatigue producing and ultimate, of the meteorological (or meteorological/oceanographic; metocean, in the case of offshore) conditions to which it will be subject.

Alongside the development of wind energy technology toward larger rotors and wind power plants, these physical approximations have been challenged in favor of an integrated model chain that would produce a more realistic representation of the interplay between atmospheric and wind power scales. The most important uncertainties in the performance of large wind energy systems still reside in the highly unpredictable turbulent flow in which they operate. As a result, such systems require consideration of a multiscale modeling approach that connects disparate scales from climatic changes, which dominate the interannual and seasonal variability of the wind resource through atmospheric weather processes, to thermally stratified boundary-layer turbulence influenced by local terrain and vegetation effects (Sanz Rodrigo et al. 2017).

Only recently has it become possible to bridge silos in flow modeling with advances in high-performance computing and large-eddy simulation models (Hammond et al. 2015). As mentioned previously, developments in computing now enable large-scale simulation across large spatial scales with high temporal and geospatial resolution (Sprague et al. 2017). This has led to a proliferation of research explicitly coupling models from the meteorology all the way down to individual turbine responses. The latter models will be discussed next.

Wind Turbine and Plant Design and Analysis Models

Flow models associated with crossing all the relevant scales are critical because ultimately wind is the fundamental resource for the entire system. However, these fluid models feed into and interact with individual turbine models that couple in the physics from a broad range of disciplines including aeroelastic, structural dynamics, controls, and, for offshore applications, hydrodynamics. Wind turbines and power plants are analogous to living systems that include hundreds to thousands of components interacting with the wind as well as each other with highly coupled and nonlinear responses. Like wind flow models, there has been an evolution over several decades in the way each component, the full turbine, and the plant physics are modeled for applications of engineering analysis, design, and turbine and plant operation. At the same time, this modeling capability still needs improvement—for example, in offshore applications where models are relatively undeveloped.

Early models for wind energy applications leveraged modeling efforts for aerospace applications, such as helicopters. However, as experience with wind turbine technology grew, several wind-energy-specific dynamic analysis codes emerged that were meant to support accurate assessment of the machine loading under a variety of operational conditions. These “aero-servo-elasto-hydrodynamic” codes have evolved along with wind turbine technology as machines have become much larger, more flexible, and deployed in offshore fixed-bottom and floating applications (e.g., Jonkman and Buhl 2005).

Recently, the focus of the wind energy scientific community has shifted from a turbine-centric view to a full wind plant design and operation view that accounts for the impact of intraplant flow on turbine responses. This shift has pushed the turbine modeling community to interact more closely with the flow modeling community to develop fully coupled models of turbine and plant dynamics using engineering flow models up to full large-eddy simulations (Fleming et al. 2013; Jonkman et al. 2017, 2018).

Through this full coupling of turbine and plant physics, the scientific community can explore questions never answered regarding the response and loading of individual turbines in plants under a range of conditions including complex terrain, atmospheric stability, heterogenous flow, various large-scale flow conditions for offshore wind turbines, and more. An important expansion in the scope of the plant-level analysis is to answer questions related to controlling the entire plant flow for increasing overall energy production, balancing system loads to improve overall plant reliability, or providing more predictable energy and services to the electric grid system. For the last point, coupling in models of the electric system to the rest of the system physics is necessary.

From Wind Turbine and Plant Models to the Full Grid System

Although developing an end-to-end modeling capability for the wind power plant as a stand-alone entity and treating the larger electric grid system as an exogenous entity is a huge challenge, it only solves part of the challenge in terms of the modeling capability necessary to realize the future converter-dominated electric grid system. In addition to coupling all the relevant disciplines together across the power plant, it is necessary to couple these models that accurately represent the full electric grid system dynamics at all timescales of interest (from short-term transients to system operation models for dispatch and commitment on the order of minutes to days to medium- and longer-term planning models for generation capacity and transmission).

There has already been significant effort in bridging models across all the relevant domains for turbine and plant physics. Similarly, within the electrical engineering community, there has been consistent advancement in power system models that represent the electrical behavior of all the various elements. However, there has yet to be large-scale efforts to bridge across these two areas for a truly integrated modeling capability necessary to capture all the interactions of the future converter-dominated electric system.

Multiscale Model Validation

Although multiscale models produce more data and include more physics than ever before, this does not guarantee that they are correct. There is still a need to confirm how well those models match reality, which is the process of model validation. As the amount of wind energy on the electrical grid increases, it will be ever more important to validate models and explore unusual situations that might endanger supply.

High-fidelity models cannot be used directly in design, but they are used to build more robust, cost-effective, and physically insightful engineering models that can systematically decrease the uncertainty in the assessment of energy yield and design conditions. Similarly, the development of data-driven design and operational models (digital twins) is also limited by the lack of standardized databases and data screening procedures that can homogenize the monitoring and diagnosis of wind power plant performance. A formal process for model-chain verification and validation and uncertainty quantification between high-fidelity models, engineering models, and observational data is lacking, partly because of the inherent complexity of the full system, requiring large investments in field and laboratory experiments (Hills et al. 2015; Sanz Rodrigo and Moriarty 2015).

One example of multidisciplinary research involving such large-scale field experiments can be found in the development of multiscale atmospheric models. To validate these models, the largest experiment related to boundary-layer meteorology in complex terrain has been recently accomplished in Perdigão (Portugal) (Mann et al. 2017). This experiment features the deployment of 50 met masts, 20 scanning lidars, and other met systems over a double-hill setup, through a joint-funding initiative between the New European Wind Atlas project (Lundtang Petersen et al. 2014) and several projects funded by the U.S. National Science Foundation. The New European Wind Atlas project is driven by the wind energy community to produce a comprehensive database of experiments that can allow wind energy modelers to work with a meteorologist to understand complex atmospheric physical phenomena and develop high-resolution turbulent models that can build the bridge across the terra incognita.

Similar efforts have been executed in the United States under the U.S. Department of Energy Atmosphere to Electrons (A2e) program with its Wind Forecasting Improvement Projects (WFIP1 and WFIP2) (Wilczak 2017), mesoscale-microscale coupling (Haupt et al. 2017), and scaled wind farm testing facility projects (Berg et al. 2014). These and future efforts are expected to provide breakthroughs in understanding around wind turbine and plant physics by targeting the full range of physics involved both spatially and temporally. Similar work remains to be done for offshore applications where understanding combined meteorological and oceanographic effects is critical to design and operation of wind turbines and wind plants.

4.4 Digitalization, Big Data, and Information/Data Science

Addressing the grand challenges identified in the different breakout areas will require the wind energy industry to harness the latest in technology innovations. Wind energy digitalization refers to the idea that there is a whole spate of digital technologies that will reshape the workings of the energy industry (IEA TEM #92 2018). These digital technologies taken together represent the ability to gather, analyze, and act on data from wind turbines and power plants and improve the interactions with the electrical grid and markets. These data will be used for historical performance analysis and validation in addition to predictive analysis, real-time control and operations, and even future system design. Increasingly, complex models will be used to understand the system and predict its performance, and decisions will be largely automated. This tendency toward interconnected devices that generate large amounts of data and act autonomously is often called "Industry 4.0" and is characterized by digitalization and the presence and exploitation of "big data." For clarity, these concepts are defined here as they are being used and interpreted within this document:

- "Industry 4.0" (Rose 2016) is a term associated with a new paradigm in manufacturing and technology businesses that involves a high-level of automation, distributed computing, decentralized decision-making, "big data," digitization, and digitalization as described in the next three bullets. Also see Figure 12.
- Big data applies to the data management, processing, and analysis of data sets that are too large and complex to handle with conventional techniques. Typically, the concept is described using the four V's: volume, velocity, variety, and veracity (Ward and Barker 2013).
- Digitization is the process of changing from analog to digital form, also known as digital enablement. Said another way, digitization takes an analog process and changes it to a digital form without any different-in-kind changes to the process itself (Gartner 2019).
- Digitalization is the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business (Gartner 2019).

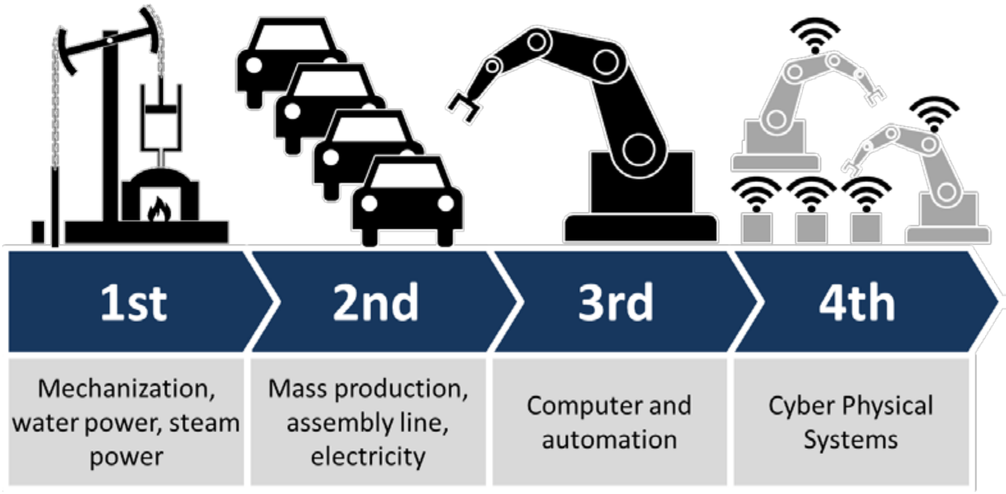

Figure 12. Illustration of Industry 4.0, showing the four "industrial revolutions" (Source: Rose 2016)

It was already noted that wind energy and the wider electrical grid is undergoing rapid digitalization that will lead to a very large body of data about turbines, the plant, and the grid (BNEF 2017). Data science, a combination of hardware and software that is designed to create, explore, retrieve, manipulate, and condense data from many disparate sources, will be a major enabler of digitalization for wind energy. Digitalization and data science are relatively recent technological and scientific paradigms that have enabled disruptive innovation in many fields and are likely to impact wind energy as well (Concolato and Chen 2017). The effective use of data could lead to more efficient planning, better use of resources, and improved decision-making throughout the wind power plant life cycle, leading to a reduction in the cost of energy and increase in the value of wind energy.

ETIPWind analyzed technological goals for wind energy and determined how they might be enabled by digitalization when tailoring information and data science to wind energy applications. The ETIPWind vision was presented in *When Wind Goes Digital* (ETIPWind 2014). The main output from ETIPWind is a diagram showing the mind map of the digitalization centered around two main objectives: integration and reduction of the cost of energy (analogous to system value and LCOE, respectively, as considered in this report), which are supported by the availability of data enabled by data sharing and data management. The objectives of digitalization according to ETIPWind are summarized in Table 19. These objectives align well with the impacts from identified innovations identified in Section 3 across the different breakout areas.

Table 19. Objectives of Digitalization According to ETIPWind

Objectives of Digitalization	
Reducing the Cost of Energy	**Wind Energy Integration**
Digitalization will help make wind energy more competitive, specifically for conventional power plants, by applying data-driven strategies and decision-making. This approach will simultaneously decrease the cost of wind energy and improve the value of wind power. In particular: • Improving productivity • Forecasting and wind plants and wind farm control • Decreasing O&M cost (OpEx) with better decision-making and efficiency • Reducing investment cost (CapEx) • Lifetime extension • Better operations and trading in the power markets.	A set of tools to create connectivity by integrating all involved parties, such as wind power plant producers, transmission system operators, distribution system operators, and consumers, and ensure synergy with other sectors in the electricity system to establish better wind integration. In particular: • Transmission system operator, Distribution System Operator integration • Real-time grid support capabilities • Faster and more efficient grid services • Synergies with other types of power generation • Consumer synergies • Sector and storage coupling.

Application of digitalization and associated capabilities to wind energy will leverage technology development in several enabling research areas. These technologies are organized into categories below and described in more detail with relation to wind energy in the text that follows:

- Digital workflows

  - Analog to digital conversion of information around technology design, use, and operation
  - "Digital twins" that mirror the real assets in a digital format over their lifetime
  - Blockchain and distributed ledger technologies for democratizing the transition of digital assets
  - Automated/distributed decision-making where there is no longer a human in the loop
- "Internet of things"
  - Ubiquitous digital communications between large numbers of big and small technology assets
  - Inexpensive and fast computing available on demand
  - Connected sensors throughout technology assets
  - Edge computing where distributed technology assets are "smart" and bare some of the burden of system analysis and associated computation
- Data science tools
  - Distributed computing and analysis (such as methods for handling analysis and synthesis of big data efficiently)
  - Machine learning and artificial intelligence for creating understanding directly from repeated interaction with data using a large variety of algorithms
  - Computer vision and associated sensory technologies that enable a higher-dimensional interaction of the computing and real world.

Digital workflows correspond to the idea that the entire wind power plant lifecycle can be digitized and simulated, allowing for improved efficiency, quick design iteration, scenario analysis, and diagnostic as well as prognostic modeling. The implementation of digital workflows and data standards can lead to increases in efficiency of up to 60%–80% in analytical processes (IEA TEM #92 2018). The idea of digital manufacturing is encapsulated in the industry 4.0 definition and is being aggressively pursued by several international initiatives (European Commission 2015). Digital manufacturing enables not only digital design but also a digital twin to which a whole host of scenarios can be applied. This can be not only digital twins of wind turbines and wind plants but also digital representations of the entire wind plant life cycle including the manufacturing line, supply chain, and end of life.

The internet of things relates to the ability to have a collection of computing devices that are interconnected, that have the ability (to a degree) to do their own computation and analysis, and that share information and computing resources with each other. In some ways, the internet of things has long been present in many technical products that have computing capabilities distributed across many subsystems. Take a vehicle, for example, that for many years has had separate computing and control devices for the drivetrain, transmission, and infotainment (the information and entertainment system with which the vehicle passengers interact) that constantly share information with each other through a local vehicle intranet system. Within wind energy systems, many separate devices (in turbines, meteorological instruments, and more) collect data through sensors and may do computation and analysis of that data and share this across the larger system network.

Although the potential for increased use of data science, digitalization, and related methods is enormous, there has already been a concerted effort by many groups to use data science and machine learning for wind energy research and commercial applications. Many stakeholders have developed approaches to mine hidden operational problems from the vast trove of SCADA data already being gathered in wind plants. From large-scale consulting firms, owner/operators, and equipment manufacturers to small-scale start-ups and research groups, there is a growing effort to leverage existing data sets for wind turbines and power plants to both identify opportunities for improved plant performance and energy production as well as to diagnose and predict potential failures and reduce O&M costs (Typoltova 2017). One example from the research community is the use of machine-learning algorithms applied to turbine power performance data, which can be used as an alternative means of dealing with the noisy data from which power curves are derived (Clifton et al. 2013). Other examples in the research community focusing on O&M include condition monitoring and predictive maintenance (Hameed et al. 2009; Garcia Marquez et al. 2012; Nabati and Thoben 2016; Canizo et al. 2017). The recognition of the need for data-driven research has even led to large-scale research programs in the European Union including such projects as the ROMEO project (https://www.romeoproject.eu/machine-learning-iot-improve-wind-farms/) and the VIS-Project Offshore Wind Operations & Maintenance Excellence (OWOME) project (http://www.owi-lab.be/content/vis-project-owome-offshore-wind-operations-maintenance-excellence).

An important consideration for machine learning and artificial-intelligence-related research is the responsibility to ensure transparency, fairness, and ethical treatment of automated decisions. There are many examples of the increased use of machine-learning and artificial-intelligence tools to help inform or automate decisions that have resulted in systematic biases and by extension harms (O'Neill 2016). Specifically, researchers have broken these harms down into two main categories: allocative harm and representational harm (Barocas et al. 2017). Allocative harms correspond to the potential misallocation of resources (e.g., financing, insurance, employment) due to algorithm biases while representation harms relate to identity and perpetuation of cultural stereotypes. These include applications as broad ranging as credit scores, university applications, and societal policing. Another critical facet is that these considerations should be extended to both computer and machine ethics (Anderson and Anderson 2011), the distinction being whether a human is using computer capabilities, or a machine is using ethics to make decisions. When we consider the application of machine-learning/artificial-intelligence technologies, we should also consider the potential harm to various stakeholder groups in the wind plant lifecycle and wind plant to grid and market interactions. Specifically, we should be considering the impacts on wind plant owners, operators, manufacturers, grid operators, and consumers.

Data-Driven Modeling and Simulation

Beyond pure data science and data-driven techniques, the coupling of physics-based modeling approaches (as described in Section 4.3) with data-driven techniques—a process referred to as data assimilation—will yield a new generation of modeling capabilities for wind energy that leverage the advantages of each technique. On the one hand, data-driven techniques are successful at representing real-world conditions, but they can be limited when extending to applications wherein data are sparse or nonexistent. Further, physics-based models that embody fundamental principles of the technology and science can predict system performance in a wide variety of conditions yet have difficulty when applied to situations that defy model assumptions. In addition, both model types can have large computational costs. Bringing together physics-based models and data-driven techniques through data assimilation may improve the combined modeling accuracy for a variety of applications and may also reduce computational costs. An example of such an approach is the use of data to improve the fidelity of less-expensive physics-based models of plant flow for design and control applications (King et al. 2018; Adcock et al. 2018).

Data Management and Sharing

Regardless of whether the research application is purely data-driven or combines physics-based and data-driven modeling, a key challenge for data science in wind energy is inconsistent data management across the industry, which limits the applicability of automated data processing and machine-learning/artificial-intelligence techniques as well as the ability to share data publicly across the research community and industry. This challenge highlights the need for more aggressive coordination across the research community and industry to develop frameworks, standards, and even incentivized systems for data management and sharing. Currently, there are a number of data standards that exist and have been catalogued by IEA Task 33. One apparent issue is not the lack of standards but rather the adoption and harmonization of existing standards such as IEC 61400-25: Communications for monitoring and control of wind power plants. It is not only a technical challenge to agree on the standards but also a social science challenge to understand how to best drive adoption and utilization of the standards.

Companies already recognize the value of their data in terms of building value and competitive advantage. The movement toward digitalization compounds this value. As a 2017 BNEF white paper on *Digitalization of Energy Systems* emphasized, “The importance of data as a commodity cannot be overemphasized. We see data strategy and security as the business area with the largest degree of change and the most significant impact on investments and returns for all parts of the value chain. Data security, privacy, collection, storage and manipulation will all determine a utility’s ability to stay competitive.”

A challenge for big data within even a single organization is to know which data are available, how to access them, and how to synthesize them into actionable information. This ability requires data management and retrieval expertise, and new large infrastructures for storing data and retrieval systems. The technical challenge of building such an ecosystem of infrastructures is being addressed through investments in the information technology sector. However, to effectively use these systems to support wind energy research and technology development applications, frameworks and standards specific to wind energy technology are needed. Research policies, such as the European Open Science Cloud (European Commission 2016), are being developed to integrate public data management and computing infrastructures and promote open science to make sure research data can be fully exploitable by being findable, accessible, interoperable, and reusable (FAIR). These so-called FAIR data principles were introduced through a collaboration of European stakeholders in a 2014 workshop and then published in 2016 in *Nature* (Wilkinson et al. 2016).

To organize and make wind energy data findable by the research community, the European-Commission-funded project, IRPWind, supported an effort to design and develop a prototype of a data portal (https://sharewind.eu/). As a first step toward a data portal, the project produced wind-energy-specific metadata scheme and related taxonomies needed for data tagging (Sempreviva et al. 2017) supporting data search. ShareWind is designed as a metadata generator with a searchable metadata catalog and data-publishing portal. Data owners can generate and store the metadata in a searchable metadata catalogue and then choose whether to upload the data and metadata on the EUDAT (https://eudat.eu/) data repository; or to upload data in another repository. The IEA Wind Task 37 on wind energy systems engineering also has an effort to create taxonomies that enable the exchange of model input and output formats, which is aligned with the efforts of IRPWind to further support interoperability and reusability (https://community.ieawind.org/task37/home). When operational, ShareWind will contain the information of data available within the wind energy community, independently where the data are stored. This approach avoids creating an expensive and time-consuming community data repository. A similar portal for data sharing has been created in the United States under the A2e Data Archive and Portal (Sivaraman et al. 2014). Going forward, a key challenge will be ensuring coordination across different stakeholder groups and establishing a general standard that will be adopted across the research community and industry.

Perhaps more critical than actual data standards are practices and guidelines that enable wider dissemination and sharing of data. Sharing knowledge and data is widely recognized as being fundamental to supporting a fast track from research to innovation. However, there are normative and structural barriers to this sharing. Although large amounts of data about wind energy activities are produced (e.g., by wind power plants) every day, access to these data by the scientific community is restricted or regulated on a case-by-case basis through data licensing agreements. Research institutions and industry typically use two different models for data: visible data (generally covered by a nondisclosure agreement) and invisible data (undisclosed proprietary data). This practice of bilateral sharing of data prevents the wind energy community from realizing the full potential of big-data exploitation to generate scientific insights and systematically improve the predictive capability of models.

An example of improving overall data sharing and management comes from the European Commission policy for Open Science (European Commission 2016), which supports open data by defining a mandatory data management plan for managing research data by documenting and connecting data gathered in each funded project. By following the FAIR data paradigm, European-Union-funded projects will guarantee data management and curation that supports the reproducibility of and future reuse of data. And, by 2020, the European Open Science Cloud will be created to incentivize data sharing, which will increase the ability of the research community and industry to exploit large data sets and ensure that critical data are accessible and used as widely as possible. The ShareWind portal is also designed with the purpose of facilitating data sharing. ShareWind contains only metadata including the information on data owners and access rights. Users will have to contact data owners to access the data. This allows owners maintaining control over the data whilst having visibility. Similarly, in the United States, the open government and open data initiatives have mandated full public access to government-funded research data.

The larger utility stakeholder community in Europe is also moving to align with data management and sharing principles as touted by the European Commission. For example, in November 2017, the European Distribution Grid Operators and other stakeholders proposed a Protocol for a European Open Data policy in distribution systems and signed the "Tallinn e-energy Declaration" (https://www.eu2017.ee/tallinn-e-energy-declaration). This protocol aims to promote the digitalization of Europe's energy systems and the use of smart solutions to accelerate the energy transition toward a clean and sustainable energy future.

Data marketplace for sharing data and accelerating energy transition

As digitalization is the process to gain insights from data-enabling new services or business models, data are considered assets that provide a competitive advantage. However, there is increasing awareness that exposing the data using metadata opens the possibility to multiply the value of the data by attracting other stakeholders from other sectors and disciplines. Data marketplaces appear to be an additional possible means of encouraging collaboration and sharing data, as they bring together data users and owners on an existing platform— either public (i.e., Qlik [https://www.qlik.com/us/products/qlik-data-market]) or commercial (i.e., DataStreamX [https://www.datastreamx.com/])—and create new revenue opportunities for data owners. However, data can be traded monetarily, exchanged on a collaborative basis, or exchanged for services.

4.5 Intersection of the Grand Vision with Emerging Science and Technologies

The next generation of wind energy design and operational tools will be based on multiscale, physics-based, data-driven and data-assimilated computational models that can produce a realistic characterization of weather (or metocean in the case of offshore), power plant performance, and grid status across all relevant scales. Full system validation will be a grand challenge because of the high complexity of the coupled atmospheric-power (or metocean-power) system and the large number of operational conditions. A formal model evaluation process is necessary to systematically improve the physical insight of the individual models and coupling mechanisms that integrate the full system model chain. To this end, high-fidelity experiments with extensive data collection and universal access will be required. Operational data from wind power plants should be accessible as well. The validation of the computational models (data-driven, physics-based, or a combination thereof) will depend on the ability to tap into the large potential using data science. By speaking a common language of data science, the wind energy community can reduce knowledge silos and develop more interdisciplinary and multidisciplinary research that can lead to drastic reductions in the cost of energy. Table 20 illustrates this point by linking the identified grand R&D challenges from the different breakout groups with the topics of sensing technology, multiscale modeling, digitalization, and data science.

Table 20. The Challenges and Opportunities of the Wind Energy Transition to Digitalization and "Openness" Toward the Grand Vision

	Grand Challenges in Wind Energy R&D	Opportunities Offered by Big Data, Information and Data Science, and Multiscale and Multidisciplinary Modeling and Advanced Sensing in Addressing the Grand Challenges
Category 1: Advanced Understanding of System Physics Within Relevant Disciplines	**Atmospheric Science and Forecasting:** • *Grand Challenge 1*: What Is the Wind Resource and How Do Wind Plants Change It? If We Knew the Atmosphere, What Could We Do? **Turbine Technology and Design:** • *Grand Challenge 1:* Complete Understanding of Physics for Design and Operation of Large-Scale Machines • *Grand Challenge 2*: Physical Understanding of the Boundary Layer Physics (Subviscous and Mixing Layer) Multiscale Characterization Driving Turbine Performance **Offshore-Specific Technologies:** • *Grand Challenge 4:* Develop Full Understanding of Offshore Environmental Conditions **Grid Integration:** • *Grand Challenge 1:* Develop Fundamentals and Paradigm Design of a Converter-Dominated System • *Grand Challenge 2:* Advanced Control of Converters in a Converter-Dominated System	• Develop and deploy advanced sensing technology to create more accurate and higher-fidelity representations of the atmosphere, metocean conditions for offshore (including bathymetry), and intraplant flow. Explore the value of remote-sensing technologies like lidar and radar for new advanced sensing (such as from direct measurement of the atmosphere) • Establish comprehensive multidisciplinary (wind energy science) experimental campaigns measuring atmospheric and ocean parameters, and technical data at wind turbines and power plant system levels, including turbine and plant supervisory control and data acquisition, turbine responses, condition monitoring, and plant electrical performance. • Encourage open data and data-sharing strategies to make data stored in cloud-distributed databases findable and visible via metadata standards with related taxonomies and ontologies ○ Use ontologies and taxonomies for easier retrieval and categorize data and models needed to structure workflow and exchange of information across disciplines • Research and validate fundamental physics within disciplines and at disciplinary boundaries/interfaces ○ Develop a new theory and principles for system operation (i.e., turbine wakes, converter-dominated system)

	Grand Challenges in Wind Energy R&D	Opportunities Offered by Big Data, Information and Data Science, and Multiscale and Multidisciplinary Modeling and Advanced Sensing in Addressing the Grand Challenges
Category 2: Improved Modeling of the Full Wind Energy – Grid-Integrated System Across All Disciplines, Spatial and Temporal Scales	**Atmospheric Science and Forecasting:** • *Grand Challenge* 2: Improved Model Chain to Better Predict Renewable Energy Resources **Plant Controls and Operations:** • *Grand Challenge 1:* Full End-to-End Model From Atmosphere to Grid • Grand Challenge 2: Power System Model with a Large Amount of Wind Power, Storage, Solar, Flexible Loads **Offshore-Specific Technologies:** • *Grand Challenge* 1: Development and Validation of Multidisciplinary, Multiscale, High-Fidelity, System Modeling Tools to Optimize Floating Wind Designs **Grid Integration**: • *Grand Challenge 3*: Multiscale Modeling Across the Entire Grid System with Accurate Modeling of Converters in a Converter-Dominated System	• Develop data-driven, multiscale, multidisciplinary models ○ Take advantage of advances in the “Industry 4.0” to leverage data and data science for resource assessment, production forecasts, state estimation, controls, and condition monitoring for diagnostics, prognostics, and more • Develop physics-based models that couple relevant physics across scales (geospatial and temporal) and disciplines ○ Coupling of high-fidelity models for wind plant flow and wind turbine dynamics with forcing from larger weather models ○ Modeling of the new grid with a lot of converters embedded in AC systems (bridge scales of slow AC and fast dynamic systems) • Combine data-driven methods and physics-based models for end-to-end modeling chains for forecasting, controls, operations, and grid integration ○ Employ uncertainty quantification for both measurement data and models (for environmental and operating conditions) ○ Employ data in verification and validation platforms to better quantify and understand modeling uncertainties in different situations and prioritize issues

	Grand Challenges in Wind Energy R&D	Opportunities Offered by Big Data, Information and Data Science, and Multiscale and Multidisciplinary Modeling and Advanced Sensing in Addressing the Grand Challenges
Category 3: Application and Demonstration of Data and Modeling Advances to System Design and Operation	**Manufacturing and Industrialization:** • *Grand Challenge 1*: Advanced Materials • *Grand Challenge 2*: Automation • *Grand Challenge 3*: On-Site Manufacturing **Plant Controls and Operations:** • *Grand Challenge 3*: Implementation of Wind Power Plant Controllers and Integration With Turbine Controllers (Including Field Trials and Validation) • *Grand Challenge 4*: Creation of Open Data Sets for Use in Open Research **Grid Integration**: • *Grand Challenge 4*: Intelligent Wind Power Plant with Integrated Data and Modeling for Active Power System Operation and Support **Offshore**: • *Grand Challenge 2*: Industrialization for Offshore: Manufacturing, Ports, Vessels, Deployment, Installation, O&M	• Leverage scientific advancements, data science, and improved modeling capability to: ○ Enable automation in manufacturing ○ Research and develop "digital twins" for the structures produced in an on-site manufacturing facility ○ Combine data and modeling approaches for state estimation and accurate performance prediction (flow and electrical) ○ Utilize big data, algorithms, and deployments of robots/drones for O&M innovation (big data for structural health monitoring, machine learning, optimization, and predictive failure including real-time machine learning, in-field/up-tower repairs, adaptive controls, and more) ○ Accelerate technology learning and industrialization of offshore technology (particularly floating)

The resulting ecosystem will allow for new insights and lead to new modes of integrating research and capturing expertise. Obtaining a better understanding of how wind power plants operate will have implications for operating wind plants and managing the full life cycle. For example, models will also be adapted for use in the design of future wind turbines and power plants. Ultimately, this upgraded framework for handling data, models, and overall wind energy science will cover all stages of a wind power plant's lifetime, thereby reducing the cost of electricity generated and increasing the value of wind energy to the electric grid system. A key need associated with the research efforts outlined in this report is to create the frameworks and mechanisms that allow effective collaboration across the relevant stakeholder groups to realize the full potential of wind energy for the future electricity system.

5 Summary

The energy sector is undergoing a paradigm shift. By 2050, many predictions identify a future electric grid system in which renewables make up a significant share (30% or more) of overall electricity generation. In the fall of 2017, wind energy experts from around the world came together to look at an even grander vision of the future electricity system where wind energy could produce a majority (>50%) of global electricity generation. This “Grand Vision” for wind energy pushes beyond even the most optimistic forecasts; however, to realize this future, significant innovation is needed to reduce the cost of wind energy and increase the value it provides to the electricity system.

Through a series of meetings, wind energy experts identified innovations in several areas: manufacturing and industrialization, turbine technology and design, atmospheric (and metocean for offshore) science and forecasting, plant control and operations, grid integration, and offshore-specific technologies. Innovations in these areas would lead to reductions in wind cost of energy and/or improve the value that wind energy has for the electricity grid in providing more reliable and dispatchable energy, higher capacity value, and improved grid services for greater reliability and stability. The groups then discussed the R&D efforts that would help accelerate and enable the development of these innovations.

This report documented the findings for each innovation area to realize a future electric grid scenario with high shares of wind energy. The authors then synthesized the discussions on R&D challenges into a high-level list of grand R&D challenges by area. Throughout all the research areas, there were common themes that surfaced: leveraging recent advances in data science, digitalization, and associated technologies, and creating multiscale and multidisciplinary modeling capabilities that could fully capture all of the complex coupling and interdependencies both within the wind power plant and the full electric grid system. Exploring these cross-cutting themes revealed a higher-level framework that could be used to coordinate and integrate wind energy research across the different areas to successfully address the grand R&D challenges.

The shear complexity and size of the wind energy science challenge merits such an integrated perspective and approach and emphasizes the need for an integrated wind energy science discipline. Future work, in the form of a follow-on journal article, will articulate more completely the different components of this discipline and discuss how execution of such an integrated research program will overcome the challenges set forth to realize the Grand Vision for Wind Energy. If successful, the resulting innovations can help realize a future electricity system with wind energy as its foundation.

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Appendix A: IEA Wind TEM #89 "Grand Vision for Wind Energy R&D" Agenda and Participant List

IEA Wind TEM #89 Agenda

Sunday, Oct. 22, 2018

The Sunday session is devoted to brainstorming and discussion of what the energy landscape, and wind energy contributions, will look like in 2050, as well as what the most challenging aspects of getting from here to there will be.

5:00 PM Future Scenario Game

During the social hour, workshop participants will be asked to participate in a casual brainstorming exercise around wind industry development objectives of 1) LCOE, 2) grid integration, and 3) deployment. For each topic, participants will be asked to think about different opportunities and barriers to the improvement in each objective and to rate the difficulty associated with each. Discussion is encouraged among the participants.

7:00 PM Grand Vision Scenario Premises

In preparation for the next day's activities, workshop participants will engage in a guided discussion over the key premises behind a Grand Vision of the future for wind energy as a primary source of energy for the world. Topics covered will include the level of wind energy as a percentage of total generation, the portion of which is offshore, the level of solar and other renewable deployment that exists, the type of computing, data management, sensing, and other enabling technologies that are available to the industry.

8:30 PM Adjourn for the day

Monday, October 23 (NREL, RSF, Beaver Creek Room)

The Monday meetings are organized around three main breakout sessions where attendees will be asked to create a list of most critical issues in achieving the needed 1) LCOE *and* 2) value *to achieve the landscape discussed in the Sunday meeting. Then, in the last breakout,* 3) research*, we will gather the fundamental issues needed to achieve the 2050 vision. Breakout sessions will be divided into small groups according to the categories below.*

Schedule

8:45 AM Introductory Addresses

- Welcome; Paul Veers
- Peter Green, NREL Director, Science & Technology
- Lionel Perret and Ignacio Marti, *Introduction to IEA Wind TCP and Task 11*

The meeting started with an overview of Task 11 activities, new developments, and the new information exchange portal.

- Joachim Peinke, University of Oldenburg: *The European Academy Publication of Long-Term Research Challenges*

This presentation highlighted the need for a new focus on long-term wind energy research. Recommended topic areas for research include:

  - A multidisciplinary approach, including environmental and sustainability aspects
  - Large scale: use of new layer of atmosphere, more focus in economics and environmental values
  - Multiscale aspects: from millimeters to hundreds of kilometers, methods to bridge scales
  - Big data: what to do this new knowledge, to extract the essential information, to identify fatigue, for example
  - Validation an precision \: new to unify and validate, need a precision, not yet the case in aerodynamics.

- Carlo Bottasso, TU Munich *The Need for Truly Open Data Sets*

This presentation highlighted the value that open data sets can provide to research communities in advancing research and innovation. The presentation pulled in examples from the Rotorcraft community, which has a stronger history than the wind industry for sharing detailed design information. A particular project involved a heavily instrumented vehicle and an extensive test campaign that yielded a large public data set for research and several workshops. The analysis of the data had an enormous impact on education and research.

The wind industry needs a similar effort and this will involve collaboration. To date, most data sets and projects involve hypothetical rotor and turbine designs and code-to-code comparison rather than validation using real machine design and operational data. This will only take the research community so far and may limit advancement of science and technology for the whole industry. One comment from the audience noted that publicly funded efforts should make a concerted effort to yield public data sets as a requirement.

9:45 AM Guiding talk

- Ryan Wiser, Lawrence Berkeley National Laboratory, LCOE projections and opportunities with concerted effort

Wind energy has grown exponentially over the past decades but its contributions to the global energy system are still small. Factors influencing growth to date have been innovations in turbines with larger rotors and higher capacity factors for overall very low cost of energy (comparable to natural gas fuel costs). However, several risks to future wind energy growth exist including:

  - Policy instability persists and the presence of policy support for wind energy is not

certain
- Falling costs of natural gas and solar energy so that wind energy needs to lower costs in order to stay competitive
- As wind energy deployment increases, the market saturates, which reduces the overall potential revenue for wind plants (falling market prices and increased curtailment).

In the future, we will have to consider balancing cost and value (returning to our overarching objectives for the workshop of looking at decreasing LCOE and increasing system value).

10:10 AM Breakouts on Wind Plant LCOE (divided into the six breakout groups listed above)

In this first session, we address the classic metric of LCOE, which is still one of, if not the, most critical metric for evaluating a wind plant. In each breakout, workshop participants will evaluate technology needs for further reduction to LCOE and its main elements: energy production, capital costs, operational expenditures, and financing.

11:30 AM Wind Plant LCOE Breakout Reporting

1:00 PM Guiding Talk

- Paul Veers, NREL, New paradigms for wind value beyond LCOE

The guiding talk to motivates the breakout session on increasing system value started again by highlighting what the future may look like with renewables providing 50% or more of the global energy supply. In these scenarios, wind power plants operate very differently than they do today. The norm of operation is curtailment and wind power plants are expected to provide significant support to the grid in terms of capacity value as well as grid services. In this future world, a greater share of the overall revenue to power plants is earned through capacity and service markets versus energy markets (the traditional dominant source of revenue).

In addition, as deployment of wind energy grows, it will have to address various nonmarket challenges, such as environmental, social, and security issues. A review of an NREL study showed that most of the United States is affected by at least one challenge to wind power development (whether environmental, radar, lack of transmission, and so on). In addition, wind energy has the potential to gain support by providing value to the local community and enabling workforce development. The breakout session that followed this talk considered innovation opportunities to address both increased system value as well as mitigating challenges to deployment and providing support for economic and workforce development.

1:20 PM Breakouts on Wind Plant Value and Deployment (divided into the five breakout groups)

In this second session, we look more broadly at what will allow or impede massive amounts of wind energy deployment. In each breakout, workshop participants will address needs for increasing deployment that are not LCOE-centric and may include grid integration issues, deployment barriers, resource availability, infrastructure, and more.

2:40 PM Wind Plant Value and Deployment Breakout Reporting

3:30 PM Guiding Talk

- Daniel Laird, NREL, Perspectives on Long-Term Research at a Fundamental Level

A short talk was used to motivate the final session around identifying R&D challenges to advance the future of wind energy toward the Grand Vision. The talk specifically highlighted some of the key research areas that are of focus to the U.S. Department of Energy Wind Energy Technologies Office research program. These included:

- System Management of Atmospheric Resources through Technology Wind Power Plants, wherein the physics across all geospatial and temporal scales are well understood to enable advanced wind power plant design, control, and operation
- Seamless and robust grid integration featuring wind plants that provide advanced grid services and energy storage
- Forecast and power system dispatch coupling atmospheric sciences, power system modeling, and system state estimation
- Advanced manufacturing capabilities enabling very large turbine deployment
- Offshore floating wind technology to enable vast deployment of offshore wind energy.

The last breakout session will be used to identify critical research needs for enabling technologies that reduce LCOE and/or enable further deployment of wind energy to achieve the scale of the Grand Vision.

Small Groups for breakout sessions

1) Manufacturing and industrialization, installation, and logistics

2) Land-based turbine technology, design, scaling, energy access, and capture

3) Offshore turbine and foundation technology, marine construction, and access

4) Wind plant technology control, storage, and design

5) Atmospheric science, forecasting, and condition-based optimization

6) Grid integration and operations; energy transfer, stability, storage, and markets (conducted during the IEA Wind Task 25 meeting on November 10, 2017).

Operations and reliability were addressed by each of the groups rather than as a separate breakout session.

Table A1. International Energy Agency (IEA) Wind Topical Experts Meeting 89 Grand Vision for Wind Energy Technology Participant List (Including Side Meetings at the Utility Variable Integration Group (UVIG) 2017 Fall Technical Workshop and the IEA Wind Task 25 Fall Meeting)

Name	Organization	Country	Meetings Attended
Aaron Barr	Wood Mackenzie	US	IEA Wind TEM #89
Aaron Bloom	National Renewable Energy Laboratory (NREL)	US	UVIG 2017 Fall Meeting
Aidan Tuohy	Electric Power Research Institute	US	UVIG 2017 Fall Meeting
Amy Robertson	NREL	US	IEA Wind TEM #89
Andrew Clifton	WindForS - Wind Energy Research Cluster	DE	IEA Wind TEM #89
Andrew Oliver	RES Americas	US	IEA Wind TEM #89
Anna Maria Sempreviva	Danish Technical University (DTU) Wind Energy	DK	IEA Wind TEM #89
Brett Wangen	Peak Reliability	US	UVIG 2017 Fall Meeting
Brian Smith	NREL	US	IEA Wind TEM #89, IEA Wind Task 25 Meeting
Bruce Rew	Southern Power Pool (SPP)	US	UVIG 2017 Fall Meeting
Carlo Bottasso	Technical University of Munich (TUM)	DE/IT	IEA Wind TEM #89
Charles Meneveau	John Hopkins University	US	IEA Wind TEM #89
Charlie Smith	Energy Systems Integration Group (ESIG)	US	UVIG 2017 Fall Meeting, IEA Wind Task 25 Meeting
Charlton Clark	U.S. Department of Energy (DOE)	US	UVIG 2017 Fall Meeting
Daniel Averbuch	IFP Energies nouvelles	FR	IEA Wind TEM #89
Daniel Laird	NREL	US	IEA Wind TEM #89
David Campos-Gaona	University of Strathclyde	UK	IEA Wind Task 25 Meeting
David Edward Weir	The Norwegian Water Resources and Energy Directorate - NVE	NO	IEA Wind TEM #89
Debbie Lew	GE	US	IEA Wind Task 25 Meeting
Derek Berry	NREL	US	IEA Wind TEM #89
Doug Rhoda	Diversified Machine Systems (DMS)	US	IEA Wind TEM #89
Ebba Dellwik	DTU Wind Energy	DK	IEA Wind TEM #89
Eric Lantz	NREL	US	IEA Wind TEM #89
Eric Smith	Keystone Towers	US	IEA Wind TEM #89
Erik Hale	Électricité de France (EDF)	US	IEA Wind TEM #89
Esmeralda Pita Jimenez	Idaho National Engineering and Environmental Laboratory (INEEL)	MX	IEA Wind Task 25 Meeting
Gavin Smart	ORE Catapult	UK	IEA Wind TEM #89
Hannele Holttinen	VTT Technical Research Centre of Finland	FI	IEA Wind Task 25 Meeting
Ignacio Marti	DTU Wind Energy	DK	IEA Wind TEM #89
Jaime Agredano Diaz	INEEL	MX	IEA Wind Task 25 Meeting
James Earle	DMS	US	IEA Wind TEM #89
James Manwell	University of Massachusetts at Amherst	US	IEA Wind TEM #89
Jan Tessmer	DLR German Aerospace Center	DE	IEA Wind TEM #89
Jason Fields	NREL	US	IEA Wind TEM #89
Jim Ahlgrimm	U.S. DOE	US	IEA Wind TEM #89
Jim Baak	West Stem, Inc.	US	UVIG 2017 Fall Meeting
Joaquim Peinke	University of Oldenburg	DE	IEA Wind TEM #89
Jody Dillon	University College of Dublin	IRL	IEA Wind Task 25 Meeting
John McCann	Sustainable Energy Authority Of Ireland (SEAI)	IRL	IEA Wind TEM #89

John Simonelli	Independent System Operator of New England (ISO NE)	US	UVIG 2017 Fall Meeting
Johney Green	NREL	US	IEA Wind TEM #89
Jonathan Naughton	University of Wyoming	US	IEA Wind TEM #89
Jose Manuel Franco Nava	INEEL	MX	IEA Wind Task 25 Meeting
Joshua Paquette	Sandia National Laboratories (SNL)	US	IEA Wind TEM #89
Katherine Dykes	NREL	US	IEA Wind TEM #89, UVIG 2017 Fall Meeting, IEA Wind Task 25 Meeting
Libing Zou	Mingyang	CN	IEA Wind TEM #89
Lionel Perret	Planair SA	CH	IEA Wind TEM #89
Lucy Pao	University of Colorado	US	IEA Wind TEM #89
Mark Ahlstrom	Nextera Energy	US	UVIG 2017 Fall Meeting
Mark O'Malley	NREL	US	UVIG 2017 Fall Meeting
Martin Kühn	ForWind - Center for Wind Energy Research	DE	IEA Wind TEM #89
Melinda Marquis	National Oceanic and Atmospheric Administration (NOAA)	US	IEA Wind TEM #89
Michael McMullin	Midwest Independent System Operator (MISO)	US	UVIG 2017 Fall Meeting
Michael Muskulus	National Technical University of Norway (NTNU)	NO	IEA Wind TEM #89
Mike Derby	U.S. DOE	US	IEA Wind TEM #89
Mike Robinson	NREL	US	IEA Wind TEM #89
Ndaona Chokani	École polytechnique fédérale de Lausanne (EPFL)	CH	IEA Wind TEM #89
Nick Miller	GE	US	UVIG 2017 Fall Meeting
Nicolaos Antonio Cutululis	DTU Wind Energy	DK	IEA Wind Task 25 Meeting
Nicole Segal	North American Electric Reliability Corporation (NERC)	US	UVIG 2017 Fall Meeting
Ola Carlson	Chalmers University of Technology	SE	IEA Wind TEM #89
Patrick Moriarty	NREL	US	IEA Wind TEM #89
Paul Denholm	NREL	US	UVIG 2017 Fall Meeting
Paul Fleming	NREL	US	IEA Wind TEM #89
Paul Veers	NREL	US	IEA Wind TEM #89, UVIG 2017 Fall Meeting, IEA Wind Task 25 Meeting
Peter Green	NREL	US	IEA Wind TEM #89
Ryan Wiser	Lawrence Berkeley National Laboratory (LBNL)	US	IEA Wind TEM #89
Sandy Butterfield	Boulder Wind Consulting	US	IEA Wind TEM #89
Scott Carron	NREL	US	IEA Wind TEM #89
Stephan BARTH	ForWind - Center for Wind Energy Research	DE	IEA Wind TEM #89
Steven Saylors	Vestas	US	IEA Wind TEM #89
Tino Oldani	Ingersoll	US	IEA Wind TEM #89
Xabier Munduate	National Renewable Energy Center CENER	ES	IEA Wind TEM #89