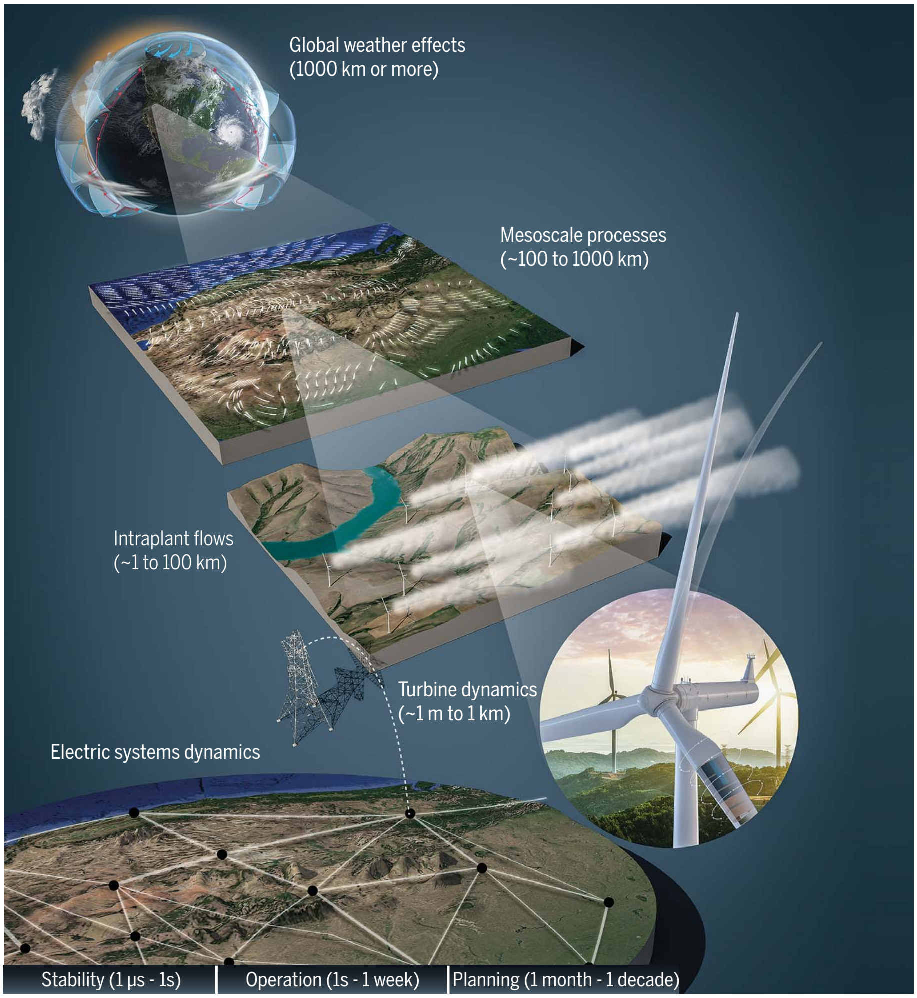
REVIEW SUMMARY

RENEWABLE ENERGY

Grand challenges in the science of wind energy

Paul Veers*, Katherine Dykes*, Eric Lantz*, Stephan Barth, Carlo L. Bottasso, Ola Carlson, Andrew Clifton, Johney Green, Peter Green, Hannele Holttinen, Daniel Laird, Ville Lehtomäki, Julie K. Lundquist, James Manwell, Melinda Marquis, Charles Meneveau, Patrick Moriarty, Xabier Munduate, Michael Muskulus, Jonathan Naughton, Lucy Pao, Joshua Paquette, Joachim Peinke, Amy Robertson, Javier Sanz Rodrigo, Anna Maria Sempreviva, J. Charles Smith, Aidan Tuohy, Ryan Wiser

BACKGROUND: A growing global population and an increasing demand for energy services are expected to result in substantially greater deployment of clean energy sources. Wind energy is already playing a role as a mainstream source of electricity, driven by decades of scientific discovery and technology development. Additional research and exploration of design options are needed to drive innovation to meet future demand and functionality. The growing scale and deployment expansion will, however, push the technology into areas of both scientific and engineering uncertainty. This Review explores grand challenges in wind energy research that must be addressed to enable wind energy to supply one-third to one-half, or even more, of the world's electricity needs.



The cascade of scales underlying wind energy scientific grand challenges. Length scales from weather systems at a global level down the boundary layer of a wind turbine airfoil and time scales from seasonal fluctuations in weather to subsecond dynamic control and balancing of electrical generation and demand must be understood and managed.

ILLUSTRATION: JOSH BAUER AND BESIKI KAZAISHVILI, NREL

ADVANCES: Drawing from a recent international workshop, we identify three grand challenges in wind energy research that require further progress from the scientific community: (i) improved understanding of the physics of atmospheric flow in the critical zone of wind power plant operation, (ii) materials and system dynamics of individual wind turbines, and (iii) optimization and control of fleets of wind plants comprising hundreds of individual generators working synergistically within the larger electric grid system. These grand challenges are interrelated, so progress in each domain must build on concurrent advances in the other two. Characterizing the wind power plant operating zone in the atmosphere will be essential to designing the next generation of even-larger wind turbines and achieving dynamic control of the machines. Enhanced forecasting of the nature of the atmospheric inflow will subsequently enable control of the plant in the manner necessary for grid support. These wind energy science challenges bridge previously separable geospatial and temporal scales that extend from the physics of the atmosphere to flexible aeroelastic and mechanical systems more than 200 m in diameter and, ultimately, to the electrical integration with and support for a continent-sized grid system.

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OUTLOOK: Meeting the grand research challenges in wind energy science will enable the wind power plant of the future to supply many of the anticipated electricity system needs at a low cost. The interdependence of the grand challenges requires expansion of integrated and cross-disciplinary research efforts. Methods for handling and streamlining exchange of vast quantities of information across many disciplines (both experimental and computational) will also be crucial to enabling successful integrated research. Moreover, research in fields related to computational and data science will support the research community in seeking to further integrate models and data across scales and disciplines. ■

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REVIEW

RENEWABLE ENERGY

Grand challenges in the science of wind energy

Paul Veers[1]*, Katherine Dykes[2]*, Eric Lantz[1]*, Stephan Barth[3], Carlo L. Bottasso[4], Ola Carlson[5], Andrew Clifton[6], Johney Green[1], Peter Green[1], Hannele Holttinen[7], Daniel Laird[1], Ville Lehtomäki[8], Julie K. Lundquist[1,9], James Manwell[10], Melinda Marquis[11], Charles Meneveau[12], Patrick Moriarty[1], Xabier Munduate[13], Michael Muskulus[14], Jonathan Naughton[15], Lucy Pao[16], Joshua Paquette[17], Joachim Peinke[3,18], Amy Robertson[1], Javier Sanz Rodrigo[13], Anna Maria Sempreviva[2], J. Charles Smith[19], Aidan Tuohy[20], Ryan Wiser[21]

Harvested by advanced technical systems honed over decades of research and development, wind energy has become a mainstream energy resource. However, continued innovation is needed to realize the potential of wind to serve the global demand for clean energy. Here, we outline three interdependent, cross-disciplinary grand challenges underpinning this research endeavor. The first is the need for a deeper understanding of the physics of atmospheric flow in the critical zone of plant operation. The second involves science and engineering of the largest dynamic, rotating machines in the world. The third encompasses optimization and control of fleets of wind plants working synergistically within the electricity grid. Addressing these challenges could enable wind power to provide as much as half of our global electricity needs and perhaps beyond.

Abundant, affordable energy in many forms has enabled notable human achievements, including modern food and transportation infrastructure. Broad-based access to affordable and clean energy will be critical to future human achievements and an elevated global standard of living. However, by 2050, the global population will reach an estimated 9.8 billion, up from ~7.6 billion in 2017 (*1*). Moreover, Bloomberg New Energy Finance (BNEF) estimates suggest that annual global electricity demand could exceed 38,000 terawatt-hours per year by 2050, up from ~25,000 terawatt-hours in 2017 (*2*). The demand for low- or no-carbon technologies for electricity is increasing, as is the need for electrifying other energy sectors, such as heating and cooling and transport (*2*–*4*). As a result of these two partially coupled megatrends, additional sources of low-cost, clean energy are experiencing increasing demand around the globe. With a broadly available resource and zero-cost fuel, as well as exceptionally low life-cycle pollutant emissions, wind energy has the potential to be a primary contributor to the growing clean energy needs of the global community.

During the past decade, the cost of three major electricity sources—wind power, solar power, and natural gas—has decreased substantially. Wind and solar are attractive because their low life-cycle emissions offer public health and broader environmental benefits. Leading energy forecasters such as consultancies, nongovernmental organizations, and major energy companies—and specifically BNEF, DNV GL, the International Energy Agency (IEA), and BP—anticipate continued price parity among all of these sources, which will likely result in combined wind and solar supplying between one- and two-thirds of the total electricity demand and wind-only shares accounting for one-quarter to one-third across the globe by 2050 (*3*–*6*). Tapping the potential terawatts of wind energy that could drive the economic realization of these forecasts and subsequently moving from hundreds of terawatt-hours per year to petawatt-hours per year from wind and solar resources could provide an array of further economic and environmental benefits to both local and global communities.

From a business perspective, at just over 51 gigawatts of new wind installations in 2018 (*7*) and more than half a terawatt of operating capacity, the global investment in wind energy is now ~$100 billion (U.S. dollars) per annum. The energy consultant DNV GL predicts that wind energy demand and the scale of deployment will grow by a factor of 10 by 2050, bringing the industry to the trillion-dollar scale (*6*) and positioning wind as one of the primary sources of the world's electricity generation.

However, to remain economically attractive for investors and consumers, the cost of energy from wind must continue to decrease (*8*, *9*). Moreover, as deployment of variable-output wind and solar generation infrastructure increases, new challenges surface related to the adequacy of generation capacity on a long-term basis and short-term balancing of the systems—both of which are critical to maintaining future grid system stability and reliability (*10*–*12*).

A future in which wind energy contributes one-third to more than one-half of consumed electricity, and in which local levels of wind-derived power may exceed 100% of local demand, will require a paradigm shift in how we think about, develop, and manage the electric grid system (*10*–*14*). The associated transformation of the power system in high-renewables scenarios will require simultaneous management of large quantities of weather-driven, variable-output generation as well as evolving and dynamic consumption patterns.

A key aspect of this future system is the availability of large quantities of near-zero marginal cost energy, albeit with uncertain timing. With abundant near-zero marginal cost energy, more flexibility in the overall electricity system will allow many different end users to access these "cheap" energy resources. Potential use cases for this energy could entail charging a large number of electric vehicles, providing inexpensive storage at different system sizes (consumer to industrial) and time scales (days to months), or channeling into chemicals or other manufactured products (sometimes referred to as "power-to-X" applications).

A second key aspect of this future system is the transition from an electric grid system centered on traditional synchronous generation power plants to one that is converter dominated (*15*). This latter paradigm reduces the physical inertia in the system currently provided by traditional power plants while increasing reliance on information and digital signals to maintain the robustness and power quality of the modern grid (*12*).

Historical development of wind energy science

Wind power was harnessed early in the history of civilization, first to propel sailing vessels and later to drive windmills that were often used for grinding grain and pumping water.

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However, it was not until the early 20th century, thanks to the pioneering work of Albert Betz and others in the burgeoning field of aerodynamics, that a foundation for wind energy science was developed (*16*) and specifically applied to electricity generation. Leveraging design principles informed by the science, "wind dynamos" were produced and deployed globally to provide power to those who could not yet access the larger electricity grid. As the modern electric system grew worldwide, however, it was the oil crisis of the 1970s that rekindled interest in renewable energy technologies and led to commercial adoption of grid-integrated wind energy systems.

Since that time, wind energy has grown from a niche resource to supply ~5% of global electricity generation (*7*). Levels in some countries have extended well beyond this global average, reaching 10%, 20%, or more in several countries around the world (*17*). This growth in wind energy deployment was associated with a marked decline in the levelized cost of energy (LCOE) driven by both research and technological learning curves (*18*). Because of the nearly half-century of sustained innovation in wind energy, levelized costs are now a fraction of the early-1970s costs. Currently, costs for wind energy are ~$0.04/kilowatt-hour (*9*, *17*) and are competitive, without subsidies, with other newly installed sources of electricity generation in a growing number of regions (*19*, *20*). The reduction in LCOE over recent decades has spurred further deployment of wind energy with annual global installations reaching >50 gigawatts and cumulative operating capacity of wind energy of more than half a terawatt (see Fig. 1).

Three fundamental drivers have reduced the cost of wind energy to date: increased hub height, power rating, and rotor diameter. These can be understood using the fundamental equation for wind turbine energy capture

$$P = \frac{1}{2}\rho C_{\mathrm{p}} A V^3$$

where P is the instantaneous power produced, ρ is the air density, C_{p} is the power coefficient (or overall machine aerodynamic-mechanical-electrical performance measure), A is the swept area of the rotor, and V is the free-stream air velocity. The design of the machine affects access to higher V, as well as performance, C_{p}, and A. Increasing hub height reduces the influence of the surface friction, allowing wind turbines to operate in higher-quality resource regimes where wind velocities are higher, with a compounding effect on power production. Larger generator capacity coupled with power electronics—which enable variable-speed operation—provides more power produced per machine installed at a given location (assuming a constant C_{p}). More power per turbine allows fewer turbine installations, lower balance-of-system costs, and fewer moving parts (for a given level of power capacity), thereby enhancing reliability. In addition, variable speed with constant frequency output allows the turbine to operate at peak C_{p} across a wide range of wind speeds for increased energy capture. The third fundamental driver is larger, more efficiently designed wind turbine rotors that sweep a greater area with advanced blades using less material. Larger rotors capture more of the energy passing by each turbine, and because blade lengths can be increased while many other costs remain fixed, they provide a substantial cost reduction on a dollar-per-unit energy basis. In addition, as the size of the rotor grows relative to the generator rating, the turbine will have a lower rated wind speed and operate more frequently at full power output. Although today's optimized, low-cost, and reliable machines—with hub heights at 100 m or more, blade lengths reaching well beyond 50 m, and power ratings of 5 megawatts and up—are the beneficiaries of decades of fundamental research and innovation, the next generation of improvement will depend on further advancements in knowledge and technology.

In this context, continued wind technology innovation is challenging, partly because of classical problems. For example, simply scaling the machine rotor diameter and rated power runs afoul of the "square–cube law," as it is commonly known within the wind industry and research community. Assuming a constant wind speed across the rotor plane, the amount

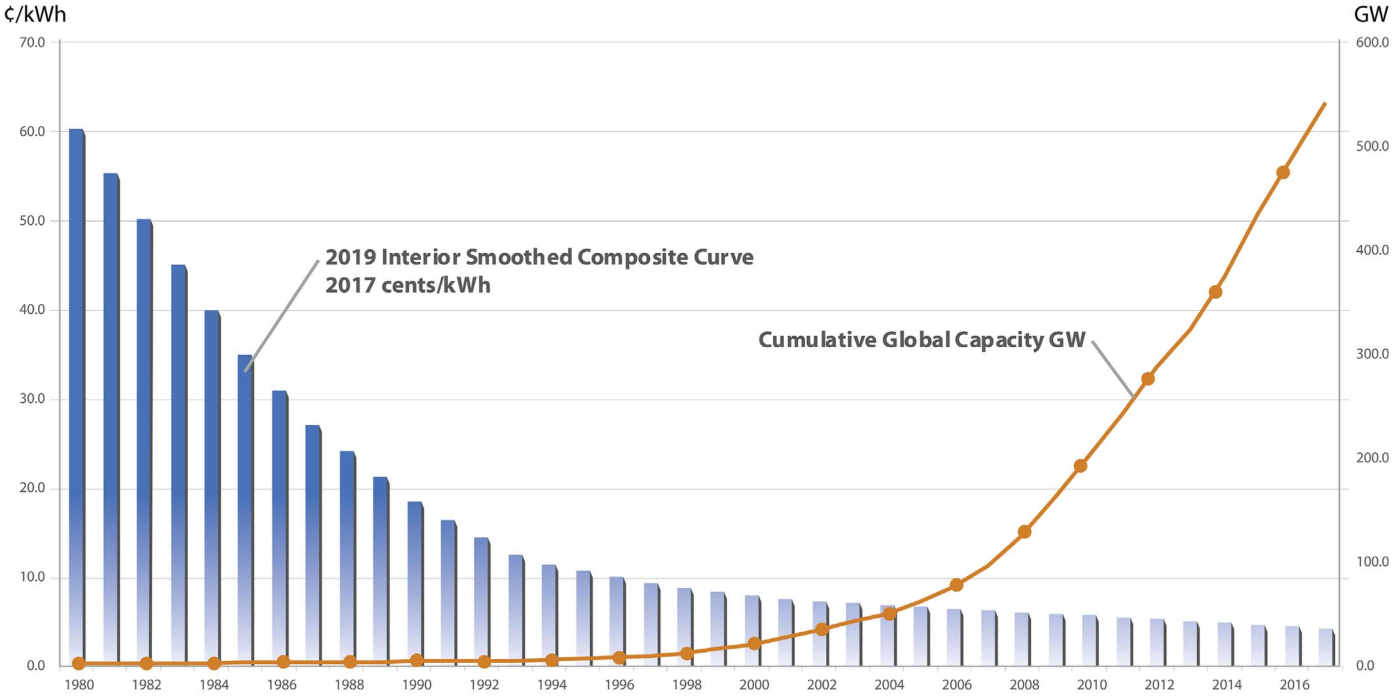

Fig. 1. Global cumulative installed capacity (in gigawatts) for wind energy and estimated LCOE for the U.S. interior region in cents per kilowatt-hour from 1980 to the present. Historical LCOE data are from (*17*) and (*20*) and have been verified for all but 5 years with the U.S. wind industry statistics database detailed in (*17*). LCOE data have been smoothed with a combination of polynomial best fit and linear interpolations to emphasize the long-term trends in wind energy costs. Historical installed capacity data are from the database detailed in (*17*), the Global Wind Energy Council, and the American Wind Energy Association.

of incorporated material scales with volume (the cube), whereas the energy capture scales only with the area of the rotor (the square). Although economies in the balance-of-system costs and elsewhere in the system mitigate the impacts of this particular problem, integrated innovation in all aspects of wind turbine design is necessary to achieve meaningful gains in per-unit energy costs.

Future wind technology innovation is further challenged by the extent of progress that has been achieved already and can be illustrated by focusing on the wind turbine blade. A modern blade is far more sophisticated in aerodynamic design, use of materials, manufacturing process, and structure than ever before (*21*, *22*) and has fundamentally different features than other aerodynamic applications such as airplane wings. Figure 2 shows a comparison of the design features of a current state-of-the-art blade versus a blade from the 1980s. Some key innovations include higher tip speeds to reduce torque and minimize drivetrain weight; higher speed and high-lift airfoils for a more slender, lighter blade; and innovative tip shapes to mitigate noise. Innovations over time have led to modern blades that are 90% lighter than the 1980s blade would be if simply scaled to current lengths. Examples include aeroelastic tailoring, which passively reduces the loads through coupling blade bending and twist; thicker flat-back airfoils, which enable improved aerodynamic performance from the load-bearing section near the hub; add-ons such as vortex generators and flow fences; and a variety of manufacturing improvements (*23*, *24*).

Grand challenges in wind energy research

The research challenges that are critical to realizing the full potential of wind energy stem from the complex and highly coupled phenomena that cross many physical and temporal scales relevant to wind energy and the broader power system. To extract maximum value at minimum cost while maintaining power system reliability and resiliency, it is important to look from global weather phenomena to regional weather activity to complex local flows, and ultimately, to the responses of the turbines within the power plant (Fig. 3). At the same time, the behavior of the wind resource varies greatly by location, as the wind resource behaves differently offshore, across plains, and over mountains. Moreover, a fleet of wind power plants must be in sync with the demands of power system operators as well as consumers at time scales ranging from the subsecond to the decade.

Although the European Academy of Wind Energy envisioned a comprehensive agenda for research challenges in wind energy in 2016 (*25*), the scale of further technology advancement and the magnitude of the challenge associated with relying on wind energy for one-third or more of the global electricity demand necessitated further examination of research needs. This additional effort sought to sharpen the focus of the wind energy research community and identify critical skills and capabilities from the broader scientific and research community that will be necessary to enable use of wind energy at very high levels. To address this need, a group of international wind power experts came together in a series of IEA Wind Technology Collaboration Programme meetings beginning in October 2017 to explore and articulate innovation pathways and associated research challenges that, if addressed, would position wind energy as a primary supplier of the world's electricity needs at levels of one-third to one-half or even more [see (*26*) for detailed findings]. These challenges were then synthesized into a set of three grand challenges requiring a comprehensive and integrated research program across many scientific disciplines (*27*).

First grand challenge: Improved understanding of atmospheric and wind power plant flow physics

Wind energy ensues from the uneven heating of Earth's surface and the Coriolis forces of Earth's rotation. It is a heterogeneous resource highly dependent on geographic location and local terrain, whether mountainous or relatively flat, in plains or deserts. The wind resource over the ocean depends on a different set of meteorological drivers, including sea and land breezes, proximity to land, water versus air temperature, and wave height. Even in specific locales, the wind varies between day and night and across seasons. Wind turbines reside in the lower levels (e.g., <300 m) of the atmospheric or planetary boundary layer. This region is referred to as the surface layer and is where obstructions such as trees, buildings, hills, and valleys cause turbulence and reduce the speed of the wind. Because the sources of wind originate in global meteorological phenomena and the subsequent extraction of energy from the wind occurs in the surface layer, the scales and physics involved reach further than those of many, if not all, other large-scale dynamic systems. Historically, simplification of the overall physics associated with different scales allowed narrowly focused research communities to thrive independently. In this context, wind designers have avoided the need to model large-scale weather effects by focusing on the flow over short durations and affected only by local topography. This approach requires assumptions such as stationarity (consistency over time) and surface-layer similarity (where momentum and heat fluxes are uniform with height) and separates the physics into flows at large mesoscales versus plant-level microscales (*28*–*30*).

More specifically, the mesoscale and the microscale are numerically modeled in fundamentally different ways, thereby making the assessment of atmospheric effects on wind plants that span these scales extremely difficult. The mesoscale processes, which influence local weather, are on the order of 5 to hundreds of kilometers in size and are typically modeled using grid spacing of 1 to 10 km. Microscale processes, the phenomena that drive wind turbine and plant behavior, extend well below 1 km and have grid spacing between 5 and 100 m horizontally. Vertically, microscale model resolution may go to within a few meters of the surface, but the flow is treated as an average over the horizontal grid spacing, making resolution of flow details that affect a wind turbine impossible. If the length scale of the process is much greater

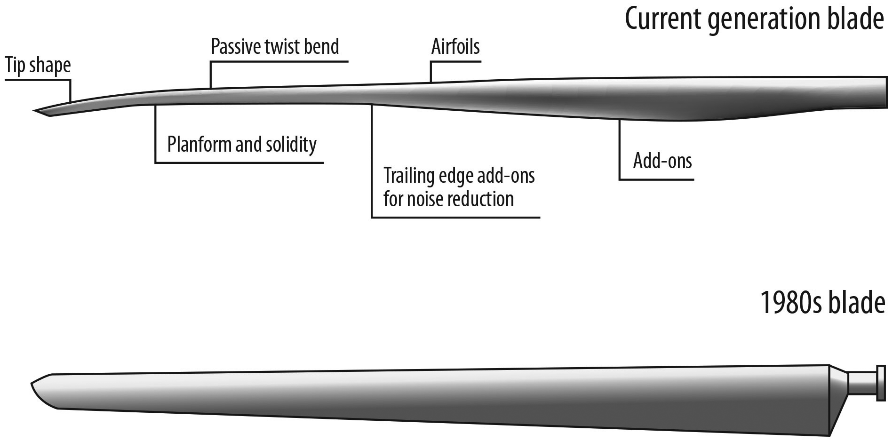

Fig. 2. Wind turbine blade innovation comparing a modern commercial blade (top) and a commercial blade from the mid-1980s (bottom) scaled to the same length. The modern blade is 90% lighter than the scaled 1980s technology.

NATIONAL RENEWABLE ENERGY LABORATORY (NREL) BASED ON A CONCEPT BY HENRIK STIESDAL AND KENNETH THOMSEN (SIEMENS GAMESA)

than the model grid spacing, the process is explicitly resolved; if the length scale of the process is much less than the model grid spacing, the process is parameterized or simplified.

Atmospheric phenomena that span approximately 1.5 to 0.5 km exist at the interface of mesoscale and microscale processes (Fig. 3). This zone, dubbed the "terra incognita" (unknown territory) by Wyngaard (*31*), spans atmospheric processes and their respective physical models of fundamentally different character and understanding. At spatial scales greater than 1.5 to 0.5 km, models resolve only average flows, parameterizing the effects of turbulence implicitly, whereas models over smaller distances resolve turbulence explicitly and simulate the time-varying, stochastic flow fields. Linking the two depends on a comprehensive understanding of the nature of the transition, an understanding that is currently elusive (*32*, *33*).

The scale that characterizes the terra incognita has become increasingly important as the economics associated with wind turbines and plants have pushed blade tip heights and rotor sizes to 200 m, with expectations for even larger sizes in the future. At this scale, wind turbines are affected by turbulent flow features that are driven by mesoscale phenomena and play out within the terra incognita. Specifically, the spatial scale of these atmospheric processes begins to match the scale and height of the turbine rotor, and accordingly, the physics of this poorly understood zone becomes critical to ensuring optimal design and performance of individual turbines and entire wind power plants (*34*, *35*).

Closely associated and interlinked with the mesoscale-to-microscale transition are additional challenges in understanding the flow physics of wind power plants. First, flow propagating through the wind power plant depends on microscale flow effects from the combined influence of the atmosphere and terrain on land, the sea surface offshore, or both. Second, interaction with the turbines themselves modifies the flow as it passes through each subsequent row of turbines in the plant.

Although past use of simplified physical models and basic observational technology has allowed for installation of wind power plants and predictions of performance in a variety of terrain types, there are still major gaps in our knowledge about wind flows in complex terrain or under varying atmospheric stability conditions that can change over the course of a day or season (*34*, *36*). Moving to offshore wind power introduces additional coupled physics of the meteorological-oceanographic (i.e., the "metocean") environment, where a nontrivial modeling uncertainty remains, especially with breaking or irregular waves, atmospheric stability, and tropical storms (*37*).

The creation of wakes—low-energy regions in the flow caused by extracting energy from that flow—is illustrated in Fig. 3 as haze streaming behind the turbines in the microscale flow graphic and behind the full wind plants in the mesoscale. The existence of wakes further complicates the process of understanding both the overall plant performance (energy production) and the loads experienced by the turbines (translating to capital and operational costs). Wind turbine wakes are complex: Their behavior varies with turbine size and design as well as different inflow and turbine operating conditions and may have long-lasting effects, both within a given wind plant and between neighboring plants (*33*, *38*–*40*).

The impact of the wake of one power plant on downstream plants and the local environment has also been explored with mesoscale modeling tools (*41*–*43*) as well as in situ measurements (*35*, *44*–*47*) but is not yet well understood. Measurable changes in the local microclimate can influence surface temperature, humidity, and agriculture (*35*, *44*), but these effects are also highly variable and difficult to predict. This is even true of offshore wind farm microclimates (*47*). Some investigators question at what point regional development of wind reaches saturation and then diminishing returns (*48*, *49*), but opinions vary widely. Wind farm wakes also change with atmospheric stability, which complicates the ability to assess interference (*50*, *51*). Finally, the regional intensity of the resource may be affected by changes in the climate (*52*), raising issues of siting and profitability for future wind power plant development. For more detailed research questions specific to relevant subdisciplines, including meteorology research and fluid turbulence, see (*53*) and (*54*), respectively.

Recent advances in measurement technologies for remote sensing (using lasers, acoustics, or radar to measure atmospheric phenomena) are being used to characterize wakes as they form and propagate through wind power plants (*55*–*60*). However, additional advances in such technologies and their use in measurement campaigns in a wide range of environmental conditions are needed to further resolve the physics of wakes and their impact on the individual turbine, overall plant, and interplant operation. In the offshore metocean environment, it is even more challenging to collect measurements (*61*). In these cases, Sempreviva *et al.* show how integration of data from lighthouses, ships, and buoys can be incorporated with remote sensing and

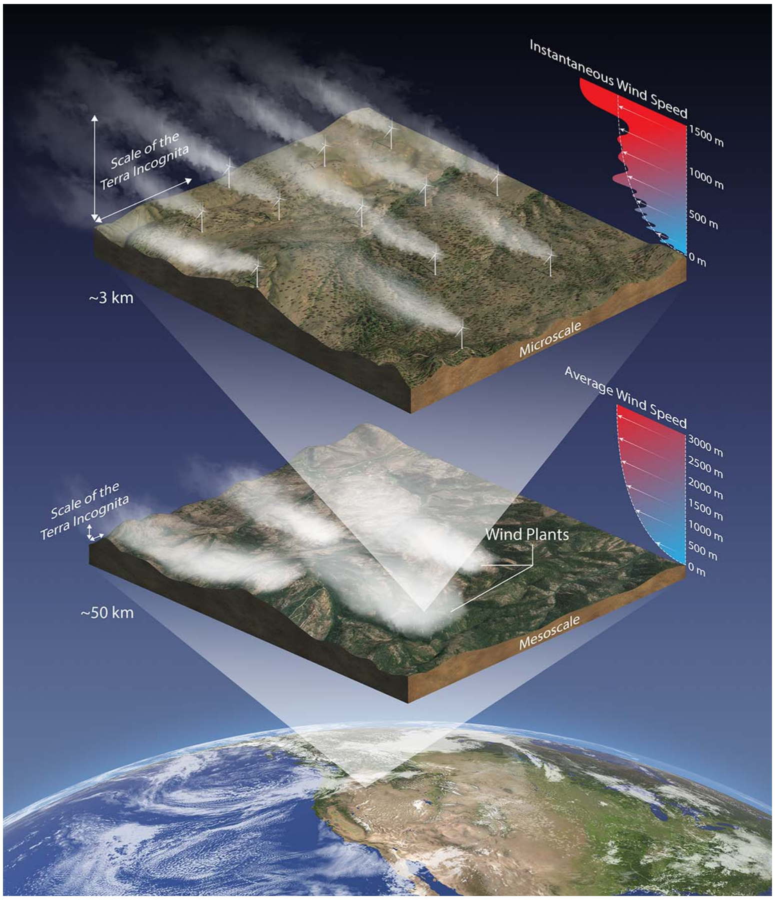

Fig. 3. Relevant wind power scales across space—from large-scale atmospheric effects in local weather at the mesoscale to inter- and intraplant flows and topography at the microscale.

ILLUSTRATION: BESIKI KAZAISHVILI, NREL

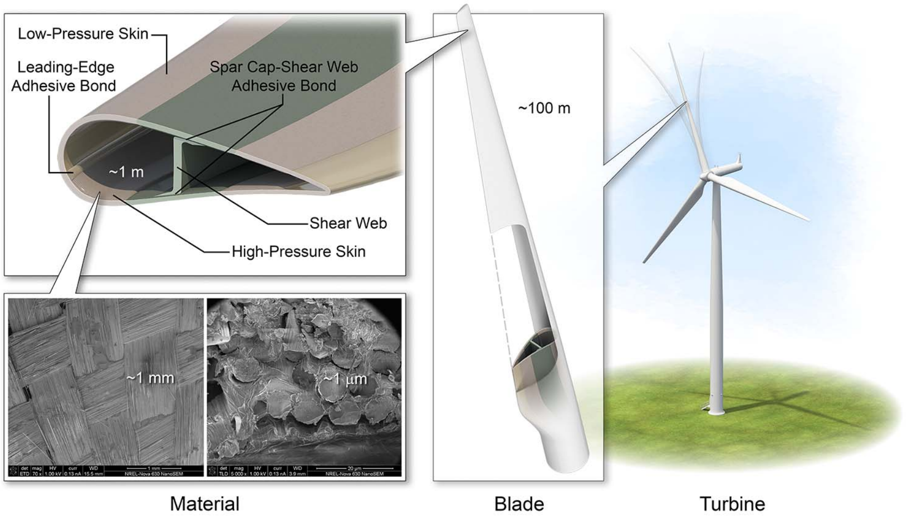

Fig. 4. Wind turbine blades are complex composite shell structures in which small-scale manufacturing flaws can grow because of the incessant turbulence-driven loading that can cause large-scale problems.

modeling (*62*). Such platforms can extend the reach of measurements but impose their own limitations, illustrating the need for greater innovation in instrumentation and techniques.

Second grand challenge: Aerodynamics, structural dynamics, and offshore wind hydrodynamics of enlarged wind turbines

An operating wind turbine may appear to be very still, apart from the rotation of the blades, yet the entire system is constantly flexing because of forces and moments in all directions and over its entire operating life of 20 years or more. Underpinning this constant movement are important couplings between the wind flow into and through a plant and the turbine responses and interaction with that flow. The dynamics of the turbine response over its lifetime requires meaningful further research.

In the past several decades, numerical wind turbine simulation capabilities that incorporate state-of-the-art knowledge of wind turbine physics (e.g., coupling aerodynamics, structural dynamics, control systems, and even hydrodynamics for offshore applications) have enabled the wind industry to design machines that deliver efficient power for years on end, surviving all weather extremes. As a result, wind turbines have grown to become the largest flexible, rotating machines in the world—massive civil engineering structures that must operate continuously for 20 years or more (a typical design and financial amortization period) under constant complex loading. Blade lengths are approaching 80 m and towers are growing well above 100 m for maximum tip heights, often exceeding 200 m, equivalent to a building more than 60 stories high. To put these dimensions in another context, three of the largest passenger aircraft, an Airbus A380-800s with a wingspan of 80 m, could fit within the swept area of one wind turbine rotor.

However, for both land-based and offshore applications, the industry is seeking even larger turbines that access higher wind speeds aloft and provide further economies of scale, reducing manufacturing, installation, and operational costs per unit of plant capacity. As machines continue to increase in size, several important research questions pertaining to wind turbine dynamics must be addressed. These questions involve the interaction of turbine dynamics with the atmosphere, wakes, and other sources of complex inflow to the rotor, as well as the high Reynolds number and aeroelastic behavior of very large and flexible machines. In addition, the dynamics associated with deployment offshore in conditions such as extreme weather events or deployment on floating platforms with additional degrees of freedom in movement must also be explored.

The larger turbines of the future would operate partly above the often-studied atmospheric surface layer where they could encounter substantial variation in inflow because of poorly characterized factors, such as shear (vertical differences in wind speed), veer (vertical differences in wind direction), and wakes of upstream turbines. The challenge lies not only in understanding the atmosphere but in deciphering which factors are critical in both power-generation efficiency and structural safety. The design perspective must increasingly consider the interdependence of the meso-to-microscale transition and the turbine dynamics to assess, accurately predict, and manage loads (*33*, *37*, *63*, *64*).

The aerodynamic assumptions themselves are increasingly being questioned. The interaction between a highly variable inflow and the unsteady aerodynamics of the moving and deforming blades is pushing the limits of current theory. Recent experiments at the largest scales now possible by the Danish Technical University (*65*) suggest that the interaction of these large blades with turbulence of different intensities could be affecting the fundamental lift and drag characteristics of the airfoil, which is not a consideration at smaller scales (*66*). Because experimental ground truth is difficult to obtain in the uncontrollable atmosphere, researchers are looking to the next generation of exascale supercomputers to provide insight that bridges the blade surface boundary layer (in micrometers) to the planetary boundary layer (in kilometers) (*67*, *68*).

The elastic displacements of these highly flexible structures complicate the aerodynamics, creating complex aeroelastic behavior of the machines as they grow in size. Blades moving through air shed vorticity, which is normally convected downstream and away from a relatively stiff structure. When the blades flex into and out of the wind, the rotor interacts with its own vorticity, calling the accuracy of the design assumptions into question. Additionally, structural dynamics of blades incorporating composite materials, built-in curvature and sweep, and large nonlinear deflection (including torsion and bend-twist coupling) further complicate models of the physics (*69*) and the assessment of crucial design aspects such as stability (*70*, *71*). In fact, although aeroelastic stability has typically not been a key design driver for rotor blades up to now, the situation may change for future highly flexible and large rotors. Indeed, stability analysis is necessary for avoiding resonance phenomena, ensuring a safe margin to flutter, and understanding the effects of low damped modes on vibrations and loading.

Offshore wind power plants require the combined modeling of aerodynamics and the hydrodynamic forces from waves and currents. Although offshore structures for a variety of applications (including oil drilling) have been designed and constructed for decades, the aerodynamic and hydrodynamic forces have not been of similar magnitudes, nor have they interacted to such an extent that coupled analysis was required (*72*–*74*). To explore configurations for offshore support structures specific to wind energy, the hydrodynamic models will need to include the combined nonlinearity and irregularity of sea states, breaking waves (*75*), viscous effects on bluff bodies at high Reynolds numbers, vortex-induced vibrations, dynamic soil-structure interactions of the seabed foundation, and more (*73*, *76*, *77*). Particularly relevant for these offshore applications are the extreme weather conditions, such as hurricanes or tropical cyclones, that are prevalent in many areas of the world where offshore

PHOTOS: NREL; ILLUSTRATION: BESIKI KAZAISHVILI, NREL

wind energy deployments are planned, such as on the East Coast of the United States or in the Pacific Ocean near Korea, Taiwan, and Japan (*78*, *79*). Han *et al.* outline the factors that must be taken into consideration when building an offshore wind power plant in regions affected by hurricanes (*80*).

Floating offshore systems, which promise to enable wind energy in large areas of the ocean with water depths of ~60 m or more, have additional degrees of freedom in the motion of the turbine platform (*74*). The uncertainty associated with the rotor interacting with its own vorticity for very large blades is amplified if the entire rotor is rocking into and out of its own wake (*81*), as could happen on a floating foundation (*82*). This aerodynamic problem is compounded by hydrodynamic complexity because the large motions undergone by these turbines violate hydrodynamic theory assumptions typically used in marine structural design (*74*, *83*). The coupled stability analysis of such complex aero-hydro-servo-elastic systems is a problem that has not been thoroughly studied in the past.

New materials and manufacturing methods are an integral part of enabling the development of these structures. Understanding the dynamics will help establish the design requirements, but materials and manufacturing breakthroughs will be needed to enable low-cost, reliable machine designs. Although wind energy has benefited from materials innovation in the past several decades—through fiber-reinforced composites, rare-earth magnets, semiconductors for power electronics, lubricants, and more—there is still a critical need to improve materials performance for particularly difficult environmental conditions and operational loads. The specific challenges related to materials science and engineering for wind energy are the need for materials to have tuned or customized properties for the specific application, as well as the need to be commoditized—that is, easily mass produced at very low cost. Ready recyclability is another desirable attribute (the blade shown in Fig. 4 is one example of a difficult-to-recycle component). The turbine blade and various subcomponents must be integrated at large scales (1 to ≥100 m), but their properties need to be tailored at small scales (1 μm to ≥1 mm).

The blade requires sufficient stiffness to avoid striking the tower, flexibility to adapt continuously to changing wind conditions, durability to last for two decades, and a surface that fights erosion while shedding moisture and dirt—all at commodity prices. Modern blades still use materials similar to those of the 1990s machines, which were based on low-cost composite fibers and durable epoxy resins. Innovations in the resin matrix, fiber reinforcement, and core materials, as well as adhesives and manufacturing protocols, are needed to achieve improved strength, stiffness, and weight properties at very low cost. Blade manufacturing would be markedly improved if thermoplastic resins could be proven viable for blades, allowing secondary welding of the composite structural elements and, perhaps most importantly, recyclability at the end of life (*84*). Beyond blades, the tower; load-bearing supports; sensors for the machine and the environment; mechanical drive components, such as bearings and lubricants; and electrical drivetrain components, such as generators, as well as semiconductors used in the inverters, power-control, and grid support functions, would benefit from further innovation.

Third grand challenge: Systems science for integration of wind power plants into the future electricity grid

The global electricity system operates on several times scales, supplying all of the demand for both bulk energy and instantaneous power. Time scales vary as a function of the need for robust grid stability and reliability, operation, and planning and extend from the subsecond to decades (Fig. 5). Within each of these broader time scales, power plants must provide many functions for the grid, including protection against lightning, short circuits, and surges; robust operation under perturbation by transients, resonance, and voltage instabilities; energy demand matching within minutes to hours; and long-term predictable and controllable supply of capacity (*10*, *11*). In addition, electricity generated by large, rotating machines, such as those now found in thermal and hydroelectric plants, creates an energy transmission grid with attributes (e.g., frequency, voltage, and phase) that are defined by the physical rotation and inertia of those generators.

As physical inertia from traditional power plants decreases relative to overall system capacity, converter-based generation, such as wind and solar power plants, must provide more predictable and controllable power as well as services that support grid reliability, stability, and formation (*85*). Wind power plants today can support many of the needs of the current grid (*86*–*88*), but additional research is needed to address how wind plants of the future and their special attributes can be used to serve the demands of a converter-based grid (*12*). The path to realizing this future will require substantial research at the intersections of atmospheric flow modeling, individual turbine dynamics, wind plant control, and the larger electric system operation. The third grand challenge encompasses three intersecting research areas: wind power plant controls, the converter-dominated electric grid, and integrated data and modeling computational methods for system analysis and operation.

As a first step, researchers must solve challenges related to wind plants by providing sufficient control authority to serve an expanding set of functionalities. Growing experience with wind plants is revealing the complexity of managing systems with hundreds of stochastically driven individual wind turbine agents. Recent research highlights the possibility of not only maximizing energy production but also managing the flow field to increase

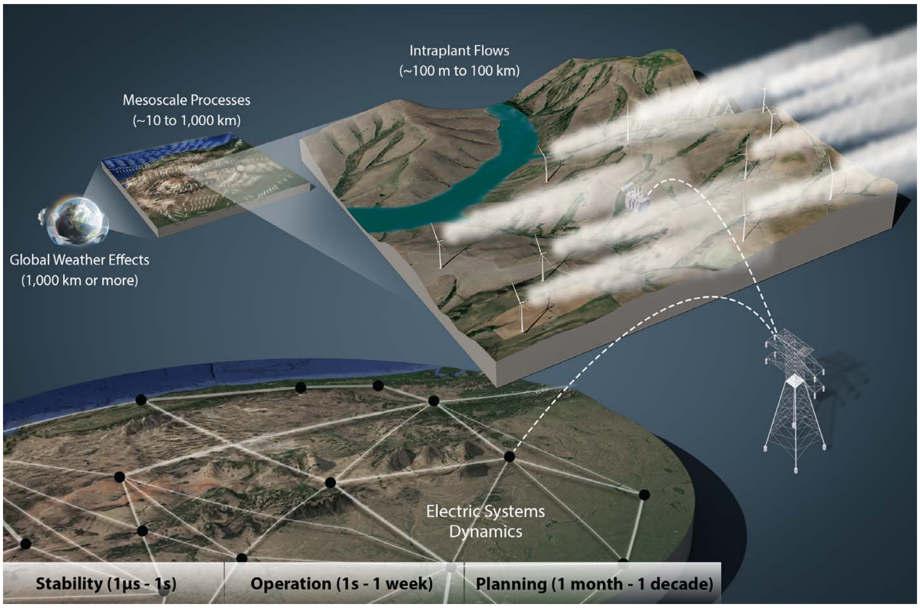

Fig. 5. Power generated by the weather-driven plant must connect to the electrical grid and support the stability, reliability, and operational needs on time scales ranging from microseconds (for managing disturbances) to decades (for long-term planning).

ILLUSTRATION: JOSH BAUER AND BESIKI KAZAISHVILI, NREL

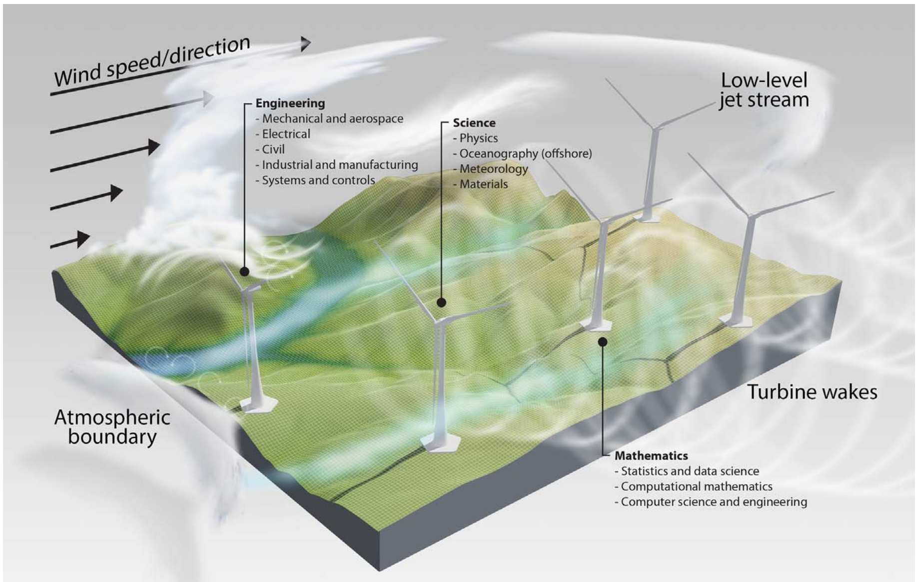

Fig. 6. A spectrum of science, engineering, and mathematics disciplines that, if integrated, can comprehensively address the grand challenges in wind energy science.

ILLUSTRATION: JOSH BAUER, NREL

system performance (*89*–*91*). By probing the collective data available during real-time operation, new opportunities for power plant control are emerging (*92*, *93*). Greater comprehension of the wind flow and dynamics enables real-time characterization of the plant operational state and the ability to control the flow and turbine responses in the short term. Innovative controls could leverage the attributes of the machines to supply ancillary services (e.g., the rotational inertia of the blades could be tapped to ride through grid faults, or the distributed power electronics in the converters connected to the generators could be used to manage grid requirements). For example, recent work has used such integrated modeling approaches to investigate the potential for active power control from wind power plants (*86*, *94*, *95*).

The research necessary to support a future converter-dominated electric grid system extends beyond individual wind power plant controls. For example, wind turbines offer a potential source of physical inertia, but the machines (as they exist today) and solar power are typically interconnected to the grid through power electronic converters, which use software and controls to confer attributes akin to traditional power plants. Wind power plants of the future equipped with the appropriate power electronics could provide physical inertia or "synthetic inertia," with the latter enabling wind turbines to function as virtual synchronous generators (*12*, *96*, *97*). Studies that have considered up to 25% contributions of renewables to the grid need to be further refined for shares that reach beyond 50% or even 80% (*98*–*101*).

New sensors and data management techniques will also be needed to obtain and transmit real-time data on the status of the future grid, which will be governed more on information than physical inertia. Data sources will comprise a combination of measurements and simulations. Opportunities are ripe for advanced stochastic system analysis and data science that can extract meaning and direction from a combination of regional weather status and forecasts, millions of signals describing individual turbine and plant states, and real-time updates from throughout the grid. In addition, the substantial sources of uncertainty in various aspects of the system operation (from the weather-driven effects on renewable energy availability and electricity demand to availability of storage and a host of other phenomena) make this an extremely large stochastic and dynamic optimization problem that will require greater involvement by the applied mathematics and computational science communities (*98*, *101*, *102*).

A role for integrative wind energy science

These wind research grand challenges build on each other. Characterizing the wind power plant operating zone in the atmosphere will be essential to making progress in designing the next generation of even larger low-cost wind turbines, whereas understanding both dynamic control of the machines and forecasting the nature of the atmospheric inflow will enable the control of the plant necessary for grid support. Wind energy science also involves the coupling of physics across an increasingly large range of spatial and temporal scales in the atmosphere, enormous flexible aeroelastic and mechanical systems, and electrical integration with and support for a continent-sized grid system.

Although advances in individual scientific disciplines will continue to be tremendously important, recognition of the value in understanding the cross-disciplinary considerations and drivers of the technology is also paramount. In a similar way to how the aerospace discipline has driven profound achievements in materials, manufacturing, aerodynamics, structures, and controls while innovating the broader systems of aircraft and spacecraft, the emerging discipline of wind energy science seeks to leverage deep disciplinary expertise with a systems knowledge that addresses complex and multifaceted challenges.

Successful examples of integrated wind energy research are already in place at several universities and research organizations where nationally and internationally funded projects are interdisciplinary by design and aimed at tackling some of the challenges described in the preceding sections. These institutions have begun to train the next generation of scientists and engineers in departments devoted specifically to wind energy. The European Wind Energy Academy, a collaboration of more than 40 European universities with major activities in wind energy research and education, is another example of an effort to organize a scientific discipline around wind energy. Future growth of wind energy to serve global clean energy needs is expected to demand more dedicated wind energy research, cutting across the traditional disciplines. A move to embrace this shift toward studying wind energy science as its own discipline can be achieved by drawing in researchers from a range of different fields, as shown in Fig. 6.

In addition to the wide-ranging science, engineering, and mathematics needs for integrated wind energy research, methods for handling and streamlining exchange of vast quantities of information across many disciplines (both experimental and computational) will be crucial to enabling successful integrated research (*33*, *96*, *101*, *103*, *104*). Research in fields related to computational and data science will further support the wind scientific community as it seeks to integrate models and data across different scales and disciplines (*105*, *106*).

This interdisciplinary wind energy science and engineering approach offers the potential to develop solutions that not only advance the state-of-the-art in turbine subsystems but also create the integrated solutions necessary for advancing the entire system—from the turbine to the plant to the overall electrical grid. These gains are most likely to be successful when activities in a respective area are informed by a comprehensive view of the realities of the larger context. The long-term research challenges are ripe for immediate action, and progress will depend on a generation of scientists educated deeply in their own specialty as well as in the breadth of wind energy science.

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Science

Grand challenges in the science of wind energy

Paul Veers, Katherine Dykes, Eric Lantz, Stephan Barth, Carlo L. Bottasso, Ola Carlson, Andrew Clifton, Johney Green, Peter Green, Hannele Holttinen, Daniel Laird, Ville Lehtomäki, Julie K. Lundquist, James Manwell, Melinda Marquis, Charles Meneveau, Patrick Moriarty, Xabier Munduate, Michael Muskulus, Jonathan Naughton, Lucy Pao, Joshua Paquette, Joachim Peinke, Amy Robertson, Javier Sanz Rodrigo, Anna Maria Sempreviva, J. Charles Smith, Aidan Tuohy and Ryan Wiser

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A multifaceted future for wind power

Modern wind turbines already represent a tightly optimized confluence of materials science and aerodynamic engineering. Veers *et al.* review the challenges and opportunities for further expanding this technology, with an emphasis on the need for interdisciplinary collaboration. They highlight the need to better understand atmospheric physics in the regions where taller turbines will operate as well as the materials constraints associated with the scale-up. The mutual interaction of turbine sites with one another and with the evolving features of the overall electricity grid will furthermore necessitate a systems approach to future development.

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