# Grand Challenges: Wind energy research needs for a global energy transition

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**Abstract.** Wind energy is anticipated to play a central role in enabling a rapid transition from fossil fuels to a system based largely on renewable power. For wind power to fulfil its expected role as the backbone—providing nearly half of the electrical energy—of a renewable-based, carbon-neutral energy system, critical challenges around design, manufacture, and deployment of land and offshore technologies must be addressed. During the past three years, the wind research community has invested significant effort toward understanding the nature and implications of these challenges and identifying associated gaps. The outcomes of these efforts are summarized in a series of ten articles, some under review by *Wind Energy Science* (WES) and others planned for submission during the coming months. This letter explains the genesis, significance, and impacts of these efforts.

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Governments and industries around the world have pledged to reduce their greenhouse gas emissions to zero during the next two to three decades, supporting the Intergovernmental Panel on Climate Change recommendations to limit the warming of the planet. Decarbonizing the energy sector, shifting the electricity supply to renewable sources within the next two decades (Cole et al., 2021; Denholm et al., 2021; IPCC, 2022), is a first step. Projections by leading energy observers (IEA, 2021a; GWEC, 2021; Larson et al., 2020) are that the new electric sector will rely on 70%–90% variable renewable generation. The increase in renewables is expected to be roughly split between wind and solar energy. Therefore, to achieve a carbon-pollutionfree electricity sector near-term and net-zero greenhouse gas emissions by mid-century, wind energy must increase its contribution to power generation from its current 5% level of global penetration to supply 35%–50% or more of future electricity demand in a highly electrified global energy system (IEA, 2021a). Clearly, wind will be a foundational energy source in the electricity grid at the heart of a future integrated-energy system, replacing traditional electricity generators powered by fossil fuels and providing grid-reliability services in addition to energy (Hodge et al., 2020; Holttinen et al., 2020). Future capabilities and functions of the wind energy sector will evolve apace with the future expansion and needs of global energy infrastructure (e.g., manufacturing green fuels to create demand flexibility and decarbonizing sectors that are difficult to electrify). However, wind turbines, as designed today, will not be able to provide the services needed to form and to stabilize the grid as a majority supplier. Meanwhile, wind power plants will have an ever-expanding footprint that will inevitably multiply social and environmental impacts. Efficiently and affordably deploying wind plants at larger scales, in diverse landscapes, and in deep water offshore, will be extremely challenging. The notion that we can simply take hardware that has been successful to this point and multiply the deployment by a factor of 5 or 10 fails to appreciate the harsh reality that the technology demands of the future will be significantly different than they have been to date. The International Energy Agency (IEA) observed (IEA, 2021b) that in moving toward a new energy economy "every data point showing the speed of change in energy can be countered by another showing the stubbornness of the status quo," which could not be more applicable to wind.

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> *"The new energy economy will be more electrified, efficient, interconnected and clean. Its emergence is the product of a virtuous circle of policy action and technology innovation, and its momentum is now sustained by lower costs…* ***At the moment, however, every data point showing the speed of change in energy can be countered by another showing the stubbornness of the status quo."***
>
> ***(IEA World Energy Outlook, 2021a)***

A review article in *Science* (Veers et al., 2019) emerged from an IEA Wind Topical Experts Meeting assessing the "Grand Challenges" for wind energy to meet its full potential (Dykes et al., 2019). The *Science* article condenses the outcome of that workshop to make the case that wind technology has grown to turbine sizes, plant scales, and grid impacts that force a re-evaluation of the very scientific underpinnings of wind energy. Three critical technical challenges emerged: the atmosphere, the turbine, and the plant/grid interaction. Wind energy systems are so intrinsically interconnected that continued progress requires attention to all three challenges—progress in any single area is insufficient. Crosscutting opportunities in digitalization and integrated education of the next generation of researchers and technicians were also noted. The publication quickly elicited two insightful letters to the editor pointing out that the focus on issues of the physical sciences missed the equally critical areas related to environmental impacts (Katzner et al., 2019) and social interactions (Firestone, 2019). In addition, the Small Wind Turbine Technical Committee of the European Academy of Wind Energy (EAWE) assessed the status of small turbine technologies and identified needs for contributing to distributed energy production; these lie in an entirely different realm of physics and application.

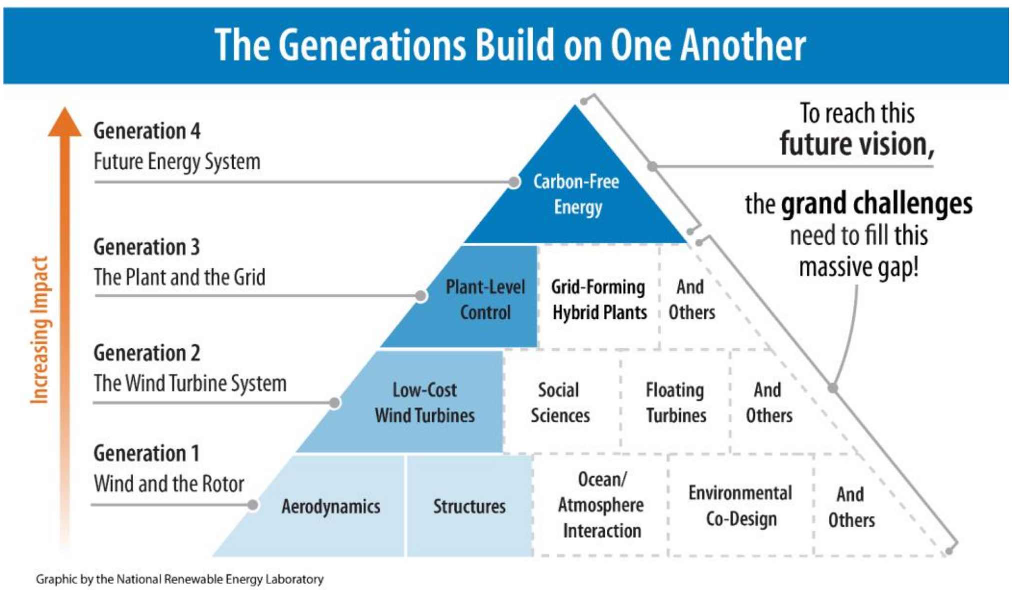


**Figure 1: This graphic illustrates the generations of wind energy development. Each generation's achievements expanded wind energy's impact (shown in the blue boxes on the left); however, in moving quickly from generation to generation, some underlying science was left unresolved (shown in the white boxes on the right). Generation 1 delivered working energy conversion systems, Generation 2 low-cost and reliable turbines, and Generation 3 is beginning to provide controllable wind plants that support the grid. The aspirational goal of Generation 4 is a carbon-neutral future energy system. Wind can be the foundation for the fourth generation, but not until the gap left behind by the previous generations is addressed. (Graphic based on (Veers, 2022))**

The *Science* article was by design a highly condensed statement of wind energy's progress, potential, and high-level scientific gaps. The need still exists to articulate a more detailed and actionable set of recommendations. The original authors engaged a larger group of experts to review each grand challenge in more depth and provide recommendations for how outstanding issues might be resolved, including the environmental and social aspects highlighted by the letters to the editor. In an article clarifying the scientific efforts related to the pandemic, Yong (2021) advises that environmental and social issues are part of the integrated problem. He states, “The pandemic made it clear that science touches everything and everything touches science.” In reality, physical, social, and environmental processes all interact to influence the growth of wind energy. We are only now beginning to appreciate and understand these competing issues, not only with regard to wind energy, but also the range of factors—technology development, policy, public acceptance, economic, public-private partnerships, etc.—necessary to ensure a successful energy transition. Continued research efforts and investments are needed to drive customizable solutions that meet local needs and scale up to achieve regional and global decarbonization goals.

Supplying half of our future projected electricity demands requires research, design, and development of wind power plants at scales and in locations where we have little experience. Offshore wind plants will need to access areas with deeper water and rely on floating foundations. Observations of the offshore wind resource and its dynamic environment remain quite sparse. Wind plants in close proximity with others offshore, as well as on land in flat, hilly, and mountainous terrain, will need to be optimized for their interactions, which are also poorly characterized. The new turbines will need to be larger, longer, lighter, and collectively controlled to both optimize plant productivity in lower resource areas and meet the electrical system operational demands. Wind power plants will be expected to serve as the backbone of the electricity system, forming the grid and providing essential grid reliability services, often hybrid with storage and other renewable energy systems, to enable more comprehensive services. Success to date has been achieved by engineering around gaps in our knowledge, with solutions often driven by experience as much as by fundamental understanding. Unfortunately, this approach can no longer provide the innovation demanded to support the systems of the future. There is both a tremendous potential for wind energy and a massive knowledge gap between where we are and where we need to be. The good news is that the community has developed a plan to address the scientific and technological challenges, which are surmountable, with appropriate investments.

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With the support and guidance of the EAWE Publications Committee, draft articles are being submitted to WES throughout 2022. This collection of articles reviews the broad sweep of wind energy research needs and proposes actions that will enable wind to be a foundation for the energy system of the future. The charter for the authors was not to suggest particular, innovative solutions or to tout specific technology advances, but to review the literature and to articulate the most critical needs, with the intent to synthesize and clarify. From this assessment of the current status of the field, recommendations for critical actions emerge. These articles are not specifically intended to be road maps but to provide the basis for road maps developed by agencies, governments, or other groups as they seek to prioritize resource allocations.

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Shifting the global energy system away from carbon-based sources will require an investment of trillions of Euros in wind energy installations. This shift cannot be expected to succeed at current research and development levels of investment. By articulating the magnitude of the gaps, required resources, and roadblocks, these articles make a case for increased resources to respond effectively to the challenge of deploying wind power everywhere.

In total, ten articles will be submitted this year; each expresses a portion of the total story and recommends needed action to fill critical gaps. To access the articles in this series, visit https://eawe.eu/organisation/committees/publications-committee/.

**Individual articles describe the research challenges in each area**

**Grand Challenge 1: The Atmosphere**

*"Impact of Atmospheric Turbulence on Performance and Loads of Wind Turbines: Knowledge Gaps and Research Challenges"*

Atmospheric turbulence at all scales, but especially at the more impactful scales of the turbine and plant, has not been characterized in the detail required to achieve optimal wind turbine performance and reliability. There is a need to better characterize turbulence and its effects under the large range of atmospheric conditions in which wind plants are expected to continuously and reliably generate power.

*"Mesoscale Wind Plant Wakes"*

Wakes, or regions of slower and more turbulent air downwind of wind plants, are still not fundamentally well understood, even as interactions between wakes and the atmosphere dictate wind plant cost-effectiveness. Further, the large-scale deployment of wind may introduce broad impacts on local microclimates, which must be assessed and evaluated.

*"Scientific Challenges to Characterizing the Wind Resource in the Marine Atmospheric Boundary Layer"*

The offshore metocean environment differs significantly from that on land, while one coastal area differs from another. The offshore environment needs greater definition and physical understanding to optimize offshore wind plants to suit their local environments.

**Grand Challenge 2: The Wind Turbine**

*"Grand Challenges in the Design, Manufacture, and Operation of Future Wind Turbine Systems"*

From the inflow to the manufacturing of massive parts, the size and flexibility of modern turbines have pushed design out of the territory where the design assumptions and modeling tools were first established, which creates unprecedented risks to applicability. Fundamentally, we lack the experimental data at the large scale necessary to validate the models and materials used to develop innovative solutions for future systems.

*"Current Status and Grand Challenges for Small Wind Turbine Technology"*

While modern wind turbines have become by far the largest rotating machines on Earth, a renewed interest in small wind turbines is fostering energy transition and smart grid development. Small machines have traditionally not received the same level of design refinement as their larger counterparts, resulting in lower efficiency, lower capacity factors, and therefore a higher cost of energy.

**Grand Challenge 3: The Plant and Grid**

*"Wind-farm Flow Control: Prospects and Challenges"*

Managing the flow through wind plants is a complex challenge, but offers opportunities to evolve optimal plant design, enhance production, lower maintenance costs, and provide the controllability demanded by the larger energy system.

*“Grand Challenges of Wind Energy Science – The Grid”*

Increased wind and solar photovoltaics (PV) penetrations are changing the very nature of the power system due to (1) the connection between generation and the electricity grid through power electronics rather than synchronous machines and (2) the inherent variability and uncertainty of the primary energy source. A grid dominated by wind and solar PV will impose system needs that will also challenge how we approach the design of individual turbines, wind plants, hybrid plants, and the grid itself.

**Crosscut: Digitalisation**

*“Grand Challenges in the Digitalisation of Wind Energy”*

A future in which digitalisation has made data accessible in the right places and at the appropriate times has many valuable outcomes, but significant technical and cultural impediments remain to be resolved before achieving that aspirational goal for wind energy.

**Beyond Technical Borders: Environmental and Social Issues**

*“Interdisciplinary Research Challenges in Wind Energy at the Intersection of Engineering and Environmental Science”*

Multidisciplinary systems engineering principles can bridge the gap from environmental stressors to wind plant design and operation and address critical wildlife impacts. Environmental research must define wildlife and habitat impacts of large-scale deployment in collaboration with engineering of turbines and plants. Custom solutions for specific environmental constraints can provide optimal designs suited to the local ecosystem, i.e., to achieve coexistence and create synergies.

*“Social Aspects of Wind Energy Development”*

Deployment of wind energy is expected to expand 5 to 10 times beyond current levels and will interact with human communities across several continents, as well as those living near and deriving their livelihoods from the sea. The social aspects of how wind plants interact with the communities where they are built as well as communities served by low-cost clean electricity need to be addressed. Solutions will need to venture beyond decontextualized and simplified assessments of acceptance and outdated not-in-my-backyard concepts to include engagement in planning processes and different ownership structures, as well as participation in design, to embrace the transition as a shared task among members of society.

**Summary**

*Wind Energy Science*, through its open review approach, offers an excellent opportunity for the wind community to engage in discussion on the nature of critical research needs and recommendations for their fulfilment. We hope that the open dialogue enabled by WES will be exercised by the research community, and we enthusiastically invite you to engage in the conversation and tackle the challenges towards realizing our future wind-based global energy system.

**Author Contribution**

PV and KD led the work and provided the initial and subsequent drafts. The entire author team supplied comments, recommended changes, and edited several drafts to achieve the final manuscript.

**Competing interests**

Some authors are members of the editorial board of Wind Energy Science. The peer-review process was guided by an independent editor. The authors have no other competing interests to declare except what is implied by their affiliations.

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