GRAND CHALLENGES REVISITED

Wind Energy Research Needs for a Global Energy Transition

Technology Collaboration Programme
by iea

IEA Wind TCP Task 11
Technical Report

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List of Acronyms and Abbreviations

AI/ML	artificial intelligence/machine learning
IEA	International Energy Agency
LCOE	levelized cost of energy
LES	large-eddy simulation
MMC	mesoscale-to-microscale coupling
O&M	operations and maintenance
R&D	research and development
TCP	Technology Collaboration Programme
TEM	Technical Experts Meeting

Executive Summary

Wind energy currently provides low-cost, carbon-free electricity, supporting the grid in many regions where it supplies more than a third of annual energy and occasionally supplies the majority of the real-time electricity demand.[1] Many countries around the world, motivated by the technology's benefits as well as national energy security motives, have set ambitious deployment targets for wind energy for the next decade and beyond (International Energy Agency 2023). Government support to achieve these ambitious targets forms a strong driver for increased wind energy deployment. However, achieving an energy system that depends on wind for half of global electricity will require deployment of wind generators around the world *at an order of magnitude greater than current installed capacity.*

This major transition requires wind plants to be deployed in more locations where to date they have not been developed and/or proven, such as deep-water offshore sites and low-wind-resource land-based sites. The targeted penetration levels should be planned with careful consideration of impacts on grid resilience, as well as the intersection of increased deployment with the environment (i.e., wildlife, waste, emissions) and society. Continuous growth in wind energy deployment requires sustained value creation, meaning a balanced spread of risk and profitability across the supply chain, while providing not only renewable energy at a cost point that is at parity with conventional sources of electricity production but also good-paying and secure jobs for the hundreds of thousands of people employed in this industry.

Superimposing these drivers and limiters for accelerated deployment with the need for sustainable value creation highlights the gaps in the current state of the science that need to be addressed to create a future in which all objectives can be satisfied. The Grand Challenges of wind energy (Veers et al. 2019, Veers et al. 2022) summarize the gaps in the scientific foundation. Specifically, the Grand Challenges of wind energy relate to our inadequate understanding of and inability to accurately model 1) the atmosphere, 2) the turbine, 3) the plant and grid, 4) the environmental impacts, and 5) social interactions. Progress in making wind energy a foundational energy source for the clean energy transition depends on making progress in all five of these Grand Challenge areas.

Prior publications have highlighted the Grand Challenges (National Renewable Energy Laboratory n.d.) and are continuing to define the issues within each area. The International Energy Agency (IEA)Wind Energy Systems Technology Collaboration Programme's (TCP's) Topical Experts Meeting (TEM) #109 was convened Feb. 28–March 1, 2023, in Boulder, Colorado, USA, to further explore these five individual Grand Challenges and their intersections.

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[1] For example, the Southwest Power Pool (SPP), a U.S. regional transmission organization that serves 14 states, reported several renewable records on March 28 and 29, 2022. On March 29, Southwest Power Pool served 90.2% of the demand for electricity across its service territory with renewable energy sources. Of total demand, 88.5% was served by wind. On March 28, the organization set a wind production record of 22,915 MW (Southwest Power Pool 2022). As another example, in Denmark in 2021, wind-generated electricity as a percentage of national electricity demand was 43.8% (International Energy Agency 2021b), and in 2017, the entire nation was powered by wind energy for a day (Wind Europe 2017).

Each expert group identified three critical issues that must be addressed in their area for wind energy to fulfill its role in the clean energy transition (Table ES-1).

Table ES-1. Wind Energy Grand Challenge Areas and Critical Issues for Each

Grand Challenge Area	Critical Issues
The Atmosphere	Increasing atmospheric observations Expanding and validating universal predictive capability Integrating and adopting improved models
The Turbine	Incorporating holistic design Developing intelligent controls, operation, and maintenance Advancing industrialization
The Plant and Grid	Improving modeling Optimizing plant design for multiple objectives Readying the next generation of wind plants for grid support
Environmental Co-Design	Avoiding, minimizing, and compensating for the direct and indirect environmental impacts Incorporating environmental costs and benefits into every decision point Accounting for immediate concerns while addressing future impacts and trade-offs
Social Science	Acknowledging the transformational nature of rapid, large-scale wind energy development Creating just processes Valuating benefits, effects, and burdens

One critical goal of the TEM #109 meeting was to examine the cross-disciplinary issues created by the intersections between the challenges. These intersections are known to some extent but do not always receive the attention needed because they stretch individual areas of expertise outside of traditional boundaries. This stretching and resultant lack of attention is most prevalent among the first three challenges, which are more technology focused, and the last two, which deal with external consequences. The TEM was organized to create space for dialogue to explore the crosscutting challenges and to document critical issues.

With five Grand Challenges, there are ten crosscutting combinations to be explored. A pre-meeting survey revealed substantial interest in eight areas (the lone exception being the intersection of social issues with the atmosphere). The organizers omitted one option—the crosscut between social and environmental issues—on the assumption that these groups would be represented by fewer participants than the others and the experts would be spread too thin to cover all the crosscuts. Feedback from the attendees confirmed high levels of interest in this intersection; perhaps counterintuitively, these groups rarely have a chance to interact. Participants concluded that a follow-on meeting devoted to social and environmental interactions would be useful. Table ES-2 summarizes the cross-cutting challenge areas and resulting critical issues.

Table ES-2. Wind Energy Grand Challenge Opportunities for Interdisciplinary Work and Critical Issues for Each

Grand Challenge Opportunities for Interdisciplinary Work	Critical Issues
Environment-Turbine	Establishing common language and definitions Understanding material needs for scale of build-out Incorporating environmental co-design Communicating research needs Deploying dual-purpose technologies Engaging turbine manufacturers Improving data collection, digitalization, and sharing
Turbine-Atmosphere	Improving open-design bases Improving annual energy production estimates Improving design standards
Atmosphere-Grid/Plant	Improving flow control Deploying dispatchable hybrid plants Connecting the grid to the weather Leveraging real-time data Conducting risk assessment across time scales
Grid/Plant-Turbine	Improving communication between groups Collaborating on turbine design requirements
Grid/Plant-Environment	Developing shared understanding between grid/plant-wildlife/biosphere communities Developing integrated approaches to wind energy systems engineering for environmental considerations
Atmosphere-Environment	Addressing data gaps related to interactions among landscape features, atmospheric conditions, and wildlife movement patterns Evaluating an alternative, overarching target for reducing carbon in the atmosphere
Turbine-Social	Creating just processes Investigating and characterizing noise Investigating and characterizing visual impact Investigating and characterizing policies
Social-Grid/Plant	Expanding data collection and decision-making processes Considering grid integration Supporting future-focused, empowered regions and communities Expanding understanding of potential benefits Addressing cost expectations

Meeting participants also noted that although many different areas of wind energy expertise were represented at the TEM #109, few turbine manufacturer representatives attended. Including industry members is crucial to identifying the gaps in science and technology to mitigate the impacts of wind deployment while ensuring sustained value creation. Although 2023 was a difficult year for the industry, this workshop operated under the working assumption that the industry will weather the storm. The community recognizes the need for a profitable industry that serves the expanding wind energy market of the future.

All crosscutting groups observed three common issues. First, the dialogue revealed a lack of understanding of some of the basic concepts and terminology foundational to one group by the other. Education that crosses traditional boundaries will be needed to support clear communication and establish collaborative working relationships. Second, the need to aggregate, manage, and control access to massive data sets while protecting intellectual property was noted across all groups. Many issues might be resolved if the data that already exist could be brought to bear. The revolution in digitalization offers solutions to this combined opportunity and challenge but is yet to be fully engaged. Third, these discussions are highly enlightening and needed in more locations and in greater number if solutions are to be found in these overlapping areas. The documented findings in this report should open the door to future cross-disciplinary efforts that can progress from identifying critical issues to finding the solutions necessary for the substantial expansion of wind energy. Success could enable wind energy to supply 50% or more of the electricity demand in a future global energy system.

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1 Introduction

In support of the Intergovernmental Panel on Climate Change and its recommendations to limit further global warming, governments and industries have pledged to reduce their greenhouse gas emissions. A first step in this effort is decarbonizing the energy sector within the next two decades by transitioning electricity generation to renewable sources. Energy industry observers have predicted that this new electric sector will rely on 70% to 90% variable renewable generation, with wind and solar energy likely contributing equally. Achieving a near-term carbon-free electricity sector and net-zero greenhouse gas emissions by midcentury means that the percentage of wind energy supplying electricity demand in a future global energy system must increase from 5% to between 35% and 50% or more (International Energy Agency 2021a).

Wind energy is poised to be a foundational energy source in an integrated energy system of the future, replacing traditional fossil-fuel-powered electricity generators while providing grid reliability services. Wind energy's future capabilities and functions will evolve as the future expansion and needs of global energy infrastructure evolve (e.g., manufacturing green fuels to create demand flexibility and decarbonizing sectors that are difficult to electrify). Today's wind turbines, however, cannot serve as a majority supplier to form and stabilize the future grid.

As wind power plants expand, social and environmental impacts will likely be magnified. It will be extremely challenging to deploy wind plants at larger scales and in increasingly diverse landscapes, both onshore and offshore, while incorporating efficiency and affordability. According to Veers et al. (2022), "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 technology demands of the future will be significantly different than they have been to date." The International Energy Agency (IEA) observed 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." This statement absolutely applies to wind energy.

1.1 Motivation for IEA Wind TCP Technical Experts Meeting #109

In 2017, more than 70 experts representing 15 countries gathered at the IEA Wind TCP Technical Experts Meeting (TEM) #89 Grand Vision for Wind Energy workshop. The experts were asked to consider the following question: "How can we enable a future in which wind energy supplies more than 50% of global electricity consumption?" To develop this vision, the experts gathered during one or more of the following meetings:

- The IEA Wind TCP TEM #89 meeting at the National Renewable Energy Laboratory in Golden, Colorado, USA, October 22–23, 2017
- The Utility Variable Integration Group 2017 Fall Technical Workshop in Nashville, Tennessee, USA, October 12, 2017
- The IEA Wind TCP Task 25 Fall 2017 Meeting at the Instituto Nacional de Electricidad y Energías Limpias in Cuernacava, Mexico, November 20, 2017.

After the IEA Wind TCP TEM #89 workshop, researchers aggregated the community observations and worked to identify how the unknowns impede progress. A 2019 *Science* article titled “Grand Challenges in the Science of Wind Energy” (Veers et al. 2019) provided an overview of the work. The three Grand Challenges were summarized as:

- Improved understanding of the physics of atmospheric flow in the critical zone of wind power plant operation
- Materials and system dynamics of individual wind turbines
- Optimization and control of fleets of wind plants comprising hundreds of individual generators working synergistically within the larger electric grid system (Veers et al. 2019).

The *Science* article attracted two critical letters[2] noting that the Grand Challenges neglected social and environmental challenges. These critical considerations were added to the Grand Challenges and incorporated into the ongoing work.

With the support and guidance of the European Academy of Wind Energy Publications Committee, researchers submitted draft articles to *Wind Energy Science* on all five Grand Challenge areas throughout 2022 and 2023. These articles reviewed wind energy research needs that, if met, would enable wind energy to be a foundation for the energy system of the future. Authors were directed to “not suggest innovative solutions or tout specific technology advances” but rather to “review the literature and articulate the most critical needs, with the intent to synthesize and clarify.” These assessments became the basis for recommendations for critical actions.

These articles provided the basis for road maps as well as a starting point for discussions during the IEA Wind TCP TEM #109, a subsequent gathering that was convened Feb. 28–March 1, 2023, in Boulder, Colorado, USA. The IEA Wind TCP TEM #109 meeting aimed to bring together the leaders of all working groups and the IEA Wind Energy Systems TCP to identify gaps in scientific knowledge, design, and deployment practice as well as identify recommendations for collaborative pathways, initiatives, and prioritized long-term research needs that can be addressed by the IEA Wind TCP.

Many of the IEA Wind TCP TEM #109 meeting participants are members of the international community of volunteers who worked on the review articles submitted to *Wind Energy Science*. IEA Wind TCP national leadership recommended experts from academia, research laboratories, and industry in their topical areas to also participate. The European Academy of Wind Energy also provided recommendations. The target audience was the government agencies, nongovernmental organizations, and industry leaders that are working to enable a carbon-neutral energy system. See Appendix B for a complete list of meeting participants. Table 1 lists the meeting organizers.

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[2] Jeremy Firestone at the University of Delaware suggested that social issues be included as a Grand Challenge, and Jay Diffendorfer at the U.S. Geological Survey suggested that environmental issues be included as a Grand Challenge.

Table 1. Wind TCP TEM #109 Meeting Organizers

Member Country	Institution
United States	National Renewable Energy Laboratory U.S. Department of Energy
Denmark	Technical University of Denmark
Germany	ForWind - Center for Wind Energy Research Technical University of Munich

1.2 Alignment With the IEA Wind TCP Strategy

IEA Wind TCP international collaboration is based on a clear vision of what topics will require coordinated and leveraged work among its member governments. IEA Wind TCP will need to conduct regular gatherings of experts to reexamine the status of its wind energy road map (International Energy Agency 2009) and draft revisions to adjust the strategic plan. The IEA Wind TCP TEM #109 meeting is the first of these regular gatherings, and it laid the foundation for updating the road map on a regular basis. The TEM's topic areas span the entire scope in the strategic plan but are divided into the areas of critical scientific uncertainty. The TEM #109 meeting focused on the following five Grand Challenges in the Science of Wind Energy:

- The Atmosphere
- The Turbine
- The Plant and Grid
- Environmental Co-Design
- Social Science.

By addressing these five categories of needs for critical scientific research, this meeting resulted in recommendations for initiatives that supply the scientific underpinnings of progress in the following four IEA Wind TCP strategic objectives:

- Maximize the value of wind energy in energy systems and markets
- Lower the cost of land-based and offshore wind energy
- Facilitate wind energy deployment through social support and environmental compatibility
- Foster collaborative research and the exchange of best practices and data.

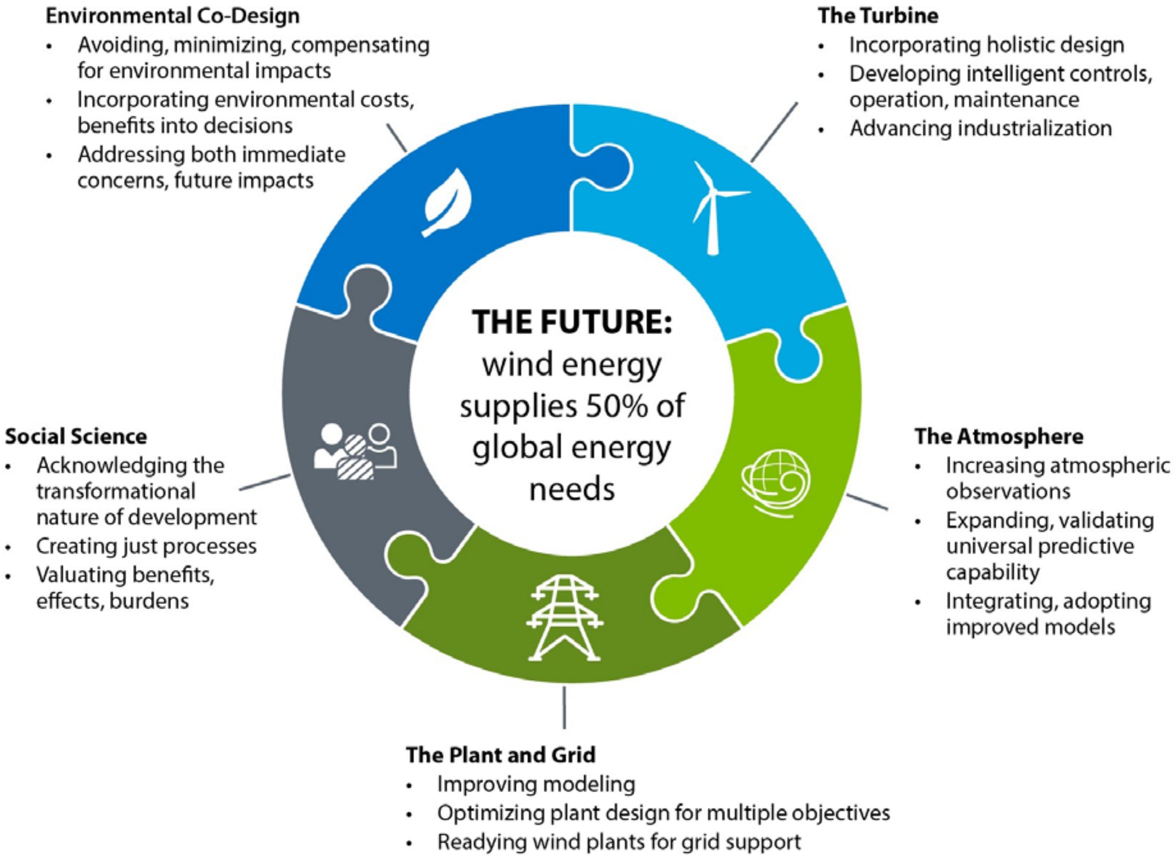

Figure 1. Addressing critical issues within each of the five Grand Challenge areas will help to ensure that wind energy is poised to play a greater role in global energy needs. ***Illustration by Taylor Henry, NREL***

The five Grand Challenges are also well matched to the following five Wind TCP Research Priority Areas:

- Resource, Site Characterization, and External Conditions
- Advanced Technology
- Energy Systems with High Amounts of Wind
- Social, Environmental, and Economic Impacts
- Communication, Education, and Engagement.

1.3 IEA Wind TCP TEM #109 Objectives and Outcomes

The successful IEA Wind TCP TEM #109 meeting in early 2023 resulted in input to address the five Grand Challenges from the IEA Wind TCP Task 11 activities leads as well as other expert participants. The meeting participants were divided into breakout groups based on their respective areas of expertise. The participants were then challenged to deliver recommendations regarding the critical issues that must be addressed to allow wind energy to become a foundation of the global energy supply. Leaders of the breakout topics summarized their findings, resulting in this report. The findings summarized in this report will serve as the foundation of a living road map for collaborative international research efforts.

One meeting objective was to collect input regarding cross-disciplinary actions to address challenges too large and complex to fit within a single category of expertise. Technical experts from academia, research laboratories, and industry gathered to identify linkages between the traditionally separate scientific areas, identify cross-disciplinary challenges, and propose initiatives. Meeting participants identified the following crosscutting topic areas and discussed during breakout sessions:

- Environment–Turbine
- Turbine–Atmosphere
- Atmosphere–Grid/Plant
- Grid/Plant–Turbine
- Grid/Plant–Environment
- Atmosphere–Environment
- Turbine–Social
- Social–Grid/Plant.

See Section 7 for the complete discussion of these interdisciplinary areas.

IEA Wind TCP members will use the TEM #109 meeting as an example for future working meetings every 3 to 4 years. Members will reexamine wind energy's ability to adapt to the ever-changing demands of supplying energy on a grand scale and will update the wind energy road map accordingly. As part of an ongoing effort, in addition to this report, the meeting conclusions will also be communicated through review articles submitted to high-impact journals.

THE ATMOSPHERE

2 The Atmosphere

The atmosphere is, in a sense, the fuel for wind turbines. The energy in this fuel arises from heating from the sun. It is greatest in large-scale atmospheric flows such as weather systems. Through three-dimensional waves and eddies, energy cascades down into smaller air currents with intermittent energy bursts and lulls on different temporal scales. These flows with smaller spatial scales drive wind turbine rotors, enabling the conversion from atmospheric energy, via rotor and generator, into electrical energy. The quality of the flow that impinges on wind turbines determines wind plant power production, reliability, and longevity. Therefore, the ability to predict flow characteristics at any given site is a necessary precursor to designing and operating efficient and long-lasting wind turbines and plants.

As technical experts from academia, research laboratories, and industry gathered at the IEA Wind TCP TEM #109 to discuss existing and future challenges facing wind energy, one of the subgroups focused on the atmosphere. The group discussed the importance of the atmosphere to specific wind energy applications such as assessing the resource and planning the details of a wind plant, operation and maintenance of wind farms, near-term operation optimization, and wind energy integration into the electric grid. Broadly speaking, the common vision of the experts was to obtain a comprehensive understanding of the atmosphere that allows the development of models that can support deploying large amounts of wind energy across the globe. To achieve this vision, highly accurate and reliable atmospheric information from measurements and simulations at multiple time and space resolutions is needed. However, this information is not sufficient in itself—it needs to be transferred to stakeholders through intentional and clear communication efforts. This requires both digitalization and outreach to create data that are organized and accessible.

2.1 Critical Issue: Increasing Atmospheric Observations

Atmospheric observations are critical for understanding and efficiently harnessing the wind. These observations are used directly in some applications such as wind resource and power performance assessments. Other applications such as wind turbine and plant design rely on atmospheric simulations, which, in turn, require observations to validate the models. Long-term and widespread atmospheric measurement networks were primarily set up based on weather forecasting and aviation. As such, they do not necessarily include the sites relevant to wind energy at sufficient coverage and resolution. As a result, wind energy resource studies and model assessments suffer from a shortage of atmospheric measurements around and within wind farms, over long records, at high spatiotemporal resolution. The initiatives proposed here address this data limitation.

2.1.1 Impacts

In general, atmospheric observations provide a basis for developing and improving upon simulation capabilities. Without observations, it is not possible to build and validate the models that drive wind energy development. Validated atmospheric models grounded in or tested against the observations created here will provide the level of prediction accuracy that enables a broad set of innovations in turbine and plant design, power predictions for both financing and grid operations, and environmental impacts of wind energy deployments at the scales required to make wind a fundamental driver of the energy sector.

2.1.2 Initiatives Needed To Address

The rapid and widespread growth of wind energy will require targeted initiatives to collect observational data. Three distinct but coordinated initiatives were identified as critical to the effort:

1. Develop measurement system technologies
2. Collect open-source data at relevant scales and make it readily available
3. Conduct data analysis that includes an emphasis on uncertainty quantification.

Initiative (1) focuses on the development of the instrumentation required to obtain high-resolution, high-accuracy, long-range measurements of the atmosphere, including dynamic and thermodynamic quantities throughout the atmospheric boundary layer. The adaptation of existing instrumentation or the development of new sensors for precipitation and lightning are also needed because these quantities have a direct effect on wind turbine blade performance and longevity.

The measurement systems developed in Initiative (1) can then be used in Initiative (2), which involves the planning and execution of large, collaborative efforts in data collection for validation of modeling capability. The collected data should be at spatiotemporal scales relevant to the application in question. Multiple actions are needed within this initiative, including field campaigns at various sites that cover the wide-range environmental and flow conditions relevant to wind energy developments; field campaigns near and within wind farms; the upgrade and expansion of existing meteorological networks in support of measurements needed for the energy system; and the development of long-term atmospheric measurement sites at complex locations. As noted here, it is important to collect data in two primary modes: shorter-duration field campaigns and longer-duration field installations. The field campaigns allow for the focused use of multiple instruments for a defined period to study the flow features at specific sites. Such field campaigns require collaboration among multiple organizations. In contrast, the longer-term installations proposed here are meant to gather observations over multiple years at representative sites (including complex sites, coastal locations, and offshore). These types of deployments allow for long-term statistical analyses, capture rare but extreme events, and provide sufficient data to train machine-learning models that could prove useful to wind energy applications.

The measurements collected in Initiative (2) need to undergo a thorough analysis and uncertainty quantification process within Initiative (3). In addition, the collected data should be used to produce benchmarks that can support the development and validation of models as part of the initiatives discussed in Section 2.2.

2.2 Critical Issue: Creating Universal and Predictive Modeling Capability

Decisions in design, siting, and operation of wind turbines and plants are often based on simulations of the atmosphere. In terms of the surrounding environment, the simplest simulation setting is a flat land surface away from any obstacles, changes in roughness (such as a coastline), or existing wind farms.

Around the world, the wind energy industry's steady growth requires development at more complex locations, such as sites with hilly or mountainous terrain, near or within forests, in urbanized zones, next to existing wind farms, and in coastal areas. In addition to added environmental complexity, the increasing size of wind turbines has pushed towers and rotors higher into atmospheric zones where the wind flows are significantly different than near the surface, creating more complex atmospheric dynamics across the area swept by the rotor.

Over the years, simulation tools were developed to account for a certain level of added environmental and flow complexity as wind plants were installed at more and more complex sites. However, these higher-fidelity codes have not been adopted fast enough to keep up with the pace of innovation in wind turbine technology and its expansion into increasingly complex locations and greater heights above the surface. As a result, current decisions in design, siting, and operation are often based on computer models that are being applied beyond where they have been validated with measurements.

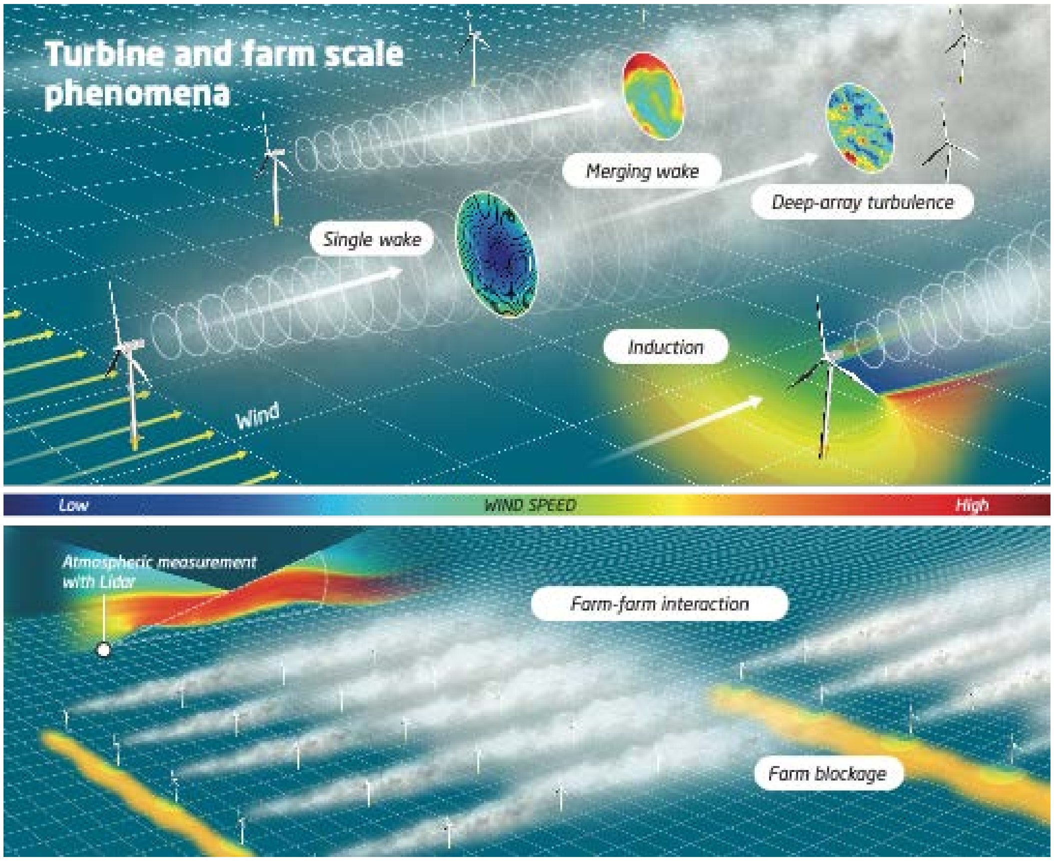

Figure 2. Turbine and wind farm-scale phenomena, including single wake phenomena such as merging wake, induction, and deep-array turbulence, as well as whole farm effects such as blockage and farm-farm interaction. ***Illustration from Jakob Mann, Technical University of Denmark***

A renewable energy future with a large share of wind generation requires accessible wind plant airflow models that can be applied to any site and any viable technology. To achieve this, the predictive capability of existing flow models needs to be expanded and validated for the reality of our energy future: tall, offshore towers with rotors that have lightweight flexible blades that are fixed to the surface or free to move with the ocean waves; hybrid power plants where solar and wind energy respond to local weather; mountainous, forested, or offshore locations where interactions between the adjacent surface and the atmosphere dictate the predominant flow patterns; sites where precipitation, lightning, and other atmospheric phenomena drive performance and reliability; and potentially crowded sites where multiple wind plants share the local resource.

2.2.1 Impacts

Models of the atmosphere are the basis for evaluating the potential for wind energy growth and innovation. Without numerical models based on solid science, every advancement opportunity will be associated with a greater risk exposure and higher costs, requiring hardware deployments that demand substantial time and financial investments. Advanced and ubiquitous atmospheric modeling capability is foundational to the rapid solution of critical design and deployment issues across the entire range of Grand Challenge areas.

If the vision presented here for this universal modeling capability is achieved, then we anticipate valuable benefits:

- Higher structural reliability. The ability to predict the interplay between specific atmospheric phenomena and wind turbine structural loads will allow for longer wind turbine lifetimes, mitigate premature component failures, and reduce maintenance costs.
- Widespread access. The ability to accurately simulate flow conditions at any site will enable deployment at complex locations where wind energy deployments are currently challenging or limited.
- Performance enhancement. Improved modeling capabilities that consider neighboring plants and other local complexities will be able to minimize wake losses and maximize the use of local flow features.
- Project de-risking. Accurate energy yield predictions at any site with quantified levels of uncertainty will increase project bankability and its chances of economic success.
- Low capital cost. The uncertainty in flow simulations propagates to wind turbine structural load predictions. When the flow simulation uncertainty is known, wind turbine design can be less conservative, leading to lower production costs while maintaining durability and safety.
- Grid integration. Local, real-time predictive capabilities will facilitate integration of wind energy into the electrical grid.
- Climate and weather awareness. The ability to account for large-scale, long-term atmospheric patterns in wind energy simulations will enable a symbiosis between the wind plant and the local climate and weather and an awareness of the changing climate and of atmospheric extreme events relevant to wind energy such as hurricanes, storms, lightning, and precipitation.
- Customization. Wind turbines and plants can be customized to leverage local resources. This customization can take place during design and throughout operation.

2.2.2 Initiatives Needed To Address

The universal modeling capability discussed here also speaks to the spatiotemporal scales of these simulations. For some applications, this capability will require models to capture the full range of scales important to harvesting energy—from weather events to turbulent wind fluctuations at high spatiotemporal resolutions, coupling the mesoscale to the microscale of atmospheric flows.

For this issue to be addressed, the key initiative is to create a comprehensive suite of numerical models that can be trusted when applied to wind energy systems. In other words, the community needs to develop and validate wind plant airflow models suitable for any application in the wind energy space. This includes models across various levels of fidelity, depending on the application and its associated computational and time constraints. In addition, models that can incorporate ocean and atmospheric dynamics are urgently needed to support offshore wind development, where wave and winds are tightly coupled. The models developed under this initiative need to be fast, accurate, and ideally open source to maximize their adoption, as will be discussed in Section 2.3. In addition, their limitations and uncertainties should be thoroughly quantified. We postulate that a combination of physical models and machine-learning methods will be needed to achieve these goals.

2.3 Critical Issue: Integrating and Adopting Improved Models

The existence of atmospheric flow models that can be applied to any site hosting any technology is not sufficient to support the envisioned future of wind energy. The third critical issue identified by experts in atmospheric science is the integration and adoption of these models. Here, the term "integration" refers to the incorporation of improved flow models into design and decision processes that already exist or the development of new processes that involve the new and improved simulation workflows. Depending on the context, the integration might be relative to wind turbine design, wind energy forecasting, wind plant siting, or any other task reliant on flow modeling. The term "adoption" refers to the widespread operational use of the improved simulation tools in decision-making spaces. It should be noted that integration should ensure adoption while protecting competition and opportunity for innovation.

2.3.1 Impacts

When enhanced atmospheric models are integrated into standardized practices, the reality of wind energy installations will be revolutionized, enabling accelerated access to more sites, more energy extraction from these sites, awareness between wind plants and the surrounding environment, better integration into the energy grid, and more efficient design and operation practices.

2.3.2 Initiatives Needed to Address

TEM #109 members identified two main initiatives to support integration and adoption:

1. Design and improve communication between communities

2. Establish a global workforce development initiative.

Initiative (1) refers to communication between the communities collecting data and developing models and the end users of those data and models. These communication efforts are not trivial and require continued, intentional effort. The first step toward this initiative is a comprehensive, large-scale survey to document specific needs and concerns of the data end users. The abilities of these users and the resources available to them should be documented and considered. End users should be viewed not only as customers of the data products but also as partners working in different tasks but toward the same goal—a future in which wind energy provides a large share of electricity generation worldwide in a harmonious and efficient manner. After the initial survey, continued communication efforts include using FAIR data principles,[3] establishing and maintaining open communication channels while projects are being proposed and executed to collect atmospheric observations and develop universal predictive capabilities, and ensuring that software and data remain open source.

Initiative (2) refers to the large-scale development of a network of graduate students and postdoctoral researchers worldwide working cohesively toward common goals to accelerate progress. This vision will create and maintain productive collaboration channels between existing research institutions and academic institutions and produce the future scientists and engineers who are prepared to lead and drive the energy transition in the context of a renewable energy system. The emphasis on open-source data and software should be maintained to facilitate this initiative. The network of experts ensuing from this effort will accelerate the pace of flow modeling improvements to match the pace of wind energy development that is required to meet current policy goals.

2.4 Further Research and Actions

TEM #109 experts identified several crosscutting aspects that require further research. See Section 7.2 (Turbine–Atmosphere), Section 7.3 (Atmosphere–Grid/Plant), and Section 7.6 (Atmosphere–Environment) for further discussion.

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[3] FAIR is defined as Findability, Accessibility, Interoperability, and Reuse of digital assets (https://www.go-fair.org/fair-principles/).

THE TURBINE

3 The Turbine

To decarbonize the energy grid, it is essential to significantly increase the proportion of wind energy in the grid, not only in large, industrialized economies but also in developing countries. This increase will require the continued exponential growth of installed wind energy capacity, which can only be sustained with ongoing research and development (R&D).

As part of IEA Wind TCP TEM #109, a subgroup of more than 30 technical experts from academia, research laboratories, and industry gathered to discuss existing and future challenges facing wind energy, with a particular focus on the turbine. The goal of the discussion was to understand whether further R&D for wind turbines is necessary and, if so, to identify the top three priorities.

TEM #109 participants concluded that several important wind turbine R&D questions remain unanswered and that failure to address these issues could seriously jeopardize the achievement of the wind energy deployment targets set by governments worldwide. Some of these unanswered questions are technical in nature, but others involve social and environmental aspects.

First, to support the exponential growth of wind energy, land-based and offshore wind turbines will need to be deployed in new areas. Wind parks will inevitably get closer to each other, and offshore turbines will leverage fixed-bottom and floating installations. The TEM #109 highlighted the need for community engagement at multiple stages, including design, installation, operation, and decommissioning. Environmental considerations must be similarly addressed at these early stages, not just after the fact. As wind energy becomes an increasingly significant electricity supplier, grid operators will impose stricter requirements for reliability and supply security. Therefore, designers, developers, owners, and operators of wind energy assets would benefit from incorporating more reliability metrics into their processes, with a stronger focus on the social and environmental aspects of wind energy deployment.

Second, as larger amounts of renewable energy are integrated into the electricity market, the reliance on variable generation sources must be addressed. To ensure that wind turbines remain a vital part of the future electricity market, they must become more intelligent and support the integration of energy storage solutions to achieve a more dependable power system. Additionally, wind turbines have the potential to implement more intelligent algorithms for controls and operations and maintenance (O&M), which are likely to lead to further cost reductions.

Third, wind energy deployment will likely need to be supported by a stronger industrialization of the sector, particularly for floating support structures. So far, only a few floating support structures have been deployed, and the technology is not yet mature. Dozens of floater concepts are under development at different technology readiness levels. Clear leadership from companies and countries has yet to emerge. Floater design has a significant impact on the supply chain, manufacturing jobs, and the environment, including wildlife, greenhouse gas emissions, energy usage, materials selection, logistics, and other aspects. Technoeconomic tools are needed to identify designs that strike the best balance among metrics characterizing the entire life cycle and the associated impact areas.

In conclusion, today's wind turbines are insufficient to meet all requirements of a future carbon-free electricity market, and further R&D efforts are needed. Failure to include such efforts in the

R&D plans could be detrimental for continued wind energy development, which in turn would hinder worldwide wind deployment targets and ultimately decarbonization goals.

Given this imperative, TEM #109 members identified three critical challenge areas for wind turbine R&D (listed in no particular order):

- Holistic design
- Intelligent controls and O&M
- Industrialization.

The three areas are shown in Figure 3 and elaborated in the subsections below.

It should be noted that a meta-need for the Turbine Grand Challenge is verification and validation of numerical tools; each critical issue includes this need.

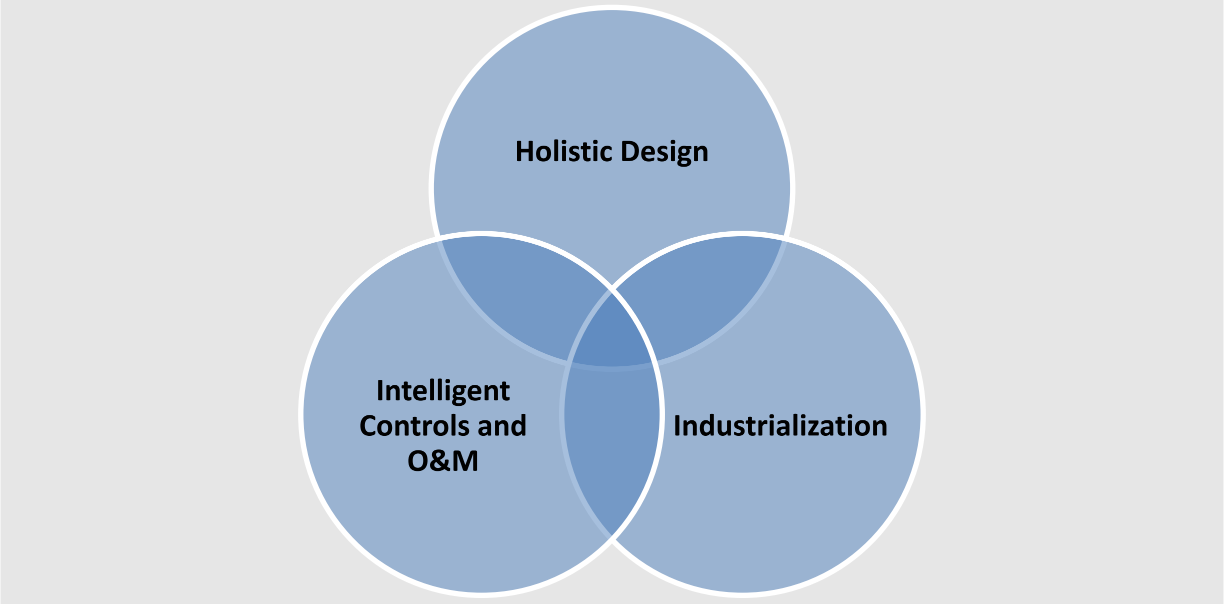

Figure 3. Topic areas for R&D in turbine technology.

3.1 Critical Issue: Incorporating Holistic Design

Historically, wind turbine design has relied on experts in areas such as aerodynamics, structures, and controls, who sought to optimize designs that extracted as much energy from the wind as possible. The individual disciplines generate conflicting goals and constraints, and integrated and more automated design approaches have recently become state of the art. Nowadays, levelized cost of energy (LCOE), which is the ratio of costs to unit energy, is the most common metric that is minimized during an integrated design process.

The wind energy community is increasingly aware that LCOE is a useful, yet incomplete, design metric. First, LCOE misses the monetary value of the energy provided to the grid system, which inherently varies spatially and temporally. In addition, LCOE does not consider social and environmental impact and benefits of an energy source. In this scenario, TEM #109 members recommend more holistic design approaches that can move beyond LCOE, embrace additional key metrics, and capture the full system value of wind energy.

3.1.1 Impacts

- Economic and financial value. The deployment of wind turbines must generate economic and financial value for all stakeholders involved, including turbine manufacturers, developers, operators, and local communities. Unfortunately, this is often not the case today, with profits and benefits being concentrated at certain stages of the electricity market. This unsustainable situation highlights the need to ensure that all stakeholders can reap the benefits of wind energy deployment in the long term. Deployments in new and challenging locations such as floating offshore and low wind speed sites will only worsen existing economic and financial challenges.
- Reliability. As wind turbines grow in size, operation and maintenance costs on a kilowatt basis are expected to decrease. Unfortunately, this downward trend is currently at risk. Due to excessively narrow financial margins, turbine manufacturers have been forced along a path of customization and upscaling of their products, which has resulted in higher-than-predicted failure rates in multiple turbine components. Failures have also increasingly been observed in components that were historically characterized by small maintenance costs, such as blades. Higher costs associated to insufficient turbine reliability will limit the share of wind power in the energy market. Low reliability also impacts the supply of clean and secure electricity in various challenging environments, limiting the dispatchability of wind power. Therefore, it is essential to prioritize the development of more reliable wind turbine designs.
- Social impact. The opposition to the installation of wind turbines is a real barrier to meeting deployment targets. To mitigate the social impact of wind energy, it is important that local communities experience a positive impact from wind energy deployment and are actively involved in the process. Wind energy stakeholders could adopt just and inclusive processes that consider the interests and concerns of local communities during deployment stages.
- Environmental impact. Wind turbines will have to meet increasingly stringent environmental requirements in several areas, such as net-zero energy impact, impact on birds, bats and marine life, carbon intensity, use of rare and scarce materials, sustainability, and recyclability. Incorporating environmental considerations may influence design choices, such as the standard 25-year lifetime or noise emissions, and may incur additional economic costs.

3.1.2 Initiatives Needed To Address

To support holistic design of wind turbines, the TEM #109 members recommend the following major initiatives:

- Continuously develop open-source, verified, validated, and predictive numerical tools for the analysis and design of wind turbines. Models for floating wind systems have additional concerns due to the complexity of the dynamic environment.
- Field data is key to validate innovations. However, concerns related to intellectual property often hinder data sharing. To overcome these concerns, novel approaches to protect industrial secrets (e.g., leveraging the ongoing digitalization of wind energy)

should be explored. Open-access, full-scale data sets that can be shared among the wind energy community should also be developed.

- Set up one or more open-ocean test facilities with broad accessibility to researchers and industry. An open-access floating wind turbine technology demonstrator would be of great value for many stakeholders across the entire value chain. The demonstrator should be complemented with an open-access meteorological ocean (metocean) data set.
- Maintain and further refine reference designs, which are key to benchmark innovation.
- Develop metrics, models, methods, and dedicated initiatives informing the social and environmental impact of different design choices.
- Improve wind turbine design standards (e.g., in the design load bases, which are increasingly unrealistic and limit innovation).
- Adopt probabilistic design approaches, which can account for inherently stochastic and lack of knowledge-based (aleatory and epistemic) uncertainties across numerical models.

Several of these R&D efforts could be supported by new Wind TCP tasks. Existing efforts such as Task 55 on reference wind energy systems and Tasks 30 and 47 on collaborative verification and validation of modeling tools could be extended, and new collaborative projects could be initiated that focus on relevant topics such as life cycle analysis for wind and beyond-LCOE metrics and designs. These activities rely on open data sets, which are necessary to advance the state of the art of wind energy science and technology. This open data set scenario contrasts with a scenario in which industry owns a wealth of data that cannot be shared because of concerns around intellectual property and loss of competitiveness. A healthy community has a continuous data exchange among all stakeholders; the sharing allows innovation to happen at all levels, ultimately benefiting the entire wind energy field.

3.2 Critical Issue: Developing Intelligent Controls, Operations, and Maintenance

Wind turbines today are equipped with sensors and control systems that make them capable of operating autonomously in complex, dynamic, and stochastic environments. However, legacy control systems lack a sophisticated perception of the entire system, as well as environmental elements necessary to implement more advanced functions. Turbines need more "situational awareness," which includes self-awareness (e.g., status of the operational conditions of the turbine in a plant, its maintenance state, and its fatigue state) and flow awareness, which is the perception of the wind flow at the individual turbines and at different points within a plant. Contemporary turbines and wind farms are capable of only relatively simple and limited forms of self-awareness and flow awareness. TEM #109 experts identified the development of more intelligent wind turbines as a key priority for future R&D efforts.

3.2.1 Impacts

Investing in intelligent controls and wind turbine O&M will increase wind turbine integration within and value to the future energy system. As the energy system becomes more complex and variable, it will be essential for wind turbines to dynamically adapt and operate with a higher level of autonomy, security, and resilience.

3.2.2 Initiatives Needed To Address

To support more intelligent controls and wind turbine O&M, the following major initiatives are proposed:

- Develop advanced measurement capabilities. Sensing and characterizing the environment faced by the turbines, together with their state (e.g., through digital twins), are key to enabling advanced controls approaches and O&M strategies.
- Verify and validate tools. Accurate numerical tools are key to advancing the state of the art.
- Develop, implement, test, validate, and commercialize new strategies and algorithms.
- Develop advanced cybersecurity. As wind turbines become more intelligent systems and cover larger shares of the electricity supply, their cybersecurity should grow concurrently.
- Leverage the ongoing revolution in artificial intelligence and machine-learning (AI/ML) capabilities. Novel AI/ML approaches can be useful to tackle multiple unsolved problems; for example, by bridging knowledge gaps and inconsistencies across model fidelities. AI/ML could also help improve our existing capabilities in design tools, environmental assessments, and operations. To be successful, AI/ML approaches need engagement from mathematical process experts as well as wind experts to ensure the methods are viable and represent the appropriate physical considerations.
- Define reference designs. Reference designs are useful to enable cooperation across industry and academia and overcome intellectual property constraints.
- Note that this report intentionally does not assign initiatives to specific stakeholders, whereas TEM #109 calls for the entire community to respond to these priorities.

3.3 Critical Issue: Advancing Industrialization

TEM #109 participants recognize the significant disparity between the ambitious deployment targets set by governments globally and the current industrial capacity to manufacture and install wind turbines. This gap is evident across all applications, including land-based and offshore wind turbines, but it is particularly pronounced for floating offshore wind turbines, where manufacturing capacity falls far short of the required output of hundreds or even thousands of multimegawatt floaters per year. Addressing this gap will require advancements in wind industrialization, including expanding recyclability, diversifying materials, and developing infrastructure while continuing to identify cost reduction pathways. New technologies are also needed to meet increased objectives of recyclability while ensuring profitability and value creation.

3.3.1 Impacts

The consequences of not accelerating the industrialization of wind energy would be grave and include the inability to reach the deployment targets set by governments around the world and the real risk of slowing down the ongoing process of decarbonizing the energy system.

3.3.2 Initiatives Needed To Address

To support wind energy industrialization, the following major initiatives are proposed:

- Support design studies of floating support structures. Floaters should be designed to meet industrialization needs, meaning that they can be easily mass-manufactured and quickly deployed.
- Conduct techno-economic and life cycle analysis of turbine upscaling. Offshore turbines are subject to a continuous upscaling, which challenges turbine reliability. The social and environmental impacts of upscaling should also be investigated. Another important aspect to investigate is the sourcing of materials (e.g., green steel, concrete, rare materials).
- The demand for wind plants on land continues to dominate deployment scenarios and requires significant innovations in manufacturing, reliability, and environmental and social adaptability. Success depends on an improved scientific understanding of all the driving elements, including aeroelastic, material, control, operations, and other capabilities, which make innovation and optimization possible.

Although TEM #109 members foresee a significant role for industry in the industrialization of wind energy, national laboratories and academia can help by supplying the scientific basis to tackle several major challenges, such as investigating designs that are optimized for manufacture and installation, R&D on novel materials and manufacturing processes, definition of design approaches and standards, and techno-economic and life cycle analyses.

In the process of industrialization, the entire wind energy community is called to find the right balance between standardization and customization. Standardization helps lower costs, raise reliability, and ultimately enable mass deployment. Customization is, however, often necessary to meet customer needs and to optimize the development of a site for specific conditions and community concerns. The balance between the two trends might need to change moving forward to meet new demands, such as the need to successfully manage fleets of hundreds of thousands of machines around the globe while respecting increasingly tight social, environmental, and reliability targets and constraints.

Industrialization will also have to address the issue of ever-increasing wind turbine size. For years researchers thought that the maximum turbine size had been reached, but predictions were always proven wrong. However, design improvements to fight the cubic law of growth might be running out. Also, wind turbines are now the largest dynamic rotating structures ever built, and several processes, from manufacturing to installation, require unique and very expensive infrastructure. Enhanced R&D (i.e., scientific basis, numerical simulation tools) can help determine if it is time to stop upscaling turbines.

3.4 Further Research and Actions

TEM #109 experts identified several crosscutting aspects that require further research. See Section 7.1 (Environment–Turbine), Section 7.2 (Turbine–Atmosphere), Section 7.4 (Grid/Plant–Turbine), and Section 7.7 (Turbine–Social) for further discussion.

THE PLANT AND GRID

4 The Plant and Grid

As the share of wind energy continues to grow, challenges around grid stability, electrical transmission, and wind energy's ability to provide grid services also increase. These issues exist at multiple scales, as indicated in Figure 4. If left unaddressed, the share of wind energy will not reach targeted levels, the consequences of which range from unfortunate to dire, ultimately resulting in the failure to meet renewable energy goals; continually worsening impacts of climate change; and an expensive, dirty, and unstable grid.

During the IEA Wind TCP TEM #109, approximately 15 experts from around the world, with representation from academia, industry, research laboratories, and governmental organizations, met to discuss the current and future challenges facing the increasing integration of wind energy into the grid. Topics of focus included wind plant design, operation, and integration into the electrical grid. The goal of this meeting of experts was to identify the top challenges and determine critical issues to address. To facilitate this discussion, two virtual meetings took place before the TEM #109—one focused on the plant and one focused on the grid. For the plant virtual pre-meeting, participants had experience with wind farm flow control and operational strategies for maximizing plant performance and minimizing negative wake effects. For the grid virtual pre-meeting, participants had backgrounds in electrical systems and expertise in wind energy plants and the grid. Attendance at these pre-meetings was broader than at TEM #109 as participants were not restricted by the logistical aspects of an in-person meeting. Several points of concern were identified in each pre-meeting, summarized below.

The following points were identified during the grid virtual pre-meeting:

- Grid support:
    - Wind-based solutions for grid support need to be improved, including adapting grid-forming technology for wind power plants.
    - Optimizing the interplay of individual wind generators and power electronics with plant power electronics for grid connection is a research need.
    - Improved forecasting will be needed to provide additional grid services from wind energy.
    - Wind turbine and power plant models for grid simulation tools need more transparency from the black-box models currently used for each turbine manufacturer.
- Multi-objective optimization:
    - There is a need to identify and communicate the value of wind energy in systems with other renewable sources (e.g., value to the grid operator, flexible dispatch, wind-to-*x* output that is not electricity).
    - Integration of controls for providing grid support and wind farm flow control is a big research challenge.
    - To help ensure that the inclusion of grid services in a development strategy is profitable for developers and makes them competitive, research is needed to

    examine how to best develop energy systems that include not only wind energy but also other technologies to provide the best value to the grid.
    - It is worth considering mixed turbine types to provide more energy around the clock, such as special low-wind turbines optimized for very low wind speeds when the value of wind is greatest in the future, to complement the turbines that provide maximal energy.
    - Other types of systems that wind energy will interact with in the future should be considered, such as solar, storage, and hydrogen.

The following points were identified during the plant virtual pre-meeting:

- Plant modeling:
    - The industry needs more trust in and validation of models for wind farm control.
    - There is a need to identify when enough is enough in terms of validation and gap analysis.
    - The use of artificial intelligence and machine learning will need to include ethics considerations (e.g., algorithms at one farm could take advantage of operation that is detrimental for neighboring farms).
    - Models should be matched to objectives. Model-free approaches could be leveraged more and could be approached from a perspective of observability instead of being purely physics-based.
    - More dynamic tools that are computationally efficient are needed.
    - For controls, there is a need for control models and simulation models.
    - Multi-objective controls that may be needed to help drive model development should be considered.
    - A good basis for research is to focus on ideal markets (not tying to short-term market conditions), but tools need flexibility to account for changes over time and cover industry needs (design of near-term systems).
- Multi-objective optimization:
    - For co-design, there is more value in examining broader systems, such as hybrids, versus wind-only plants.
    - More value than just economic value can be achieved.
- Grid support:
    - Wind should be an active player, not just reactive, in the grid/markets.

These concerns were then condensed into three critical issues that were the focus of discussion during TEM #109:

- Plant and flow control physics, artificial intelligence, and data-driven modeling. This includes uncertainty quantification and validation, standardization of flow control analysis and data, and intelligence.

- Multi-objective optimization of the plant, including for hybrids, power to X (P2X, where X is electricity/other output), and grids. This includes uncertainty and integrated plant and flow control for optimized operation and grid services (and may even include spatial planning).
- Next generation of intelligent wind plants. This includes grid-forming and interacting with other inverter-based resources and improving wind-based grid support.

These three issues are discussed in detail below, along with impacts and initiatives to address them.

4.1 Critical Issue: Improving Plant Modeling

The first critical issue identified during the plant and grid pre-webinar discussions of TEM #109 pertains to modeling. Throughout the development of wind energy systems, models of varying fidelity have been used. These models have spanned many scientific and technical areas ranging from atmospheric science to mechanical engineering to data science. A sampling of the many disciplines is shown in Figure 4. Lower-fidelity models enable fast and repeated computation that is beneficial for optimization but can lack key details for more refined design. Higher-fidelity models can capture many of the needed physics, providing near-realistic simulation of performance, but require significant amounts of computation and are often specialized or narrow in scope.

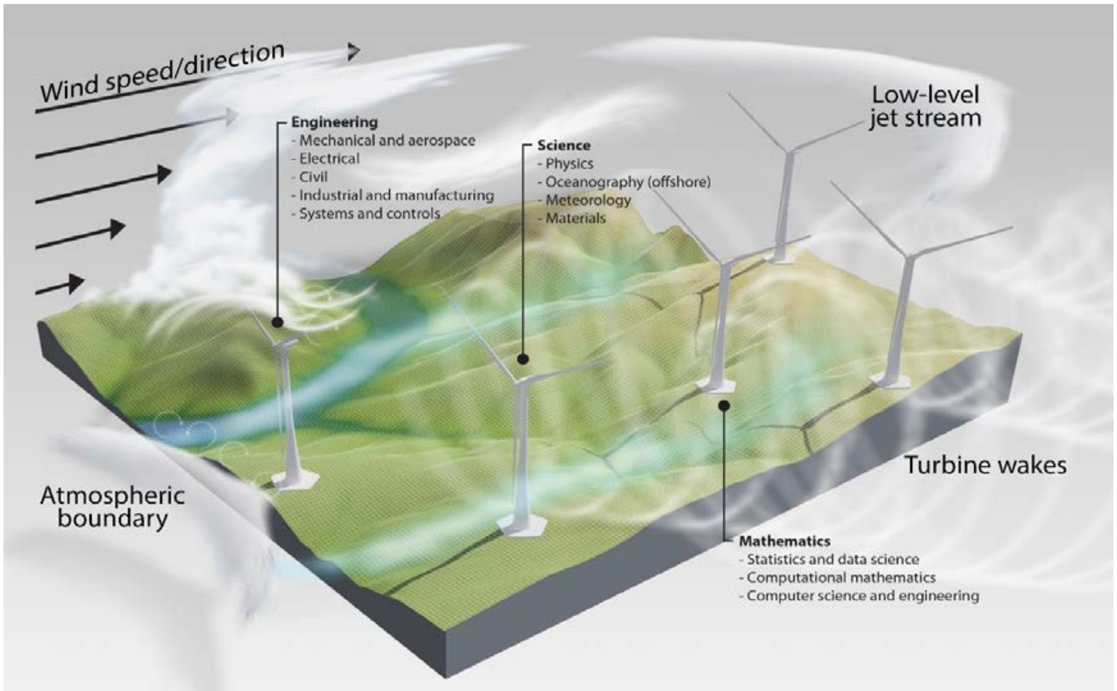

Figure 4. Modeling of wind plant and flow characteristics

More recently, modeling efforts have tried to leverage the immense amount of data that is produced from operating wind energy systems, working to develop digital twins of specific systems and predictive models that can update over time. Artificial intelligence has played a role in these efforts and has been particularly helpful in addressing the challenges of uncertainty quantification in the models. While significant research has occurred on these topics, the application and validation of the work is still in a nascent stage, facing challenges in generalizability, scaling, cybersecurity, and the overall feasibility of field implementation to advance in maturity.

Lastly, regarding the time scales at play, when considering the electrical characteristics of a wind plant, they occur at a near instantaneous rate compared to the time scale of the aerodynamics of the atmosphere and interturbine interactions, such as wind farm flow control. Similarly on the grid, time scales spanning from subsecond to multiday are needed to ensure proper frequency control, load balancing, and forecasting of demand. While there are models to capture these properties at their relative levels, a multi-time-scale model or framework that consists of several models and allows for system-level design is missing.

4.1.1 Impacts

The TEM #109 subgroup focused on the plant and grid determined that if the modeling needs described above are not addressed, the impacts to the expansion and greater integration of wind energy into the grid would be significant. The major impacts identified during the discussion are summarized below. With the proper model advancements:

- Wind energy will increase its profitability, which will increase deployment and acceptability overall.
- The capability for providing advanced grid services can be developed, ensuring grid stability with high amounts of wind energy and further increasing grid resilience.
- Wind power control and coordination can be developed across spatial scales not currently possible, supporting grid stability, adding to profitability, and allowing the needed level of wind energy deployment to meet renewable energy goals.

4.1.2 Initiatives Needed To Address

To help address the modeling needs and challenges, the TEM #109 experts identified the following major initiatives:

- Developing standards and best practices for computer models, operational data, and targeted experimental campaigns. This includes, but is not limited to:
    - Developing open-source data sets for multiple sites and campaigns
    - Sharing of performance indicators
    - Agreeing on best practices for data processing and analytics.
- Creating multiscale, multifidelity, and dynamic models for analysis and design of wind power plants and operational strategies, including inverter-based resources.
- Integrating wind farm flow control with grid service objectives.

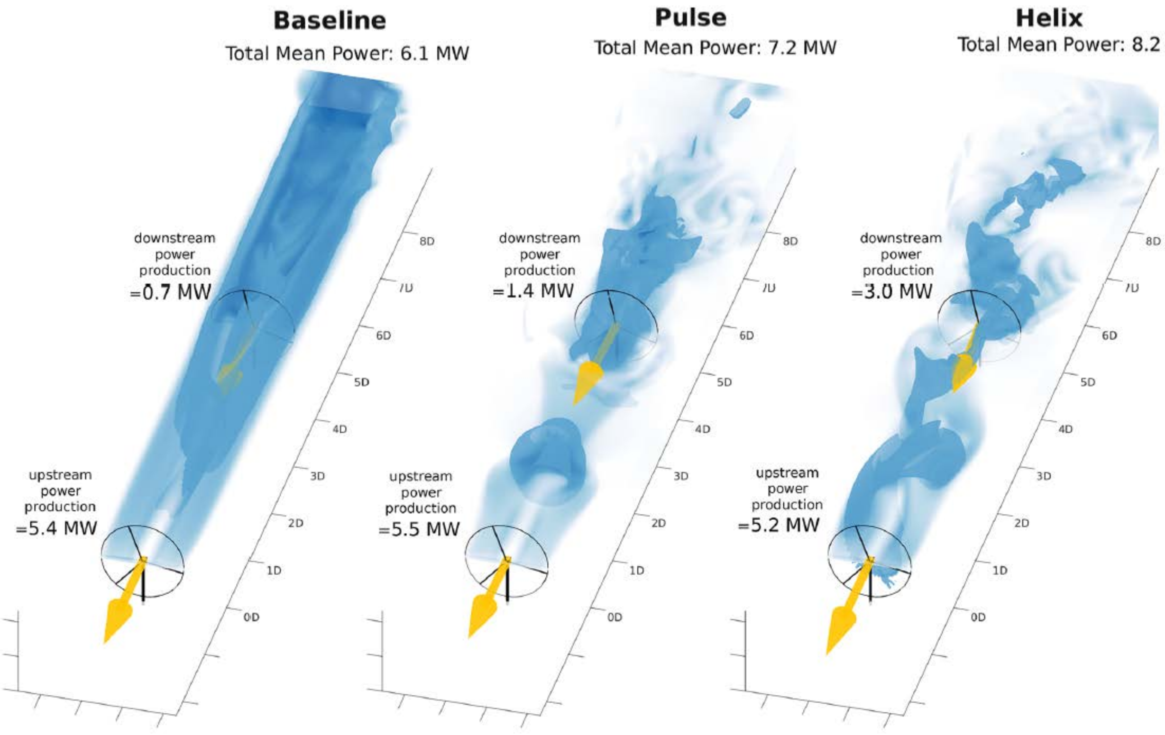

Figure 5. Modeling of wind farm flow control. ***Adapted from Meyers et al. 2022*[4]**

4.2 Critical Issue: Optimizing Wind Plant Design for Multiple Objectives

Building on the first critical issue of modeling, the second critical issue is optimization and design. With proper models, effective and efficient optimization and design of wind power plants can occur. Current tools exist for performing design steps such as siting, turbine layout, component design, and controller development, although most of these tools are utilized in a linear or isolated fashion. Some allow for the concurrent design of multiple aspects of a wind power plant, but the application of true co-design to wind energy is very much an emerging area of research.

Figure 6 shows an example of co-design, integrating the system design of the wind power plant with the development of the controls while considering various system-level objectives. These objectives can extend beyond traditional economic objectives such as LCOE to include the time-value of energy, or to account for noneconomic objectives such as turbine structural loads or wildlife impacts. Meyers (2022) has an expanded discussion on co-design for wind energy systems.

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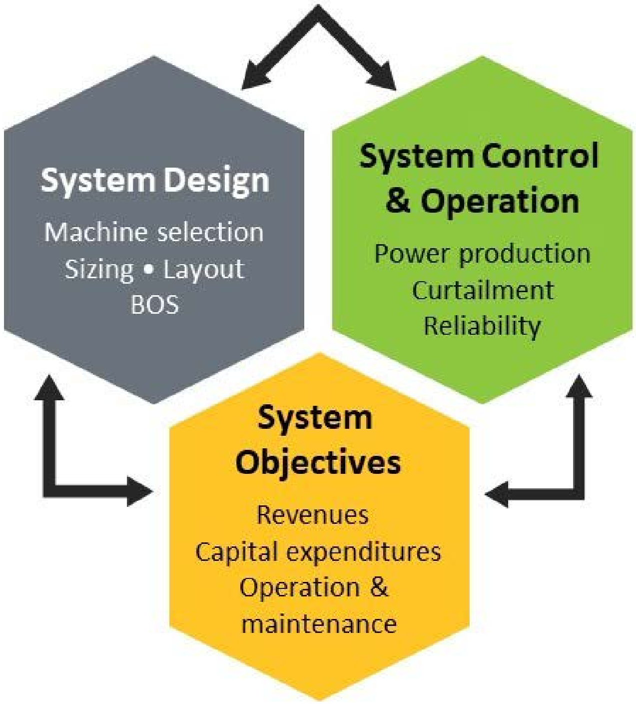

Figure 6. Illustration of interdependencies that consider system design, control strategies, and objectives. ***Adapted from Meyers et al. 2022***

In addition to co-design, the TEM #109 experts agreed that multi-objective optimization is a key challenge and is needed for future design to account for several criteria. Of particular interest is including the grid support functionalities in the multi-objective optimization, spanning over several time scales and system services provided from wind power plants. Also of interest is optimizing wind plant design alongside other systems within hybrid power plants. Considering current grid infrastructure limitations and the difficulty of adding new transmission capacity, wind-based hybrid power plants offer a unique added value. It has been shown that co-located complementary resource profiles of wind and solar irradiance can significantly increase the around-the-clock power production of a hybrid power plant while leveraging an existing grid connection (Clark 2022). And as the cost of energy storage continues to decline, properly sized wind and storage hybrid plants can provide more grid support and flexible energy to the grid. Lastly, hybrid plants can include other energy outputs (P2X) such as hydrogen or even end-use processes such as steel or ammonia production. To achieve various decarbonization and renewable energy goals, the ability to design wind energy systems alongside other technologies is imperative.

4.2.1 Impacts

Without the continued optimization of wind energy systems, the TEM #109 experts agreed that the necessary deployment and integration of wind energy into the grid would not be possible. They identified the following specific impacts:

- Increased value through optimization and better integration of wind energy with other energy technologies

- Improved performance and efficiency through the co-design of turbine and plant components.

4.2.2 Initiatives Needed To Address

While there are many tasks needed to improve the optimization and design of wind energy systems, select major initiatives identified during the TEM #109 meeting included:

- Development of co-design techniques, including integrated plant and flow control for optimized operations and grid services
- Development of multi-objective optimization for wind energy, including:
    - Create models to consider loading and lifetime constraints within the optimization
    - Analyze value metrics beyond LCOE as well as other social and environmental metrics (such as perceived noise and acceptability of projects)
    - Include uncertainty in optimization (e.g., forecasts and operation)
    - Develop wind energy models for integration with hybrid power plant optimization.

4.3 Critical Issue: Readying the Next Generation of Wind Plants for Grid Support

The third critical issue identified by the TEM #109 experts regarding the plant and grid is the required technical capabilities for grid support of the next generation of wind plants. These capabilities include the need for wind plants to perform grid-forming functions, interact with other inverter-based resources, and deliver effective wind-based grid support. As more inverter-based resources replace traditional synchronous machines, the needs of the grid and the services provided by wind energy will continue to change.

Although these needs will shift over time, Figure 7 shows eight fundamental needs of the grid: energy, capacity (timing of energy), and six technical services. Wind-based solutions already exist for part of these services. For the technical services, frequency control and voltage regulation can be further improved, while the other needs for damping, synchronization, protection, and restoration can be the focus of new research and development. Some of these capabilities will need storage to be fully functional. A move from current grid-following to grid-forming capabilities will be needed for operating wind- and solar-dominated grids, and interactions with other inverter-based resources will need to be studied in detail. An expanded discussion of these needs and solutions can be found in O’Malley (2023).

Figure 7. System needs and services of the next generation of wind plants. ***Adapted from Holttinen and Cutululis, to be published***

Lastly, as indicated in Figure 8, the integration of wind energy with the grid happens at several spatial scales, which can vary from individual turbine components to wind plants and the surrounding site to grid interconnects to where mesoscale atmospheric conditions meet continental-scale transmission demands. Although computational models exist to understand the integration of individual wind plants into electrical networks, highly accurate models that can consider large numbers of wind turbines dispersed widely across geographic regions and connected to the electrical grid across transmission and distribution systems will be needed to perform the system-level design and analysis required to meet local and national renewable energy and carbon goals.

Figure 8. Plant and grid integration. ***Illustration by Josh Bauer, National Renewable Energy Laboratory***

4.3.1 Impacts

For wind energy to provide evolving services to the grid, new strategies likely need to be developed, and wind turbine and plant designs would benefit from expanding to include the correct power electronics. Failure to do so will result in grid instability and frequent reliability issues. This can translate as a shift from “maximum power production” to “on-demand power production.”

4.3.2 Initiative Needed To Address

The TEM #109 experts identified one major initiative—the development and demonstration of grid-forming services and operation for wind power plants. This will include model and technology development as well as extensive experimental campaigns and validation to ensure grid stability with large amounts of wind energy. Vendor-neutral tools will need to be developed for grid stability analysis. Also, these campaigns will need to be performed at multiple scales, including the individual wind turbine/technology level, the wind plant level, and the grid level.

4.4 Further Research and Actions

While the TEM #109 group of experts endeavored to identify a select few critical issues for the plant and grid, many other areas of work remain outside of these issues. Some of these areas that have connection to other topics discussed at TEM #109 are listed below.

Plant and flow control experts identified the following crosscutting areas:

- Atmosphere: For accurate and effective modeling of wind farm control, proper understanding and inclusion of atmospheric physics and conditions are required. See Section 7.3 for further discussion.
- Turbine: Like atmosphere, accurate models of turbine performance and characteristics are needed to develop effective flow control schemes; of particular interest are computationally efficient models of turbine fatigue and loading. See Section 7.4 for further discussion.
- Social: Better understanding of the social barriers to wind energy adoption can lead to the development of new plant control techniques. See Section 7.8 for further discussion.
- Environment: Models of wildlife interactions and better understanding of environmental impacts will influence controller design and development. See Section 7.5 for further discussion.

The grid experts identified several crosscutting topics as well within their focus area:

- Turbine: Collaboration on turbine design, specifically the power electronics, will be needed to provide the necessary grid services. See Section 7.4 for further discussion.
- Social: Better understanding of social concerns about wind energy and its integration into the grid will inform the developed grid solutions. See Section 7.8 for further discussion.
- Environment: Impacts on the environment will need to be integrated into the grid control solutions. See Section 7.5 for further discussion.

ENVIRONMENTAL CO-DESIGN

Technology Collaboration Programme
by IEA

IEA Wind TCP Task 11
Technical Report

5 Environmental Co-Design

As technical experts from academia, research laboratories, and industry gathered at the IEA Wind TEM #109 to discuss existing and future challenges facing wind energy, one of the subgroups focused on the aspect of environmental co-design. Wind energy deployment results in unintended impacts to the environment. The impacts can occur during different phases of development (e.g., construction, operation) and result in direct mortality, disruptions to wildlife behavior and physiology, habitat loss and fragmentation, and changes in ecosystem processes. Quantifying and reducing wind-turbine-related impacts to the environment often require interdisciplinary research and integration of technology with wind turbines or wind plants. Co-designing a project with environmental considerations from inception can increase development efficiency by accounting for regulatory requirements and costs for monitoring and mitigation. More broadly, environmental co-design can avert impacts that may delay or restrain future deployment goals.

The mitigation hierarchy is a framework that can be used to identify and address the environmental impacts of wind energy. In its simplest form, the mitigation hierarchy consists of three stages: avoid, minimize (reduce), and compensate (restore, offset). For this report, the term "mitigation" encompasses the three stages of the mitigation hierarchy. The hierarchy can be applied from the project evaluation phase through decommissioning to better understand and mitigate environmental impacts.

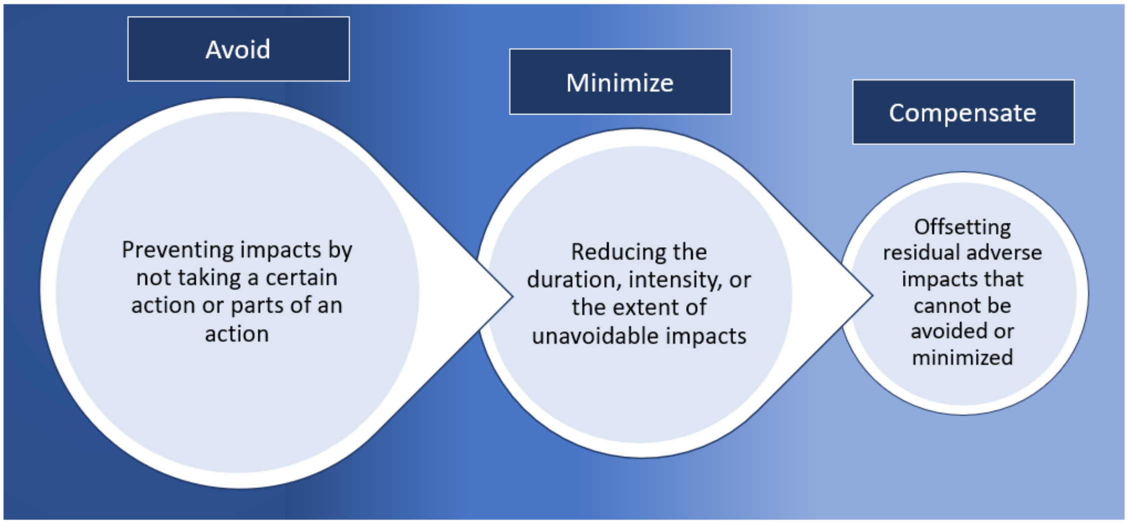

Figure 9. The core tenets of the mitigation hierarchy in relation to effort and project development phase

Prior to the in-person TEM #109 meeting in Boulder, Colorado, the environmental co-design subgroup held two virtual pre-meetings. The conversations ranged from specific topics (e.g., impacts of turbine strikes on bat populations) to broader issues regarding the environmental impacts of wind energy in emerging markets. Using the mitigation hierarchy, the environmental co-design experts categorized examples of knowledge gaps from the pre-meetings and sorted them by crosscutting research area (i.e., atmosphere, turbine, grid/plant).

Table 2. Knowledge Gaps at the Intersection of Environmental Research and Wind Energy Science That Should Be Addressed Across the Mitigation Hierarchy Framework

	Avoid	Minimize	Compensate
Atmosphere	Influence of atmospheric conditions on wildlife use/movement patterns Influence of topography on atmospheric conditions Effect of atmospheric conditions on the ocean surface/subsurface (e.g., turbidity, food webs)	Opportunities for wake steering to optimize wind turbine layout and minimize land use	Effects of wind turbine wakes on local vegetation and microclimate (e.g., aridification)
Turbine	Impact of different foundation types (fixed or floating) Specifications of wind turbines (height, blade length, cut-in speed, capacity factor) Life cycle of turbine components (e.g., recycling or reusing components vs. landfills)	Opportunities to integrate monitoring and minimization technologies with wind turbines Advances in wind turbine control systems to facilitate complex curtailment strategies	Impacts on habitat from forest harvesting (e.g., balsa wood) and mining practices for wind turbine components
Grid/Plant	Trade-offs of development scenarios (e.g., fewer, larger wind turbines vs. numerous, smaller wind turbines)	Influence of the number of turbines and layout on movement and use patterns Impact of curtailment on the grid and power purchasing agreements Impact of transmission cables/lines on wildlife movement and behavior	Challenges meeting compensation requirements under high build-out scenarios because land for compensation has already been acquired or developed

During the in-person TEM #109 meeting, the environmental co-design experts synthesized the discussion from the virtual pre-meeting and conversations from the breakout groups to establish three succinct critical issues. The group also discussed several major initiatives needed to address the following critical issues:

- Evaluate, design, site, source, transport, build, operate, and decommission wind energy and associated infrastructure to avoid, minimize, and compensate for the direct and indirect environmental impacts
- Identify and incorporate environmental costs and benefits into every decision point, from evaluation to decommissioning, of turbine/plant development
- Account for immediate project-level concerns while assessing broader spatial and temporal scales to address future environmental impacts and trade-offs.

5.1 Critical Issue: Avoiding, Minimizing, and Compensating for the Direct and Indirect Environmental Impacts

The environmental co-design experts recommended the following approach: evaluate, design, site, source, transport, build, operate, and decommission wind energy projects and associated infrastructure to avoid, minimize, and compensate for the direct and indirect environmental impacts. The steps are discussed further below and in Figure 10.

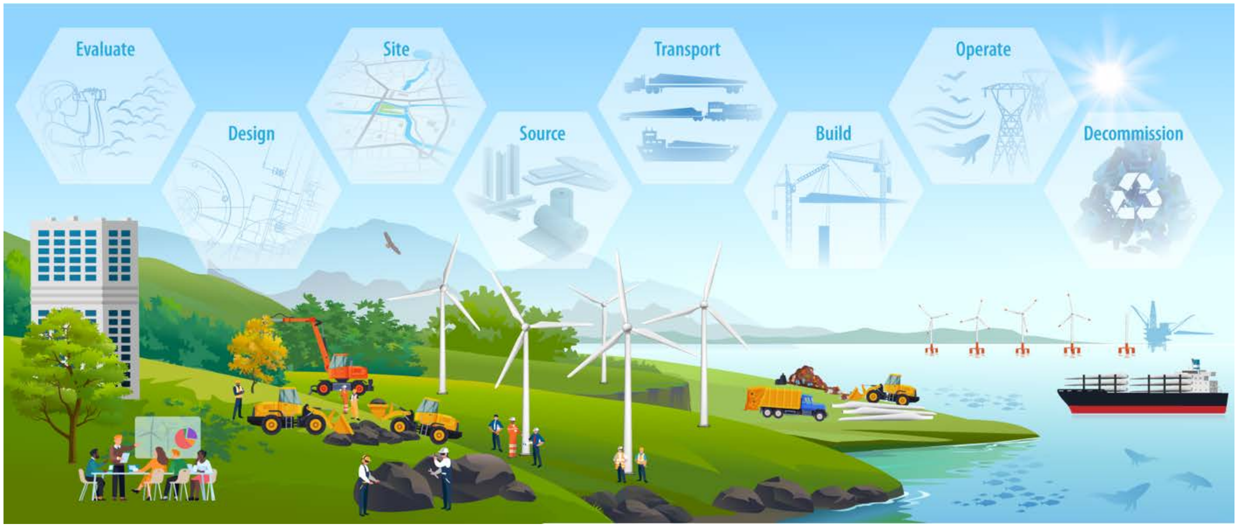

Figure 10. Opportunities for mitigating environmental impacts occur at each stage of the wind turbine and wind plant life cycle. ***Illustration by Al Hicks, NREL***

5.1.1 *Impacts*

- Evaluating a proposed project site involves desktop analyses of several factors, including the wind resource, presence of sensitive habitat or ecosystem processes, and species occurrence and movement patterns. This initial assessment can identify potential concerns and inform the type of environmental field monitoring necessary during later phases of a project.
- Designing a cost-effective wind plant includes considerations for environmental monitoring and mitigation strategies. These strategies can vary in the timing and scale of implementation. Examples include informing decisions for turbine layout to avoid impacts to the local habitat or ecosystem processes and integrating technology to quantify or reduce collision risk in the wind turbine manufacturing process. Early engagement among scientists, turbine manufacturers, and project planners can help select the appropriate number of wind turbines, turbine models, foundation types, turbine placements, and technologies necessary to meet regulatory requirements for monitoring and mitigation.
- Siting wind plants to mitigate environmental impacts incorporates information from the evaluation and design phases, plus field monitoring studies to macro-site the location of the wind farm and micro-site individual wind turbines. Environmental impact assessments for a site often focus on species presence and spatiotemporal patterns of activity to help predict the location and timing of risk. Results from these studies can be used to avoid sensitive habitats and areas of high wildlife activity, inform the layout of

the wind plant to limit indirect impacts to use and movement of wildlife, anticipate necessary minimization activities to limit direct impacts, and plan for any compensation associated with habitat loss or other impacts.

- Sourcing materials for the development of new or repowered wind farms requires sustainable practices for mining and forestry. Mineral extraction and harvesting wood products result in habitat loss or alteration, and indirect impacts to species (e.g., loss of mating, nesting, or foraging sites). Methods used to achieve sustainable sourcing include conducting material life cycle analyses, prioritizing the use of recycled and renewable materials, establishing ethical and responsible supply chains, and accounting for end-of-life disposal.
- Transporting materials to the manufacturing facility, transporting wind turbine components to the wind plant, and removing materials during decommissioning all contribute to increased vehicle and vessel traffic. The environmental impacts of this traffic primarily include additional carbon emissions, collisions between vehicles/vessels and wildlife, and noise pollution for sensitive wildlife. Mitigating these impacts can include locating manufacturing facilities near hot spots for wind energy development and planning the timing and routes of traffic to avoid the presence of sensitive species or important life cycle stages like migration or mating. In addition, using electric vehicles or offsetting carbon emissions may help mitigate the use of fossil fuels in transport.
- Building a wind plant requires coordinating numerous activities over several months. The activities can result in the loss or alteration of habitat (e.g., removal of trees for roads and turbine pads), noise pollution (e.g., pile driving monopoles into the ocean floor), and disturbance of local ecosystem processes (e.g., changes in atmospheric or oceanic flow patterns) and animal behavior (e.g., reproduction or migration). Environmental considerations during this phase of development can include selecting the appropriate foundation type to limit impacts to the local habitat, avoiding construction during sensitive periods for local species, and using technologies to minimize sound propagation.
- Operating a wind plant results in both direct and indirect impacts to wildlife. Direct impacts include collision events with bats and birds. The presence of turbines may also indirectly impact species behavior, physiology, and survivability. Certain species may be attracted to wind turbines, or alternatively, species may avoid or be displaced by wind plants. These indirect impacts may occur at the landscape or turbine scale. There also may be disturbances to ecological processes, including atmospheric and oceanographic flow patterns, which may impact the local habitat and communities. Mitigating the direct impacts may be achieved through targeted curtailment strategies or the use of deterrent technologies. Indirect effects are best minimized during the siting phase of development.
- Decommissioning a wind plant involves the removal of all infrastructure from a project. Since wind plants have a relatively short life span, decommissioning is rather common and requires careful planning to properly dispose of or recycle the wind turbine components. Encouraging reusable or recyclable materials in the manufacturing stage is essential to limit the need for additional extraction of minerals and wood products and limit the need for landfills, especially when wind farms are repowered and thus do not meet their original anticipated life span. Decommissioning is also the phase when owners can compensate for any impacts that were not avoided or minimized during previous phases of development and by restoring the site to its previous condition.

5.1.2 Initiatives Needed To Address

See Section 5.4 for a list of initiatives to address all three critical issues related to environmental co-design.

5.2 Critical Issue: Incorporating Environmental Costs and Benefits Into Every Decision Point

To help facilitate the environmental co-design of wind turbines and wind plants, it is necessary to identify and incorporate the environmental costs and benefits into the business model for proponents for every phase of turbine/plant development, from evaluation to decommissioning. Quantifying the costs and benefits of wildlife and ecosystem services is complex, but a better understanding will allow industry and government agencies to make informed decisions on where to focus resources for monitoring and mitigation. To be cost-effective, innovative solutions are needed to obtain the necessary information, reduce the levelized cost of energy, and keep up with the pace of deployment.

5.2.1 Impacts

By looking at every phase of the wind farm life cycle, it may be possible to assess potential trade-offs and make decisions to move forward with, modify, or abandon a project. There may be trade-offs between designing and siting a wind plant, including the number of turbines, turbine model, macro- and micro-siting, and the environmental impacts associated with building and operating a facility that are not sustainable.

5.2.2 Initiatives Needed To Address

See Section 5.4 for a list of initiatives to address all three critical issues related to environmental co-design.

5.3 Critical Issue: Accounting for Immediate Concerns While Addressing Future Impacts and Trade-Offs

One of the critical issues identified by environmental co-design experts was accounting for immediate project-level concerns while assessing broader spatial and temporal scales to address future environmental impacts and trade-offs.

5.3.1 Impacts

While it remains important to assess the environmental impacts at the project level, it is necessary to examine the broader cumulative impacts of wind energy at existing capacity and under future deployment scenarios. Project-level assessments can help determine local impacts, but there is often a disconnect across projects, which limits broader spatiotemporal analyses. To fully address the cumulative impacts or predict potential future impacts of wind energy on the environment will require broad-scale adoption of data standardization methods and data sharing tools (e.g., digitalization). By anticipating the cumulative environmental impacts from future deployment scenarios (e.g., 50% of electrical generation by 2050), interdisciplinary researchers, regulatory agencies, and the wind industry can begin to implement cost-effective mitigation measures that allow for a more sustainable wind energy industry.

5.3.2 Initiatives Needed To Address

See Section 5.4 for a list of initiatives to address all three critical issues related to environmental co-design.

5.4 Initiatives Needed To Address Critical Issues in Environmental Co-Design

The TEM #109 experts determined that the following initiatives are needed to help provide the scientific and technological basis on which environmental co-design can be used as a key tool for resolving conflicts:

- Network of wind farms for transdisciplinary research. Establish a strategic network of research-driven, commercial-scale projects to conduct transdisciplinary studies and validate monitoring and minimization technologies across all phases of development. These sites should account for variability across regions, turbine technologies, deployment type (e.g., land-based, fixed-bottom, or floating wind farms), environmental conditions, and spatial scales.
- Cost and benefit metrics. Adapt existing frameworks to identify and convey metrics for environmental costs and benefits for project developers.
- Standardized practices. Develop an ISO-like standardization (or recommended practices) for data collection, analysis, and reporting to facilitate comparability across projects.
- Data sharing framework. Develop a publicly available data framework that is transparent, standardized, and objective-based, for multiscale decision-making.
- Interdisciplinary data. Identify and aggregate data and metrics from other research areas (atmosphere, turbine, plant/grid, economic, social) to facilitate environmental research.
- Mitigation system. Design a mitigation system for all stages of wind plant development (i.e., evaluation through decommissioning), incorporating measures for avoidance, minimization, and compensation that are additional, achievable, and verifiable.

5.5 Further Research and Actions

A common theme from the virtual and in-person meetings was that discussions for environmental co-design should include multiple stakeholder groups, including the five research fields represented in the TEM, plus industry and government agencies, and occur early in the wind turbine/plant design process. Frequent interdisciplinary engagement and collaborative research are needed across research fields and relevant stakeholder groups, including the wind industry. The actions listed below are relatively easy, near-term activities intended to socialize the need for interdisciplinary research and help facilitate the major initiatives listed in Section 5.4. See Section 7.1 (Environment–Turbine), Section 7.5 (Grid/Plant–Environment), and Section 7.6 (Atmosphere–Environment) for further discussion.

- Disseminate findings from TEM #109 through manuscripts, research briefs, and presentations to socialize the critical issues and recommended actions
- Engage with participants at non-environmental conferences and promote multidisciplinary panels/sessions at environmental conferences

- Conduct a horizon scan of the potential environmental impacts of future deployment scenarios to help with long-term decision-making for both industry and government agencies
- Establish a common language of terminology to facilitate interdisciplinary discussions
- Quantify and articulate the value proposition of sharing data and minimizing impacts to better inform industry decisions throughout development phases
- Develop specific research topics/questions to initiate multidisciplinary working group discussions
- Write proposals based on initial findings from TEM #109 to secure funding for multidisciplinary working groups and research initiatives
- Establish multidisciplinary working groups with other research fields to define research gaps and recommendations for follow-on work
- Act on the research recommendations established by the working groups.

SOCIAL SCIENCE

6 Social Science

As technical experts from academia, research laboratories, and industry gathered at the IEA Wind TCP TEM #109 to discuss existing and future wind energy challenges, one of the subgroups focused on the social sciences aspect. Their discussions centered around the pressing need to rethink how social science is positioned in the research and decision-making aspects of wind energy development. TEM #109 participants highlighted how the social dimensions of wind energy typically focus on the concept of social acceptance, which generally endeavors to have communities and those close to infrastructure development accept what is proposed to them, as opposed to wind energy proponents (e.g., industry, policymakers) co-creating projects with communities that align with their articulated needs and priorities. Further, group discussion highlighted how the social dynamics of wind energy development are frequently considered separately and often after efforts that focus on the technical elements of the field. To reenvision these dynamics and bolster opportunities for win-win outcomes, the group identified three critical topics for researchers and implementers to address:

- Acknowledging the transformational nature of rapid, large-scale wind energy development
- Creating just processes and proactive consideration of local community needs
- Valuating benefits, effects, and burdens.

6.1 Critical Issue: Acknowledging the Transformational Nature of Rapid, Large-Scale Wind Energy Development

To date, the social dimensions of wind energy development have typically been considered at the individual project level or individual community level. However, TEM discussions strongly aligned on the need to shift to broader, “landscape-level” ways of thinking, as policy and private sector goals point toward large-scale, decades-long deployment efforts. Doing so requires researchers and implementers to enhance their focus on understanding, planning for, and communicating the potential for a significantly increased presence of wind turbines. It also points to the need for development and decision-making processes to evolve in ways that will increase the likelihood that society will allow deployment at this scale. Specific topics discussed under this concept included the role of wind energy in the energy transition, scale and concentration of deployment, and the need for focused communications across stakeholder groups.

6.1.1 Impacts

The increased scale and concentration of wind turbines on the landscape present challenges and opportunities for the increasing number of people who will live near them. The geographic distribution of wind energy projects must be proactively considered, as is currently happening in Germany, where each state must identify their contribution to a national requirement that 2% of the country’s total land mass be designated for wind energy use by 2032. To prepare for this sustained development, communities will need to identify their values and preferences regarding the expansion of renewables, including the siting of generation and related infrastructure (e.g., transmission, storage). In addition, communities can benefit from support in anticipating how wind energy technology may change over time (e.g., increasing tower heights, repowering opportunities). Further, as technology advancement and policy measures enable existing wind turbines to be kept in service through repowering, communities and regulators will also need to revisit any initial expectations that land used for wind energy generation would be temporary (Windemer 2019).

The transformational nature of change also points to a need for wind energy proponents to develop new approaches to their work. One participant noted the tensions between current mindsets about siting and future deployment goals in remarking that “we can’t move turbines away from people anymore.” Instead, turbine design, planning processes, and operations must evolve to better address host community concerns and priorities, or deployment goals will not be reached. Mitigation strategies may already be available to address local concerns with minimal impact to operators (e.g., targeted curtailment, reduced turbine lighting), while other impacts to things like place identity (or how an individual’s connection to the place around them shapes their sense of self) are likely much harder to address. Increased collaboration and co-creation between developers, policymakers, and communities are critical to exploring these options and identifying opportunities to better align wind energy deployment with local goals.

The idea of co-creation will likely require an openness to explore customized technology design, siting, and operations, and creativity to address the ways in which such an approach could challenge goals for the standardization, industrialization, and cost reductions that are needed for expanded deployment. The group considered a comparison to the automotive industry that showed that customization (i.e., creating different vehicle models) was an integral part of scaling the industry. They also considered an example from the Netherlands where a community voiced support for a local wind project only if it used smaller turbines that the industry had stopped producing as a result of the upscaling process. Further investment to find synergies in technological and social goals and create “win-win” opportunities will be key to realizing the transformational change needed to meet ambitious deployment targets.

Finally, members noted communications as an important component in realizing transformational change. Policymakers and community-level stakeholders need better insight into how much of the transition remains and the changes that lie ahead. Additionally, articulating the value of wind energy must go beyond the benefits of a carbon-free future and include factors such as lower energy costs and increased national security. However, work is needed to ensure that the types of information produced and the communication methods used are responsive to local realities, priorities, concerns, and cultural identities. A range of actors—including skilled communications professionals, planners and landscape architects, community-based organizations, and other trusted messengers—must be engaged to create a robust and effective communications strategy that informs and supports an increase in equitable wind energy deployment.

6.1.2 Initiatives Needed To Address

As with the preceding critical issues, TEM #109 participants proposed a mix of investment in research and changes in practice to address the challenges posed by the rapid, large-scale development of wind energy. The group identified opportunities for expanded research efforts to help achieve the following outcomes:

- Increased understanding of the cumulative impacts of energy and other forms of industrial development on landscapes, human connections to and uses of those landscapes, and opportunities to advance energy justice within this topic. Future energy landscape research can build on existing work (e.g., Devine-Wright 2020).

- Updated insights into general attitudes toward wind energy technology, with a focus on how reactions may shift in scenarios with significantly increased deployment levels and over longer periods of deployment.
- Self-identification of salient benefits of the transition for local workers and communities and a vision of an energy future that goes beyond individual project outcomes.
- Expansion of initiatives to help consumers better understand the value of wind energy on the grid and the ways in which they can support its integration while also addressing their concerns and the barriers they face in understanding these topics and modifying their energy use patterns.
- Collaboration with communities, policymakers and regulators, researchers, and industry to better understand specific areas of societal transformation that will be necessary to achieve wind energy deployment targets, as well as ways those aspects of societal transformation can be facilitated.
- Collaboration with developers, policymakers and regulators, researchers, and communities to better understand specific areas where transformation of the wind industry will be required to support long-term societal needs.
- Development of initiatives that identify opportunities to reconceptualize the relationship between technology and people, and the resources and actions needed to make progress on this challenge.

The group also recommended that the research findings and other outcomes from the aforementioned activities should be broadly disseminated and applied to support actions such as:

- Broadening understanding and use of existing mitigation measures (e.g., demand-oriented turbine lighting) and new mitigation strategies as they are developed
- Capacity-building and educating on the transformational changes that are needed for all stakeholders, with a focus on policymakers who can then set goals and enact policies to ensure those changes occur in a just and equitable manner
- Expanding initiatives that support community-led planning processes for large-scale deployment of renewables, such as Denmark’s local climate councils
- Investing in communication strategies and messaging, tailored to be responsive to the needs and priorities of a range of audiences (e.g., decision-makers, industry, labor, communities)
- Changing policy and regulation to better prepare societies for large-scale deployment of renewables and support industry to be responsive to community priorities.

6.2 Critical Issue: Creating Just Processes

As plans for the deployment of wind energy generation scale, so too does the need for more just processes throughout all stages of the wind energy project life cycle. Just processes meaningfully include communities and others who may experience the burdens of wind energy development to identify opportunities to enhance positive outcomes and minimize negative impacts. Topics discussed in this area included local engagement, participation, co-creation, and alignment with local priorities.

6.2.1 *Impacts*

Limited engagement of host communities and other potentially burdened stakeholders can result in inequitable outcomes, increased vulnerability, public opposition, and increases in the cost and time needed to deploy clean energy. Increasingly, authorities are establishing goals or requirements for equity and justice in clean energy transitions, yet those goals may not be met without further attention to these topics. While researchers and other actors have explored this concept to some extent, more research is needed to deepen understanding of how to best implement just processes and then revise planning and decision-making processes to apply research findings.

Barriers to just processes include engagement that is performative (versus meaningful), narrowly focused to certain stakeholder groups, and/or limited to the planning process of a project (as opposed to extending through construction, operation, and any decisions around decommissioning or repowering). Capacity to engage was also noted as a barrier to just processes, in terms of the time and skills needed to navigate complex and, in some cases, sensitive relationships; provide input; and understand and act on input received. Just processes must also address the growing potential for stakeholder fatigue, value stakeholder input as an opportunity for trust-building and co-creation, and be culturally relevant.

6.2.2 *Initiatives Needed To Address*

A concerted effort is needed to support researchers, developers, policymakers, and others to effectively increase their ability to understand, commit to, and implement just processes as deployment rapidly expands. The group identified the following research areas to explore:

- Examine the fundamental questions of what makes a process just, how to implement just processes, and a broader understanding of potential outcomes that goes beyond social acceptance concepts
- Determine ways to achieve alignment with local priorities while recognizing the developer’s needs at all phases of a project’s life cycle
- Identify the value of just processes, both in terms of avoided negative impacts (e.g., project failures and delays) and delivered positive impacts (e.g., additional utilization of rewind resource, higher socioeconomic value creation, greater well-being)
- Identify entry points for meaningful, appropriate, and equitable ways to access and engage communities and other potentially burdened stakeholders, not only in the development of a project, but also in the development of the technology being used.

More focused efforts are needed to ensure that research findings on just processes are readily accessible to developers, regulators, policymakers at different levels of government, and other stakeholders and can be applied as they reconsider their approaches. For example, research findings could be integrated into initiatives that would:

- Build individual and institutional capacities to design and engage in just processes that include a broad range of stakeholders such as government authorities, developers, operators, local authorities, community members, community-based organizations, and labor/workforce interests. Such an effort would require appropriate funding and could include focused technical assistance and the creation of locally relevant information to be used by communities.

- Enable direct process experimentation by creating spaces where technology design, project planning, and permitting processes can be evaluated and changed. This could include co-creation initiatives and utilization of less traditional, more flexible planning approaches.
- Build on research and experimentation findings and redesign policy and regulation to require just processes throughout the stages of wind energy development, as is needed and as jurisdictional authority allows.

6.3 Critical Issue: Valuating Benefits, Effects, and Burdens

The third critical social science issue explores how aspects of the clean energy transition, including wind energy deployment, are measured and valued by different actors, as well as how that valuation informs wind energy decision-making processes. The group discussed the need to differentiate among positive valuation (benefits), neutral valuation (effects), and negative valuation (burdens). Topics discussed within this challenge included noise, visual impacts, shadow, annoyance, place attachment, local identity, and community benefits.

6.3.1 Impacts

Current limitations to how the impacts of wind energy development are understood and measured constrain our ability to effectively communicate them and integrate them into decision-making processes. The human impacts of wind energy development can be difficult to measure quantitatively and require analysis from multiple disciplines (e.g., economics, psychology, sociology). This can challenge efforts to create just processes (see Section 6.2), as there may be insufficient data available to understand and act on a community's questions, concerns, and priorities.

The issue of valuation was explored through impacts related to noise emissions from wind energy plants. While the primary impact from noise emissions is annoyance, the definition of annoyances currently varies, and there are many challenges to measuring it. Interdisciplinary research is needed to fully understand this complex topic. While some progress has been made (Hübner et al. 2019), the lack of a shared definition and more dynamic measurement approaches are likely to lead to blanket curtailment scenarios that reduce energy production and may or may not effectively address the root cause of annoyance. The group acknowledged that, while noise emissions were a leading example of a human impact in need of greater understanding, there are many other impacts with a similar set of issues that should also be explored.

6.3.2 Initiatives Needed To Address

The group's discussion focused on the need to reconceptualize the energy transition and what it means for a range of stakeholders, including communities that will host or be impacted by energy infrastructure deployment, by investing in ways to better express and act on the valuation of wind energy development impacts. TEM #109 participants identified the following additional research elements to support this effort:

- Better identify benefits, effects, and burdens, including cumulative effects and cross-dependencies; also, explicitly acknowledge when no effects are identified
- Collect data to evaluate exposure to benefits, effects, and burdens, particularly through repeating and/or expanding research in more situations and countries

- Examine cumulative or indirect effects on health, well-being, and economic indicators
- Create standardized valuation methods and value metrics for benefits, effects, and burdens to allow for comparison across projects and/or different countries
- Analyze distribution of benefits, effects, and burdens (e.g., Who is impacted and how? How are impacts valued? How and why do different communities or different stakeholders within communities perceive impacts differently?)
- Determine ways to reduce burdens or enhance benefits, including through experimentation with technical design changes.

As with the first critical issue, the group discussed the need to effectively connect research to practice. Examples of how developers, regulators, and others can build on this research included:

- Create new value metrics that can be integrated into turbine design and plant development from the beginning
- Translate findings into regulations, policies, and standards to make them more effective, targeted, and dynamic, and thus more responsive to challenges identified.

6.4 Further Research and Actions

While each critical challenge initiative noted specific areas of research that should be pursued, the group also identified additional topics to be explored, including (as examples):

- Interdisciplinary research, as well as review of projects, that integrates social and technical issues. See Sections 7.7 and 7.8 for further discussions.
- Creation of tools (e.g., algorithms) to enable multi-criteria plant control and incorporate feedback from people into the operational process, testing that the software and hardware work, and validation in the field that adjustments lead to a reduction in annoyance and/or other negative impacts.
- Utilization of other types of field experiments for verification and validation of reduced social impacts of dedicated initiatives.
- Development of guidelines and/or standards for best practices for social engagement and processes for implementation in regulation and policies. This could include the creation of a new “Social and Environmental Impact Assessment” regulation or an investigation into the potential for an ISO standard or “social label” for wind turbines/plants on social issues to characterize efforts to reduce negative impacts such as annoyance.
- Engagement with financing stakeholders (e.g., banks, tax policymakers) to inform them of research findings regarding value of just processes and other social enhancements in reducing project risk.
- Development of projects that demonstrate the creative potential of local communities to design their own just process (through a prize or similar effort to incentivize process experimentation).
- Technical assistance and co-creation of resources to be utilized at the community level.
- Research on the impact to community and regulators when there is deviation from original plans (e.g., change in project ownership, extension of project through repowering). How can just processes be applied? How do perceptions change?

- Enhancement of communications across all critical challenge areas. Consider developing one-page summaries or brief case studies on key topics to provide a more universal understanding of how issues are being addressed.

Notably, these recommendations reflect similar themes to those captured in comparable research (Gill 2022, Rogge et al. 2023) where additional context may be helpful to consider.

7 Opportunities for Interdisciplinary Work

Often a scientific challenge is expected to delve deeply into a specific area of expertise, but this can lead to a loss of context for the nature of the problems that need solving. The wind energy Grand Challenges are a prime example of this issue. There are few problems as interconnected and interdisciplinary as wind energy. One cannot determine the manufacturing requirements of a turbine without specifying the atmospheric conditions it must withstand. The design of the drive train is intrinsically tied to the nature of the electrical demands of the grid, and both present and future power are driven by the ability to predict the airflow in the plant.

With the addition of social and environmental challenges, the interdisciplinary complexity increases. These key elements have, in the past, been treated as exogenous outcomes that need to be mitigated and are not able to be addressed in the early stages of technology development or design implementation. The breakout design of the TEM #109 meeting intentionally created opportunities for dialogue and brainstorming over better pathways forward. The second day of the meeting focused on crosscutting breakout sessions devoted to exploring these intersections.

There are potentially 10 bilateral crosscuts between the five Grand Challenge areas. Prior to the meeting, attendees were surveyed as to which crosscuts were of greatest interest to them so assignments could be made for relatively even coverage. While the intersection between social and environmental experts and the traditionally more technical areas of atmosphere, turbine, and grid/plant were of highest priority, the greatest interest still lay within the technical areas, which is not surprising given the background of the attendees. Figure 11 shows the outcome of that survey. However, the environmental and social experts agreed that there is still a lot to be done between these groups. The lack of a breakout on the environmental/social crosscut leaves that intersection to be explored in a future meeting (perhaps a co-located meeting of Tasks 28 and 34 that currently address these areas).

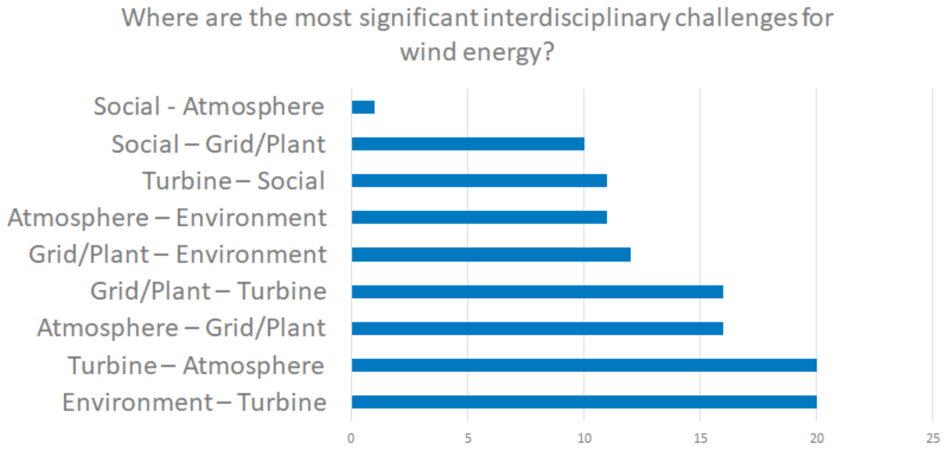

Figure 11. Those invited to the TEM #109 were surveyed to determine the level of interest in each bilateral interdisciplinary challenge. The results were quite evenly distributed with only one area showing little interest. Attendees were then assigned to crosscuts where they were the most interested. The option for the Environment–Social crosscut was not offered to keep from diluting the limited numbers in those groups. However, many in those groups noted the need for additional conversations between environmental and social issues.

The crosscutting breakout groups discovered critical elements that could only be addressed in cross-disciplinary efforts. Common to all, and perhaps first on everyone's mind, was the need for clarity in communication and the ability to cut through discipline-specific language that can make such interactions challenging. The challenges and proposed actions recommended by each crosscutting group are recorded here.

7.1 Environment–Turbine

For many in attendance at TEM #109, the meeting was the first opportunity to engage with others outside their area of expertise. One of the first discussions of the Environment–Turbine group was to define "environment." Historically, the conversations and research around environmental impacts from wind energy have been focused on wildlife, but the attendees determined that the scope of the TEM is much broader than wildlife. Most attendees in the engineering field, for example, had never had the opportunity to interact in a setting like this with experts from the environmental sciences. The group therefore spent much of their time discussing the greater challenges in environmental sciences such as understanding behavior and populations of impacted species and how they interact with wind turbines (i.e., many competing interests when designing different wind turbine components). The group discussed how increased communication between both parties could be used to identify challenges that span the life cycle of a turbine.

7.1.1 Challenges

The group of experts identified seven main challenges at the Environment–Turbine intersection.

7.1.1.1 Establishing Common Language and Definitions

There is a need for a common language when working with cross-sectional groups. For example, there is a need to define "environment" and establish a clear understanding of the meaning when used in the discussion of wind energy.

7.1.1.2 Understanding Material Needs for Scale of Buildout

To meet future deployment goals, we need to understand the materials needs for wind turbines. This also provides an opportunity to optimize design and materials in a sustainable way for future deployment scenarios.

7.1.1.3 Incorporating Environmental Co-Design

There are many opportunities to evaluate components, perform cost benefit analyses, and better map environmental impacts by turbine component.

7.1.1.4 Communicating Research Needs

There is a significant need to communicate early and often about research needs and new ideas to avoid and minimize the impacts of wind energy deployment on the environment. Sensory ecology was a topic that was discussed in more detail as a place to start.

7.1.1.5 Deploying Dual-Purpose Technologies

The collaboration between turbine designers and ecologists presents an opportunity to deploy technologies that can simultaneously improve turbine performance and monitor impacts to wildlife. An example of this would be multipurpose sensors installed on turbines.

7.1.1.6 Engaging Turbine Manufacturers

Although many different areas of expertise were represented, it was clear that there was an absence of turbine manufacturers in the Environment–Turbine crosscut discussion. Engaging early and often with turbine manufacturers will be crucial to integrating dual-purpose technologies and minimization strategies into turbine design and operation.

7.1.1.7 Improving Data Collection and Sharing

An improved shared understanding of the data needs and collection opportunities would facilitate research and advancements at the environment-turbine intersection. With respect to data needs, continued dialogue is needed regarding the specifications of technologies installed on wind turbines to monitor and minimize environmental impacts. These include the size and weight of the technology and where it is positioned (e.g., nacelle, tower, blades), power requirements, and access to external communications.

7.1.2 Proposed Actions

Although the terminology used to describe the critical issues in the prior breakout sessions differed between the Turbine and Environment groups, the group members realized how well they aligned with each other in the crosscutting discussion. They connected each critical issue between Turbine and Environment (Table 3), which will help facilitate future discussions and align action items from each of the greater topic areas. Both groups found the conversation beneficial and will continue to engage on how to design more environmentally minded wind turbines while meeting wind energy deployment goals.

Table 3. Environment–Turbine Crosscutting Critical Issues

Turbine	Environment
Holistic design	Evaluate, design, site, source, transport, build, operate, and decommission wind energy and associated infrastructure to avoid, minimize, and compensate for the direct and indirect environmental impacts
Industrialization	Account for immediate project-level concerns while assessing broader spatial and temporal scales to address future environmental impacts and trade-offs
Intelligent operations	Identify and incorporate environmental costs and benefits into every decision point, from conception to decommissioning, of turbine/plant development and operations

7.2 Turbine–Atmosphere

As described in Section 3: The Turbine, today's wind turbines require further R&D efforts to meet the requirements of a future carbon-free electricity market. TEM #109 participants identified three high-priority research areas: holistic design, intelligent controls and O&M, and industrialization.

Meanwhile, as discussed in Section 2: The Atmosphere, atmospheric turbulence has not yet been characterized in sufficient detail 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 generate power.

The turbine-atmosphere breakout session at the TEM #109 meeting allowed technical experts in wind turbine technology to discuss potential crosscutting issues with atmosphere experts, and as part of these discussions, the attendees identified the following challenges.

7.2.1 Challenges

TEM #109 meeting attendees identified the following three crosscutting challenges in the research areas of turbulence and atmosphere:

7.2.1.1 Improving Open-Design Bases

The participants identified the need for open data sets that focus on the metocean measurements required to evaluate the feasibility of wind deployment in different offshore regions (e.g., wave characterization, turbulence spectra in three directions, spatial coherence in three directions, component correlations, wind/wave misalignment, current direction and profile, joint probabilities of these, plus 1-, 50-, 100-, and 500-extremes, sea surface temperature, air temperature at multiple levels, wind speed and direction profiles, boundary layer height, and precipitation rate/amount and type). To enhance the data set's value, the measurements should incorporate an evaluation of associated uncertainties, and long-term measurements should be included for a better understanding of extreme estimations. Digitalization is also crucial to engage various stakeholders through common data formats and storage approaches (such as the DOE Atmospheric Radiation Measurement User Facility[5] and FINO[6]), ensuring consistent use. Furthermore, improved communication is necessary between atmospheric modelers and load analysts to guarantee that atmospheric measurements and models provide the necessary information that structural load modelers require. For example, coherence measurements require turbulence measured at the same horizontal level separated by a turbine rotor width, whereas typical atmospheric measurements provide profiles. Researchers should also address the question, "How will climate change impact the design basis for a given site?"

7.2.1.2 Improving Annual Energy Production Estimates

There is a need for improved estimates of annual energy production that consider the actual variability of the atmosphere, rather than relying on single-point-derived annual energy production estimates. Factors such as wind shear, turbulence, and wake behavior can affect turbine and performance annual energy production estimates and need to be accounted for. It is also essential to evaluate how curtailment can affect these estimates. Related to this topic, forecasting and optimizing plant operation are also essential to maximize annual energy production.

7.2.1.3 Improving Design Standards

Participants noted that additional improvements are needed in wind turbine design standards. One significant area requiring attention is the gust case, which is not realistic for large, offshore wind turbines, as it is characterized for smaller turbines. Another area is the treatment of neutral atmospheric stability whereas stable and unstable conditions are heavily prominent in real life. Currently, the level of risk that an operator accepts is not apparent within the design standards.

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[5] https://www.arm.gov/

[6] https://www.fino3.de/en/

There is a need to understand the rationale behind their development to facilitate necessary updates. To ensure that the loads analysis captures the right components, a better understanding of the atmosphere is required. Additionally, researchers need to have a better understanding of extreme events, including more knowledge of the joint probabilities of wind and wave conditions. The participants suggested considering air-sea interaction as a part of the design process, treating it as a complex flow; initial studies suggest that there may not be much need for two-way coupling, but further investigation is required to confirm this. A reliability-based design approach could help address some of these issues. A final note was the cost of design standards inhibits the access for researchers and therefore limits research progress, and the participants strongly argued for open-source access to design standards for research purposes to enable broader participation and more rapid progress.

7.2.2 Proposed Actions

The experts identified two actions to address the critical crosscutting issues: develop improved open-design bases and develop more atmospherically aware design and operational approaches.

Developing open-design bases is a critical step in ensuring the safety and cost-efficiency of wind turbines. To achieve this, more cooperation between atmospheric modelers and structural engineers can expand research beyond power estimates toward developing an understanding of the characteristics that affect the loading on the structure, particularly under different atmospheric stability and surface conditions. Researchers should also develop models that assess how these characteristics may change over time due to climate change, as well as evaluate how needs will evolve with technology advancements (e.g., size, topology, etc.).

To create an open-design basis, it is essential to facilitate deeper collaboration between atmospheric and oceanographic (metocean) modelers and turbine experts. Collaborative design groups with loads analysts and atmospheric modelers working together can help ensure they understand each other's needs and provide the required information. Additionally, researchers must be well integrated with industry (original equipment manufacturers, developers, and support structure designers) to ensure that the industry's needs are directly addressed and the knowledge is integrated into their wind turbine designs. Participation in standards development is open to those who want to participate (after approval by national committees). Open access of standards for research purposes and R&D groups being able to discuss changes to the standards with standards-development bodies would be helpful. Working together on standards committees is one way to achieve this, and the process for joining should be made more open to researchers.

To ensure the usefulness of an open-design basis, digitalization concepts such as application programming interfaces and community data formats should be used to simplify data exchange across organizational and discipline boundaries. Long-term measurements can provide valuable insights for evaluating extreme values. The design standards and tools should be updated based on better understanding derived from the measurements and models developed for the open-design bases. Lastly, making standards free can lead to an integrated discussion across standards, the application process, and the research community, which rarely has access to standards residing behind paywalls.

The second proposed action is to develop atmosphere-aware design and operations. Wind turbine design and operations could be better optimized with more integration of atmospheric measurements. Present control operations consider only the wind speed measurement at the turbine hub height to determine how it will operate. If the turbine could take in more atmospheric knowledge both at the turbine and farm levels, as well as knowledge about how that wind will change through forecasting, improvements could be made to the power output as well as life extension. More extensive measurements could include wind speed and direction profiles, turbulence profiles, and upwind measurements to anticipate upcoming changes driven by atmospheric conditions.

To develop an atmospherically aware turbine, atmospheric researchers and wind turbine designers need to collaborate to identify the critical measurements needed and develop new control methods based on this information. This will require the development of new measurement technologies and techniques, such as better integration of LIDARs, to provide the necessary data to the turbine. By doing so, it is possible to optimize the turbine's performance and increase its longevity.

7.3 Atmosphere–Grid/Plant

TEM #109 participants met to discuss crosscutting issues related to the atmosphere and the grid/plant. As the industry moves to large-scale renewable energy deployments, leveraging atmospheric science becomes essential to managing wind plants and the electricity grid. As one participant stated, the wind plant has two eyes—one is turned to the atmosphere and the other to the grid. The experts identified several high-priority research areas: using atmospheric information to control the flow in the wind farm, planning for dispatchable hybrid plants, connecting the grid decision-making process more directly to the atmospheric models at multiple temporal and spatial scales, leveraging real-time atmospheric observations, and assessing risk across multiple time scales. Methods of digitalization and the associated software revolution associated with it are key enablers for this process.

7.3.1 Challenges

The challenge of the variability of renewable energy resources is extremely important because it impacts the grid and the reliable delivery of energy to consumers. Thus, in this crosscutting area, researchers highlighted the need to measure, model, and predict the wind, as well as to validate models from wind farm to power system to support the optimization and design of wind farms in future energy systems. In addition, the big-picture view of a national system is important to being able to balance across a large renewables-heavy energy grid. The Atmosphere–Grid/Plant group identified the following challenges:

7.3.1.1 Improving Flow Control

As we seek to optimize the power generated by each wind farm, controlling wind turbines will become a prevalent way to maximize total plant output. The TEM #109 participants recognized the importance of real-time, high-resolution atmospheric information and prediction to enable this level of wind farm control. If one wishes to optimize the plant control, it is essential to provide realistic information about the atmospheric conditions. Wind speed and direction vary during a normal diurnal cycle as well as with passing weather patterns, but that connection to the plant is under-studied. Because large-eddy simulation (LES) models typically treat the atmosphere as an inflow, they model behavior more like a wind tunnel than like the real undulating, constantly changing atmosphere that exists. This observation points to the need for mesoscale-to-microscale coupling (MMC) to provide realistic conditions for the wind plant by supplying a connection to those outer changes. That process is necessary to even reproduce a basic diurnal cycle of the atmosphere where the boundary layer cycles from stable through neutral into convective stability conditions throughout the day before returning to a more stable condition as the sun goes down. Additionally, wind direction typically varies with height, and that wind veer can further complicate optimizing control.

A challenge, however, is that the type of MMC modeling that is needed to provide information for flow control is computationally expensive. In addition, the atmospheric models must couple with the engineering models for an optimized system. Although current efforts to speed LES with implementation on graphics processing units is helpful, it is still currently prohibitive to run for long periods of modeled time. One solution on the horizon is building low-order models, including those based on machine learning and trained with LES simulations.

7.3.1.2 Deploying Dispatchable Hybrid Plants

As we deploy hybrid plants that blend wind, solar, and storage, it becomes yet more critical to be able to predict the atmosphere over the short term for grid integration. One must understand the interplay between the wind and solar resource availability and make prudent decisions on when to store energy and when to discharge batteries. To integrate these hybrid plants into the grid and to ensure grid stability across multiple time scales, real-time prediction is needed. However, where there are no long-term measurements or statistics to base the forecast on, this becomes challenging. This process is location-dependent, involves short-term forecasting, and must consider fluctuations in the flow that lead to intermittency. Note that excellent forecasts could alleviate the need for overbuilding storage facilities or overdeploying wind plants.

7.3.1.3 Connecting the Grid to the Weather

The grid is already difficult to control, but by deploying large amounts of renewable energy, we are connecting it directly to chaotic weather patterns. These rapid changes can lead to transients on the electrical side, as well as resonances and bifurcation. The interconnection between the atmosphere and the electrical system needs to be incorporated into modeling the system as a whole. In the past, mechanical and electrical subsystems were decoupled, but that is changing with a high penetration of renewables.

Past operational focus has been on short time scales, and planning for the longer term was static. But all of that now relies on Earth system modeling data, which are required for different systems across a range of scales and fidelities for multiple purposes. One must consider what Earth system data are needed for decision-making at the longer planning time scales. A range of grid stability impacts blackout models that may include determining when transmission lines are overloaded. This is a large-area problem that includes grid connectivity across regions to alleviate local problems. Particularly with the deployment of large amounts of variable renewable energy, it becomes critical to balance across those larger regions where weather patterns may be less correlated in time. Such an approach could avoid the rapid ramps that come with smaller-scale regional changes in weather patterns.

Thus, it is becoming necessary to introduce atmospheric boundary conditions into engineering models to reduce the uncertainty that comes with the variability of the renewable resources. Because engineering models are parametric and based on multiple assumptions about those boundary conditions, we would ideally like to capture how the atmospheric conditions affect their accuracy.

7.3.1.4 Leveraging Real-Time Data

Typical wind plants are instrumented to provide real-time wind data that can be used for operation and to discern the response of the wind turbines to the current conditions. Those conditions extend beyond the basic wind speed and direction and include wind shear and veer as well as important stability information. The power output is itself an indication of atmospheric conditions, and that data set could be used as a low-order model and to verify and validate our existing physical models and provide uncertainty quantification. Thus, the turbine can be used as a sensor, with output used to indicate atmospheric conditions, including its impact on the structure of wakes and the structure of the resulting turbulence. But that is not sufficient. It is important to include atmospheric data sensors in the wind plant. Developers should consider the cost trade-offs of adding new sensors that provide firsthand information, which could pay back in plant optimization. That information can be accessed through the application of modern digitalization practices and then mined to detect faults in the machines.

One needs to have vertical profiles of wind speed and direction plus a measurement of horizontal variability. While we cannot install meteorological towers everywhere, we do have turbines everywhere in the regions of interest. Ideally, wind farms would share data to avoid errors that lead to inefficient power usage.

One could build an operational system that works from real-time sensed data of conditions. Such a system would be connected to a repository of simulations for a given area that could be mined to develop models and control systems. A systematic study of the environment that the plant works in would be used to determine situational awareness connected to that repository of simulations.

One can imagine building atmospheric models that can provide real-time input to make decisions rapidly. Ideally, models would be built to include flow control, manage frequency fluctuations, and aid in making large-scale grid operational decisions. Such a system would include validated atmospheric models with uncertainty quantified. Those models would connect to real-time observations of the current state of the atmosphere. It would also leverage artificial intelligence/machine learning for flow control and grid services. Very short-term forecasting could leverage in situ lidars combined with observational data from the wind farm. A critical issue is to detect and forecast ramp events, particularly detecting down ramps that might cover a large spatial scale. It would connect to the mechanical and electrical models to optimize the wind plant and grid system.

7.3.1.5 Conducting Risk Assessment Across Space and Time Scales

In addition to the shorter-range risks of not being able to cover the load with a renewable-heavy energy system, many risks derive from long-duration events. A major gap is our inability to predict such events with appropriate uncertainty quantification. One example is a large-scale wind drought, which could be caused by a high-pressure system that remains stable over a region for a period of days to months. Such systems can be exacerbated by large-scale atmospheric patterns on a multiyear or even multi-decade time scale. We must consider these issues as we are designing wind farms and grid systems to enable resilience in the face of environmental change, and we need to coordinate to decrease the risks. One must consider the potential spatial extent of large-scale weather patterns in designing a grid system. Local grid control could either help or hurt. By decentralizing control, the local grid may not depend as much on the large scales, but it would also remove the potential to leverage more remote resources during such wind droughts.

This risk assessment point of view affirms the need for predictive modeling and control of a national dispatch strategy if we wish to run a renewable-heavy national grid. The system needs to be designed for high renewable penetration in parallel with mass deployment. A formalized numerical risk assessment is needed. We also need to overbuild capacity. A multicomponent power grid must understand the whole system.

Note that if we plan with all power sources treated independently, we may miss the worst-case scenarios. Working together is necessary. Large areas of connectivity could alleviate the risk and its uncertainty.

7.3.2 Proposed Actions

With the wind plant solidly positioned between the atmosphere and the grid, there is much to be done to optimize its contribution to the energy system. The TEM #109 experts proposed greater industry collaboration to address the crosscutting challenges. More holistic research planning would provide a greater perspective on how to improve a renewable-based energy system. Some specifics include:

- Provide better real-time situational awareness for grid operators through a systematic approach that connects Earth system data and models with mechanical and electrical models, including wind draughts.
- Work internationally across all players, including both those advanced in renewable energy deployment and those in emerging nations. Atmospheric phenomena do not respect borders, so optimizing across large areas brings advantages.
- Develop ways to use meteorological measurements and models to determine the health of wind plants and monitor their operation.
- Continue to develop the data sets and methods to validate MMC models for improved wind farm operation across scales.
- Do not ignore the social dimensions, which are also important. The experts proposed greater industry collaboration to address the crosscutting challenges.

7.4 Grid/Plant–Turbine

During TEM #109, a smaller group of experts from the Grid/Plant community and the Turbine community met to discuss crosscutting research topics and challenges between the two areas. The discussion took many paths, describing the need for individual turbines and plant-level controllers to provide grid service capabilities as well as the need for turbine researchers to be able to give feedback to grid operators. While the conversation involved many area-specific details, two main topics emerged from the discussion.

7.4.1 Challenges

The TEM #109 experts identified the following two challenges:

7.4.1.1 Improving Communication Between Groups

The first challenge identified is a need for better communication between the Grid/Plant and Turbine groups. One participant clearly made this point by saying that there is "a gap in perspectives" between the relevant parties. In this example, the three parties were the wind plant owner, the turbine manufacturer, and the grid operator. From the perspective of some plant owners, it is unclear why they should purchase grid service capabilities on turbines from the turbine makers. Likewise, some turbine manufacturers do not see the need to spend valuable research dollars on developing turbine-level grid services without clear value. Moreover, most grid operators do not believe they can get the necessary grid services from wind, which completes this gap in perspectives between many members of the three main groups of players. The experts in the room expressed the strong opinion that for wind to reach the levels of deployment necessary to meet the world's renewable energy and carbon goals, this gap in perspectives between these important groups will have to be reduced through increased communication and understanding.

7.4.1.2 Collaborating on Turbine Design Requirements

As the wind portion of the generation mix grows to become the generation resource that forms the grid rather than following the grid, the grid-based requirements will play a much greater role in the expectations of what the wind plants must provide. Again, to meet target levels of wind energy development, wind turbines must provide the needed grid services that more traditional energy generation technologies have been able to provide. Power electronics and controls will play key roles here, requiring specific design considerations at the turbine level as informed by grid requirements.

7.4.2 Proposed Actions

Increased communication and collaboration are needed among wind energy researchers, manufacturers, and operators from both the Grid/Plant and Turbine communities; while already happening among some players, these actions are needed to develop a common set of requirements and a broad consensus on future energy markets that will provide the value structure to spur needed investments.

7.5 Grid/Plant–Environment

Interactions between the grid/plant and the environment occur locally, regionally, and globally, and include effects that cross scales. The joint group of experts representing both grid/plant and environmental interests considered two main areas of interactions: grid/plant–wildlife (which may include from local to global impacts) and grid/plant–global environment (which includes considerations of materials and energy usage, pollutant emissions, and other effects that are considered, for example, in life cycle assessment of renewable energy projects and energy systems). In both cases, participants noted that impacts from the grid/plant to the environment can be both negative and positive (and can be framed both as problems and opportunities). Another key point of the discussion focused on data and metrics: What metrics are relevant, how do we quantify them, and what data do we need for that purpose? Although global environmental impacts were noted as an important area for discussion and research collaboration, the breakout focused largely on wildlife considerations.

7.5.1 Challenges

TEM #109 meeting attendees identified the following crosscutting challenges in the research areas of Grid/Plant and Environment:

7.5.1.1 Developing Shared Understanding Between Grid/Plant–Wildlife/Biosphere Communities

From the context of design and operation of wind farms and energy systems for wildlife/biosphere considerations, quantitative metrics would be helpful as design relies heavily on quantitative models that assess system performance and costs (typically on a monetary basis). Data were identified as a key challenge for quantifying metrics of interest and validating models for design. Data are collected during the development and operation of wind farms, but these data do not currently feed back into the design process. Types of data collected depend on the project but can include wildlife data related to birds, bats, or (for offshore) marine life as well as impacts to habitats on or offshore and crops on shore. Notably, impacts can be both negative (e.g., harm to wildlife) and positive (e.g., habitat creation for food sources). Preconstruction data help identify habitat and species of concern. Operational data typically support compliance monitoring to understand impacts to populations where actions may be needed (e.g., curtailment). Such processes often lead to implementation of aftermarket solutions to mitigate impacts for individual projects. However, these data are sensitive and not shared beyond the specific organization or even used beyond the original use case for collection (i.e., compliance monitoring). Thus, data do not affect future wind farm designs. Thinking about collection of environmental data to inform design leads to a number of questions: What data to collect? What are the design levers that might be relevant from a wildlife perspective (e.g., is it better to have higher densities of small turbines or lower density of large turbines)? What are the metrics of interest, and how can we accurately quantify the impact of a design innovation on such metrics? And finally, who should pay for systems to measure and collect data of interest?

On the latter point, the impacts of inaction to industry are important to consider. Currently, curtailment may be required in various projects to mitigate wildlife impacts. In addition, aftermarket technology solutions have associated costs with implementation and operation. Thus, there is an impact to the project LCOE that may not be accounted for during preconstruction. Furthermore, there may be indirect costs to future projects as the lack of information and inability to predict when/where problems are highly likely can lead to conservative approaches to exclusion of available areas for future project development. This is largely the current status in the United States, whereas in Europe there are some examples of more proactive planning (e.g., in the Netherlands where development and environmental impact assessment proceed in parallel with an iterative feedback process between the two).

Overall, improved data collection and sharing throughout all stages of the project life cycles would support improved:

- Design: Realization of nature-inclusive design that integrates environmental considerations into engineering design practice
- Design and operation: Validation of models for estimating wildlife impacts from local to global scales for improved prediction of impacts and evaluation of designs and technical innovations

- Operation: Development and implementation of aftermarket solutions for addressing habitat/wildlife impacts.

The bottom line is that we cannot currently design for wildlife considerations because we lack holistic understanding within and across scales. To create this understanding, we need to collect and share data in a systematic way between stakeholders of interest in industry and research. However, this requires engagement of the right stakeholders and clear communication of the attainable benefits to overcome the risks of data sharing (e.g., legal, regulatory) and the protection of data through federated data and other digitalization techniques. This last step requires a shared understanding between the engineering and environmental communities that does not yet exist.

7.5.1.2 Developing Integrated Approaches to Wind Energy Systems Engineering for Environmental Considerations

Although wildlife was the focus of the Grid/Plant-Environment group discussions, the members also explored the topic of global impacts—from wind farms and energy systems to materials usage and circularity, energy consumption, and positive and negative impacts to emissions and other pollutants. There are several active research communities engaged on these topics, including recyclability and toxicity of wind energy industry materials (e.g., in wind turbine blades) as well as significant efforts on life cycle assessment for wind farms and energy systems. More recently, researchers have performed work to integrate these fields with wind energy systems engineering (i.e., Canet et al. [2022] investigated multi-objective optimization of wind farm layouts for LCOE and emissions metrics). Studies to date are exploratory and demonstrate the need for more such research.

7.5.2 Proposed Actions

Integration of environmental considerations with engineering of wind farms and energy systems will require several steps:

1. Share environmental impacts data with the public to inform future design.
2. Define design variables (levers), constraints, and objectives that integrate environmental and engineering considerations.
3. With respect to objectives and constraints, define metrics and assess ability to accurately quantify and model metrics.
4. Demonstrate the value to key stakeholders of integrated approaches to engineering wind farms and energy systems for environmental considerations.

Notably, work on Steps 2–4 may be a necessary precursor to convincing stakeholders of the importance of Step 1. Thus, these steps should be pursued in parallel.

Furthermore, and perhaps the overarching recommendation of the session, there is a need to develop a shared understanding of the opportunities and challenges of integrated approaches to wind energy systems engineering for environmental considerations. These two communities historically have not had strong interactions. To initiate progress, Step 0, we need a dialogue between environmental and engineering communities in wind energy to develop a shared understanding and define what is needed for data, models, metrics, and the like. Such an understanding would serve as the foundation for developing capabilities to design intelligent and nature-inclusive wind farms and energy systems in the future.

7.6 Atmosphere–Environment

The atmosphere is the fuel for wind energy. The environment is the space in which wind energy developments occur—including the geosphere, hydrosphere, biosphere, and all human activity. In the context of wind energy development, the Atmosphere–Environment crosscut discussion revolves around the airspace that is shared between wind turbines and bird and bat species, interactions between the atmosphere and the ocean surface (e.g., gas exchanges, nutrient cycling), and relationships between the land surface (e.g., vegetation, crops, sand dunes, steep topography) and the atmosphere.

7.6.1 Challenges

The TEM #109 experts identified the following crosscutting challenges for the atmosphere and environment:

7.6.1.1 Addressing Data Gaps Related to Interactions Among Landscape Features, Atmospheric Conditions, and Wildlife Movement Patterns

Interactions between the atmosphere, the Earth's surface, and wildlife are extremely complex and difficult to measure. A lack of experimental data precludes the mathematical modeling of these systems to the level of detail and accuracy required to affect wind energy decisions. The consensus among experts is that technical solutions in wind turbine and plant design and operation can and will be found once environmental constraints and incentives are known. However, these constraints can only be defined once the data gaps in environmental science are addressed. To that end, collaborative research and field measurements at large scale are the primary needs in this space. Once this challenge is overcome, the gains expected from a holistic design and operation paradigm are hypothesized to be even greater than the efficiency gains possible with independently applied constraints, which seek to maximize wind turbine power and lifetime.

7.6.1.2 Evaluating an Alternative, Overarching Target for Reducing Carbon in the Atmosphere

In addition, the experts agreed that a consideration of environmental constraints might reveal that our current goals (i.e., a specific percent of wind energy by a certain date) might not be the right target. An alternative overarching target could be to reduce the amount of carbon in the atmosphere with technologies that benefit the economy and the environment. A holistic analysis could indicate different shares of wind, solar, and other renewable energy sectors than what might be the current targets around the world.

7.6.2 Proposed Actions

The proposed initiatives to overcome the data and knowledge gaps facing an environmentally conscious wind energy future are:

- Perform targeted research that focuses on atmosphere-environment interactions in and out of wind plants

- Establish long-term monitoring sites, leveraging measurement networks that already exist and finding commercial wind plants that can host interdisciplinary research initiatives. The vision is for a project or series of projects that include experts from multiple disciplines and institutions.

In addition to these initiatives, follow-on interdisciplinary discussions are warranted to exchange information needs and research ideas. A workshop focused on atmospheric and environmental sciences could cover a range of topics including:

- Connecting environmental researchers to existing atmospheric data sets and advising them on how to use them. One example is modeling the wind shear (or vertical distribution of wind speeds at different heights) to refine curtailment decisions to reduce bat collisions. Turbine operational decisions are currently made based on wind speed data at the height of the nacelle, but bat activity may be closer to the ground, near the lower portion of the rotor-swept area. If the wind speeds are greater at nacelle level, then the blades may begin spinning when bat activity is still relatively high.
- Connecting environmental and atmospheric researchers regarding the use of lidar so the same system can be used to detect wildlife and measure winds.
- Communicating meteorological topics of interest for environmental research to atmospheric researchers.
- Determining whether other fields (e.g., weather or aviation) are already making measurements of interest that could be leveraged.

Table 4 summarizes the research gaps and potential research opportunities discussed during this session. This is not intended to be an exhaustive list but rather an initial attempt to find areas where the two research groups could collaborate in the future. The group did not rank these in order of importance.

Table 4. Atmosphere-Environment Crosscutting Issues and Opportunities

Topic	Research Gaps	Opportunities
Environment	• Lacking data on the specific timing and conditions when wildlife fatalities occur. • Limited understanding of how birds and bats respond to atmospheric conditions and the presence of wind turbines precludes determination of thresholds/constraints that can be used to drive wind turbine design.	• Conduct studies that relate interactions and collision events of wildlife with atmospheric conditions. • Determine whether the presence of one wind plant (e.g., the wake profile) influences wildlife activity and movement patterns.
Atmosphere, Wind Plant, and Environment	• Limited understanding of the atmospheric changes that result from the presence of a wind farm (e.g., what are the potential changes in moisture content in and out of the wake profile?). • Are there feedback processes that might enhance or alleviate effects on the environment? • Effects of wind plant wakes on land cover and vegetation communities—does it average out over time, or are	• Determine whether wake steering can benefit the habitat or agriculture, not just maximize power production. • Measure wildlife response to wind farms in sites that receive winds from all directions vs. sites that have clear predominant wind directions and a persistent wind farm wake.

Topic	Research Gaps	Opportunities
	some places becoming more arid over time downwind of wind farms? • How do changes to the environment (brought on by wind development) in turn affect the winds?	• Wind plant wake modeling and forecasting (including not just winds but other atmospheric variables) for each wind plant. • Interfacing between wind modeling and migration modeling. • Measure ocean ecosystem (e.g., gas exchange, nutrient cycling) pre- and post-construction to determine the wake impacts of the wind plant.
Atmosphere, Cluster of Wind Plants, and Environment	• Impacts of large-scale developments on coastline (e.g., erosion, sand dune movement) and local meteorology (e.g., offshore cloud systems that constitute important source of moisture for local vegetation communities). • Impacts of large-scale developments on wildlife: (a) Within a constrained space, should we maximize spacing between rows of wind turbines within a wind farm, or spacing between farms? (b) When foraging, do birds and bats need to go around wind turbines only, or also around the wake of the wind plant? • The trade-off between positive (carbon emission reduction) and negative (environmental impacts) effects of large buildouts is unclear.	• Determine the influences of multiple wind plants (e.g., combined wake profile) on wildlife activity and movement patterns. • Conduct pre- and post-construction studies to assess baseline conditions and potential changes. This may be more important once clusters of wind plants are developed to assess the cumulative impact of multiple wind plants on a coastal ecosystem. • Assess the trade-offs of the wind farm design in relation to power generation, animal movement, and habitat or ecosystem interactions (e.g., atmosphere/ocean surface gas exchange). • Model the influence of various build out scenarios (e.g., 1 TW of wind energy) on the global atmosphere to determine whether there is a critical threshold where additional wind energy results in a negative impact.
Atmosphere	• It is unknown how wind plant wake effects on the environment compare to natural (e.g., interannual) atmospheric variability. • Atmospheric research in wind energy largely focuses on wind. For environmental effects, other variables are also important: temperature, barometric pressure, moisture, precipitation, and topography.	• Perform more detailed atmospheric modeling for pre- and postconstruction settings (e.g., including more variables) at higher resolution.
Atmosphere and Environment	• Effects of nighttime atmospheric boundary layer on insect population	• Perform preconstruction surveys to obtain baseline data set. Assess changes in atmospheric

Topic	Research Gaps	Opportunities
	(with and without presence of wind turbines). • Effects of atmospheric processes (e.g., vertical gradients of wind and moisture, vertical velocities) on wildlife flight decisions (e.g., timing, flight height).	processes and wildlife flight decisions after the wind plant is operational.

7.7 Turbine–Social

The Turbine–Social breakout session brought together experts in wind turbine technology with experts in social science who have been studying the relationship between society and wind energy. The first reaction of the two groups was that before TEM #109, there were few opportunities for the two groups to meet and talk about topics crossing the two areas. The two teams of experts were therefore curious and looking forward to discussing and learning from each other. TEM #109 should be seen as the first of many meetings between the two communities; moving forward, the two groups should work closer together or wind energy deployment and ultimately progress toward energy sector decarbonization will slow.

7.7.1 Challenges

The discussion regarding challenges revolved around the themes summarized below.

7.7.1.1 Creating Just Processes

The importance of just processes behind the deployment, operation, and decommissioning of wind energy systems is key to have community support and continue the growth of wind in the energy mix. Third parties must support the discussion around benefits and impacts to create an environment of trust among parties. Trade-offs in wind farm layout but also turbine design aspects such as size, visual impact, noise emissions, and shadow flicker should be discussed with communities impacted by installations. Community engagement performed from the early stage of a project is key to deploying wind energy, and it is often more impactful than community compensation, which can be perceived as a bribe. The ability to share feedback across the lifetime of the turbine and across stakeholders is also key for a just process. Just processes have the potential to speed up the approval processes of wind farms, ultimately reducing wind energy costs.

7.7.1.2 Investigating and Characterizing Noise

Noise emissions from wind turbines are a major obstacle to deployment. Communities might not necessarily be familiar with wind turbines, which are often perceived as ugly and noisy machines. The engagement of turbine designers and neutral parties with local communities can help ground discussions to facts and facilitate wind energy deployment. Although newer machines are much quieter than older ones, noise emissions from turbines are often not rigorously characterized, and numerical models in the near and far fields are limited in accuracy. Also, limiting noise emissions causes power and financial losses, and smarter approaches to limiting noise when needed should be developed. The topic area of intelligent controls for wind turbines (described in Section 3.2) can help limit the social impact of wind.

7.7.1.3 Investigating and Characterizing Visual Impact

The visual impact of wind turbines is undeniable, but it is also hard to quantify. Studies should investigate the trade-offs between rotor size, rotor speed, turbine height, and number of turbines in terms of visual impact, without forgetting about noise emissions. Also, efforts should harmonize regulations, which are currently not set up consistently across countries and regions. In addition, relatively simple technical solutions that are available today such as the synchronization of the blade azimuth positions, the synchronization and the use of nacelle lights at night, and the installation of sensors to avoid shadow flicker should be pursued.

7.7.1.4 Investigating and Characterizing Policies

Clear policies that manage wind energy deployment should also account for its social impact. Technologies to minimize the social impact of wind often exist but come at a cost. Policies can help enforce their adoption, for the benefit of local communities and the overall perception of wind energy as a clean, reliable, and sustainable energy source.

7.7.2 Proposed Actions

The turbine and the social teams concluded the breakout session highlighting that some solutions to minimize the social impact of wind already exist but come at a cost. The social impact of wind needs to be better quantified so that new solutions can be developed and new policies can be implemented. Turbine technology impacts the ability to conduct just processes, it changes noise emissions and visual impact, and it affects the required policies, but all of these effects are not well understood and should be better characterized. Offshore wind energy deployment will present a new set of challenges in terms of balance of stations, workforce, logistics, installations, and decommissioning.

As additional action items, the two teams highlighted the need to include wind farm owners and developers in future meetings. Also, breakout session participants only had experience with wind energy deployed in Europe, North America, and China, and they indicated that the social impact of wind installations around the globe should be considered moving forward.

7.8 Social–Grid/Plant

The Social–Grid/Plant breakout provided an important opportunity to explore a critical, yet rarely made linkage in the Grand Challenges space, as well as a chance to ground broad, high-level social concepts in a specific set of technical issues. While representatives from both tracks were generally aware of the challenges faced by their colleagues, it was noted that there had not been much collaboration across research areas to date. The group also acknowledged the close connection to the Turbine area of focus but sought to focus on the plant- and grid-level implications of the social issues discussed.

The group quickly coalesced around the need to address the Grand Challenges in new ways. Members suggested that it is time to “move into solution mode” and find concrete ways to support both the integration of wind energy onto the grid *and* the priorities of local communities, instead of taking siloed actions and perpetuating the perception that these issues are inherently in conflict. To do so, the group acknowledged that both technical and nontechnical solutions will be needed to address the challenges that each track had identified. For example, one participant noted that this will require a shift from seeing turbines and plants as “dangerous things to keep away from people" by finding ways to enhance the safety of wind turbines to allow for greater proximity to people.

The group discussed a range of technical solutions that are currently possible, including mitigation for plant operations that cause annoyance (e.g., shadow flicker, noise, lighting) and innovations that can address other societal and environmental concerns (e.g., blade recyclability, distance from shore of offshore wind turbines). One participant offered an example of a wind farm in Europe that chose to synchronize the rotation of turbines on Sunday mornings to provide a more pleasing experience for local residents traveling to church. The group also discussed how plant controls can be used to not only maximize plant performance but also to address any outstanding environmental or noise concerns, which can, in turn, increase acceptance and the overall success of the project. Awareness of these existing options will have to expand as new modifications are considered as well.

7.8.1 Challenges

The group identified five key areas where further exploration and action are needed to help address Social–Grid/Plant issues.

7.8.1.1 Expanding Data Collection and Decision-Making Processes

The group aligned on the value of creating opportunities for various stakeholders to participate in plant design, grid integration, and overall operations as it can increase acceptance and the ability of wind energy to address locally defined priorities. For example, real-time feedback on noise-reduced operation scenarios can empower communities to inform the operations of intelligent turbines. However, participants also discussed the importance of defining the bounds of the decision space and the need to set clear expectations of the engagement. The group also highlighted the critical importance of fully understanding a concern through extensive data collection before investing in multi-objective optimization. While it can be difficult to measure concerns, particularly as experiences can vary even within households, such quantification is needed to motivate and inform solutions. Validation will also be key to ensure that any adjustments are able to achieve desired effects.

7.8.1.2 Considering Grid Integration

The significant scaling of wind energy deployment will require equally significant changes in how patterns of production and grid integration are considered, as wind energy production benefits from demand flexibility. For example, there may be opportunities to create value for unused/curtailed power if a nearby locality can increase demand. Such a scenario could include a local discount scheme that provides local benefits while simultaneously alleviating larger grid constraints, creating a win-win situation. However, advanced controls and investment in robust communications efforts may be needed to increase local understanding of grid issues and the value of using power locally. The effort should also include significant engagement with end users to ensure their input is factored into the plant/grid design and ongoing communications through apps and other tools to increase understanding of energy production and pricing. The group discussed the success seen in Europe with this approach. In general, the redesign of energy markets should be considered to better understand these issues, as well as to anticipate periods of potential curtailment that may stem from an increase in the conditions that contribute to annoyance.

7.8.1.3 Supporting Future-Focused, Empowered Regions and Communities

As the scale of wind energy deployment increases, there is a need to address the industry's expansion at both the regional and local levels through proactive, inclusive engagement and long-term planning. Such an approach must also shift from plant-to-plant thinking to planning for multiple plants that acknowledges cumulative, landscape-level impacts. The group acknowledged that this would require tremendous capacity at the sub-state (below the national) level, in terms of the expertise needed to facilitate the process as well as the contributions of those living in landscapes that will be affected by wind energy deployment. Important strategies to consider in such an approach include engaging organizations and individuals who can serve as neutral intermediaries between varied interests, younger residents (who will need to live alongside scaled deployment), and social networks to exchange knowledge. Planners, landscape architects, and virtual technology should be engaged to support communities to anticipate impacts and develop scenarios that forward local priorities over an extended period.

The group discussed several examples of ways to support communities to identify priorities, plan for, and engage in wind energy development. This included Denmark's approach to creating local climate councils to prepare for long-term transition plans, an example of a Finnish project that created a landscape shield of trees to make turbines less visible, and the need to address the ways in which offshore wind transmission cables are being connected to the mainland grid, as one participant reported that up to two-thirds of project transmission costs are spent on engagement and compensation. Finally, the group also considered the justice components of these efforts, including the need for equitable spatial distribution of plants, as is currently being forwarded through German national policy.

7.8.1.4 Expanding Understanding of Potential Benefits

Building on discussions about the end users of wind power and the definition of community benefits from wind energy, the group continued to discuss the connection between plants and flexible local energy consumption and the value of that power to industrial operations. In Norway, companies seeking to produce green steel have sited their facilities in areas where there is significant wind energy production. The group discussed the opportunity this creates to rethink development patterns and advertise the potential for co-location between wind energy production and green manufacturing.

7.8.1.5 Addressing Cost Expectations

The group posited that, as the scale of deployment rapidly expands, industry and society may need to consider the potential for a higher cost of energy if additional investment is not made to find synergies in technological and social needs. This could result from reduced efficiencies due to customization of turbines and plants to manage for issues like annoyance, acceptance, and integration with community goals. However, if data are available to enable investment in multi-objective optimization, intelligent turbines and plant controls will likely minimize impacts and the need for reductions in power production, as well as avoid or minimize the potential for increased costs. Policymakers may need to accept a more customized, community-responsive approach at potentially higher costs as the only way their deployment targets and/or emissions reduction goals will be met if additional investment is not made in these issues, or that they may need to adjust those goals.

7.8.2 Proposed Actions

While the discussion of this breakout group was engaging and fruitful, participants also acknowledged its limitations in that it did not include members of industry such as developers (though they were represented in other parts of the TEM and offered feedback on these proceedings), representatives of indigenous or otherwise disadvantaged communities, or those who are best positioned to support constructive dialogue between sectors, further underscoring the need to build a shared understanding between an interdisciplinary and international group.[7] Once such a group has been convened, next steps should include:

- Expand data collection to support new approaches to social-grid/plant issues. While some progress has been made, more is needed to achieve our goals.
- Invest in resources to support expanded regional and local level engagement and planning processes.
- Analyze these evolved approaches to inform prioritization and other decision-making. Can we put a price tag on these initiatives? Can we find out if they can lead to more efficient, timely deployment processes?
- Conduct more purposeful, interdisciplinary research and implementation, particularly among the Turbine, Plant/Grid, and Social groups, as well as between the Environment and Social groups. For the latter, it was noted that many social concerns may stem from concerns about environmental impacts.

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[7] External industry members were engaged in the review of this report, and their inputs were incorporated as much as possible.

8 Conclusions and Next Steps

8.1 Conclusions

A comprehensive roadmap to address all the critical elements of making wind energy a major source of the primary energy derived for human purposes is a very wide tent that covers a range of topics, each with its own critical issues to be resolved. The five Grand Challenges of wind describe these topics and illustrate how broad they are. When the intersections among the five topics are also explored, an even larger set of individual issues becomes evident. The participants in this TEM were encouraged to move from the particular gaps to the higher-level areas of need, to move from details to directions, keeping in mind that we are developing a roadmap, rather than a research list. While the preliminary virtual meetings in each Grand Challenge area resulted in extensive lists of issues, the TEM participants rose to the call and crafted high-level "Critical Issues" that are the essential elements of a roadmap. Table 5 summarizes the five Grand Challenge areas and three critical issues identified for each.

Table 5. Wind Energy Grand Challenge Areas and Critical Issues for Each

Grand Challenge Area	Critical Issues
The Atmosphere	Increasing atmospheric observations Expanding and validating universal predictive capability Integrating and adopting improved models
The Turbine	Incorporating holistic design Developing intelligent controls, operation, and maintenance Advancing industrialization
The Plant and Grid	Improving modeling Optimizing plant design for multiple objectives Readying the next generation of wind plants for grid support
Environmental Co-Design	Avoiding, minimizing, and compensating for the direct and indirect environmental impacts Incorporating environmental costs and benefits into every decision point Accounting for immediate concerns while addressing future impacts and trade-offs
Social Science	Acknowledging the transformational nature of rapid, large-scale wind energy development Creating just processes Valuating benefits, effects, and burdens

The crosscutting breakout sessions were very high energy and self-organizing as the groups tried to understand each other's area, exploring assumptions and exploding some of the misconceptions. The single breakout session for each crosscutting topic was likely not enough time to really work out a high-level description of research directions, so the outcomes of the crosscuts are perhaps more a list of activities than a synthesis of critical need. Nevertheless, the critical issues identified by the cross-cutting groups represent a first step toward better understanding and engagement. Table 6 summarizes the cross-cutting challenge areas.

Table 6. Wind Energy Grand Challenge Opportunities for Interdisciplinary Work and Critical Issues for Each

Grand Challenge Opportunities for Interdisciplinary Work	Critical Issues
Environment-Turbine	Establishing common language and definitions Understanding material needs for scale of build-out Incorporating environmental co-design Communicating research needs Deploying dual-purpose technologies Engaging turbine manufacturers Improving data collection, digitalization, and sharing
Turbine-Atmosphere	Improving open-design bases Improving annual energy production estimates Improving design standards
Atmosphere-Grid/Plant	Improving flow control Deploying dispatchable hybrid plants Connecting the grid to the weather Leveraging real-time data Conducting risk assessment across time scales
Grid/Plant-Turbine	Improving communication between groups Collaborating on turbine design requirements
Grid/Plant-Environment	Developing shared understanding between grid/plant-wildlife/biosphere communities Developing integrated approaches to wind energy systems engineering for environmental considerations
Atmosphere-Environment	Addressing data gaps related to interactions among landscape features, atmospheric conditions, and wildlife movement patterns Evaluating an alternative, overarching target for reducing carbon in the atmosphere
Turbine-Social	Creating just processes Investigating and characterizing noise Investigating and characterizing visual impact Investigating and characterizing policies
Social-Grid/Plant	Expanding data collection and decision-making processes Considering grid integration Supporting future-focused, empowered regions and communities Expanding understanding of potential benefits Addressing cost expectations

The Social and Environmental group members iterated that although the structure of the meeting did not offer them a chance to discuss the Environmental/Social intersection, there is great interest and even greater need to begin to work out that connection. The leaders of those groups have committed to exploring their joint interests and intersecting issues in the near future.

The path forward for wind energy will need to deal with an ever-expanding set of influences on design for both individual turbines and the energy systems within which they operate. The Grid and Plant Grand Challenge identified ways in which the technology will need to deliver capabilities for plant operational control and grid resilience that is unprecedented. The Atmospheric Grand Challenge noted that advanced, validated models are only half of the solution; the actual adoption of these models into the design process is also a major effort. The Turbine Grand Challenge recognized the need for a more holistic design approach that incorporates the Grid and Atmosphere challenges and also extends into manufacturing, control, maintenance, and other desired outcomes. There is much to be done when considering the intersection of these three technology-driven Grand Challenges by themselves. All three of these areas highlighted the critical need to be able to model the systems with high accuracy and validate those models with comprehensive observations and experimentation. Only then will the models be truly predictive and capable of driving the designs to solutions that work.

The Environmental and Social Grand Challenges have in the past been treated as being downstream of the design process, as illustrated in Figure 12.

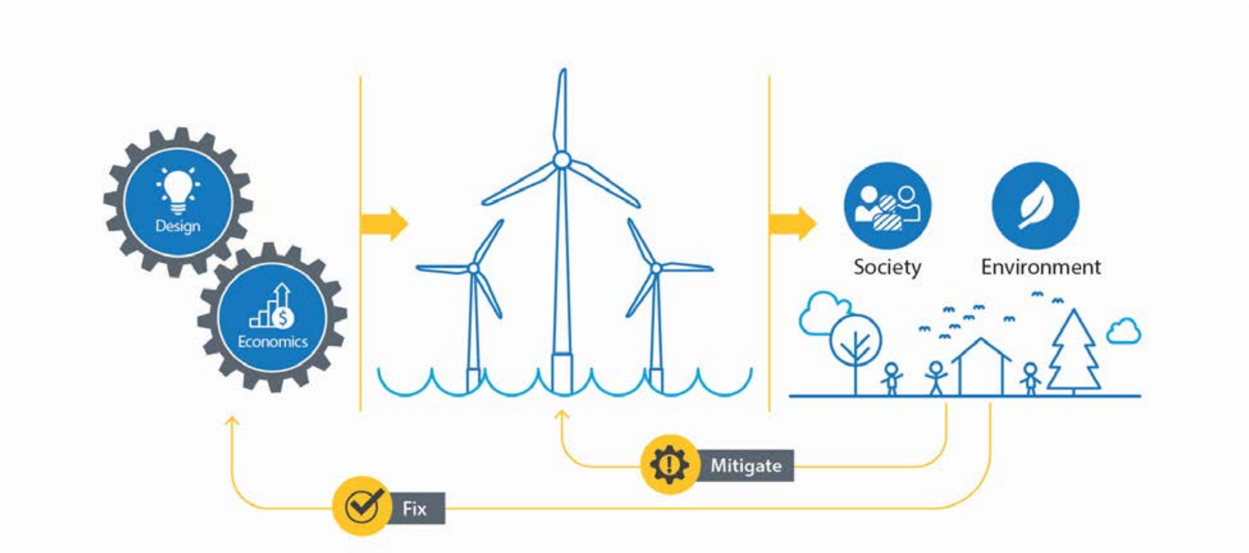

Figure 12. Today's cost-centric design***. Illustration by Taylor Henry, NREL, based on an illustration from Carlo Bottasso, Technical University of Munich***

In this paradigm, the consequences of a system optimized for survival, productivity, and hence economics are a suite of environmental and social consequences both positive and negative. While clean and low-cost energy is produced to the benefit of society and the environment, there may be negative impacts on species or habitat, and host communities may not perceive the presence of turbines to be beneficial. Social and environmental activities are then constructed to fix or mitigate the problems.

The TEM #109 experts proposed a view of the future that moves the social and environmental issues up front into the original design process for technology development, as illustrated in Figure 13.

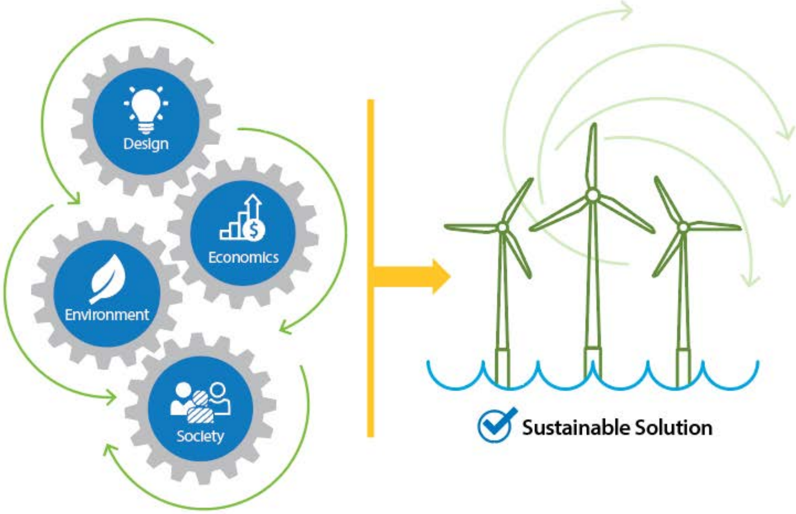

Figure 13. Tomorrow's environmental and social co-design. ***Illustration by Taylor Henry, NREL, based on an illustration from Carlo Bottasso, Technical University of Munich***

This future vision recognizes the inevitable footprint of wind development as so wide that it cannot avoid difficult social and environmental issues. Therefore, design capability will need to capture social and environmental issues up front and encompass them in the optimization process. Such a design process requires turbine and plant design to be flexible enough to create bespoke solutions and accurate enough to evaluate those solutions with computer models that reflect reality. It also will have to incorporate a robust understanding of environmental and social impacts beyond what now exists. A key finding of the TEM #109 meeting is that we should expand the design process to encompass the full range of downstream outcomes, both positive and negative, with all the consequent needs for enhanced models and supporting data.

8.2 Next Steps

Following a brief two-day meeting (long by some TEM standards but short relative to the challenges before wind energy), there is certainly much left to be done. The crosscutting meetings were often the first time two topical groups attempted to ask each other how synergistic activities could foster solutions to troubling problems. Continuing to gather to flesh out a higher-level understanding of how all the challenges identified in the crosscutting breakouts can be pursued is important. Of special note is the crosscut between social and environmental areas. The importance of an environmental issue often cannot be separate from its social context. Experts working on the three technical Grand Challenges have made good progress identifying more detailed crosscuts, but there is much work to be done.

The IEA Wind TCP has the expressed intent to foster research initiatives and make them more successful through international collaboration in an organized and effective way. The TEM #109 report provides a set of activities and a structure on which to build a 5-year roadmap. By structuring the roadmap around the five Grand Challenges and paying attention to the intersections between them, progress on enabling wind energy systems to meet their full potential can be sustained. The IEA Wind TCP will structure a roadmap from these findings to guide their work into the future.

The IEA Wind TCP may want to consider a regular schedule of Grand Challenge TEMs moving into new critical topics as they emerge. The 2017 “Grand Vision for Wind” TEM #89 focused solely on the technical aspects of wind energy and resulted in an article that explained the “Grand Challenges in the Science of Wind Energy” (Veers et al. 2019). TEM #109 expanded that discussion to include Environmental and Social Grand Challenges, and its findings should similarly be summarized in a highly focused journal article in a high-impact publication. Both TEMs engaged the issue of transitioning the already developed energy system from fossil fuels to renewables highly powered by wind. The next step in a global transition will be to engage energy systems that are in earlier development stages. TEM participation, which has been heavily weighted toward European and North American representatives, should engage Asia and the Global South. The IEA Wind TCP will need to begin planning now to explore the underlying issues and make such an event a reality within a 5-year horizon.

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Appendix A. IEA Wind TCP TEM #109 Meeting Agenda

The IEA Wind TCP TEM #109 convened on February 28-March 1, 2023, at the University of Colorado-Boulder, USA. The meeting agenda is presented below.

TOPICAL EXPERT MEETING #109

Grand Challenges in the Science of Wind Energy

Tuesday, Feb 28, 2023	
8:00 AM	**Check-in, Badging, Coffee/Tea**
8:30 AM	**Welcome, Overview of IEA Wind** Speaker: Jim Ahlgrimm, U.S. Department of Energy's Wind Energy Technologies Office
8:40 AM	**Opening Remarks by the IEA Renewable Energy Working Party (REWP) Chair / REWP Vice-Chair** Speaker: Alejandro Moreno, Office of Energy Efficiency and Renewable Energy at the U.S. Department of Energy
9:00 AM	**Workshop Objectives and Expectations** Facilitators: Paul Veers, National Renewable Energy Laboratory (NREL) and Katherine Dykes, Technical University of Denmark (DTU) Background to the Grand Challenges and identify the research directions and initiatives needed for wind to become the backbone of a carbon neutral energy system.
9:30 AM	**Grand Challenges Future Vision** Facilitator: Stephan Barth, IEA Wind Chair, ForWind What is the vision of the Grand Challenges long term in the eyes of IEA Wind?
9:45 AM	**Group Photo**
10:00 AM	**Networking Break**
10:15 AM	**Setting the Stage – Grand Challenges Presentations** Facilitator: Paul Veers, NREL
10:20 AM	**The Atmosphere** Facilitator: Sue Haupt, National Center for Atmospheric Research Wind resources, atmospheric science, and the physics of air flow at wind farms.
10:40 AM	**The Turbine** Facilitator: Carlo Bottasso, Technical University of Munich System dynamics and materials involved in wind turbines and wind farm technology

11:00 AM	**The Plant and Grid** Facilitator: Hannele Holttinen, Recognis, Oy Optimization and control of wind farm operation for reliability and resiliency.
11:20 AM	**Environmental Co-Design** Facilitator: Cris Hein, NREL Environmental co-design to situate wind farms to local constraints and opportunities
11:40 AM	**Social Impacts and Issues** Facilitator: Lena Kitzing, DTU and Suzanne Tegen, Center for the New Energy Economy Social science to identify how wind plants can add value to host communities.
12:00 PM	**Networking Lunch**
1:00 PM	**Instructions for Breakouts** Facilitator: Paul Veers, NREL Identify critical issues that will need to be resolved for wind energy to supply half or more of electricity supply by mid-century and potentially half of total energy in the long run.
1:15 PM	**Parallel Sessions** Each group will prepare a description of the high-level critical issues in their area (1-4 per group) and the major initiatives needed to address them (supporting rationale should be captured as well)
2:45 PM	**Networking Break**
3:15 PM	**Parallel Sessions** Discuss how each identified major issue impacts potential cost and value, as well as scale of deployment. Can the scientific issues be related to these metrics to articulate their impact? Also, does this perspective help identify other issues?
4:45 PM	**Wrap Up for the Day. Dinner On Your Own**

Wednesday, March 1, 2023	
8:00 AM	**Check-In Coffee/Tea**
8:15 AM	**Facilitated Discussion** Facilitator: Katherine Dykes, DTU Summaries by each group on the findings of the previous day. Discussion of results with emphasis on cross-area linkages and collaborative activities. Charter/instructions for morning breakouts with combined and crosscutting groups.
9:45 AM	**Networking Break**
10:15 AM	**Parallel Sessions** How does each scientific topic intersect with environmental and social issues. Document cross cutting issues and potential initiative to address them.
12:00 PM	**Networking Lunch**
1:00 PM	**Facilitated Discussion** Facilitator: Katherine Dykes, DTU Each group presents the cross-area linkages and opportunities identified in the previous breakout
2:30 PM	**Networking Break**
3:00 PM	**Parallel Sessions** Each of the original 5 groups refines their conclusions from all prior breakouts as input to the TEM report
4:00 PM	**Wrap Up, Open Forum, Next Steps** Facilitators: Paul Veers, Katherine Dykes, Stephan Barth, and Carlo Bottasso. Wind resources, atmospheric science, and the physics of air flow at wind farms.
5:00 PM	**Adjourn**

Appendix B. IEA Wind TCP TEM #109 Meeting Participants

The IEA Wind TCP TEM #109 convened on February 28-March 1, 2023, at the University of Colorado-Boulder, USA. The list of meeting participants is presented below.

Participants to TEM#109 on
Grand Challenges in the Science of Wind Energy

February 28th- March 1st 2023

First Name	Last Name	Country	Affiliation
Jim	Ahlgrimm	US	US Department of Energy
Greg	Aldrich	US	Duke Energy
Andree	Altmikus	DE	Wobben Research and Development (ENERCON)
Cristina	Archer	US	University of Delaware
JAKE	BADGER	DK	DTU Wind and Energy Systems
Ruth	Baranowski	US	NREL
Ian	Baring-Gould	US	NREL
Stephan	Barth	DE	ForWind / Chair IEA Wind TCP
Christopher	Bay	US	NREL
Larry	Berg	USA	Pacific Northwest National Laboratory
Rogier	Blom	US	GE Research
Pietro	Bortolotti	US	NREL
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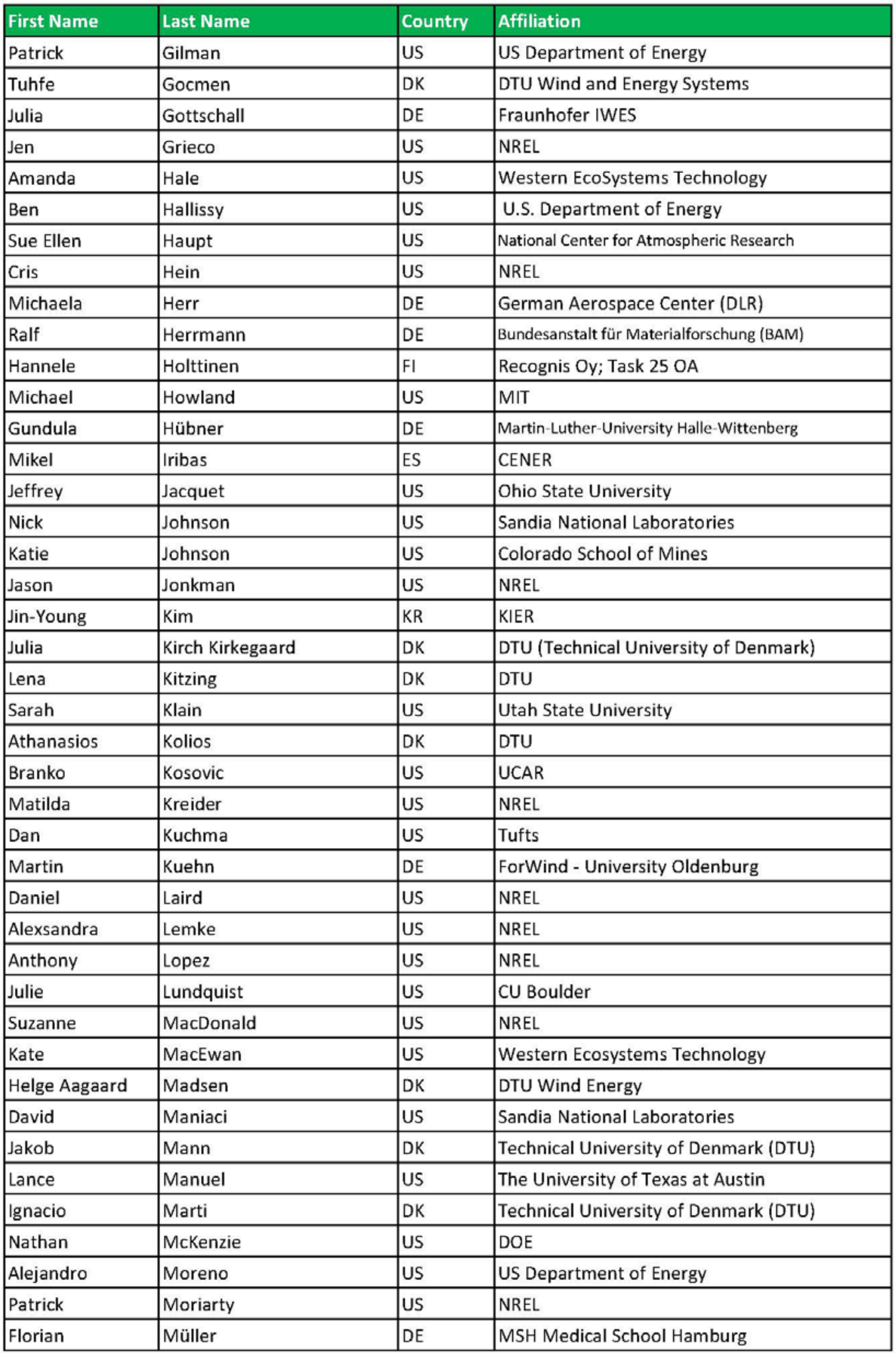

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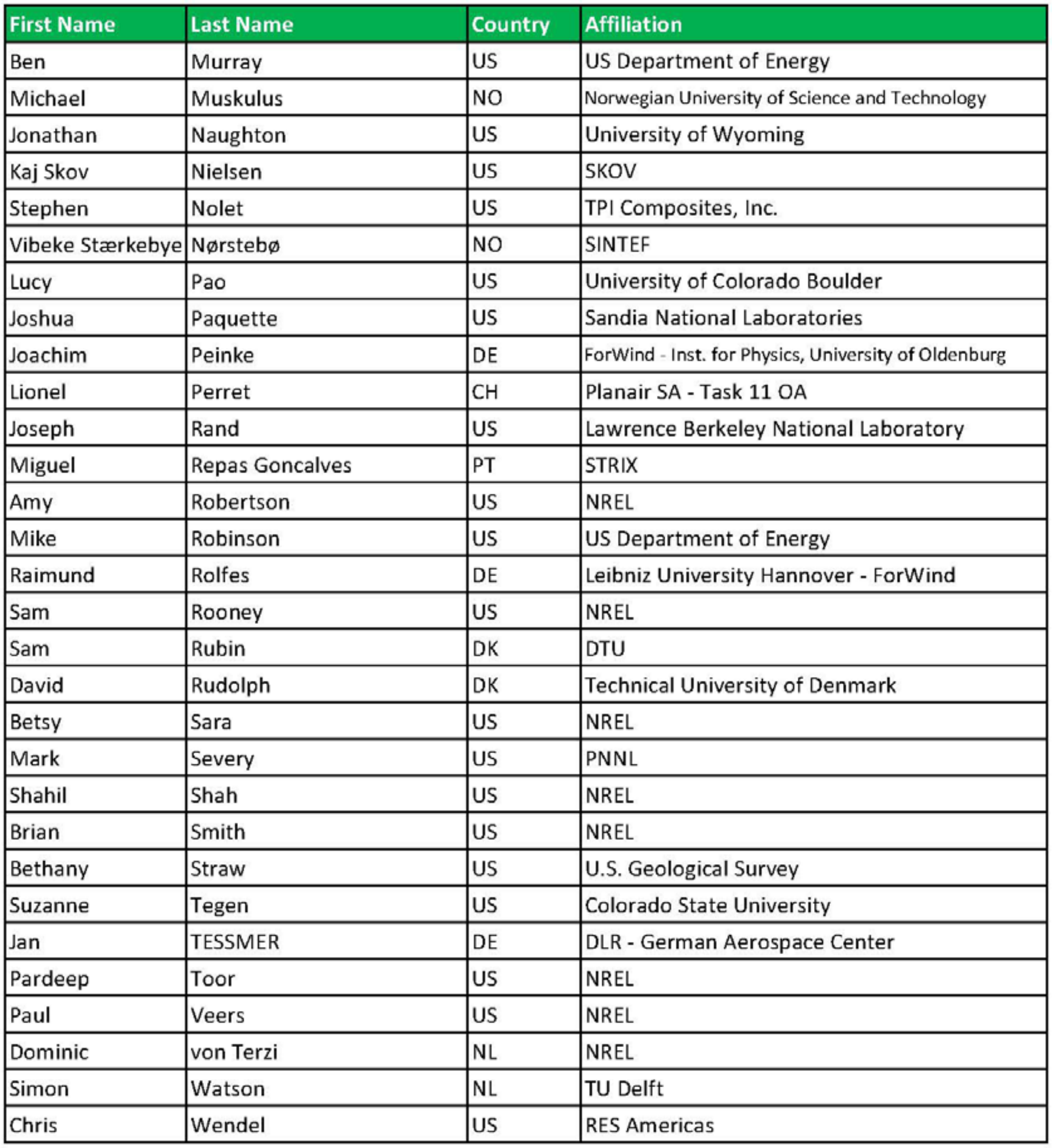

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