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UNIVERSITY COLLABORATION ON WIND ENERGY

edited by

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EXECUTIVE SUMMARY

Environmental, political and social reasons are compelling us to turn to clean, renewable sources for electric power production. Wind is a viable power source with potential to grow from its present share of less than two percent of the US electricity production, to twenty percent by 2030. To achieve this, significant advances in cost, performance and reliability are needed. Environmental and social impacts must be well understood and a workforce capable of designing, manufacturing and deploying wind turbines at large scale must be educated. The relative maturity of the subject compared to other renewable sources such as photo-voltaics, implies that cutting edge scientific and engineering research is needed since the easier gains have already been achieved. But many largely uncharted problems remain: Unlike conventional power sources, wind turbines are distributed, covering large land areas. There are new, emerging problems on the two-way coupling of the meso-scale atmospheric winds to the turbines, and the wind farms' effects on the local meteorology. Due to the large land area covered and the large size of turbines themselves, environmental and social impacts are directly coupled to technology through concerns related to bird strikes, noise, landscape and other factors. The control of wind farms and integration of wind power into the utility grid will be a growing problem as the percentage of wind energy in the grid increases. How to build the very large scale blades and floating foundations anticipated for offshore wind energy is an open question. These are just a few examples; a great number of additional research questions and needs are identified in the accompanying report.

Universities in close collaboration with national laboratories and industry are the appropriate venue for the study of the cutting edge and emerging problems: they are able to focus in depth on fundamental issues and are the right environment for the open, cross-disciplinary research that is required. Further, universities are where the needed technological work force is to be trained. Here we outline a set of fundamental research questions on wind energy that encompass the wind field, blade aerodynamics, control, grid integration, power systems, structures, materials, offshore wind energy and social and environmental considerations. We advocate the development of long term, appropriately scaled, university based program of basic and applied research. Researchers in this program would be expected to collaborate with each other and with national laboratories, wind turbine manufacturers, and wind farm operators to perform research whose long-term goal is to overcome barriers to the large-scale deployment of wind energy.

Our goals for the proposed university research program are to develop a world-class national research and development program, enabling U.S. industry to develop wind energy at large scales, both on and off shore; to create analytical and numerical tools for designing next-generation turbine and wind farm systems; to bring a large-scale systems engineering approach to the wind industry; to address environmental and social issues that pose a risk to offshore wind energy development; to develop science-based public advocacy for offshore wind energy development and to encourage and foster university education in wind energy at the undergraduate and graduate levels.

This white paper is the result of the collective efforts of participants at the Workshop to Plan for a University Collaboration on Wind Energy, held on December 6–7, 2010, at Cornell University. The workshop was supported by the Academic Venture Fund of Cornell's Atkinson Center for a Sustainable Future. Participants at the workshop are listed below. We are also indebted to Mark O'Malley (University College, Ireland) and William Devenport (Virginia Polytechnic Institute), J.Charles Smith (Utility Wind Integration Group) and several others for their edits and comments.

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INTRODUCTION

The objectives of this white paper are to outline fundamental research questions on wind energy that are appropriate for universities to address and to recommend the development of a program supporting basic research in utility-scale wind energy. The complex character of wind motions and the varying demands on power make this an immensely difficult problem, with many basic questions that have only recently emerged. The scale and interdisciplinary nature of the problem, in which fluid dynamics, control, structures, power distribution, and economic, social and environmental issues are inextricably linked, is ideally suited to collaboration among universities, national laboratories and industry, where a multiplicity of disciplines can freely exchange ideas. This initiative is of the utmost urgency, given continuing political instabilities in the Middle East, the earthquake and tsunami in Japan, the concern over coal mine safety, e.g. the West Virginia, Upper Big Branch Mine explosion of 2010, the Deepwater Horizon oil spill, the environmental problems associated with hydraulic fracturing to produce natural gas and the overriding problem of climate change.

Wind energy is playing an ever-increasing role worldwide as a renewable energy source. Denmark, Spain and Germany now produce 19, 11 and 7 percent of their electricity by means of wind while the United States, although second only to China in installed capacity, meets only 1.7 percent of its electric power demand with wind. However figures from the American Wind Energy Association show that the U.S. wind industry has added over 35% of all new generating capacity over the past four years, second only to natural gas, and more than nuclear and coal combined. Today, U.S. wind power capacity represents more than 20% of the world's installed wind power. The U.S. Energy Information Administration (EIA) estimates that U.S. electricity demand will grow by 39 percent by 2030, reaching 5.8 billion megawatt hours (MWh). In the Department of Energy's 20 percent wind scenario, 1.16 billion MWh would be generated by wind turbines (U.S. Department of Energy 2008). Wind would supply enough energy to replace 50 percent of electric utility natural gas consumption and 18 percent of coal consumption. The potential environmental impact of this substitution includes an annual reduction of 825 million metric tons of carbon dioxide emission and a savings of 4 trillion gallons of water. The economic activity generated by wind turbines would exceed $27 billion per year, and total wind energy–related employment would exceed 215,000 jobs (U.S. Department of Energy 2008).

Despite the growing worldwide demand for wind energy, the present technology is far from optimized and harvesting wind energy presents significant challenges. The state today is analogous to aircraft technology in the 1970s: the broad principles are well known, with a fair expectation that wind turbines in 40 years will resemble today's turbines in their general design. But wind turbine components and systems will undergo significant evolution, increasing the efficiency of both individual units and entire wind farms, decreasing upfront and maintenance costs, decreasing noise and extending lifetime.

Harvesting wind energy at large scales presents many challenges. Modern wind turbines at high-quality sites operate at less than 30 percent of their capacity on average, and individual turbines operate at full capacity less than 10 percent of the time. Wind energy is variable and difficult to predict over a long time horizon making it more difficult to tie to a distribution grid than traditional power-generation technologies. The inability to dispatch both wind and solar power resources remains a significant barrier to achieving higher penetration levels without ancillary support services. To compete with fossil fuels will require significant, further developments to increase energy capture, reduce initial and operating costs and improve reliability. Potential adverse environmental impacts, lack of public acceptance and issues surrounding permitting also represent barriers to the large scale deployment of wind energy.

Wind technology R&D is evolving beyond a wind turbine centric focus to address large multi-megawatt wind plants. A more holistic view of technology development, deployment and integration crossing multiple disciplines is required. The turbine contribution to the overall on- and off-shore wind plant system is 60% and 25% of the total capital cost respectively. Full integrated systems development and optimization is needed to realize future economic and reliability goals. The potential to achieve large fractions of the nation's electrical power from wind raises significant questions of scalability, construction and operation of a national grid based on renewable resources, potential impacts on macro and micro climatology, wildlife, social acceptability, economic benefit and disruptions associated with significant future deployments.

To date much of the research and development of wind turbines has occurred in industry, both in the United States and abroad. The gains that we are seeking will require new innovations in fluid dynamics, control, materials, manufacturing, structures, and electric power distribution, as well as new ways of engaging the public in appreciating and accepting this technology, the associated transmission infrastructure and its effects on reducing climate change. Design and analysis tools need to be developed. Common computer codes need to be shared and refined in an open collegial way that cannot occur in industry. Researchers need to disseminate, debate, and share results openly, accelerating innovation in the subject. Thus, universities must play a double role: making new discoveries in the science, technology, and social acceptance of wind energy technology *and* fostering an open and collegial forum for the dissemination of these results.

To achieve these crucial advances and help mitigate potential impacts, universities must increase their role. Here we advocate for the establishment of a long-term, university-based collaborative research program. Researchers in this program would be expected to collaborate with each other and with national laboratories, wind turbine manufacturers, and wind farm operators to overcome barriers to the large-scale deployment of wind energy.

A unified program for basic, university-led research performed in close collaboration with national laboratories and industry would serve to attract the best and brightest engineers and scientists of the next generation to work in the wind energy field for their advanced degrees. We see the universities as playing the dominant role in increasing the quality and quantity of the workforce devoted to wind power. At present the percentage of undergraduate degrees in science and engineering is in decline (National Science and Technology Council 2000), and while the number of doctorates is growing, their rate of increase is slowing and even showed a decline in engineering in 2008 (NSF InfoBrief, NSF 11-305, Nov. 2010). Few courses are offered specifically on the subject at the undergraduate level, and few Ph.D.s are awarded in the subject, both in stark contrast to the state of education in aeronautics as that subject was coming to maturity. The national laboratories are well suited as a bridge between universities and industry. In the proposed collaboration they would continue to perform both basic and applied research, manage and run large scale test facilities and perform cooperative projects supporting graduate students and post-doctoral students. Industry would provide context, guidance on identifying the important problems and would be the recipient of the developed expertise, be it highly trained engineers, new technologies, improved design tools, or approaches to mitigating social and environmental impacts.

Our aim is to identify and then enable the research required for this vital initiative to thrive, not to argue for funding to be directed toward particular universities. The overall goals of the proposed collaboration are to:

- Develop a world-class national research and development program, enabling U.S. industry to develop wind energy at large scales, both on and off shore.
- Create analytical and numerical tools for designing next-generation turbine and wind farm systems.
- Bring a large-scale systems engineering approach and discipline to the wind industry.
- Address environmental and ecological issues that could impede offshore wind energy development.
- Develop science-based public advocacy for offshore wind energy development.
- Encourage and foster university education in wind energy at the undergraduate and graduate levels.

The report is divided into five sub-sections--Wind field, flow, and aerodynamics, Control, grid integration, and power systems, Structures and materials, Offshore wind energy, Social and environmental considerations—followed by a conclusion section. In these five sections, we outline basic research needed to overcome the barriers to large-scale deployment of wind energy and indicate ways that this research may be approached. The research needs discussed in each section focus on reducing the cost of wind energy and mitigating adverse impacts. A concluding section offers our recommendations, summarizing the necessary research agenda. Engineering and technology must go hand in hand with social and environmental considerations, thus the research needs include technical, economic, social, and environmental factors.

In this report efforts were taken to incorporate input from a broad range of wind energy researchers but clearly not all aspects could be covered, particularly in the light of the rapid developments occurring in the field.

WIND FIELD, FLOW, AND AERODYNAMICS

The major goals of basic and applied research in wind energy are to reduce the cost of this renewable resource by a significant margin and mitigate adverse impacts on wildlife and humans. Costs may be reduced both by increasing energy capture and by extending durability of components. Meeting these goals will require new hardware designs and wind plant layouts and advanced turbine and plant control approaches. Effective design tools need to be developed and applied, with the goal of increasing blade efficiency, wind plant production and reducing detrimental effects on wildlife. The physical causes of wind turbine noise must be identified and this knowledge used to design turbine systems to reduce noise, one of the principal barriers to onshore wind deployment.

From the point of view of flow and aerodynamics, if the incoming wind field were completely steady, with no significant spatial gradients, turbulence, or coherent structures, wind turbine and wind farm design would be essentially solved (Snel 1998, Burton 2001). The unsteadiness and mixture of stochastic and deterministic loadings define the problem of wind turbine and wind farm design. Fluid dynamics research is needed in the following three areas in wind energy:

1. Wind farm fluid dynamics at the intersection of engineering and geosciences
2. Wind turbine blade load management to increase durability and efficiency
3. Wind turbine noise reduction to mitigate siting impacts, improve rotor performance and glean societal acceptance

Each of these topics leads to specific research questions. A successful research portfolio in wind energy will include support for both applied and basic research that addresses these questions.

Topic 1: Wind farm fluid dynamics at the intersection of engineering and geosciences

Motivation

The low energy density of wind implies planning for much larger geographic footprints than is common for conventional energy sources. The recent move toward ever-larger wind turbines and wind farms has taken them to the relatively unexplored intersection of engineering and geosciences. Increasing energy capture in larger wind farms—that need to be viewed as "power plants"—will require improved understanding of wind turbine arrays' collective behavior and their interactions with the atmospheric boundary layer flow. Relevant wind farm size scales range from tens of meters at the rotor scale,

Figure 1: Horns Rev off-shore wind farm in Denmark captured by a helicopter pilot. Horns Rev 1 owned by Vattenfall. Photographer Christian Steiness.

to hundreds of meters characteristic of turbine spacings, to many kilometers for large wind farms. Interactions between entire wind farms occur at scales of tens of kilometers and above—that is, at the atmospheric mesoscale. Figure 1, showing condensation and mixing in the wakes of the Horns Rev wind farm, appropriately conveys the complex multiscale couplings of flow in wakes and the atmospheric boundary layer. Wind resource estimation requires an integration of large and intermediate scale meteorology, a subject that has not received detailed attention from the traditional meteorological community. National Oceanic and Atmospheric Administration (NOAA) and U.S. weather prediction and tracking capabilities need to be coupled with developments in turbine technology.

State of the art

Flow prediction software currently in use for wind farm siting is relatively coarse (for example, see Petersen 1999, Lange 2001). More recently Large-eddy simulation (LES) has become a powerful tool, see Calaf et al.(2010), Lu and Porte-Agel (2011) and references therein. Available tools fail to account fully for the variation and interactions among turbine wakes, the terrain, and the wind flow field (mean field and turbulence) and for the interactions of coherent structures with turbulence. In complex terrains the performance achieved can be over 30% less than predicted. At present, it is not well understood how the various scales interact.

Research questions

- How do wind farms with their multiple wakes interact with the atmospheric boundary layer to determine the net power that can be produced? Examples of meteorological boundary layer phenomena that need to be accounted for include low-level jets in stably stratified conditions, terrain effects, vegetation, and urban effects.
- Fluctuations due to turbulence are on a much shorter time scale than are described by the Weibull distribution. How do multiple length scales affect the probability density function of the turbulence fluctuations (Peinke et al. 2004; Good and Warhaft, 2011)?
- How do uneven terrain, roughness of the land or sea surface, and turbulence above the boundary layer and turbine wakes affect unsteady loading of downstream wind turbine blades (Frandsen 2007)?
- What is the role of large-scale coherent structures in the atmospheric boundary layer and the wakes in determining wind turbine power fluctuations, cross-turbine spatial and temporal correlations, and unsteady loading of downstream wind turbine blades?
- What is the effect of atmospheric stability (convective, neutral, or stably stratified) on the performance and loading characteristics throughout a typical daily cycle?
- What are the effects of wind farms on wind resource and regional meteorology (Baidya-Roy 2004)? What are effects of global climate change on overall wind resources and the effects of wind energy on global climate change (Keith 2004)?

- What is the optimal placement of wind turbines in an array, so that the kinetic energy capture can be maximized and unsteady loading be minimized? What is the optimal placement of entire wind farms? What is the maximum energy extraction potential per unit land area?
- Can active control and/or design innovations at the turbine level be implemented to provide both optimized plant performance and mitigate environmental impacts of array effects?
- What monitoring and forecasting capabilities are needed to be developed to provide wind plant systems control? At what scale and fidelity?

Topic 2: Wind turbine blade load management to increase durability and efficiency

Motivation

The design of wind turbine blades has a long history and is quite advanced (Burton 2001). Current designs are nearly optimal for steady, nonturbulent, smooth inflow conditions. Design tools that account for incoming turbulence and unsteadiness to decrease effects of unsteady loading and augment durability, however, are far less developed and mostly ad hoc. The complexity of the flow field behind a turbine is shown in Figure 2 in the large eddy simulation (LES) of water flow past a hydrokinetic turbine. As offshore markets and the drive to lower energy costs lead to continuously increasing rotor diameters and hub heights, load management has become a significant technology barrier. Technologies are needed to reduce the penalties of increased weight, cost, and loads associated with blade rotor diameter growth.

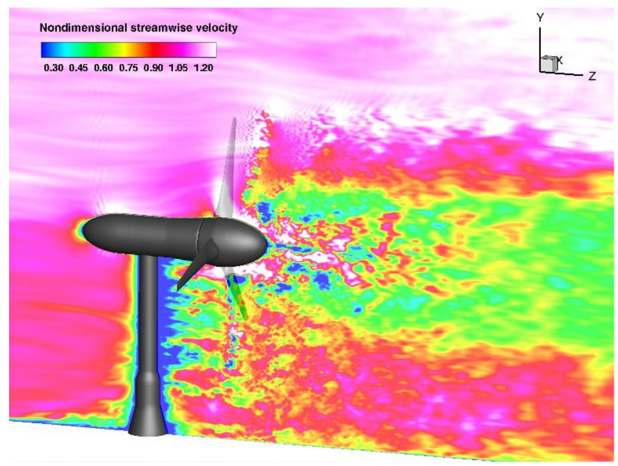

Figure 2: LES of flow past a hydrokinetic turbine on a grid with 150 million nodes. Re=237,000, tip speed ratio=4.7, F_r=0.14. The turbine is mounted on the bottom of a rectangular open channel. Hub height is 0.8D and channel depth is 2.3D. F. Sotiropoulos, Univ. of Minnesota.

State of the art

Currently, loads are controlled with rather limited means, such as pitch systems. Recent introductions include cooperative control between turbines, a first generation of passive load management via sweep/twist-bend, and other aeroelastic tailoring.

Research questions

- How can we improve the fundamental understanding of boundary layer physics and its impact on performance and noise and exploit modern materials and surface engineering to gain performance advantages?

- What are the new passive and active aerodynamic load management rotor concepts that can break past current systems and loads design constraints to enable effective blade design, increase reliability and reduce the cost of blades?
- Can reliable sensors and actuators for active aerodynamic load control be found that are efficient and cost effective?
- Can we develop aeroservoelastic design tools with fast, appropriate-fidelity physics models that include uncertainty quantification, as well as accounting for all of the effects laid out under Topic 1? This will lead to intelligent turbines with look-ahead sensors and actuators.
- Are there specific fluid mechanical processes that affect wildlife, such as low pressure regions in tip vortices or the like? Are there mitigating control strategies that can be pursued?

Topic 3: Wind turbine noise reduction

Motivation

Noise is still one of the key limiters to social acceptance of wind farms—and consequently a significant technology barrier to large-scale deployment of wind energy. The sources of noise are diverse and poorly understood, and their quantitative prediction remains heavily empirical, however it is accepted that noise increases with higher blade tip speeds. Increasing tip speed without increasing noise would allow reduction the torque into the gearbox and generator, and reduce overall structural loads, reducing cost. Significant changes in blade design, which may be desirable from other perspectives, involve high risks in the area of noise. The modeling and reduction of noise is closely linked to the detailed aerodynamics of blades, particularly factors that may reduce abrupt stalling. Stall and the inability to predict it also remain significant drivers for higher safety margins, limiting efficiency and keeping costs higher. Recent developments in wind tunnel facilities, measurement instrumentation, high-performance computing, and computational fluid dynamics (CFD) and computational aeroacoustics (CAA) technologies can enable fresh efforts to tackle these problems.

State of the art

Current design tools are based on empirical understanding and limited-fidelity measurements that are now decades old. The primary noise sources are driven by small-scale turbulent boundary-layer eddies on the blades, which produce broadband noise as they cross the trailing edge. Interaction of the blades with atmospheric turbulence can modulate this source and also serve as a noise source itself, particularly at low frequencies. Other noise sources include tip noise and separation noise, but these have not been well characterized for wind turbine configurations. The inability to predict stall, due to limitations in turbulence models, currently restricts the development of aggressive aerodynamic concepts. Wind tunnel experiments are needed.

Research questions

- What is the detailed physics of trailing-edge noise generation as it relates to the distribution of vorticity in typical wind turbine blade boundary layers? Studies of a heavily idealized configuration (Shannon 2006) have shown that fundamentally different roles can exist for large- and smaller-scale structures and for the suction and pressure side boundary layers.

- To what extent and by what means can the vorticity distribution be usefully manipulated to influence noise generation? How can this be done in combination with controlling the aerodynamics of airfoils that are close to stall?
- What are the effects of inflow turbulence and its characteristic length and timescales on performance and noise? Such studies need to encompass detailed fluid mechanics experiments in anechoic wind tunnels and in the field, as well as computational studies (as in Figure 3).

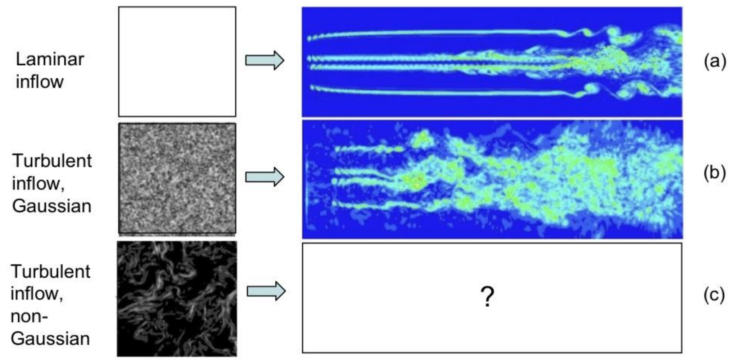

Figure 3: Simulations of wind turbine wakes for varying inflow conditions. (Troldborg et al 2007) (a) laminar inflow and (b) Gaussian synthetic turbulence inflow. Possible effects of non-Gaussian inlet conditions (c) are still an open question (Rosales & Meneveau 2006).

- How do manufacturing limitations (on geometrical accuracy and residual roughness, for example) and environmental conditions (such as blade fouling) impact noise? How can these effects be expressed as parameters and incorporated into design methodologies?
- At what level and in what circumstances do other noise sources become dominant? What are the dominant physical characteristics of these sources for wind-turbine configurations, and how do these scale? How are these sources best modeled for wind turbine blades?
- Are there better rotor geometries that weigh less and offer improved aerodynamic and acoustic characteristics?
- Can we develop and demonstrate advanced CFD/turbulence models for improved capture of two important phenomena for blade performance and noise: near-field wake evolution and flow separation or stall?

Tools to support this research

A combination of high-performance computing and laboratory experiments in conjunction with field measurements are needed to address these research topics. Specific tools needed include the following:

- Multiscale simulation framework with an ability to couple variable geometry and length and timescales of the wind farm array with the flow physics that govern its interaction with the wind resource. These simulations will require high performance computing at the peta- to exo-scale and will need to include near-field and far-field turbine wake evolution and interactions (e.g., using actuator line techniques, Sørensen 2002), turbine-turbine and turbine-farm interaction with atmospheric boundary layers (Jimenez 2007, Calaf 2010), and effects of atmospheric stratification and convection on wind farms. Figure 3 shows the effects of increasing the complexity of the incoming wind field. Much work is required in this area.

- Enabling measurement techniques to provide validation and verification data for the above multiscale simulations of the wind field and wakes, from sub- to full-scale (Hassan 1990, Medici 2006, Chamorro 2009).
- Uncertainty quantification and inclusion into a simulation and design framework. This will be coupled with the development of efficient techniques to capture important variability effects on farm output and optimization.
- Simplified descriptions, such as analytical models for first order designs and insights, reduced order models for the dynamics and controls, and synthetic 3-D velocity fields for "cheap" inflow boundary conditions (Mann 1998, 2007). New theories and methods to include effects of non-Gaussian statistics and intermittency are needed.
- Differentiating design tools created on high-performance computing platforms.
- Novel experimental facilities and measurement techniques capable of hi-fidelity anechoic noise measurements at turbine-scale conditions (Mach numbers, Reynolds numbers, and frequency ranges). Ideally, these would be capable of providing direct flow–noise state linkages via acoustic and aerodynamic measurements.
- Standard aeroacoustic experimental data sets for airfoils and blades (e.g., blade tips) to drive tools development across the world.
- High-fidelity CFD/CAA methods that can characterize primary sources of wind turbine noise, such as trailing edge noise, separation noise, and tip vortex noise.

Such a suite of simulation tools, validated for accuracy with appropriate data will allow wind farms to reach their entitled yields. Using high performance computing to link these tools to cost and grid models will enable full system optimization (turbine, array, grid) with respect to performance and cost. The technologies that will be developed are analogous to those needed for—and will have a similar impact on—hydrokinetic energy systems.

CONTROL, GRID INTEGRATION, AND POWER SYSTEMS

Control and power systems link all areas of wind energy, from utilization of the wind inflow through the turbine and into the utility grid, where policy and public perception play an integral role. Fundamental gaps exist in flow and pitch control, power systems, grid integration, systems-based design, and other areas that limit the reduction of energy costs. Figure 4 places control, power systems, and grid integration in a wider context of wind energy research.

In this section, we provide details on two primary topical areas and brief introductions to additional areas that have the potential to reduce the cost of wind energy through control and power systems advances. We conclude that methods for the realization of full-span blade pitch control need to be developed in order to increase energy capture and mitigate fatigue loads. Controlling individual turbines in a wind farm will optimize the output of the entire farm and mitigate loads on the turbines; appropriate methods need to be developed and tested through computational and experimental modeling. An important question is how wind energy and other intermittent energy sources can best be integrated into the electric utility grid. Although intermittency can be mitigated through advanced forecasting, a new vision for power collection and distribution is required to seamlessly integrate wind and solar energy production with traditional power generation technologies at a national scale.

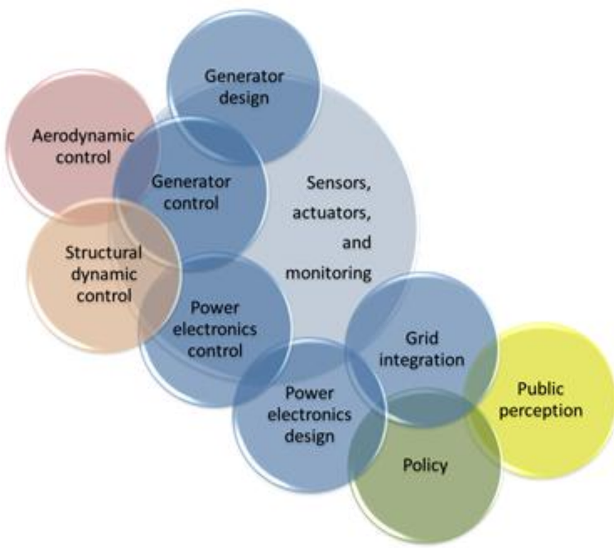

Figure 4: Schematic showing subcomponents of the control and power systems research area and connections to other areas of wind energy research.

Topic 1: Novel sensor, control, and actuation systems for individual turbines

Motivation

This area has drawn considerable interest in recent years, with the goals of reducing loads on turbine components and increasing energy capture by increasing operational efficiency of individual turbines. A control system involves three basic elements: sensors to measure process variables, actuators to manipulate energy capture and component loading, and control algorithms to coordinate the actuators based on information gathered by the sensors.

Just one of the above elements, the application of novel actuators in load reduction, is discussed here. Other needs are addressed in the research questions section that follows. The axial induction factor, *a,* is a measure of the slowing of the wind as energy is extracted by the turbine. Figure 5 shows significant variation in the induction factor along the blade span for a constant-speed wind turbine over a range of wind speeds, indicating that the turbine is not extracting the full amount of power available at winds below the 13 m/s rated speed. Modern variable-speed turbines would have less variation of the induction factor with wind speed, but variation along the blade span would remain. Full-span blade pitch control, a common feature for most modern utility-scale turbines, cannot eliminate these variations along the blade span.

State of the art

The current state of the art in load reduction is largely focused on full-span blade pitch control, since individual pitch motors are the actuators currently available on commercial turbines. Significant load mitigation has been demonstrated in simulations for blades, tower, and drive train (Darrow 2011, Dunne 2010, Geyler 2008). Increasing turbine efficiency and energy capture is also an active research area (Creaby 2009, Cutululis 2006, Johnson 2006).

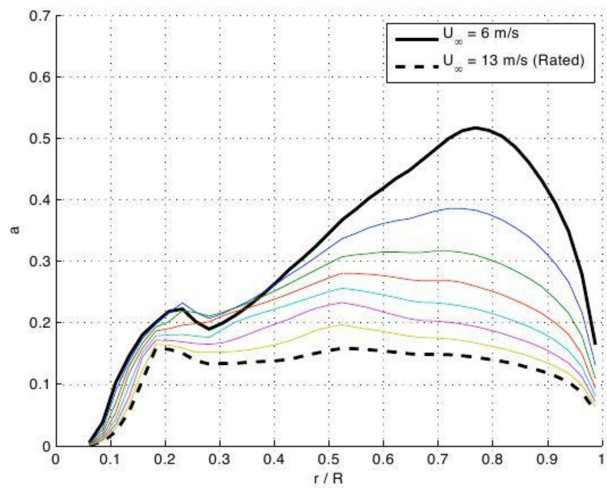

Figure 5: Rotor axial induction factor as a function of the normalized radial position over a range of wind speeds for a constant-speed wind turbine.

The next generation of wind turbine blades may also be equipped with distributed actuation in the form of smaller actuators distributed along each blade (Johnson 2010, Rice 2010), including segmented trailing-edge flaps, deployable tabs or microtabs (van Dam 2007, van Wingerden 2008, Lackner 2011), steady and unsteady blowing of air (Cerretelli 2009) and plasma actuators (Hall 2005, Nelson 2008, Corke 2010). Preliminary results are promising for these distributed actuation systems.

Research questions

- What is the best way to model wind turbines for the purpose of advanced control design, analysis, or simulation? What is the appropriate model fidelity for the task at hand? What methods are amenable to reduce model complexity, and how can we validate models?
- What opportunities are there to amplify advancements in fluid mechanics and solid mechanics through collaboration with control systems researchers? Enhanced understanding of turbulent (gusty) wind fields, for example, may enable anticipative control strategies.
- What sort of experimental facilities are needed to enable the next generation of onshore and offshore wind power technology? Physical experiments are crucial for validating new models and controllers. A particular need is data from utility-scale turbines amenable to public domain publication.
- What is the effect of load mitigation on turbine lifetime and turbine-system weight, cost, operation, and maintenance? These relationships are uncertain, since a given controller can influence design drivers for some components but not others.

- How should we formulate the problem of balancing energy capture and loads to improve cost of energy? To date, cost models relating controller signals, especially load reduction, to cost of energy have high levels of uncertainty.

Topic 2: Grid integration and regulation control

Motivation

Integrating a nondispatchable source like wind energy into the utility grid can be problematic, as grid operational strategies are designed for traditional dispatchable sources such as coal, natural gas, and nuclear. A central challenge is balancing generated electrical energy with demand across wide geographic areas experiencing a variety of wind resources. Wind resource prediction, voltage regulation, frequency regulation, and fault ride-through are among the wealth of research topics falling under this subheading.

Here we focus on one particular issue, the potential for wind energy to contribute to the frequency regulation of a utility grid. Other issues are listed in the research questions section that follows. The grid frequency becomes more sensitive to supply-demand imbalance as system inertia is reduced. Wind turbines normally contribute less to the system inertia than conventional generators. Consequently, increased sensitivity to supply-demand imbalance will become a critical issue as wind energy displaces a significant fraction of conventional generators (Morren 2006, Lalor 2005).

State of the art

Research in this area (for example, Erlich 2010, Miller 2010, Tarnowski 2010) indicates that wind turbines and wind farms may be able to assist the grid in recovering lost frequency caused by a sudden decrease in generation by another facility or increase in load. Frequency controllers can act by extracting kinetic (rotational) energy from the wind turbine either immediately upon notification of a grid fault or several seconds later. The turbine will eventually need to speed back up, but other generation sources will have come online by that time. Since wind turbines are often dismissed based on concerns about their negative effects on the utility grid, this newfound capability to provide grid support has the potential to be a key contributor to wind power's future success. Initial results in this area are largely based on simulation and proprietary tests thus additional research is needed. Research questions related to grid support and to larger issues concerning the integration of wind energy into the grid are outlined below.

Research questions

- What are the side effects on wind turbines from using regulation control strategies?
- What pricing structures should be put in place to promote frequency control support by distributed generation sources like wind?
- What public incentives and policy decisions will encourage development of wind energy as a shared resource? How can wind farm operators be protected in closely located wind farms, where one farm may utilize wind at the cost of the other?
- Can improved forecasting technologies compensate for the nondispatchability of wind energy? What resources are necessary to create these improved technologies?

- What changes can be made on the demand side of the utility grid to promote renewable energy integration?

Additional topics of interest

Transmission Planning

Power transmission is a key to enabling the effective utilization and integration of wind energy at large-scales. Transmission network planning for wind and other renewable differs from planning for conventional power sources (Smith 2010). The network needed for wind energy must be capable of carrying large amounts of power over long distances and must be sufficiently flexible and interconnected to allow power to be aggregated over large areas to reduce variability and increase reliability. Transmission planning for wind must address the complex interface of economics, technical requirements, environmental concerns, social concerns and policy. Research is needed to scope out the high voltage AC and DC transmission networks needed for wind energy and to identify policies that will enable the building of the network and the effective operation of markets across broad geographical regions. A related need is to develop innovative transmission technologies to bring down cost, reduce visual and other impacts and to allow the development of hybrid AC/DC systems.

Wind farm control

The goal for wind farm control systems is to aggregate and coordinate aerodynamic, structural, and electrical aspects of wind energy across wind farms. In the area of aerodynamic and structural system control, optimizing loading and generation across the farm is the top priority. Farm-scale models linking wind plant aerodynamics and control for the purpose of enabling control design need to be developed. In the area of electrical system wind farm control, electrical power quality, ancillary services, ride-through requirements, and forecasting for grid integration are all important topics.

Generators and power electronics

The goals are to increase power quality, reduce cost, and reduce risk. Advanced generator designs (hybrid and direct-drive systems), materials, and power electronics are all important research areas. Non–rare earth metals and advanced composites and alloys are necessary materials to enable the generators and power electronics. High-frequency switching semiconductors, high-voltage systems, and AC/DC interface and transmission architectures offer needed improvements in power electronics.

Offshore wind turbines

Control will be critical for offshore wind turbine operation, with the additional complexity of wave excitation in both fixed and floating platform configurations. The wave-to-structure interface represents a dynamic coupling that significantly alters the overall system dynamics, which can significantly affect loading. Simulation studies by Jonkman (2009) and Namik (2010) suggest the damage equivalent load for the fore-aft tower-base bending moment is amplified over the onshore baseline by about 25 percent for the tension leg platform and 300 percent for the barge platform. Further investigation is needed to ensure turbine designs that are even more reliable than onshore turbines. This may entail advanced control algorithms, novel actuators, novel sensors, and multidomain synergy; see the offshore section of this report for additional discussion on the unique research needs related to offshore wind energy.

Summary

In summary, for success in improving wind energy control and power systems, the following barriers must be overcome:

- We must address multidomain aspects of wind energy design.
- We must create system risk management and multilevel system analysis tools.
- We must design controllers and sensor networks for systems of systems, starting with individual turbine components and extending through a sophisticated electric grid of the future.
- We must address disparities in resources and consumption at differing locations. Investment to reinforce the connection between regional grids will offer a partial solution.
- Within the power grid, we must provide balance between load and generation, economic and policy incentives, cost-effective storage, and robust and distributed control.

STRUCTURES AND MATERIALS

Reducing the cost of wind energy by a significant margin will require wind turbines that are less expensive to fabricate, erect, and maintain, yet able to perform for decades under highly variable loads and environmental conditions. A key driver for reducing cost and enabling larger rotor diameters is the development of dynamically stable, light weight structures. Designing such structures will require new materials, or better use of existing materials in novel structural configurations. Multi-disciplinary design tools linking structural mechanics, aerodynamics, materials and manufacturing are needed to facilitate the development of innovative turbine concepts. Advances in sensors and computational techniques for effective model-based structural health monitoring, new materials and new fabrication processes are also needed to decrease cost and increase reliability.

Major needs in structures and materials-related wind energy research cluster around following three main topics: wind turbine structures and structural analysis, materials and failure prediction, and fabrication of wind turbine components.

Topic 1: Structures

Motivation
The modern wind turbine is a complex, integrated system, with the structural elements comprising the majority of the weight and cost. From the foundation to the tower, nacelle, drivetrain, and blades, the structure must be inexpensive, lightweight, manufacturable, and durable under highly variable environmental and loading conditions. Achieving turbine systems that are lighter, have fewer failures, require less maintenance, and last longer will translate directly to reducing the cost of wind energy. Developing innovative solutions to reduce cost of energy for both land-based and offshore wind turbines will require well-documented, validated analysis codes. Such codes must integrate uncertainties in loads, environment, and materials, as well as linking a broad range of physics such as aerodynamics, structural mechanics, and materials . These codes should be made available in the public domain, which will accelerate their development by allowing researchers to build on and improve them and through the experience developed by a large base of designers using the codes to develop new own wind turbine system designs.

As discussed in the wind field section, mitigation of loads is critical to design lower cost, longer lasting systems. In addition to the consideration of the wake and the flow control methods discussed in the controls section, loads can often be reduced by making a structural system softer, or more flexible. This could be accomplished through using downwind rotors where blade tip clearance of the tower is not an issue, or by curved blades that naturally twist to reduce angle of attack at higher wind speeds. Such systems will be highly nonlinear and will strongly couple the structure to the flow field. Thus design tools must evolve to dynamically model these nonlinearities.

As wind energy systems get larger and more complex—and especially as they are placed in more remote locations, such as floating offshore platforms—prognosis and health-monitoring systems will become more and more critical. These systems can reduce operations and maintenance costs by enabling just-in-time maintenance and better planning (Amirat 2009, Hameed 2010, Odgaard 2009). Advances in sensor fusion, fault detection, fault-tolerant control, and advanced, yet inexpensive, sensors are all important to this research area.

Making field data on loads, power, and wind field from deployed turbines available would be invaluable in validating complex analysis codes used for turbine design. Existing analysis codes require significant startup effort. Reducing this barrier would contribute to the education of engineers specializing in wind energy. A collaboration of universities and national laboratories would be well suited to the task of developing student versions, tutorials, and "getting started" guides.

State of the art

Wind turbine structural analysis starts with a definition of the turbine configuration; the blade aerodynamic and structural properties; and load inputs, such as the wind spectrum and, for offshore systems, the wave spectrum (Jonkman 2010). Researchers simulate the turbine system with a nonlinear, multibody dynamics analysis that combines the aerodynamic loads (including turbulence and wind shear), hydrodynamic loads, and control to compute the motions and dynamic loads of various components of the turbine. Accounting for the loads, components of the turbine are analyzed for stability, strength, and fatigue life, and further design iterations follow. Given the stochastic nature of both the loads and the material and structural properties, this analysis must be probabilistic (Sørensen 2010). In the area of structural health monitoring, efforts are under way to investigate sensors, placement, and data analysis for prognosis and structural health monitoring of wind turbine blades (Rumsey 2008). This monitoring presently includes the use of acoustic emission sensing, fiber-optic strain sensors, traditional strain gauges, and other types of transducers, but much remains to be done.

Research needs

- Design tools that integrate aerodynamics, structural mechanics and materials to allow for design optimization and incorporate the stochastic nature of loads, defects, and material properties. These next generation coes must also account for the non-linear effects of large, dynamically soft structural systems.
- Field data from deployed turbines to use in the validation of analytical tools.
- Exploration of novel sensors, analysis of sensor placement, and development of methods for powering the sensors and collecting data.
- Algorithms and computational techniques for model-based structural health monitoring.
- Development of tutorials and getting started guides for existing design codes.
- Novel concepts for blade and tower designs to reduce weight and cost.

Topic 2: Materials

Motivation

Successful turbine design relies on thorough understanding of material performance, defect and damage tolerance, durability, and aging. Wind turbine design presents a very large design space, with many opportunities to introduce new materials. Examples include the use of carbon fibers for the very large blades anticipated for offshore use or the introduction of new types of glass fibers, resins, adhesives, and coatings. Structural joints, a potential failure point, can become more robust through the application of principles of advanced mechanics of materials, combined with best practices in design and fabrication. New materials that last longer and existing materials better utilized and characterized will relate directly to reduced cost of energy through longer system lifetime, less downtime, and fewer repairs. Recently identified as an issue for wind turbines, radar interference is another barrier to large-scale deployment of wind energy that materials developments may mitigate.

State of the art

Wind turbines are built from a number of materials, including glass fiber composites for blades, polymeric adhesives, coatings and insulation, steel for tower and drive train components, and concrete for foundations. Most of these materials operate under variable loads and environmental conditions, including potentially extreme temperatures, humidity, ice, salt, lightening strikes, and other factors. Methods for designing with these materials and predicting how they will perform over long periods and under cycles of loading are often specific to each material. As an example, the current practice for life prediction in blades is based on data compiled in an extensive uniaxial fatigue database (Sutherland 1999, Mandell 1997). Complex geometries, thick sections, loads in more than one direction, tapering of the number of plies of the composite, joints, and core materials all greatly complicate life prediction relative to the uniaxial method now used. Environmental effects such as moisture, salt and other factors contributing to material aging are not explicitly modeled. Stochastic models of material failure and life, based on sound theory, are needed for incorporation into the multidisciplinary structural analyses discussed above.

Research needs.

- Advanced models for fatigue failure and life predictions for composites and other materials under anticipated wind turbine loads.
- Adhesive joint design, analysis, and modeling
- Life-prediction calculations that incorporate environmental conditions, such as salt water, icing, moisture, and extreme temperatures.
- Incorporation of stochastic, advanced failure models into structural design and analysis.
- Development of new or better use of existing materials and coatings for blades, towers, nacelles and other turbine components.

Topic 3: Manufacturing

Motivation

Anticipated increases in turbine power and size and the deployment of many thousands of wind turbines will require improvements in both turbine manufacturing throughput and the quality and consistency of both turbines and components. Although a wind turbine has many components, we confine the discussion here to blades, as they are the key structural elements and unique to wind energy. Very large blades for offshore wind turbines, which may need to be fabricated in waterfront facilities or in two pieces, present additional challenges due to their weight and the scale of the fabrication. There is as yet, no experience with the design, manufacture and use of such blades. Manufacturing defects, such waviness, bad bonds, delamination, voids, and trailing edge splits, are responsible for a number of blade failures (Laird 2010). Higher quality blades with less manufacturing variability will improve overall system reliability and predictability, reducing risk and operating costs such as rework, repair, and maintenance.

State of the art

Wind turbine blades made of glass fiber–reinforced polymer matrix composites are largely fabricated using hand lay-up into two-piece molds, a technique based on boat building, or in newer methods, into one-piece molds. The composites can be pre-impregnated, where layers of fibers embedded in uncured resin are laid up, or fibers can be laid up dry and then infused with resin and cured at an elevated temperature under vacuum pressure. If made in two pieces, the two halves of the blade are then joined to each other and to a spar. At this point of the process, poor fit and tolerance of the parts may require additional handwork, such as filling and grinding. Hand lay-up can also lead to waviness of the fibers, gaps, and other defects. Additional finishing steps, such as application of surface coatings and bonding of hub attachment studs, are then completed.

The resin's infusion and curing introduce many variables, including the type and viscosity of resin, infusion speed, curing cycle (temperature and pressure history), placement of heating elements, and configuration of the resin infusion system. A current goal is to decrease the time and cost of this step, without compromising quality by inducing defects such as dry regions or voids. New validated process models could accelerate the introduction and evaluation of novel resins, fibers, and cure cycles. Such a program would combine modeling with bench-scale experiments, followed by small-scale prototyping. Given the nature of the research needs and scale of the problem, this work must be carried out in close collaboration with wind turbine industry blade fabricators and designers.

Research needs

- Validated process models for the design of improved infusion and curing cycles, in order to improve throughput and quality of wind turbine blades.
- Concepts and techniques for low-cost automation of ply cutting, fiber placement, and other manufacturing processes.
- Blade designs optimized for not only structural and aerodynamic performance, but also manufacturability.
- Concepts for manufacturing of blades on shore or in two-parts to facilitate transportation.

- Automated, fast, low cost inspection methods to detect defects during manufacturing and final assembly.
- Novel uses of new and existing materials and coatings.

OFFSHORE WIND ENERGY

Offshore wind power represents a large, untapped potential, but also significant risk. The total offshore wind resource in the US is over 4,000 GW, with 1,000 GW of this in shallow waters (less than 30 m) and the remaining 3,000 GW in waters deeper than 30 m (U.S. Department of Energy, 2011). The major challenges to deployment of offshore wind power in U.S. waters include the high costs of offshore balance of station (BOS) hardware and supporting infrastructure and facilities; unknown resources, energy yield, and environmental conditions; demanding technical challenges and a lack of current infrastructure to support fabrication, installation, interconnection, and maintenance of these systems; and untested permit requirements for siting wind projects in federal and state waters (American Wind Energy Association 2009, U.S. Department of Energy 2010, Carbon Trust 2008).

The unique wind resources, wave characteristics, and weather patterns and site specific bathymetry relevant to offshore wind turbines need to be identified for wind farm siting and wind turbine design studies. Waves, currents, and floating ice will strongly impact the structural design of floating and fixed-bottom offshore turbines. Offshore-specific models and computational fluid dynamics codes need to be developed to address offshore conditions. Cost effective offshore wind is an extremely challenging area. Overcoming the barriers to deployment of offshore wind energy will require significant research advances in the following five areas.

Topic 1: Assessment of wind resources and external design conditions

Figure 6: The offshore wind environment.

Motivation

Essential starting points for assessing potential offshore wind project sites include accurate and comprehensive information on offshore wind resource characteristics across a range of spatial and temporal scales and field data on external conditions such as waves and currents, seabed properties, and marine growth. A long-term, concerted effort to collect and disseminate critical field information beyond wind characteristics is an important research priority. Necessary data include water depth, currents, seabed migration, and wave action, which drive mechanical and structural loading on potential turbine configurations. Other quantifiable factors of the design environment include marine growth, salinity, and icing, as well as the geotechnical characteristics of the sea or lake bed. These data provide the basis for technical requirements governing structural design and establish operating parameters of turbines and towers and balance of plant structures and cables. Application of these requirements to facility design will impact determinations of practicality, reliability, and economic viability (Bailey 2009).

Research needs

- Wind resource characterization for the Outer Continental Shelf and Great Lakes.
- Analysis of extreme events such as hurricanes.
- New International Electrotechnical Commission (IEC) requirements for both salt- and fresh- water systems in the United States
- Quantified details of air-sea interfacial dynamics and hydrodynamics.
- Existing and innovative hardware and methodologies for measurements, including Light Detection and Ranging (LIDAR), Sonic Detection and Ranging (SODAR), radar, autonomous underwater vehicles (AUV), and remote satellite sensing, must be assessed and refined.
- Siting and planning tools that account for multivariate constraints to identify optimal locations for offshore wind farms.
- Offshore resource data, analyses, bathymetry, environmental, multiple-use and other site specific design criteria maintained as public domain information to help facilitate technology development and deployment.

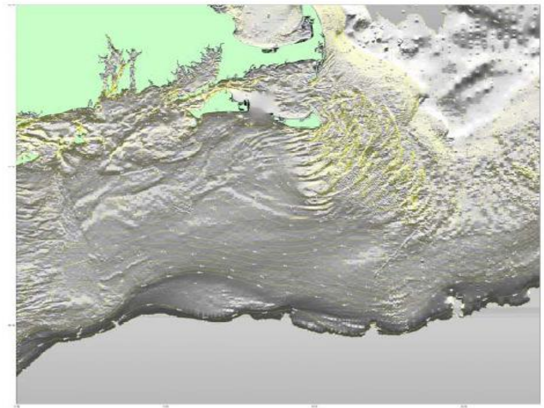

Figure 7: Continental shelf off Massachusetts

Topic 2: Modeling and analysis tools for design of offshore wind turbine systems

Motivation

Development of accurate and validated computer tools to predict the motions of and dynamic forces acting on turbines deployed at sea is needed before the next generation of turbines can be designed. One of the immediate challenges common to all support structure designs is the ability to predict loads: particularly the dynamic responses of the wind turbine and support structure when subjected to combined wave and wind loading (Tarp-Johansen 2008, Cordle 2010). Additional offshore loads arise from the impact of floating debris and ice and from marine growth buildup on the substructure.

Offshore turbine structural analysis must also account for the dynamic coupling between the translational (surge, sway, and heave) and rotational (roll, pitch, and yaw) platform motions and turbine motions, as well as the dynamic characterization of mooring lines for compliant floating systems. Foundations and substructures make up a large fraction of the cost of offshore wind systems. Taking into account installation costs, long-term maintenance, coupled turbine loads and weight, and the cost of the substructure itself, the optimal turbine-substructure system can be identified.

In deep water, designs should be evaluated for bottom-mounted turbines out to 60-meter depth and for floating foundations in transitional waters (30-60m) and beyond 60 meters. Concepts for and models of the anchors needed to maintain position and stability of floating foundations are needed. Finally, better models of scour processes are needed in conjunction with improved design methods for scour protection.

Research needs

- Fundamental understanding of floating platform dynamics in transitional (30 to 60 meters) to deep water (greater than 60 meters), including how nonlinear air-sea interaction effects (e.g. nonlinear waves and breaking wave impact loading) and different anchoring and mooring systems affect wind turbine performance.
- Improved understanding of fixed platform dynamics in shallow (less than 30 meters) and transitional water, including how ice loads affect the structural design of the wind turbine system.
- Improved aeroelastic modeling tools for simulating highly compliant lightweight turbines and support structures.
- Accurate method for assessing seafloor conditions and soil properties, paired with a better understanding of soil and structure interaction.

Topic 3: Offshore wind farm simulation models

Motivation

With no complex terrain or landscape to disturb the windfield, offshore wind farms are suited to placement in regular arrays. The performance of such arrays is sensitive to atmospheric boundary layer stability, wind turbine array effects and the impact of entire wind farms on each other.

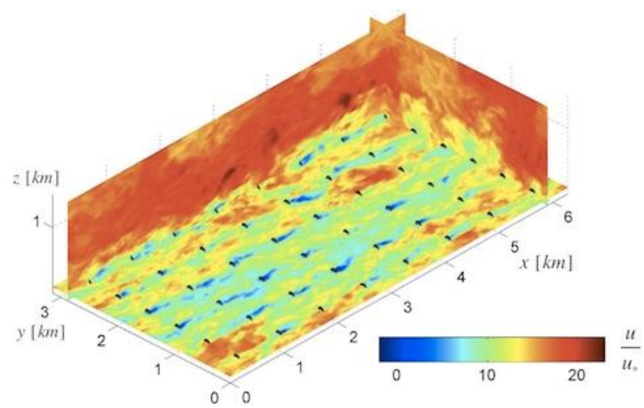

Figure 8: Wind farm wake effects (Meyers and Meneveau, 2011)

Current wind farm models do not adequately represent the boundary layer stability effects. Accurate characterization of the atmospheric boundary layer behavior and more accurate wake models will be essential to designing turbines that can withstand turbulence. Since turbulence causes wear and tear on the turbines, as the offshore industry grows, it will be a high priority to be able to quantify turbulence under a wide range of conditions and develop tools to design wind farms that minimize turbulence at the source.

The configuration and spacing of wind turbines within a farm has been shown to have a marked effect on power production from the entire wind farm, as well as from each individual turbine. Typical offshore wind farms lose 10 percent of their energy to wake effects; improvements in wind farm layout may allow some recovery. Uncertainties in power production represent a large risk factor for offshore development. Today's wake codes attempt to model performance, but empirical data show inadequate representation of individual turbine output. Analytical models to predict optimum spacing between arrays are presently immature. The inability to predict actual performance accurately is a critical shortcoming in financing billion-dollar offshore facilities. Thus improving wind farm performance models offers an opportunity for significant cost reduction (Barthelmie 2009, 2008).

Offshore wind farms' impacts on each other are likely to be greater than in land-based systems because the open ocean offers continuous tracts of unobstructed windy territory, and wind farms introduce downstream turbulence that regenerates over some distance. Wind farms installed upstream must take into account their effect on downstream wind farms in both energy capture predictions and structural loads due to modifications of wind characteristics. "Wind rights" and setbacks will become important considerations.

Research needs

- Advanced numerical modeling to understand how design conditions and the wind resource are influenced by the presence of other wind farms.
- Optimization tools that take into account such factors as water depth, soil conditions, cable costs, wind statistics, and wake losses.
- Energy-capture estimation tools for wind farm arrays.

Topic 4: Offshore wind turbine design

Figure 9: 2-blade offshore wind turbine (2B Energy)

Motivation

Design of offshore turbines presents significant challenges beyond the land-based state of the art. Economic considerations drive offshore systems toward larger turbines with increased energy capture to justify the extra infrastructure required to go offshore. The turbine represents less than one-third of the costs in today's offshore projects. Efforts are already under way to develop 10-megawatt turbines. Reducing the relative weight of these turbines, developing manufacturing methods and materials for 90- to 100-meter composite blades, eliminating problematic gearboxes, and increasing autonomous reliability and availability are all difficult engineering problems that must be solved to make offshore wind practical. Top-down systems engineering methodologies developed in complex aerospace projects can be fruitfully applied to achieve these objectives (Jamieson 2009).

Research needs

- Advanced wind turbine concepts designed specifically for the marine environment, with power ratings of 10 megawatts or more.
- Analysis of two- and three-blade, upwind and downwind rotor configurations.
- Advanced, high-speed rotor design, materials, and manufacturing.
- Turbine load-mitigation controls and strategies.

- Turbine and rotor designs to minimize hurricane and typhoon damage.
- Gearless generators utilizing permanent magnets and superconducting coils.

Topic 5: Installation and infrastructure

Motivation

Figure 10: Float-out foundation (MBD Ocean Power)

Offshore wind turbine installations have higher capital costs than land-based installations per unit of generating capacity, largely because of turbine upgrades required for operation at sea and increased costs related to turbine foundations, balance-of-system infrastructure, interconnection, and installation. One-time costs are incurred with the development of the infrastructure to support the offshore industry, such as vessels for turbine installation, port and harbor upgrades, manufacturing facilities, and workforce training programs. Gigawatt-scale offshore wind farms also offer significant grid-integration challenges in bringing large-scale power to shore, linking multiple wind farms, and optimizing internal wind farm AC/DC power conversion (Norden 2009).

Offshore wind foundation structures to date have been gravity and monopole structures deployed in shallow waters. Many interesting concepts are proposed for transitional and deep waters. The potential to assemble turbines on shore and float out turbines and foundations to be held in place by tethering, sinking, or ballasting could greatly simplify the construction of offshore farms (Ali 2003, Loma 2009, Butterfield 2005).

Deep water floating platforms such as tension leg platforms, semi-submersibles and spar buoy designs pose the most significant technical challenges as well as the highest potential cost of energy payoff. Fixed bottom platforms can access over 1,000 GW of wind in waters less than 30m deep, however, by accessing waters deeper than 30m, floating platforms open up an additional 3,000 GW of potential wind resource within 50nm of both coastlines.

Decoupling the turbine design from local bathymetry conditions by removing the supporting foundation has tremendous advantages in cost. On site marine construction can be four to eight times more expensive that the same work performed in a factory environment. Similarly, on station marine service requiring specialized equipment including barges and specialized service ships can be cost prohibitive. Development of floating wind farms and float out systems from an integrated systems perspective may provide even lower cost alternatives to fixed bottom technology. Weight is even more important in floating systems than on land. Saving 1 kg of mass above the waterline translates to saving as much as 5-6 kg of buoyancy supporting structure. The control of dynamically active, lightweight floating systems subject to a broad spectrum of wave and wind loading is much more complex and critical than on land based systems.

Research needs

- Economic modeling and optimization of costs of the overall wind farm system, including installation, operations, and maintenance.
- Design of installation systems, such as specialized vessels and barges and float-out systems.
- Service methodologies, remote monitoring, and diagnostics.
- Offshore electrical grid including in-farm turbine interconnect subsystem and shore-cable infrastructure subsystem.
- Shallow-, transitional-, and deep-water foundation systems.
- Design of floating platforms and float out turbine systems for deep water installations.
- Methods for control and stabilization of dynamically active floating turbine systems.

SOCIAL AND ENVIRONMENTAL CONSIDERATIONS

The full potential of wind energy has been hindered by public opposition and uncertainties associated with potential environmental impacts. Public opposition is particularly strong in the U.S. and sometimes bewilders our European colleagues. It provides strong impetus for social science studies. The opposition spans a range of issues, including an overall lack of understanding of global warming and its short-term and long-term effects; the perceived negative aesthetics of wind energy projects; the failure of agencies, regulators, industry, and scientists to compare the potential negative impacts of wind energy with those of existing systems for generating and delivering electricity; and publicity that misrepresents environmental risk by ignoring the available science. Replacing energy produced by plants powered by fossil fuel with wind energy could benefit the environment as a whole, reducing risk to human health and some types of threats to terrestrial and marine wildlife. Individual wind turbines and farms, however, have been documented to result in negative effects to humans and wildlife. Residents living near wind turbines experience annoyance due to noise, shadow flicker, and other visual effects. Collisions with turbines cause direct mortality to some species of birds and bats, marine noise-generating activities have unknown potential impacts on marine mammals, and both land and marine activities can produce indirect negative impacts, such as habitat loss and fragmentation.

There is growing concern in some quarters about how wind energy development, especially at large scales, might impact populations of birds and bats (Bright 2008) and marine mammals. Recent research has focused mostly on estimating wildlife mortality at existing wind turbines, with only very limited work on developing risk assessment models to guide siting of proposed wind facilities. Furthermore, much of the existing research has been spatially, geographically, and temporally limited and has lacked coherent scientific objectives and methodological and analytical standardization among sites (Allison 2008, Kerlinger 2001). Standardized, applied research that samples the full range of expected wind facility development scales is needed (Kunz 2007, Kerlinger 2010). This approach is critical to constrain scientific uncertainty and environmental risk and to build public confidence in wind energy as a viable, long-term contributor to our national energy needs.

Understanding what underlies public support or opposition to wind farms and the relationship between fair process and project support are missing pieces if wind energy is to gain major acceptance (Kempton 2005, Firestone 2009). The fact that many projects fail because of a lack of social acceptance of wind energy—whether perceived or real—underscores the critical need for research on basic public attitudes, understandings, and perceptions related to wind energy.

We believe the following research priorities will help policy makers, agencies, and the wind industry make informed, publicly accepted, science-based decisions about future wind energy projects. These recommendations embrace a broad range of topics, from public attitudes, to cost-benefit and life-cycle analyses, to basic scientific research, and engage all vested parties with the fundamental objective of enabling a successful, sustainable wind energy policy in this country. Much of the focus is on the development of data collection, analyses, and interpretation and modeling processes to estimate risks to individuals, communities of people, and wildlife and their habitats.

Inform preconstruction siting decisions.

The wind industry and government decision makers have been operating under the assumption that communities will not accept offshore wind installations that are visible from shore. Recent research by Krueger (2011) suggests otherwise, and further states that society would be worse off if all in-view development opportunities were avoided. Often wind project opponents are stereotyped as NIMBY (not in my back yard). A growing body of work suggests that the NIMBY label describes a result (that is, opposition), rather than explaining the reasons underlying the opposition (Kempton 2005). Indeed, people's relationship to their surroundings (a landscape or seascape, for example) and expectation that those surroundings will remain the same appear to be more germane to an understanding of wind power project opposition (Short 2002, Pasquelleti 2002, Firestone 2009). Wolsink (2007) puts it succinctly: "It's the landscape, stupid." In order to advance siting decisions generally, we thus agree with Devine-Wright (2005) that additional research should focus on the ways in which individuals perceive how wind power developments impact surrounding land and seascapes. In addition, this research should explore the extent to which siting decisions and place attachment may differ for sea- and land-based wind facilities.

Most animals (including bats, birds, frogs and toads, fish, and marine mammals) potentially at risk from direct impacts by wind energy construction, operations, and maintenance are either seasonally resident or migratory. The major factor that presently limits our ability to model and thereby constrain risk is uncertainty in species-specific occurrence, density, distribution, and biological context. In other words, there are limited data on the spatial and temporal occurrences and distributions of animals of concern, including marine mammals, fishes, and nocturnally migrating birds and bats. Although songbirds migrating over land make up approximately 75 percent of bird mortality at land-based wind facilities, for example, there are almost no data to inform estimates of risks to birds migrating over water.

Modeling the spatiotemporal patterns of migratory and residential wildlife with respect to geographic features and weather would provide a basis for science-based decisions about where to site new wind projects. Some specific suggestions follow:

- Use existing data on migratory and other movements of wildlife to develop predictive models of risk.
- Use new and emerging technologies, including radar, acoustics, and thermal imaging, to fill gaps in knowledge of wildlife movements; focus studies on potentially important geographic features, such as ridges, rivers, coastlines, and currents.
- Develop new analytic and modeling techniques for combining datasets on animal presence and movements with environmental and topographic factors potentially affecting risk.
- Identify factors that influence movement of wildlife within the rotor-swept area of wind turbines in order to identify potentially hazardous or safer sites.

- Identify specific species or sets of species most at risk in areas of high potential wind resources.
- Map risk factors with wind energy potential in order to "score" the potential effect of proposed wind facilities on critically important migration and movement corridors.

Secure data and site access for researchers at existing and new wind farms.

Instituting measures to increase access to post-construction sites and data *without jeopardizing industry production or profits* will be key to ensuring that decisions and policies regarding wind energy development are based on the best available science. Developing an open and honest partnership among industry, environmentalists, government, and academics (e.g., scientists, sociologists, and public policy experts) is an important next step in implementing this research agenda.

Further examine the relationship between fair process and project support.

Although there is a rich literature on the benefits of community engagement, consultation, and ownership (Wolsink 2007), the existing literature should be supplemented with more quantitative data and analysis of the relationship between such engagement and project support. Little is known about whether satisfaction with the process leads to project support, whether process satisfaction and project support are mutually reinforcing, or whether they are jointly influenced by the same variables (including age, gender, income, length of residency, distance from the wind farm, and so on).

Conduct surveys on human attitudes over time.

Several studies have found that local support for a wind project increases after construction ends and operations begin. Support and opposition often follows a "U" or "V" pattern, with initially high acceptance that falls during construction and is followed by a rebound after the wind farm commences operation, but little research using consistent metrics and sampling methodologies over time has been accomplished.

Examine the relationship between support for wind energy and other means of electricity generation.

Much research has focused on support of and opposition to wind energy in general or to a specific project without comparing these attitudes to the status quo option of fossil or nuclear fuel. Research must be conducted to examine public attitudes toward the socioeconomic and life-cycle environmental trade-offs (from mining and manufacturing through decommission and disposal of waste) associated with producing energy from various sources. For examples, see Krueger (2011) and J. Lilley (2010).

Develop a plan for studying and forecasting the social and environmental risk from offshore wind energy production.

There is very little known about the potential impacts of large-scale wind energy production on seabirds, shorebirds, marine mammals, or fishes. Offshore wind power is becoming an increasing fraction of the new wind power supply in Europe, and similar trends will be apparent in the U.S. over the next decade or two. We know comparatively less about public preferences, perceptions, and knowledge of offshore wind as compared to land-based wind. Fruitful areas of research include tourism impacts (M. B. Lilley 2010), effects on recreational fishing and boating, perceptions of and preferences toward near-shore developments and offshore transmission, and the relationship between wind energy support and concerns over factors such as climate change, electricity price, environmental effects, and energy independence.

Examine and model the potential population-level effects of wind energy development.

The effects of habitat loss and fragmentation on flora, fauna, and general ecosystem integrity have been studied for more than 25 years and are reasonably well documented. Determining the direct and indirect population-level impacts of large-scale wind energy will require a meta-analysis of existing bird and bat mortality data from across North America and a large-scale approach to estimating habitat loss and fragmentation. To estimate the overall potential impact, results from these analyses will need to be comingled and modeled over numerous build-out scenarios.

Standardize methods, metrics, and definitions used in studying bird and bat impacts at existing wind facilities.

Because fatality rates of birds and bats show great variability among wind facilities and geographic regions, it is unwise to draw broadly applicable conclusions from only a few studies or sites. Scientifically robust comparisons of potential and real impacts across individual turbines, sites, seasons, and years are extremely difficult because of gross differences in study designs and methods. The changing size of wind turbines—from today's current standard of 1.5 megawatts to units that are 3–5 megawatts, or more—necessitates investigation of how exposure-risk and reported fatalities varies based on potential turbine output. For example, exposure-risk might better be expressed as "probability/megawatts/day" or mortality as "individuals/megawatts/year."

CONCLUSIONS

We have outlined a number of fundamental research questions that are appropriately addressed by university based researchers working in close collaboration with national laboratories and industry. These questions focus on reducing barriers to large scale deployment of wind energy. The urgency for carbon-free energy sources on a large scale cannot be overstated. Recent political events in the Middle East and natural catastrophes are powerful calls to action—and the failure of nuclear plants in Japan reminds us that the science and technology of large-scale engineering projects must be at the highest level, taking into account complex contingencies. The ability of the U.S. to compete in the high technology arena of wind energy, to create jobs and to ultimately deploy wind energy without relying on taxpayer subsidies is dependent on research and innovation.

Wind, unlike traditional power plants, is a distributed source: wind farms cover large areas and their fuel, the wind, varies spatially and temporally. Consequently, wind energy links atmospheric physics with engineering, and because of the large footprint of utility-scale wind energy, social and environmental issues take on new significance. In this report, we have shown the interdisciplinary nature of the problem. Its solution requires the involvement of scientists, engineers, naturalists, and sociologists. The university is the only setting where this complex interdisciplinary interaction—and the education of the future workforce—can occur.

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