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Review

Wind energy research: State-of-the-art and future research directions

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ABSTRACT

This paper reports the findings from the *2016 Wind Energy Research Workshop* held in Lowell, MA. The workshop examined the state-of-the-art in wind energy research within the following three core topic areas: (A) Wind Turbine Design and Manufacturing including: blades, towers/foundations and nacelle, (B) Wind Farm Development including: offshore installations/siting, flow characterization and loads/waves/wind characterization, and (C) Wind Farm Operations including: controls, power production, wind farms, sensing, diagnostics, testing, structural health monitoring, reliability, energy storage, the grid and power transmission. Research challenges and future directions were discussed and are reported for each sub-topic area.

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List of abbreviations

ACMA	American Composites Manufacturers Association
AC	Alternating Current
AEP	Annual Energy Production
AMO	Advanced Manufacturing Office
ANSI	American National Standards Institute
API	American Petroleum Institute
AWEA	American Wind Energy Association
BAAM	Big Area Additive Manufacturing
BOEM	Bureau of Ocean and Energy Management
BRC	Blade Reliability Collaborative
BSH	German Federal Maritime and Hydrography Agency
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CMS	Condition monitoring systems
CNC	Computer Numerical Control
CREW	Continuous Reliability Enhancement for Wind
DC	Direct Current
DD-RANS	Data-driven Reynolds-averaged Navier—Stokes model
DONG	Danish Oil and Natural Gas (DONG) Energy
DNS	Direct Numerical Simulation (of Navier-Stokes Equations)
FLORIS	FLOw Redirection and Induction in Steady state
GIS	Geographic Information System
GRC	Gearbox Reliability Collaborative
ICC	Initial Capital Cost
IEC	International Electrotechnical Commission
IPC	Individual Pitch Control
IWES	Institute for Wind Energy and Energy System
LCOE	Levelized Cost of Energy
LES	Large Eddy Simulation (for simulation of the Navier-Stokes Equations)
Lidar	Light detection and ranging
LC	Levelized Replacement Cost
MCEC	Massachusetts Clean Energy Center
MCP	Measurement-Correlation-Prediction
MEDIN	Marine Environmental Data and Information Network
NREL	National Renewable Energy Laboratory
NWTC	National Wind Technology Testing Center
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
OTJ	On-the-job
RANS	Reynolds Averaged Navier-Stokes Equation
ROMs	Reduced Order Models
SHM	Structural Health Monitoring
SME	Small and Medium Enterprise
SNL	Sandia National Laboratories
SOWFA	Simulator for Wind Farm Applications
SWAN	Simulating Waves Nearshore
SWiFT	Scaled Wind Farm Technology
U·S. DOE	United States Department of Energy
WTTC	Wind Technology Testing Center
WRF	Weather Research and Forecasting

1. Introduction

Wind energy is one of the fastest growing sources of new electricity generation capacity in the United States of America [1]. As wind energy continues to grow towards the U.S. goal of achieving 20% electricity generation from wind energy by 2030 [2], new challenges and opportunities have arisen due to: the growing competitiveness of the industry [3], the intermittency of wind energy production [4–6], operations and maintenance [7–9] as well as power distribution and grid integration related considerations [10–12]. These challenges are being addressed in part by more advanced design and control [13,14], deployment, and condition monitoring [15,16] in addition to more robust power electronics [17], grid transmission and advanced energy storage infrastructure [18–21]. More specifically, these topics include research into larger wind turbines [22,23], improvement of wind farm layout [24], examination of offshore wind installations [25], improved wind/wave load predictions [26], novel approaches to wind turbine and wind farm control [13,14,27,28], as well as improved sensing and monitoring of wind turbines [15,16]. Ultimately, these efforts are directed at improving wind energy responsiveness and applicability in the modern energy landscape.

This paper presents the findings of a two-day Wind Energy Research Workshop held in Lowell, Massachusetts on 15th-16th March 2016. The goal of the workshop was to bring together a diverse audience comprising academic, industry and government stakeholders to summarize current state of the art, understand current trends and define the future directions and opportunities in wind energy research. Experts, practitioners and participants were invited from around the world and across the United States of America to present and discuss their perspective of the future of wind energy research in a series of panel sessions as well as user contributed talks and posters. The key findings of this workshop are presented here along with several promising proposed research directions. Suggestions were also made for improving sharing, dissemination and collaboration amongst wind practitioners, specifically from academia to industry and vice versa.

The workshop was designed to spur conversation in three core topic areas. Each of these areas was sub-divided into three more specific topical areas that were discussed in panel sessions. The topics have broad relevance to academic, industry and government research:

- **Topic Area A: Wind Turbine Design and Manufacturing**

  o Section 1: Blades: Manufacturing, Composites, Materials and Modeling
  o Section 2: Towers and Foundations
  o Section 3: Nacelle: Gearbox, Rotors and Generators

- **Topic Area B: Wind Farm Development**

  o Section 1: Offshore Installations and Siting
  o Section 2: Flow Characterization
  o Section 3: Characterization of Loads, Waves and Wind

- **Topic Area C: Wind Farm Operations**

  o Section 1: Controls, Power Production and Wind Farms
  o Section 2: Structural Health Monitoring (SHM), Sensing, Diagnostics, Testing and Reliability
  o Section 3: Energy Storage, Grid and Transmission

Summaries of the sub-topic areas are presented in the sections that follow. This paper summarizes the panelist presentations, the ensuing panel discussions and the discussions throughout the workshop.

2. Topic A1: Wind Turbine Blades: Design, Manufacturing, and Testing (Lead: C.J. Hansen, Panelists included: R. Barnhart, *Wetzel Engineering*; S. Johnson *General Electric*; D. Miller *Montana State University;* and A. Schoenberg *CERL-MCA*)

Modern utility-scale wind turbine blades are fabricated from composite materials molded into an aerodynamic shape designed to generate aerodynamic lift (i.e., mechanical power) that is subsequently transformed by a generator into electricity. Half of the levelized cost of energy (LCOE) for wind energy is associated with turbines, and wind turbine blades represent 25% of this cost [29]. Over the past decades, installed rotor diameters have grown to increase energy capture and reduce LCOE. This underlying trend required innovative approaches to turbine blade designs, the materials used to fabricate blades, and blade manufacturing schemes. This section discusses the state-of-the-art and future directions in four focal areas critical to wind turbine blades: blade designs, manufacturing of blades, materials development and testing for blades, and workforce development strategies for the turbine blade industry.

2.1. State-of-the-art

Design of wind turbine blades is driven by the conflicting demands of structural capability (i.e., thicker airfoils) and aerodynamic efficiency (i.e., thinner airfoils). These competing demands manifest as four primary aims typical within turbine designs to optimize the aerodynamic blade shape for an improved power coefficient, to increase the length of the turbine blades for increased swept rotor area and associated energy capture, to design the blade for manufacturing, and to increase field reliability. Typically, computationally predicted airfoil designs are provided to structural engineers, who establish structural designs that dictate the composite laminate ply lay-up scheme and structural features. The drive toward longer blades has resulted in higher structural loads, which in turn result in more slender blade designs to reduce blade loads and materials usage. Maximum deflections to avoid striking the tower and modal analysis to avoid natural frequencies have now become dominating constraints. Models must prescribe reasonable manufacturing approaches and tolerances, particularly for bond gaps within the trailing edge or between the shear web and skins. Overall, the designer must recognize the need for system-rather than subcomponent-level optimization that requires iterative design cycles and input from the manufacturer.

Materials and component testing data is key to the longstanding challenge of increased confidence that designs will translate into robust manufactured turbine blades. As materials comprise up to 50% of the cost of a manufactured turbine blade [30], new materials and materials characterization offer scope for meaningful cost reductions. Turbine blades are fabricated from fiber-reinforced polymer composites, which offer advantageous specific modulus and stiffness values. However, composites possess complex failure modes with statistical failure distributions that necessitate significant characterization efforts. Since 1989 Sandia National Lab and Montana State University have partnered to test and report on fiber-reinforced composite materials used in wind turbine blades. This publicly available database contains over 16,000 tests on 500 materials and includes both static and fatigue data [31]. Laminates tested include unidirectional, ±45°, and multi-directional configurations. Neat resins, adhesives, lap shear, ply drops, and environmental effects have been characterized as well. A significant effort in recent years has focused on the effect of defects in manufactured materials [32,33]. Wind turbine blade manufacturers cannot afford the degree of quality control associated with aerospace composites fabrication and so are susceptible to defects that significantly impact structural performance. Examples of defects include in-plane and out-of-plane waviness and wrinkles [34], dry spots, and porosity [35]. Characterization efforts have produced materials databases, factors of safety, and design rules that are fed into structural models. Blade certification presently requires a full-scale turbine blade to be tested in static and in fatigue loading per each new design [36]. The significant cost (~$1 M) and time (~3 months per fatigue test, with a 6 month lead time to begin testing) hinders the deployment of new blade designs and leads to risk-averse, incremental design modifications.

The translation of these recent designs and materials into fabricated blades increasingly challenges composites manufacturers. Average rotor diameters in U.S. onshore installations have increased by 36%–99.4 m in the decade to 2014 [37], and blades lengths and masses of 55–60 m and 14–17 metric tons are now common [38]. Global off-shore wind installations rotor diameters averaged 115 m in 2014 and are projected to increase to 153 m by 2020 [39]. The mass of the blade grows nonlinearly with their length [40], yet more concerning are costs that increase at a yet steeper rate (Fig. 1); a typical on-shore, 60 m blade weighs approximately 20 metric tons and costs ~$150–250 K, depending on the manufacturer. The industry cannot afford aerospace grade tooling, imposing a formidable challenge to consistently achieve millimeter-level accuracies over distances of greater than 50 m. State-of-the-art blades increasingly incorporate aerodynamic enhancement features, including plasma actuator control of vortex shedding [41], trailing-edge serrations [42], and other noise mitigation techniques [43]. Though schemes for automated manufacture have been described or demonstrated, prohibitive costs restrict automation primarily to ply cutting and in drilling of the root section. Hence, blade manufacturing remains labor-intensive and labor costs contribute 30% to the cost of a blade. The already physically demanding work of material placement, environmental exposure and interaction with large-scale structures will be exacerbated as heavier and lengthier blades require more lifting, walking, grinding, and inspection from the workforce.

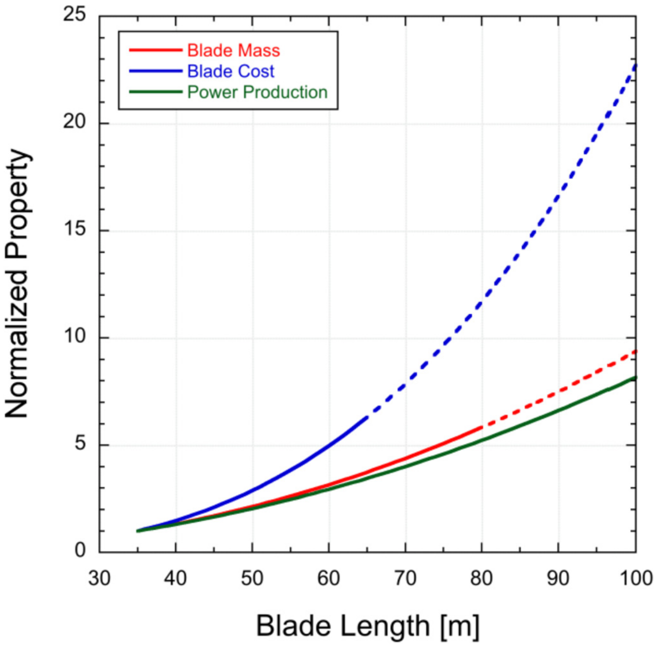

Fig. 1. Wind turbine blade mass, cost, and turbine power production as a function of blade length. Current trends in data (solid lines) are extrapolated (dotted lines) to blade lengths envisioned for projects in the next five years.

An estimated 73,000 full-time workers are employed by the U.S. wind industry [37], and over 200 workforce training schemes have developed to meet industry needs [44]. Manufacturing plant operations staff can be grouped into operators, shift supervisors, and engineers or managers. Operators benefit from certificates or similar credit or non-credit bearing formal training that teach key knowledge of composites' chemical safety and impacts of material composition and reinforcement orientation. Credited programs include the American composites manufacturers association's (ACMA) “Certified Composites Technician” program [45] in resin molding and in wind blade repair, and associates programs in wind energy offered by community colleges. Supervisors benefit from increased training in statistical process control, metrology, and composites, training which is acquired at the advanced associates level or at universities. Engineers and managers require skills in engineering problem solving, design of experiments, and lean manufacturing protocols; these details are available at the university-level, but are not always included in undergraduate engineering curricula. The U.S. Department of Energy has conducted an in-depth manufacturers needs assessment [44] and frequently updates a catalogue of wind energy related education and training programs under the WINDExchange website [46].

2.2. *New achievements*

Several prominent research efforts are expanding capabilities in new designs and manufacturing approaches. Blade designs, such as the Segmented Ultralight Morphing Rotor [47], may reduce blade mass at large scales by folding in extreme weather, thereby enabling designs for lower loads and lighter mass. Design for transport has led Blade Dynamics, Gamesa, LM, and Enercon to develop modular blades that are more easily transported on roads, but which require continued research into joint design and lifetime. Modularity is also the basis for the U.S. Department of Energy Advanced Manufacturing Office (AMO) to additively manufacture wind turbine blade molds in an effort to create modular molds that are more rapidly replicated and which can be expanded and reused in the future [48]. The “Big Area Additive Manufacturing” (BAAM) printer at Oak Ridge National Lab is used to print mold segments, which are post-processed to obtain adequate surface finish. Fraunhofer IWES has recently commissioned a BladeMaker Demonstration Center. The demonstration of automation in manufacturing features a 6-axis gantry robot with a working envelope of 25 × 4.5 × 3 m capable of a series of automated tasks, including computer numerical control (CNC) milling for blade mold manufacture, handling of textile and sandwich preforms, and quality management [49].

2.3. *Future research directions*

The relentless drive toward lower LCOE will sustain long-standing trends in wind turbine blades: larger blades for increased energy capture manufactured at minimal cost. This trend will drive both incremental and radical innovations in the design, materials, and manufacture of these blades. The cross-cutting opportunity for systems-level optimization offers greatest scope for progress but will require unprecedented levels of sophistication and collaboration. An effective implementation of this optimization requires knowledge and data flow between blade designers, materials suppliers, blade manufacturers, turbine manufacturers and wind farm owner-operators to transition the iterative design process presently implemented at the design level to encompass the entire manufacturing chain. The dominance of vertically integrated wind energy companies is reinforced in part by their ability to transfer data between all levels of the manufacturing chain, from designers to the operating turbines in wind farms. These data transfer needs should be established at the outset of contracts, as data agreements for blades after field deployment have met with limited success.

Blade designers will require innovative approaches to meet the structural requirements of future blades while addressing the materials usage and manufacturing challenges of long blades. Segmented (or modular) blade designs [50] will continue to be a research focus requiring new studies into optimal joint designs and designs for robust dimensioning and alignment. In recent lighter blade designs, reduced materials usage in the skins defining the aerodynamic surface is now producing buckling-prone designs. Designers are incorporating data from field failures and increasingly request sensors to collect greater quantities of data. Failure modes of active design interest include shear web debonds, manufacturing flaws, resistance to lightning strikes, soiling of the aerodynamic surface, de-icing concerns, and general improvements to damage tolerance.

Blade designs will benefit from materials innovations in lowering the cost of materials systems and from materials and structural testing. Composites will continue to be chosen primarily on a “stiffness per dollar” basis. Researchers must therefore consider the potential cost impacts of innovative materials. Research into lowered energy input and cost of carbon fibers are of interest, but must be placed in the context of continued advances in lowered cost and property improvements of high-modulus S-glass reinforcements. Improved technical basis for safety factors associated with manufacturing defects offers scope to reduce blade overdesign; for instance, innovative material systems (e.g., RodPack technology [51]) and structural components (e.g., pultruded beams [52,53]) which result in improved quality and specific properties offer potential if they meet cost targets. Fatigue behavior of composites remains a challenge, with gaps in knowledge regarding effects of imperfections, porosity, residual stresses, crack initiation and damage evolution, and the associated safety factors all active research topics. End-of-life concerns regarding recyclability and disposal threaten the industry with future regulation, due to the sheer material volume associated with the tens of thousands of blades to be decommissioned in the coming decade. Thermoplastic matrix composites and recyclable thermosets (e.g., Recyclamine® by Connora Technologies [54]) are foundations upon which new innovations can grow [55]. Use of recycled carbon fiber as reinforcement [56] in future blades requires research into achieving reliable stiffness at competitive price points.

Manufacturers need to radically rethink the blade manufacturing process in order to address the unsustainable increase in cost per length of blade. Blade cost projections from evolutionary process changes are insufficient to meet future LCOE targets. Modularity offers a potential solution. Segmented blade designs result in shorter molds, benefiting both the manufacture and transportation of lengthy blades. Segmented molds, in which varying central mold lengths join separate root and tip molds, could amortize the cost of molds over a family of blades of increasing lengths. Segmented blades require in-field assembly, and yet more radical field-assembly designs require attention to the environmental impacts (e.g., hygrothermal, contamination) on mechanical or adhesive joints. Cost-effective automation offers scope to concurrently reduce labor costs per blade and to improve blade quality via defect count reduction. Finally, for defects that occur, a scientific basis is needed to decide whether a defect is cosmetic versus critical to structural performance. Though in-house manufacturer guidelines exist, ad hoc decisions are made regarding new defect types and whether the repair will be more damaging than the embedded defect.

Expansion in the coming decade of a skilled workforce must build on the wind-related workforce training programs developed in the past decade. These programs required concerted collaboration between industry and local educational institutions. Exemplary best practices approaches to develop industry-driven curricula, such as those of Composites Washington, should be adopted more widely. Constant renewal of curricula is necessary to account for new manufacturing techniques and to assist existing employees who need professional development. Community colleges and universities need to reconsider which topics are relegated to on-the-job (OTJ) training based on industry input; many small and medium enterprises (SMEs) lack the in-house expertise to offer statistics of materials, design of experiments, lean manufacturing protocols as OTJ training.

2.4. Summary

Wind turbine blades will continue to evolve in their design and manufacture due to the central role in influencing LCOE. An emphasis on data sharing and analytics, modular designs, cost-effective automation, and equipping the future workforce with composites-relevant skills will fuel continued growth of the wind energy industry and assist in competitive energy production in more challenging environments, such as locales with poor wind resources and off-shore sites.

3. Topic A2: Towers and Foundations (Lead: S. R. Arwade, Panelists included: K. Wei, *Northeastern University*; Z. Finucane, *Keystone*; S. Ozmutlu, *Vryhof Anchors*; A. Rodriguez, *Alstom;* and S. Hallowell, *Northeastern University*)

The towers and foundations that support the turbine are a critical part of the wind energy infrastructure and their design and maintenance present unique challenges to structural engineers. This is particularly true in the offshore environment where a combination of unpredictable wind and wave conditions combine with challenging construction conditions and difficult-to-characterize geotechnical conditions. In this session, which was focused on offshore systems, a cross section of academics, designers, and suppliers presented the state-of-the-art in offshore towers and foundations and thoughts on future challenges and opportunities. As the US embarks upon offshore wind development, the contributions to this session set the stage for future development and advancements.

3.1. State-of-the art

Nonlinear analysis of offshore structures and breaking wave analysis: Dr. Kai Wei and Spencer Hallowell presented work of research groups at the University of Massachusetts Amherst and Northeastern University related to the post-elastic assessment of structural performance in the offshore environment and the role of breaking waves in driving extreme structural loads [57–62]. Consideration of extreme events, such as hurricanes that can produce very high wind speeds and wave heights [63–65], prompts the development of methods for evaluating the performance of offshore wind structures after they have exceeded the elastic limit. In a case study of a jacket structure, Wei presented methods and results that show how environmental models can be converted to predictions of structural reliability, predictions that can inform risk-assessment of the offshore infrastructure. Using a case study of the Blyth wind farm in the UK, Hallowell showed a novel approach to identifying breaking wave events when only coarse data regarding the sea surface elevations and structural response are available, and also quantified the large uncertainties present in any assessment of breaking wave effects on offshore wind structures (Fig. 2).

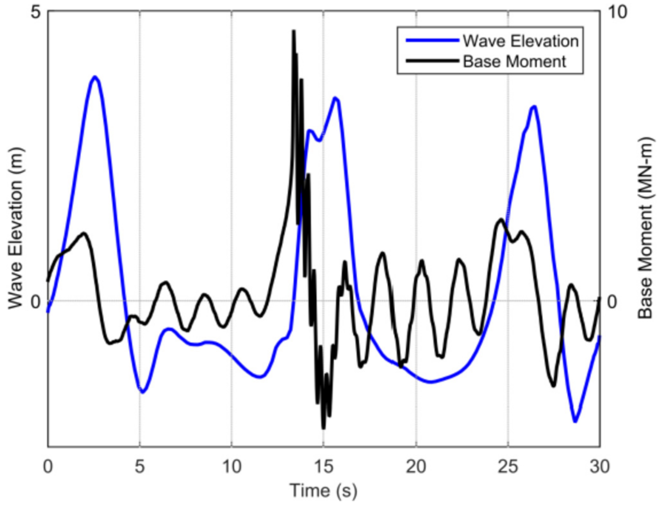

Fig. 2. Method for identifying breaking wave events from recordings of structural response. High frequency response in base moment of a monopile indicates slam load associated with breaking wave impact.

Fig. 3. Block Island Wind Farm support structures (image courtesy Z. Finucane, Keystone Engineering).

Fig. 4. Mooring and anchorage systems (Image courtesy S. Ozmutlu, Vryhof Anchors).

Design and installation of the support structures for the Block Island wind farm: Mr. Finucane, the Block Island project manager for Keystone Engineering, presented the jacket designs (Fig. 3) that were installed in the summer of 2015 for the Block Island wind farm [66]. These jacket designs build upon the expertise of the US in the design and construction of offshore oil and gas platforms and are designed specifically for the US east coast environment, including the use of robustness checks to assess the performance of the structures during hurricanes. Some important comments were offered regarding the challenges of inspection and the possibility of repowering or extending the life of support structures after the initial 20–25 year design life is exhausted. Discussion addressed challenges of expanding offshore wind development to scale in the US and although significant expertise exists already in the US a major bottleneck is likely to be installation vessels.

Anchoring and mooring systems for floating offshore wind turbines: Mr. Senol Ozmutlu of Vryhof Anchors presented current solutions for mooring floating platforms for offshore wind turbines. Floating solutions hold the promise of eventually providing the vast majority of offshore wind energy due to the mitigation of coastal impacts by the 'over-the-horizon' features of deeper water development. US west coast development will likely require floating solutions. A very wide variety of anchor types is available, each of which provides different capacities and requires different installation systems (Fig. 4). In order to make floating systems competitive for offshore wind, greater efficiency and more streamlined design processes are needed. Key issues in mooring and anchor design include redundancy, installation and retrieval.

Integrated design processes for wind turbine structures: Arturo Rodriguez Tsouroukdissian of GE Renewable Energy described an integrated design process in which the tower and foundation is treated as part of the integrated wind turbine system rather than as a separate system design in isolation to support the generating machine. Uncertainties in loading, materials, and design process play an important role in developing such an integrated design process since, with integration, those uncertainties must be propagated across domain boundaries (e.g. from aerodynamics to structural dynamics). Although each of the component analysis models is well developed there is a need for greater integration and coupling among the different subsystems and a key aspect is structural and foundation damping. Integrated life cycle management framework are also key for post-installation projects cost reduction and requires continuous and intensive data collection, which might bring a lot of value to the developers and utilities and must be integrated into future developments.

3.2. New achievements

This panel highlighted new achievements in the design, fabrication and installation of towers and foundations. Methods for assessing the performance of offshore structures subject to extreme loads and with behavior into the nonlinear range will allow more thorough, performance-based design approaches to be implemented. The Block Island Wind Farm, first offshore wind farm in the US, is now operational and has demonstrated the feasibility of constructing and operating an offshore wind farm in US waters. Selection of jacket support structures also highlights the need to integrate design, planning, and supply chain considerations. With the Hywind project currently being installed off the coast of Scotland, the advent of commercial-scale floating systems has arrived, and technologically advanced anchoring systems promise flexible and economical fabrication and installation. Finally advances in modeling capabilities is for the first time allowing the support structure to be treated integrally with the foundation and turbine in the modeling and design space, promising increased efficiency and reliability.

3.3. *Future research directions*

Several promising directions for future research were identified, including:

- Improved models for operational and extreme structural loads
- Dramatically better methods for considering soil-structure interaction and subsurface effects on structural performance
- Rationalized and streamlined design procedures for floating systems
- Increased construction and installation capability for offshore systems generally
- Risk-based framework for performance assessment of offshore wind structures
- Demonstration projects to prove numerical methods and environmental challenges.

3.4 Summary

The initiation of offshore wind construction in the US with the first commercial offshore wind USA farm, Block Island, RI project (30 MW–5 GE Haliade 150-6 MW) from Deepwater Wind, provides opportunities and illustrated challenges as the US moves to deploy offshore wind at scale. In the challenging offshore environment, with environmental and geotechnical conditions unique to the US, greater attention must be paid to load and geotechnical uncertainty, and continuous monitoring of coupled systems is needed to allow a truly integrated design paradigm to prevail.

4. Topic A3 – Nacelle: Gearboxes, Rotors and Generators (Lead: M. Inalpolat, Panelists included: P. Haberlein, *Pattern*; R. Schkoda, *Clemson University*; W. Qiao, *University of Nebraska-Lincoln;* and J. Signore, *General Electric*)

Although reported to be improving recently [67], the components and subsystems within the nacelle still cause the highest reliability and operability problems for a wind turbine in the field. Gearboxes cause the longest downtime per failure with significant levelized cost of energy (LCOE) increases [67,68]. Electrical systems and generator problems have the highest failure rate and the average downtime for a turbine in an operational year is reported to be ~170 h [67,68]. While wind turbine OEMs, industrial and governmental agencies, wind farm operators and academic institutions have been looking into ways to improve the reliability of the existing turbines, gradually increasing size and power generation rates make this a continuously moving target and a challenging effort. This section will discuss the main reliability and operability concerns, address the gaps in the current state of the practice and the technology and indicate future direction for improving the wind turbine nacelle-related components and subsystems. The main focus of the discussions will be on the gearboxes (being the most problematic) with some emphases on generators and rotors.

4.1. *State-of-the-art*

Wind power captured by the blades of a wind turbine is transmitted by the main shaft to the gearbox where it is speed-amplified. The mechanical energy transmitted by the gearbox usually has some speed/frequency fluctuations and thus it is first frequency-rectified by the electrical inverters and later converted into electrical energy by the generator. Wind loads are captured by the blades at very low rotational speeds (~10–20 rpm) and high torque levels (depends on the turbine power capacity). On the other hand, generators tend to like operating with lower mechanical input loads and constant (with some tolerance) and relatively high rotational speed equal to the electrical frequency (50 Hz/60 Hz depending on the country etc.) to be generated by the turbine. This requires a high capacity and efficiency kinematic chain, gearboxes, to meet the both end goals. Consequently, the highest mechanical loads observed in the nacelle are taken by the first planetary gear stage of the gearbox generating relatively frequent mechanical failures. Unsurprisingly, the bearings and gears in this stage along with the higher speed parallel axis gear stage have historically been the most problematic parts of the gearboxes and the nacelle [68].

Drivetrains and gearboxes have been reported to be one of the major root causes of failures that cause the longest wind turbine downtime [67–69]. In fact, the majority of wind turbine gearbox failures (76%) are caused by the bearings per the latest reports by U.S. DOE NREL (National Renewable Energy Laboratory). An average size wind turbine gearbox is cost prohibitive (~$500 K) and in some cases costs even more to maintain over the lifecycle. This factor increases the importance of maintenance and the clever designs that allow shorter period and cost friendly maintenance cycles for keeping the turbines running [70]. Recently, the most pronounced challenges regarding the wind turbine gearboxes have been planetary gear bearing axial cracks due to dynamic loads and torque reversals, the lack of monitoring capabilities with high signal-to-noise ratio sensing, and difficulties in applying the outcomes learned from the laboratory and unison test boxes on the wind turbines.

Axial cracks that form on the bearings of the high- and intermediate-speed stages are the leading cause for bearing failures and are the focus of a joint research effort by NREL and Argonne National Laboratory to identify the root causes and develop mitigation measures. The recent investigations indicate that unexpected transient loads and load reversals cause frequent rolling element bearing failures in wind turbines in the field [71–73]. Several institutions in collaboration with NREL have initiated detailed investigations. NREL's GRC is well-aligned with this research effort and has unique experimental capabilities including a large-scale gearbox test dynamometer. The information about the test article and the dynamometer used is given in the previous NREL reports [74,75]. Many researchers have also developed different scale and complexity analytical and computational models. Simplified lumped parameter and more advanced finite element based computational models were developed to model the dynamics of the test rigs and for benchmarking reasons [76–80]. The Ohio State University (GearLab), Technical University of Munich (FZG), Pennsylvania State University (GRI), NASA Glenn Research Center, Newcastle University, and Aachen University are some of the institutions with significant gear testing capability. More specific to wind turbines, Clemson University has a unique nacelle testing capability [81]. They have one 7.5 MW test facility readily available for testing the nacelle components by applying non-torque loads and measuring their effects on the mechanical as well as electrical systems. They also have a grid simulator to perform the tests on the electrical parts. University of Massachusetts Lowell, with its Center for Wind Energy Research, has the unique capabilities to perform the modeling and data processing for wind turbine drivetrain modeling [82,83].

The condition monitoring technologies specifically developed for wind turbine gearboxes have mostly been matured to an extent. There are multiple monitoring hardware and software developers including General Electric's (GE) Bently & Nevada [84], Siemens' Gram & Juhl [85], Bachmann Electronics [86], Bosch Rexroth [87], Wolfel [88] along with many others in this market. Their gearbox monitoring technologies mostly rely on accelerometer-based vibration and thermocouple-based oil temperature measurements. Magnetic particle filters are also used in many new turbine gearboxes to filter out small chips and metallic particles that is generated and down to ~5 μm in size [89].

However, it is challenging to implement the gearboxes with internal sensors because of the limited space and the harsh environment due to lubrication. This restricts some of the important components of the operations technology which are: (i) detection, (ii) accessibility, (iii) reparability, and (iv) reliability [70]. It also limits the achievable signal to noise ratios from the sensors used for the monitoring system. Development in feasible harsh environment sensing capabilities and high sensitivity measurement systems are clearly needed for further development of the wind turbine gearbox monitoring technologies.

Continuously increasing rotor sizes requires not only architectural changes and optimization of the drivetrain designs, but also requires better understanding and controls of the system loads. Moreover, delivering reduced LCOE values drives more accurate and tighter design margins. This can be achieved by better system level modeling approaches and laboratory tests where the lessons learned can actually be applied on the full-scale turbine gearboxes. One of the gaps in this area is the need to find ways to measure the real-time loads on the drivetrain due to misalignments, bending moments, temperature variations and torque fluctuations. This is extremely challenging to do on a full-scale turbine up-tower. Consequently, the common practice is to do laboratory and unison tests on the ground [90]. This has been reported to generate loads, vibration levels etc. different than what has been experienced up-tower [91]. Better quasi-static and dynamic loads of the drivetrains and laboratory tests with less uncertainties, realistic boundary conditions and loads would close the gap in the future allowing greatly improved products. Some of the more recent adaptations by the wind industry to solve some of the other reliability and design problems have been using case hardened gears and bearings with higher contact fatigue endurance levels to avoid surface initiated pitting and subsurface initiated micropitting and cracking. Integrated outer race planet bearings used for the planetary gear stages have also been reported to increase the useful life of the gearboxes [92]. Flexible planet pins significantly improving the planet to planet load sharing is also reported to be a good design implementation for wind turbine planetary gears [93]. The main shaft has not been reported to be as problematic and has limited to no growth space in the research and development side. However, as the rotor sizes grow different bearing arrangements, balancing requirements and their relation to rotor bows and cracking will still be of interest and a focus area for researchers.

Generators are the key subsystems for power generation and their size, configuration and capacity selection becomes critical in determining the power generation capability of a wind turbine (along with other component sizes-blades, gearboxes etc.). Different generator types and technologies are available with certain misunderstanding and disagreements on which one is the best for certain turbine types. The three generalized categories for wind turbine generators are (i) DC generators, (ii) AC Synchronous generators, and (iii) AC Asynchronous generators [94]. Doubly-fed induction generator is a type of AC asynchronous generators and dominates the medium to large size wind turbine market at the moment. Permanent magnet synchronous generators are a type of AC Synchronous generators and dominate the small scale wind turbine market. The trend in generator applications and selection is towards variable speed and brushless types with reduced cost, weight and failure frequencies. Generator selection is also critical for new generation ideas such as “Direct Drive” turbines, where the drivetrain does not have a gearbox and only consists of a multiple pole generator that rotates at low speeds. The coupling between the mechanical components and subsystems and the electrical components should be investigated closely to understand the influence of torque ripples and generator feedback on the drivetrain etc. this requires better electromechanical models of the drivetrain coupled with the electronic components (inverters etc.) and the generator. The torque ripples generated by the input torque coming through the blades and feedback from generators back to the gearbox components have been observed to cause failures [95]. This may be avoided up to an extent using torque limiting couplings. However, these coupling cannot filter the dynamic torque ripples unless above a certain preset large value. Better health monitoring for avoiding these failures is needed. Use of generator output voltage fused with the vibration signals obtained from the driveline should be studied for better health monitoring. Further research and developments are also needed on prognostics of the drivetrain components and the generators to enable better remaining useful life prediction and smart maintenance scheduling.

4.2. New achievements

There have been significant developments both in hardware and software related to the components and subsystems in the nacelle. Some of the developments that were highlighted during the 2016 Wind Energy Research Workshop included: i) integral planet gear bearings, ii) stiffened dual row tapered roller bearings for planet gears, iii) use of super-finishing for improved bearing/gear contact surfaces, iv) case hardened ring gears, v) use of cleaner steel for manufacturing, vi) improved on-line condition monitoring systems, vi) new system-level modeling and simulation tools, vii) hard bearing coatings, and viii) improved drivetrain torque dampers. The benefits of these new developments are summarized in this section.

Integral planet gear bearings are used mostly in the first planetary gear stage of the wind turbine gearboxes. The inner bore of the planet gear is used as the outer race for the bearing that supports this gear (see Fig. 5). The motivation for using this integral design comes from the need for higher power density, lower weight, better planet-to-planet load sharing, and reduced fretting on the bearing races. Moreover, reduced number of parts help increase overall system reliability. The use of new dual tapered roller bearings further increase system stiffness while keeping the planet branches relatively flexible in the tangential direction that improves the planet-to-planet load sharing. Tapered cylindrical rollers allow preloading of the bearing and thus the stiffness increases. The combination of these two new design features have been reported to significantly reduce planet gear rim deflections providing a life improvement of more than 150% [96–98].

The new heat treatment and coating options also improve the overall gearbox reliability. Instead of the conventional through-hardened gears, manufacturers now prefer case hardened (carburized) gears. This way, they obtain gears with harder outer surface with higher strength and resistance to contact fatigue, fretting and wear. At the same time, by only diffusing carbon into the outer surface of the steel help retain a substantially lesser hardness levels in the gear core. As a result, the core is protected from becoming brittle and retains a higher damping value in average. The use of cleaner, white-etching resistance steels with fewer impurities and hard coatings assist with the mission of increasing reliability of the gearbox. Recently, torque dampers have been developed to dissipate the torsional shock loads on the drivetrain components, including gearboxes and rotors [99]. Moreover, wind farm owner and operators have much better handle in real-time operational signature of drivetrain and generator with the improved on-line condition monitoring systems. These systems mostly monitor the gearbox (mostly using accelerometers and thermocouples), main shaft and generator bearings and main shaft (accelerometers) in real time and are helpful in converting unscheduled maintenance

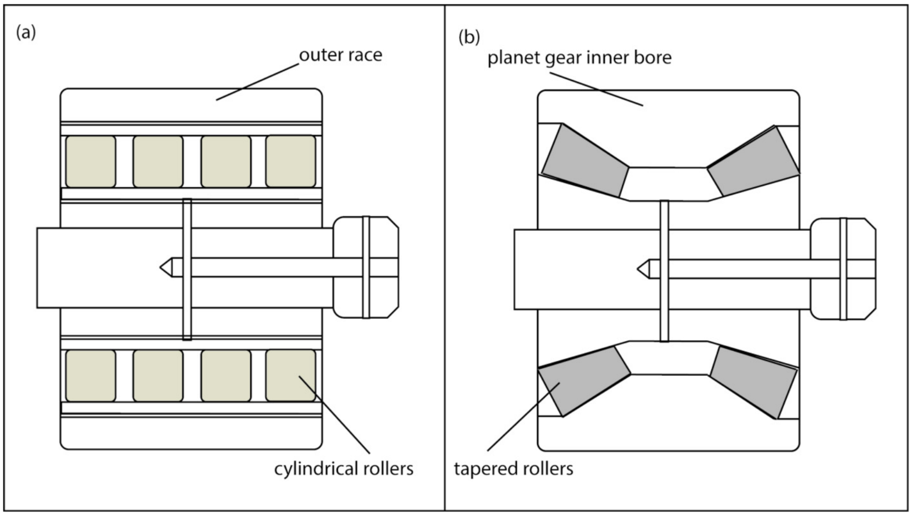

Fig. 5. The schematic description of (a) conventional four row cylindrical roller bearings, (b) new integral dual row tapered roller bearings.

into scheduled maintenance scenarios that are much less expensive. There have also been new developments in software and modeling. System level modeling tools allow design, analyze and optimize wind turbine nacelle components. These models range from materials based simulation tools to topology optimization tools [100–102] and immensely helpful in understanding system level fatigue life, dynamics and reliability.

5. Topic B1: Offshore Installations and Siting (Lead: D. Kuchma, Panelists included: T. Quiroz, *Fraunhofer IWES;* J. Borkland, *APEX;* and D. Degroot, *University of Massachusetts Amherst*)

The objectives of this session were to: (i) provide a broad introduction to regulations controlling the siting, installation and design of offshore wind turbine support structures; (ii) present an example of recently completed site characterization study; (iii) present challenges in the US environment, opportunities for improvement; and (iv) and describe the state-of-the-art in research on installations.

5.1. State-of-the-art (as presented by four panel members)

"Regulation Frameworks and Requirements" Dan Kuchma (Tufts University): There are a broad array of national and international regulations that control the siting, design, and installation of offshore wind turbine support structures [103]. They are developed and maintained by a number of organizations including the American Petroleum Institute (API) [104], the International Electrotechnical Commission (IEC) [105–107], the US Code of Federal Regulations (CFR), the American Wind Energy Association (AWEA) [108], the American National Standards Institute (ANSI), and others [109–112]. Most of these regulations are high-level documents that do not provide comprehensive rules and guidance, and many of them were originally written to serve the offshore oil and gas industry. Several organizations, including the Bureau of Ocean and Energy Management (BOEM), the National Renewable Energy Laboratory (NREL), and AWEA, produce guidelines and tools for working within this complex regulatory environment. The current state-of-the-art is much less mature than for other types of structures and foundations (i.e. bridges and buildings) for which there are comprehensive standards that have been developed by strong national technical communities and matured over many decades. A particularly challenging aspect of fulfilling regulatory requirements is that of site characterization. For this, BOEM is responsible for ensuring compliance of lease holders and developers with CFR Part 585 – Renewable Energy and Alternate Uses of Existing Facilities on the Outer Continental Shelf [113]. This includes the conduct of surveys to assess wind, waves, currents, marine habitats, as well as the physical characteristics of the seabed.

"Integrated Geotechnical Engineering Site Investigation Practice for Offshore Wind Farm Development" Don Degroot (UMass-Amherst): Significant information is needed on the properties of the seabed to properly select and design foundations, determine installation requirements, and predict the short and long-term performance of offshore wind turbine support structures [114]. Surveys are used to obtain necessary information on Stratigraphy (soil types, spatial distribution, slope stability), Initial State Variables (current and past geologic stress states), and Engineering Properties (strength, stiffness, cyclic behavior). This survey information is gathered using geophysical (acoustic methods) and geotechnical (borings and penetration) tests (see Fig. 6). Major challenges in conducting these surveys are the very large size of Wind Energy Areas (WEAs), the high variation in local conditions, and that these very expensive investigations need to be done with speculative monies (i.e. prior to a permit and in advance of power purchase agreements). To illustrate this point, consider that the UK Dogger Bank WEA is one third of the size of the state of Massachusetts, has extensive boulders that effect the location and installation of the foundations elements (monopiles and other anchors), and the cost of the site investigation was several tens of million pounds.

"Site Characterization and Installation" Jay Borkland (APEX Corporation): The CFR that governs site surveys are nearly identical to the requirements for the oil and gas industry. Factors that dictate the cost of this work include the required spacing and width of measurement lines; resolution, accuracy and types of required data; possible variation in soil properties; and how marine habitats need by protected. Since creating the final development plan is often multiyear process, this survey work usually needs to be done 2–4 times. Another challenge is that the data collected is often too coarse to ensure ease of installation, with the effect of expensive problems in the field; daily costs of installation vessels can exceed $1 M. European developers have gained substantial experience in conducting site investigations, but in a notably different regulatory environment than in the US. The ability to conduct more effective site surveys in the US will depend on the size of the pipeline of

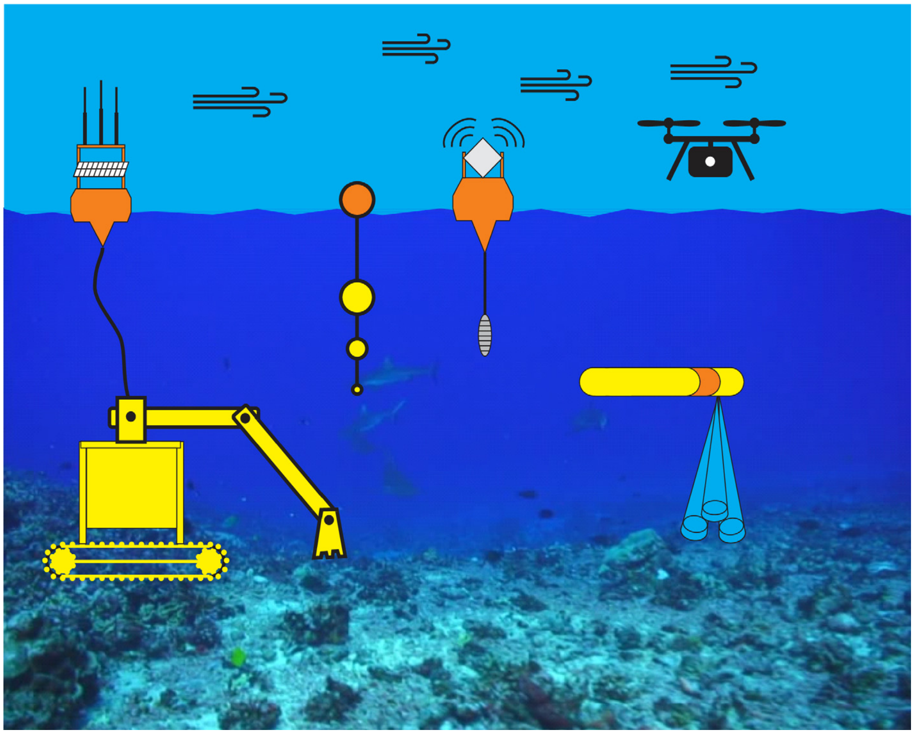

Fig. 6. Approaches used for offshore site characterization.

projects (controls value of developing new technologies), and the regulatory authority's interest in adopting and promoting the use of improved technologies, methods, and requirements.

"Improving Installation of Foundations for Offshore Wind Turbines by Realistic Testing" Tulio Quiroz López (Fraunhofer IWES): The Fraunhofer Institute for Wind Energy and Energy System (IWES) technology has 500 employees and has created several state-of-the-art research facilities for testing many of the components of an offshore wind energy system. This includes the support structures test facility located at the University of Hannover which has a large soil pit (14 m × 9 m x 10 m) onto which different foundation systems can be installed and loaded. This facility makes it possible to scientifically study different methods of installation (i.e. pounding, vibrating, pushing) and the effect of high-cyclic loadings on the changing stiffness and strength of support conditions for multiple types of foundation systems. The data collected from research in this facility is critically important to the selection, design, and installations of foundation systems, and to validate models used in the design, operation, and life-span assessment of offshore wind turbine support structures.

5.2. New achievements

There have been several recent developments that point to revolution changes in offshore siting and installations. One the promising new directions in siting is that some countries and regions are taking responsibility for conducting much of their own site characterization work (i.e. evaluating winds, currents, waves, habitats, ecosystems, and engineering properties of the seabed). For example, the Netherlands conducted detailed site characterization studies for the Borssele I-IV wind energy areas prior to going to tender. This yielded by far the lowest strike price bid for wind energy of its time in 2016 of €72.7/MWh by Danish Oil and Natural Gas (DONG) Energy. The large reduction in cost is largely attributed to the de-risking of the project by the site characterization. The German Federal Maritime and Hydrography Agency (BSH), which is the regulator for German wind energy areas, has followed the lead of the Netherlands and is now conducting their own site characterization in advance of the bid process. The New York State Energy Research and Development Authority is also looking into directly funding the conduct of site characterization in their wind energy areas. In addition to driving down price, the other motivation for a country or region conducting the site characterization work is that the collected data can be used for advancing science and other wind development projects; in the traditional approach where the wind energy developer pays for the site characterization studies, the data is nearly all proprietary. Another recent achievement is that public/private initiatives have been maturing to provide data portals for public data; two examples of these are the UK's Marine Data Exchange [115] and the Marine Environmental Data and Information Network (MEDIN) [116].

Major advancements and changes are also underway in installations. While >95% of offshore wind energy foundations are monopiles, which are now up to 8 m in diameter and more than 80 m long, many other foundation solutions are being developed and deployed in both demonstration and commercial projects. The most significant of these are the use of "jackets", which is the type used in the Block Island Wind Farm (see Fig. 3). There are also a large number of foundation types in projects in various phases of development that do not require pounding piles into the seabed. These new developments include: (i) mono-suction buckets in Lake Eric; (ii) concrete gravity-base structures that are floated to site and ballasted to rest on the ocean bed, as being deployed by BAM-Nuttall in the Blyth field; (iii) floating spar buoys as used in Statoil's Hywind Scotland project; (iv) the VolturnUS floating concrete structures to be deployed off the coast of Maine in 2019; and (iv) the Articulated Wind Column by ODE, MEES & DORIS Engineering that is designed for water depths of 70–200 m. There are more than a dozen other foundation concepts that have been developed and/or deployed. Most of these concepts are expected to have less environmental impact, particularly in the area of noise effects on habitats. It is expected that the range of new foundation types will greatly affect the needed regulations, and the areas of needed scientific and engineering advancements, and of industrial developments.

5.3. *Future research directions*

Several directions for future research were identified. These include existing challenges as well as promising future research directions.

- Review gaps and inconsistencies in regulations, and the challenge and value of improving regulations
- Review the decision making process and identify opportunities for improvement and design iteration
- Update CFR 585 site characterization requirements to be offshore wind specific and flexible
- Study formats for all survey data, and develop data structures and digital archival formats
- Identify opportunities for making proprietary data public, including the development of GIS (geographic information system) based maps of existing and future WEAs (wind energy areas)
- Develop and/or improve material, component, and system testing standards
- Develop strategies for learning from installation and survey practices
- Investigate application of high resolution acoustic methods for determining boulders and other seabed features that are impediments to installing monopiles and other anchor systems
- Develop methods to enable geophysical studies to better inform geotechnical investigation
- Develop improved and more cost-effective methods for guarding against disturbing marine habitats
- Advancing laboratory testing techniques so to be able to conduct more fully realistic tests of soil-foundation interaction, installation methods, and the impact of multi-degree of freedom, complex, and high-cycle loading regimes
- Use of a next generation of measurement strategies in laboratory testing and field work so to develop, calibrate, and validate models that have predictable accuracy.
- Investigate the use, and further develop, the capabilities of Autonomous Vehicles (underwater, surface, and flying) for conducting multi-metric measurements
- Identify regulatory changes that would spur improvements in methods

The efforts of US federal organizations that support offshore wind should be better coordinated so that a system-level approach to site characterization, impact assessment, design, installation, operation, and analysis can be pursued. This system level approach should enable uncertainty analysis, model validation, and the assessment of benefits of innovations on first costs, operational costs, and lifespans.

5.4. *Summary*

Offshore installations and siting practices are challenged by the multitude of regulatory requirements, the deficiencies of many requirements, the size and complexity of the seabed, the expense and difficulty of making site investigations, and the deficiency of our scientific understanding of the short and long-term performance of the many different types of installations. None of this should be surprising since the heavy offshore industry is only about a decade old, and that the size and characteristics of the developments advance anything that mankind has previously done in such a complex environment and ecosystem. There are many opportunities to improve regulations and US practices, and this can be done providing that there is a pipeline of projects to warrant the effort, incentives to make improvements, and an adaptive regulatory environment.

6. Topic B2: Flow Characterization (Lead: R.J. Barthelmie, Panelists included: G. Qualley, *Pentalum*; S.C. Pryor, *Cornell U.*; J. Manwell, *University of Massachusetts Amherst;* and M. Wosnik, *University of New Hampshire*)

One of the great challenges in wind energy is characterizing flow because meaningful time and space scales cross many orders of magnitude. Natural and anthropogenic climate changes impact wind resources and operating conditions on decadal and smaller time scales [117]. Quantifying turbulence at sub-second time scales is important for fatigue loading [118]. In between these time scales, annual variability of wind resources, seasonal and diurnal variability and planning of maintenance and short term forecasting are examples of other timescales that are relevant for the operation and economics of wind farms.

6.1. *State-of-the-art*

The state of the art in flow characterization includes a large range of measurement techniques from remote sensing (satellite derived observations [119] and ground based light detection and ranging or lidar) for wind and turbulence [120] to direct techniques including turbine mounted condition monitoring [121]. Professor R.J. Barthelmie, Cornell University, discussed the importance of wind turbine wake losses to overall power production and loads in large wind farm and their dependence on meteorological conditions [122]. There is a need to advance wake modeling that requires field measurements for wake characterization. Lidars are excellent tools for quantifying wake characteristics but are challenging in terms of defining scanning strategies, developing processing protocols and managing large data volumes [123]. It is essential for funding to become available for these type of full-scale field measurements using lidar, which are expensive, but quantifying the details of wake characteristics and behavior in the atmosphere cannot be found by model simulations alone. Grant Qualley from Pentalum described the SpiDAR lidar which operates by direct detection. The SpiDar [124] has a vertical range between 30 and 200 m. The laser beam is directed in eight directions at an angle of 5° from the vertical and thus makes a density map of aerosols in the atmosphere from which it can detect the volume of maximum reflection and the speed and direction in which it is moving. The small cone angle is better suited to deriving wind speeds in complex terrain where velocity can change rapidly in small change of height. It has a temperature range of $-40\,^{\circ}\mathrm{C}$ to $60\,^{\circ}\mathrm{C}$ and an easy user interface and is low power so can be operated with a portable solar panel and backup batteries. It is well suited to power curve measurements. Professor J. Manwell from UMass Amherst focused on the need for offshore wind data to estimate potential energy production. Data are essential to the design process of offshore wind turbines and their support structures [125] so is critical for developing and evaluating design conditions. It is likely that turbines deployed offshore will continue to grow in size (height and rotor diameter) so extending observations and model to beyond the surface layer (lowest 100 m of the atmosphere) will continue to be an urgent research need. Beyond using tall towers with anemometers at multiple heights, lidar is the only realistic option. Lidar are much cheaper to build and operate than tall towers in deep waters and can quantify wind shear and turbulence profiles. Lidar can be operated from fixed or floating platforms.

Similarly, a range of models is required from fundamental fluid dynamics through wind farm operation and modeling of turbine responses. Professor S.C. Pryor gave a comprehensive account of how and why climate change might impact regional wind resources operating conditions [126]. Most current wind development areas are in mid-latitude storm tracks and so wind speeds are affected by the location of mid-latitude cyclone storm tracks, their frequency and intensity. These are driven by the intensity of the equator to pole temperature gradient the location of the storm tracks steered by the jet stream and the intensity of cyclones is impacted by momentum transport and the latent energy from water vapor. Global climate models can simulate these changes but downscaling to the regional level is required using either dynamical or probabilistic methods [127]. There is great potential for improved modeling future wind climates using new and advanced techniques such as the application of adaptive grid global model, finding optimal resolution for regional model applications and hybrid downscaling including statistical techniques such as machine learning.

In addition to the range of available numerical simulations (RANS, LES, DNS), full-scale and scaled wind farms Professor Martin Wosnik from the University of New Hampshire elaborated the role of wind tunnels of varying scales in modeling large wind farms. Over these multiple scales for testing, full scale measurements and SWiFT [128] have to manage varying conditions while large rotor scale facilities work in controlled conditions but cannot model the far downstream wake. For example, very large wind tunnel such as the one at New Hampshire [118] have controlled conditions and can evaluate wake evolution to 20 D downstream.

6.2. New achievements

As indicated, flow characterization is complex because of the order of scales that have to be resolved in both time and space for a very wide range of applications in wind energy (Fig. 7). The introduction of lidar suitable for measuring wind speeds to the required precision and accuracy has been the greatest achievement in measurement technology in recent years and new developments are continuing to expand the range of scales that can be measured (both larger and smaller than the first vertical lidars that measured over a similar range to sodar i.e. about 200 m in the vertical at a resolution of 10–20 m). In addition, a number of companies are working on introduction of lidars at reduced cost – these may have a reduced measurement range or be used for specific functions such as power curve measurements. For offshore, lidar have a big advantage in that, even if a specific platform is required, the foundations need not be as extensive as required for a very tall mast. Further, developments in floating and nacelle-mounted lidar may eliminate the need for fixed platforms altogether. The availability of lidar that can scan in detail over large volumes are starting to provide process-level detail of wind turbine wakes and their interactions. Nonetheless, most applications in wind energy are model-based. The increased availability of computing resources means that variability of wind resources can be characterized over long-scales and the drivers of this long-term variability can be understood and included in economic forecasts and risk assessment. Improvements in model including the development of large-eddy simulation models for smaller scales (<1 km) but developments in computing and modeling techniques are expanding the range and types of issues that can be tackled. Further work is needed to bridge the scales of modeling. Lastly, experiments in wind tunnels enable the conditions to be controlled to evaluate process-level responses. The development of new large-scale wind tunnel facilities is enabling high Reynolds number experiments that are more similar to atmospheric flows.

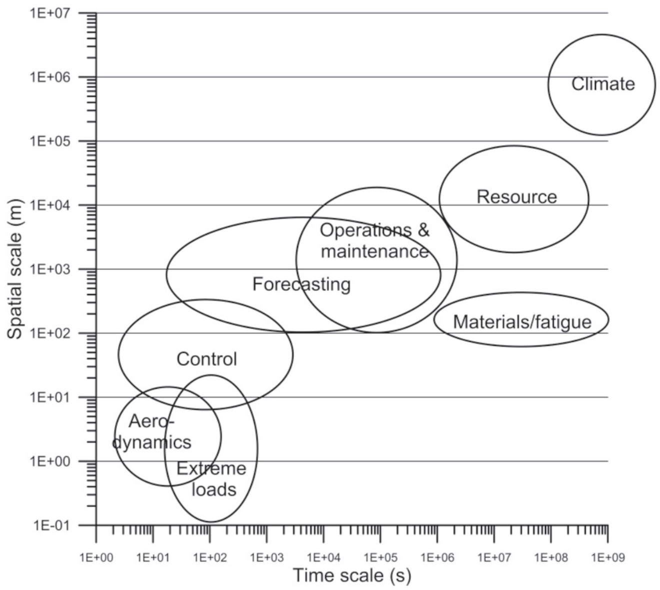

Fig. 7. Integration of wind energy systems crosses many orders of magnitude in both temporal and spatial scales.

6.3. Future research directions

In terms of future research funding the importance of interdisciplinary research is likely the most critical element. As elaborated above there is no individual model or experimental technique that can answer all questions regarding flow across so many temporal and spatial scales. In addition to modeling and measurements/experimental validation of wind farms and wind turbine wakes that extend to tip heights and across multiple scales beyond are required. New approaches are needed such as development of a continuum of finite models could be built into a platform that is truly elastic across spatial and temporal scales. More integration of numerical tools for full physics based engineering models for turbine-atmosphere interactions will start to produce more integrated simulations on both power and turbine loading that can then start to address realistic control strategies. More effort needs to be expended in quantifying assessment of variability on longer-time scales and potential changes in turbine operating conditions. Many industries already use limited modeling but the industry is not ready for more advanced models until better characterization of wind farms is available.

Lastly, beyond the critical element of research funding, some challenges that could be addressed include better sharing of resources and leveraging of existing data and closer ties between industry and academia. Last but not least we need to create a more inclusive environment to encourage more women and minorities to join the wind energy field.

7. Topic B3: Characterization of Loads, Waves and Wind (Lead: A. Myers, Panelists included: A. Kirincich, *WHOI*; L. Manuel, *University of Texas Austin*; A. Yamaguchi, *University of Tokyo*, D. Arora, *Alstom;* and Z. Finucane, *Keystone*)

Designing structures for the offshore environment is a fascinating example of a multi-hazard situation where hazards, such as wind speed and turbulence intensity, wave height and period, current and others contribute to structural loads. While all of these hazards can be generated by multiple sources, extreme values of these hazards often result from a common source, such as a hurricane or winter storm. This creates important correlations of the hazard in both space and in time. In this session, the focus was characterization of wind, wave and loads for offshore wind energy structures. Specific topics covered included (1) estimation of metocean conditions for offshore wind farms in regions exposed to loads from tropical cyclones, (2) the evolution of coupled loading from wind, wave and current during hurricanes, (3) the use of lidar to characterize wind speed shear and low-level jets and evaluate power performance for offshore sites, (4) remote sensing of spatially varying offshore winds using land-based radar, and (5) the loads analysis used for the design of the support structures for the US's first offshore wind farm off the coast of Block Island, Rhode Island.

7.1. State-of-the-art, (as presented by five panel members)

"Estimation of metocean conditions for offshore wind farms in tropical cyclone-prone regions" Atsushi Yamaguchi (University of Tokyo): The most widely used design standard, IEC 61400-3 [105], requires that the design of offshore wind turbines include loading from storm conditions, defined as the wind speed, wave height, and current with a 50-year recurrence period. The most common method for estimating these conditions is the Measurement-Correlation-Prediction (MCP) method with statistical extrapolation of measurements [129]. This method has been successfully applied to the design of many wind farms across Northern Europe, however, farms at these locations are not exposed to risk of tropical cyclones. As wind farms begin to be installed in locations exposed to tropical cyclone risk, there are many questions about how the MCP method compares with alternative approaches, such as Monte Carlo simulation of synthetic tropical cyclones [130], which are designed specifically to assess tropical cyclone conditions. The Monte Carlo approach is shown to be a useful tool for assessing condition in locations exposed to tropical cyclones. Wind speed can be modeled with the Monte Carlo approach using a standard pressure field model, combined with a tropical cyclone specific vertical wind profile model and site-specific local terrain modification based on CFD. Wave height can be modeled with the Monte Carlo approach with numerical models such as SWAN [131–133], but it's important to also consider the contribution of winds outside of the tropical cyclone wind field.

"The influence of offshore wind turbines of couple wind, waves, and currents during large-scale storms" Lance Manuel (University of Texas Austin): An "integrated" framework to assess design loads for wind turbine loads would combine loads with external conditions determined by a coupled physics model of the air and sea and their interface [134]. This is a complex engineering problem, but shows promise for refining future editions of design standard and load cases. One particular coupled model, developed at the University of Miami, [135,136], combines a hurricane atmospheric model (WRF) [137] with a wave model (UMWM) [138] and an ocean model (HYCOM) [139] with an interface model to couple and air-sea physical processes. This model has been applied to study the relative importance of swell versus wind seas for hydrodynamic loading, aerodynamic versus hydrodynamic loading including second-order wave kinematics, and the effect of yaw misalignment on loads for a monopile during Hurricane Ike and a jacket during Hurricane Sandy [140]. These applications of this coupled model have shown that realistic inputs are possible to assess coupled offshore conditions during hurricanes, but requires some scale bridging to achieve turbine-scale resolution [134].

"Wind profile characterization for offshore mid-Atlantic US" Dhiraj Arora (General Electric): Extensive measurements in the onshore environment have shown that winds in a stable atmospheric boundary layers have higher wind shear than winds in an unstable or neutral atmospheric boundary layer and that the stable atmospheric boundary conditions frequently result in low level jets [141]. In the offshore environment, similar measurements are scarce, but the limited existing data from Europe has suggested that a stable atmospheric boundary layer does not occur over the ocean. Recently, lidar measurements of wind for two offshore sites in the US (in the Atlantic Ocean near Virginia [142] and in Lake Michigan [143]) have shown that the winds were highly sheared, often showing characteristics of low level jets, unlike the European measurements which showed infrequent occurrence of low level jets. The presence of the low level jets at the two US sites can reduce power performance by 2–5%.

"High resolution remote observations of oceanic surface winds using HF radar" Anthony Kirincich (Woods Hole Oceanographic Institution): The efficiency of offshore wind installations can be increased with (1) better estimates of the spatially-distributed wind energy resource at various locations and (2) more accurate short-term forecasts of the spatially dependent wind field. A novel approach, based on an existing network of onshore high frequency radar sensors, has the potential to provide both of these improvements by empirically relating surface wind speeds with measurements of radar energy loss due to scatter caused by sea surface waves. For wind speeds between 2 and 6 m/s, the optimal range for the frequency of the radar, this method is shown to estimate spatially distributed wind fields with accuracy of ~1 m/s. This approach has potential to improve offshore site characterization, monitoring and forecasting.

"Block Island wind farm loads analysis" Zach Finucane (Keystone Engineering): The first utility-scale offshore wind farm in the United States is located off the coast of Block Island, Rhode Island [66]. The farm includes five 6 MW turbines, each supported by a four-legged 400t jacket and a 300t deck. This project is the first of its kind in many regards and required the clearing of several technical and practical obstacles. In particular, the loads analysis for these structures was based on the novel "Partially-Coupled" methodology. In this methodology, aero- and hydrodynamic loads are analyzed in GH Bladed [144]. The results of these analysis are combined with a detailed structural model of the jacket in SACS [145] to obtain rational estimates of combined aero- and hydrodynamic loads. The jacket and deck structures for this project were installed in Summer 2015 and the turbines and towers are expected to be installed in Summer 2016.

7.2. New achievements

The information in this panel highlighted several new achievements relevant to the offshore wind energy industry including (1) demonstration of comparable uncertainty in the estimation of extreme winds during tropical cyclones using Monte Carlo and MCP methods and demonstration of the importance of modeling wind conditions outside of the tropical cyclone wind field when estimating extreme wave heights, (2) showcasing of the potential of a coupled air-sea model in estimating loads on offshore wind energy structures, (3) evidence of the frequency of occurrence of low level jets for locations off the United States Atlantic coast and the negative impact of these jets on the power output of offshore wind turbines, (4) a description of a novel idea, which uses existing high frequency radar sensors to estimate wind field information and short-term forecasts that can increase the efficiency of offshore wind turbines, and (5) a summary of the novel loads analysis which was used to design the first utility-scale offshore wind farm in the United States.

7.3. Future research directions

- Develop consensus for considering tropical cyclone/hurricane conditions in the design of offshore wind turbines
- Advance coupled physical models of the air and sea to improve characterization of offshore environmental conditions during storms and estimation of structural loads during such conditions
- Understand the character of the vertical wind profile at offshore wind locations in the U.S. and use this understanding to better estimate wind farm performance and structural loads.
- Develop cheaper, more accurate and spatially-distributed methods for measuring the offshore wind resource and making short-term forecasts of the wind field
- Identify and investigate design approaches and software tools for rationally estimating coupled aero- and hydrodynamic loads on offshore structures

7.4. Summary

Offshore structures, such as those supporting offshore wind turbines, require the accurate estimation of environmental offshore conditions during extreme events such as hurricanes and during operational conditions. Such estimates should ideally consider both measurements and models of the environment. If offshore structures are to be designed optimally, the environmental conditions must then, in turn, be linked to accurate estimates of structural loads and power performance. This session considered several innovations with potential to improve environmental modeling, structural loads modeling, environmental measurements and structural design.

8. Topic C1: Controls, Power Production and Wind Farms (Lead: M. Rotea, Panelists included: J.W. van Wingerden, *TU Delft*; A. Wright, *NREL;* and F. D'Amato, *General Electric Global Research*)

Wind turbine and wind farm control schemes play a significant role in lowering the levelized cost of energy (LCOE) and increasing the installed wind energy capacity. The market has created several areas where controls have or are expected to have a strong influence: increasing power capture, reliability and grid responsiveness, lowering the LCOE, and accelerating the turbine and farm design cycles.

8.1. State-of-the-art

Successful wind turbine and wind farm control systems require effective implementation of sensors, algorithms and actuators. Current single turbine control algorithms [146–149] yield a wide range of results under different conditions. Collective blade pitch actuation has been studied extensively, however current research suggests that individual pitch control (IPC [150,151]) and advanced control surfaces [13] may have some advantages. In regards to wind farm control algorithms [27,152,153], efforts are being made to develop and unify control algorithms in a systematic multivariable framework. However there still exist open fundamental questions concerning the most desirable wind farm control mechanisms as well as control system architectures and algorithms. Axial based control mechanisms, such as adjusting the rotor speed [154] or blade pitch angle [155] have received more attention from researchers. Yaw based wake steering [156] appears to offer another viable alternative in regards to farm-scale production maximization and steady/unsteady blade load reduction.

Several models are being developed to study axial and yaw based control approaches. SOWFA (Simulator for Wind Farm Applications [27]) is a high fidelity, multi-scale dynamic model under development by NREL that is attempting to unify farm-scale control schemes with farm-scale dynamic simulation in mesoscale atmospheric boundary layers. Currently, line actuator models and lookup tables are used to characterize the turbine blades. Yaw based optimization has been performed with encouraging results. UTD-WF [157] is another high fidelity Large Eddy Simulation package to predict power in wind farms and loads in the turbines. This code uses actuator line models or actuator disk model to compute forces and it incorporates an immersed boundary method to model turbine details and topography. These high fidelity simulation tools typically aim to capture larger scale wake turbulence evolution and dissipation while using lower fidelity models to represent the impact of the turbine blades on the flow. Lower fidelity models are commonly used to represent the turbine due to the large disparity in turbulence scales observed in the turbine blade boundary layer versus the overall wind turbine wake. On the other end of the fidelity spectrum, farm-scale ROMs (Reduced Order Models) are also in use and under development. These lower fidelity models are popular due to their rapid estimation of the turbine performance and wake evolution. To gain the benefit of computational efficiency, these models do not simulate the detailed flow around the turbine or the wake and often rely on integral conservation of mass, momentum and/or energy expressions. The models typically require some parameter tuning or some dimensional reduction from higher fidelity computational simulations or experiments. The FLORIS (FLOw Redirection and Induction in Steady state [152]) model employs enhanced versions of classical analytic formulations with site specific tuning parameters, wake deflection models and wake deficit blending schemes. A dynamic extension is also being developed (FLORDyn [153]) that uses a time lag approximation to convect wake parameters downstream. DD-RANS [158] is a data-driven Reynolds-averaged Navier–Stokes model for estimation of wake effects and power production. These models are sufficiently fast to perform optimization and control studies and retain accuracy through careful reduction of the model physics and/or data assimilation. Finally, methods using differential deficit control volume analysis are being examined to decrease solution time while retaining fast simulation times [159]. Overall, despite the reduced fidelity, reduced order computational models are still powerful tools for modeling and optimizing windfarm power output.

Low cost sensors and actuators help lower the LCOE and contribute to a successful wind farm control scheme. Lidar technology has become an effective, relatively low cost solution for estimating large area wind fields. Lidar is a tool that can deliver real-time site information to a dynamic model and execute real-time dynamic optimization. However, the use of lidar for wind farm control is yet to be explored.

8.2. New achievements and future research directions

Many challenges exist in implementing advanced controls. Control algorithms are typically a *hidden* technology. The turbine manufacturer under the manufacturer's contract maintains the control software. This may represent an intellectual property hurdle for innovation in the control space. In addition, there are still fundamental questions concerning control strategies. These questions require experimental testing (wind tunnel, field experiments) to obtain answers that guide future development. Some studies have looked at load reduction, others have examined power optimization; however, the integration of the two is work in progress.

Advanced wind farm controls will require dynamic models, efficient solvers, and robust objective functions that can account for the uncertainty associated with the wind resource knowledge. At present there is nothing available to industry in terms of a reliable dynamic model that is capable of farm optimization. Future models may be physics based and data driven. Model-based control solutions need to be complemented with model-free approaches for wind farm control. A promising model-free approach requiring further investigation is extremum seeking control for wind farms [160,161]. This method has been field tested in a single experimental turbine with encouraging results; i.e., 12% and higher improvements were demonstrated in the energy capture of the NREL 600 kW experimental turbine known as the CART 3.

Integrated design is another significant area for future development. Controllers and turbine properties can be optimized in an aero-structural simulation environment. Rotor design methodology can be advanced by developing fast and robust models to aid in design optimization. This may lead to new control surface designs that employ IPC as well as individual blade surface control. Structural control is also envisioned as a means to allow for the larger turbines of the future [162].

New technologies must also be investigated. Several of potential new research areas were identified. A pumping system was discussed wherein a cluster of turbines may pump water to a single central generator, similar to Garcia-Gonzalez [151]. The potential of movable offshore turbine platforms was also discussed briefly. These platforms could be repositioned on-the-fly based on current wind knowledge and simulations. A similar concept was identified by Haier [163].

8.3. *Summary*

Numerical simulation, model reduction, and frameworks for control system design and analysis are seen as areas where government and academia have aligned interests and may be able to work together. Academic research works well when risks are high. Universities tend to have the resources to develop new algorithms. Government can bring ideas from academia to industry through field-testing, proof of concept studies, and equipment testing/monitoring. Common themes across the presentations and question session were that controls are driving the current generation of wind development and advanced controls can drive the next generation. The speakers highlighted research opportunities related to all three aspects of wind-farm control: sensing, algorithms and actuation. The potential exists for field testing new wind-farm control concepts in facilities such as the Scaled Wind Farm Technology (SWiFT) facility that possesses 3 fully instrumented wind turbines. This could lead to fruitful collaborations and assets leveraging between government, academia and industry.

9. Topic C2: SHM, Sensing, Diagnostics, Testing, Reliability (Lead: C. Niezrecki, Panelists included: S. Sheng, *NREL*; N. Post, *NREL*; L. Breuss, *Bachmann;* and J. Paquette, *Sandia*)

One of the most important metrics for wind turbine performance and successful implementation is the levelized cost of energy (LCOE). The LCOE is the net present value of the unit-cost of electricity over the lifetime of a generating asset and is typically considered as the average price that the generating asset must receive in a market to break even over its lifetime. The factors that structural health monitoring (SHM) systems and turbine component testing influence in the calculation of the LCOE include: the Initial Capital Cost (ICC), Levelized Replacement Cost (LRC), Operations and Maintenance Costs (O&M), and the Annual Energy Production (AEP). SHM systems and testing do add cost to a turbine thereby increasing the ICC, however as an example for blades, it has been estimated that blade SHM systems yield an $807/year/turbine cost benefit over the same turbine with no blade SHM system [164]. SHM systems and testing increase performance, reliability, and turbine availability, which positively affect the LRC, O&M, and the AEP. Advancements in SHM and testing systems will enable new technologies that will reduce the time and cost required for unnecessary wind turbine down time, maintenance, and failures. An improvement in reliability will help to accelerate the deployment of U.S. and global based wind energy by lowering the LCOE.

9.1. *State-of-the-art*

Condition monitoring systems (CMS) are typically used for monitoring rotating machinery including the drivetrain components (e.g. main bearing, gearbox) and the generator [165–169]. The most common approach uses accelerometers to measure vibration along with temperature sensors for transformer and generator monitoring. Gearbox oil CMS focuses primarily on measuring the particle contamination in the lubricant fluid and is not widespread in the industry. Borescopes are used by some to perform visual inspections internally of gearboxes and also some blades. One of the primary challenges that exists with respect to CMS systems is the large number of components involved with complicated and multiple failure modes. Approximately 76% of gear box failures are due to bearings and about 17% of failures are due to gears. A large issue is white etching cracks, which is a dominant failure mechanism for almost all bearings. Several root cause hypotheses have been developed, but none have been completely verified.

For blades the primary downtime issues include: rotor imbalance, trailing edge disbonds, leading edge cracks and erosion, edgewise vibration, lightning, and icing (see Fig. 8). Manufacturing induced defects (in- and out-of-plane laminate waves), typically in the spar cap can lead to stress amplifications that cause cracks and premature failure. Icing is an issue that impacts performance and reliability and current algorithms to detect icing sometimes shut turbines down leading to loss of energy production.

Lightning strikes are an issue in the USA primarily in the region between Texas to Manitoba and approximately one lightning strike occurs per turbine per year. In North America Vaisala [172] can identify the location where lightning strikes have occurred. In other areas it would be beneficial to put in an equivalent system to track lightning strikes. A diverter strip usually only works once because a lightning strike will usually decouple the strip from the structure. Unfortunately, the responsibility is put on the owners by the OEMs to demonstrate that the lightning protection system did not work if installed and the OEM will typically claim extenuating circumstances to devoid warranties. Lightning strikes are somewhat random, sometimes hitting the leading or trailing edge and leading to the puck at the tip of the blade. There can be extenuating circumstances make it difficult to assess that the lightning protection systems work. For example, water or hydraulic system leaks tend to

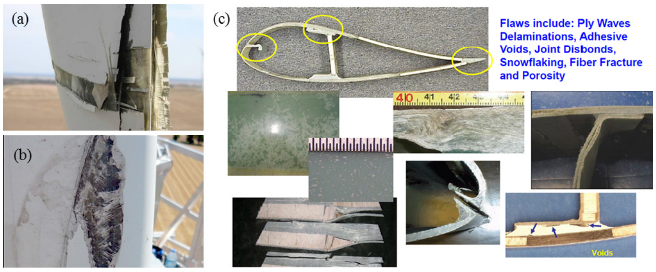

Fig. 8. (a) Trailing edge blade damage [170]; (b) leading edge blade damage; (c) various blade inspection areas and common flaw types of interest [171].

flow to the tip of the blade causing degradation of the electrical protection. The lightning systems seem to work but the significant problem is catching the damage and effecting repairs in a timely manner before the damage grows. Although lightning damage doesn't always result in a blade being removed from service, it usually will lead to eventual blade failure.

SHM systems have advanced over the last two decades and some of the related background can be found in Refs. [173–176]. SHM for wind turbines typically includes the blades, tower, and foundation. The traditional sensing approaches (e.g. strain-gage networks, acoustic emission sensors, fiber optic cables, ultrasonic, laser-Doppler sensing, and piezoelectric transducers) heavily depend on contact-type measurement sensor arrays that are either difficult to instrument, challenging to maintain, unreliable, costly, ineffective in identifying and localizing distributed damage, or are impractical to be implemented in service. For example, accelerometers are generally used for detection of icing on blades but not for damage detection. Likewise, past research has demonstrated conclusively that modal frequencies [177,178] and mode shapes [179] are by themselves poor indicators of damage. Significant changes in experimental mode shapes and natural frequencies exist only in the presence of very severe damage. Most commercially available SHM systems rely on sensing vibration (e.g. accelerometers) or strain. For blades, there are very few commercially available monitoring systems and they are generally only used to monitor for ice accretion by observing changes to the blades resonant frequency. A laser based position sensitive system is commercially available by Bachmann that can measure blade deflection in the flap-wise direction. As the blade ages, the stiffness is reduced which leads to an increased blade deflection for a given amount of power. The increased deflection due to decreased stiffness can be used to help predict remaining life. Another approach to measure blade damage includes using the blade cavity acoustics via active and passive measurement techniques [180]. A ground-based microphone was able to measure the acoustic Doppler shifts of a rotating turbine in which external acoustic pressure fluctuations were a direct result of blade damage and infrared cameras have been used to detect thermoelastic and frictional heating from damaged blade material due to cyclic loads [181]. Thermal imaging is starting to be done during operation to identify leading and trailing edge splits. Thermography is used to detect localized damage in blades by using a heat source and observing damage. These blades are inspected on the ground. Tower vibration monitoring systems are also being used track tower motion and perform rainflow fatigue analysis.

To assist in improving turbine reliability and performance several testing facilities exist. The Wind Technology Testing Center (WTTC) in Charlestown, MA and the National Wind Technology Testing Center (NWTC) in Boulder, CO have the capability to test and certify utility-scale blades and are operated by the Massachusetts Clean Energy Center and NREL respectively (see Fig. 9). There are also other blade test facilities at the University of Maine and Clarkson University. These facilities measure dynamic loads for model verification, perform nondestructive evaluation and accelerated structural testing, as well as blade certification. Testing is typically performed in a single axis (flapwise or edgewise) or bi-axis configurations by exciting the first flap or first lead-lag mode shape using a moving mass (shaker) on the blade or a hydraulic actuator. During a test the mode shape (bending moment distribution) is adjusted by adding masses as required. The torsion strain measurement needs to be accounted for when considering the bending moments and forces on the blade, and should be applied to models and fatigue testing. Significant errors occur when not accounting for cross-sensitivity using strain gages to make bending moment measurements on wind turbine blades.

Fig. 9. (a) SWIFT Facility, Lubbock, TX [170]; (b) Flap fatigue test at Wind Technology Testing Center, Boston, MA-NREL from NREL Image Gallery #34756; (c) Inertial mass flap fatigue test at National Wind Technology Center, Boulder, CO, from NREL Image Gallery #16269 [182].

Sandia National Laboratories (SNL) runs the Scaled Wind Farm Technology (SWiFT) facility that possesses 3 instrumented wind turbines that are being used to help understand turbine wakes (see Fig. 9). With a suite of mechanical, aerodynamic, and wake imaging sensors capable of making high-fidelity measurements, the facility will help model validation and verification data gathering. SNL also runs the Blade Reliability Collaborative (BRC) while NREL runs the Gearbox Reliability Collaborative (GRC) that help to resolve issues related to manufacturing, transportation, installation, and operation of blades and gearboxes that can have large effects on COE as failures can cause extensive down time and lead to expensive repairs. SNL also possesses a Wind Turbine Blade Test Specimen Library in which different researchers can quantify the performance of different inspection techniques on prepared samples. One objective is to generate industry-wide performance curves to quantify how well current inspection techniques are able to reliably find flaws in wind turbine blades. Montana State University possesses a Multi-Scale, Multi-Axis Test Facility to test subcomponents in a variety of test configurations (combined loading: flexural bending plus and torsion). The facility allows for characterizing materials as an intermediate step between coupon and full-scale testing. NREL's GRC investigates gearbox dynamic responses under different loading conditions through both dynamometer and field testing of utility-scale wind turbine gearboxes, along with modeling & analysis to identify possible gaps in gearbox design standards, compiling gearbox failure event statistics to catalog top failure components and modes, and condition monitoring to improve operations and maintenance of wind turbines with a focus on gearboxes. To characterize wind turbine and wind plant reliability performance issues and identify opportunities for improving reliability and availability performance within the wind industry, SNL also runs the Continuous Reliability Enhancement for Wind (CREW) Database and Analysis Program [183].

It is also important to mention that NREL and Clemson University can test multi-MW drivetrains and nacelles at the Dynamometer Test Facility at the NWTC and the SCE&G Energy Innovation Center in Charleston, SC, respectively. Additionally, both the NWTC and the Clemson facility allow for testing of wind turbine generators and have Hardware-In-the-Loop grid simulators allowing manufacturers to test both mechanical and electrical characteristics of their machines in a controlled and calibrated environment.

9.2. Future research directions and new achievements

There are several new technologies that have the potential to disrupt wind turbine monitoring and reliability. The first is a new inspection technique for blades that leverages infrared scans for blades. This approach scans a turbine while a blade is in operation during the night. The scans reveal the presence of defects and damage due to an increased heat radiation from the damaged area [184,185]. Another approach uses microphones to identify the presence of cracks and holes in blades either in a passive or active monitoring configuration [186,187]. Finally, the recent increase in performance and capability of unmanned aerial vehicles (drones) to perform inspection of a wind turbine or farm is currently revolutionizing how turbine inspection and monitoring is being performed. Several companies are actively involved in wind turbine drone inspection (e.g. Advanced Aerial Inspection Resources, AeroVision Canada, AirFusion, Availon, Brains4Drones, LLC, Cyberhawk, Deutsche Windtechnik, ECI, GeoDigital, HUVRData, InspecTools, Pro-Drones, Skeye B·V. SKYDRONE UAVs, Sky-Futures, SkySnap, Strat Aero, UpWind Solutions, Ventus Wind, WindSpect, and others) [188].

There is a need in both CMS and SHM to identify new techniques or technology to improve sensing. For SHM and inspection, distributed and large area sensing techniques are needed and currently fall short because of cost, implementation challenges, wiring, or data transmission issues. It is highly desirable for a small number of sensors to be able to interrogate what is happening throughout the structure. Current sensors largely do not provide details about the health or status of the blade. Normal blade inspection is primarily performed using ground-based telescopes, but drones are starting to be used. The software behind the drone and the experience of the interpretation of the operator or engineer is what adds value. The drone itself is not a significant cost. Drone inspection is in its infancy and presents numerous opportunities for future blade and tower inspections.

For blades, inspection techniques are needed that can identify and quantify flaws and damage that include: ply waves (in- and out-of-plane), delaminations, adhesive voids, joint disbonds, snowflaking, fiber fracture, and porosity. Ultrasonic inspection is effective, but can only scan a small area and it is time consuming and impractical to analyze a large blade. The structural integrity of a composite laminate repair or the effect of an embedded defect compared to an undamaged structure in wind blades is poorly understood. Water droplets and sand can impact leading edge erosion and there is no field evaluation of whether water or sand is more significant. The performance of leading edge protection systems are dependent on who applies them and their long-term effectiveness remains unclear. The meteorology and understanding of the icing problem is not well understood. A better understanding of the performance of a lightning protection system's effectiveness is needed along with a better assessment of what quantifies a lightning strike. The interpretation of the IEC standard is somewhat unclear. It remains unclear if moisture build up in the blade composite or within the blade cavity impact the blades. Some would argue that a breathing phenomenon that initiates the bond stresses leads to transverse cracks in blades, but this phenomenon is not well understood. A better understanding of how the resonant frequency on an installed blade or turbine changes over time when the blade is operating in normal use is needed.

There are no physical measures on the actual turbine blades in operation. A better set of distributed sensors is needed to understand the loads imparted on the blades while in operation. There appears to be a gap between the actual loads that are applied to the operating blade compared to the loads that are applied during design, modeling, and blade testing. The correlation between damage assessed in testing to the damage assessed in the field is unclear.

With regard to signal processing and monitoring, improvements in diagnostic decision making are needed. There needs to be more confidence and better interpretation of the data for damage detection (e.g. fatigue damage accumulation assessment), prediction, and prognosis for wind farm operators. Once condition based damage is identified during operation, maintenance needs to be made easier, streamlined, and automated.

9.3. Summary

SHM, CMS, and testing systems for wind turbines are continually advancing but numerous places for improvement exist. As improvements are made, so will come a more reliable and efficient turbine that is less expensive both to install and to operate. These advancements will help to drive down the LCOE and make wind energy systems more cost competitive and widespread.

10. Topic C3: Energy Storage, Grid, & Transmission (Lead: J. Hunter Mack, Panelists include: S. Blazewicz, *National Grid*; D. Alderton, *NEC Energy;* F. Brushett, *MIT*; and A. Sakti, *MIT*)

An increase in electricity from renewable resources presents a new set of technological challenges not previously faced by the grid. This includes the variability of renewable sources and the location of renewable resources far from population centers [189]. The variability of renewable resources, due to characteristic weather fluctuations, introduces uncertainty in generation output on the scale of seconds, hours and days [190]. Greater uncertainty and variability can be dealt with in a few ways: (1) by switching in fast-acting conventional reserves as needed on the basis of weather forecasts, (2) by installing large scale storage on the grid, and/or (3) by long distance transmission of renewable electricity enabling access to larger pools of resources in order to balance regional and local excesses or deficits.

10.1. State-of-the-art

Currently, a number of approaches are being proposed as possible energy storage solutions including pumped hydro, compressed air, batteries, thermal storage, and flywheels [191]. Each technology is able to address variances in the electricity supply caused by the intermittent nature of renewable energy sources (such as wind), though their efficacy is varied with respect to short-term and long-term storage. The most well developed approach is pumped hydro, where excess electricity is used to transport water to a higher elevation. When this electricity is required, the water is then run downhill and converted to back to electricity using a turbine or other mechanical conversion approaches. While this approach is inherently geographically limited, it still receives significant interest due to relatively high efficiencies and ease-of-use considerations [192].

Compressed air energy storage is currently in use commercially in a few different configurations [193]. The approach uses energy to compress air, either in large underground caverns or smaller distributed containers; the air is then used to power a turbine to generate electricity on demand [194]. Flywheels store energy by accelerating a rotor and maintaining the energy in the system as inertial energy [195]. One advantage of flywheels is a relatively fast response rate, which makes them quite suitable to peak-shaving applications.

Another proposed storage approach stores energy as chemical energy in the form of hydrogen, most likely generated via the electrolysis of water. The hydrogen can then be stored, blended with other fuel streams, or converted to electricity using a fuel cell or internal combustion engine. Hydrogen-based storage technologies have a great potential for long-term storage applications, but the main challenge to their adoption is related to economic uncertainty due to high system costs [196].

Several types of batteries are used for large-scale energy storage including lead-acid batteries, lithium-ion batteries, nickel–cadmium batteries, sodium–sulfur batteries, and flow batteries such as vanadium redox or zinc–bromine [197]. One of the problems with lithium-ion and sodium–sulfur batteries, which

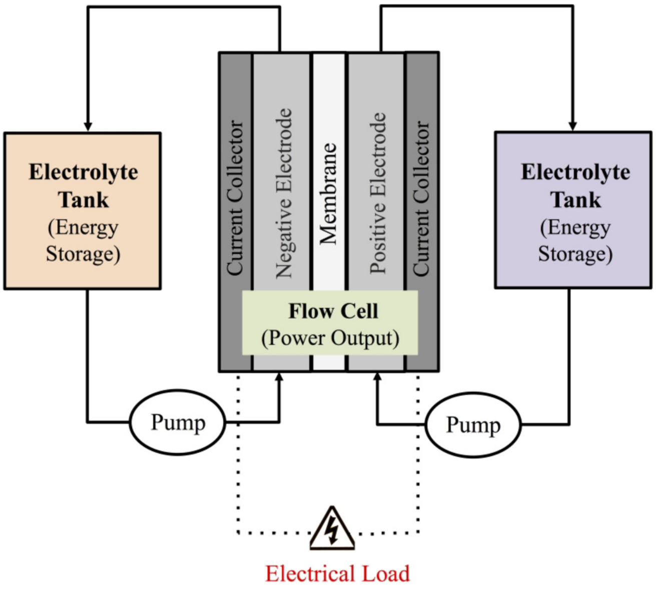

Fig. 10. Diagram of a redox flow battery for energy storage (courtesy: Ertan Agar).

can have high power and energy densities with high efficiencies, is that they have high production costs [190,198]. Redox flow batteries exhibit very high potential for several reasons, including power/energy independent sizing, high efficiency, room temperature operation, and extremely long charge/discharge cycle life [199,200]. An example of a redox flow battery is shown in Fig. 10.

In terms of transmission and the grid, much of the infrastructure is aging and unable to handle non-traditional generation sources and large-scale storage. Investment and clear policy guidelines are needed to support the continued evolution of how electricity is distributed reliably and at a low-cost to the consumer. Wind energy faces distinct siting challenges that other renewable sources such as solar do not, which adds to the complexity of transmission infrastructure.

10.2. New achievements

A significant amount of progress has been made towards increasing efficiencies and lowering costs of the various approaches to energy storage highlighted above. The continued development of advanced materials, including graphene-based materials, zeolites, aluminophosphates, and metal-organic frameworks promises to push the boundary of these technologies [201,202]. Since the widespread adoption of energy storage not only relies on technological advances, but also systems-level analysis and validation [203]. Therefore, progress in the techno-economic analysis of deployments, based on both early-stage and demonstration projects, has helped quantify and elucidate the benefits of energy storage. Furthermore, an increased interest in micro-grid and smart grid applications, has shown promise in limited applications with the potential to positively affect the current approach to transmission [204].

10.3. Future research directions

The continued expansion of energy storage within the grid relies heavily on advancing the current portfolio of proposed solutions and identifying new approaches, all while creating a regulatory and infrastructure backbone that supports the efforts. The adoption of grid-scale energy storage to complement the expansion of intermittent renewable energy sources faces many key challenges [205], including:

- Understanding the economics of each proposed storage technology for different scales and applications
- Development of new materials with respect to both electrochemistry and mechanical properties
- Improved system-level compatibility and performance
- Pursuit of revolutionary designs, concepts, and architectures that can significantly reduce capital and maintenance costs with low environmental impact
- Improved safety and reliability

As personal transportation increasingly relies on electric vehicles, the increased battery development has helped drive costs down through design and manufacturing improvements while increasing efficiencies and reliability [206,207]. Research in advanced materials and mechanical design show promise in improving the performance of high-speed and low-speed flywheels. The efficient splitting of water into hydrogen and oxygen has further enabled fuel cell and internal combustion engine approaches; advanced thermodynamic approaches such as the argon power cycle getting increased traction [208]. The cost of flow batteries, both aqueous and nonaqueous, is progressively seen as a viable approach [209].

10.4. Summary

A variety of grid storage solutions currently exist, each of which has distinct advantages or disadvantages based on economics, capacity, and geography. Technological advances, in conjunction with clear policy and regulatory approaches [209,210], will shape how wind energy and other renewable resources are integrated into the electrical grid. Continued research into material challenges facing mechanical, thermochemical, and other conversion technologies will undoubtedly target issues with cost, efficiency, and reliability in order to address the needs of the grid.

11. Overall paper summary and conclusions

This review paper presented the findings of the 2016 Wind Energy Research Workshop. From the summary of the current state-of-the-art, it is clear that in the past two decades significant progress has been made on improving and deploying wind energy. Federal funding of wind energy research coupled with positive policy has encouraged researchers, government laboratories as well as industry to commit to the improvement of wind energy as not just a viable player, but a leader in the renewables market.

The future research directions that derived from this workshop illustrate the vibrant and exciting potential wind energy research has in academia, government laboratories and industry. As wind energy research continues into the future, industry-academia-research laboratory collaborations will be critical in defining productive pathways forward. Finally, the sharing of information at this workshop prompted further calls for sharing information, data and research results in a timely and open manner between industry, academia and government researchers. While this poses challenges in a competitive market economy, it is believed that significant benefit could be derived for all in such an endeavor.

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