



Proceedings of the National Renewable Energy Laboratory Wind Energy Systems Engineering Workshop

K. Dykes

National Renewable Energy Laboratory

**NREL is a national laboratory of the U.S. Department of Energy
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Executive Summary

The second National Renewable Energy Laboratory (NREL) Wind Energy Systems Engineering Workshop was held in Broomfield, Colorado, from January 29 to February 1, 2013. The event included a day-and-a-half workshop exploring a wide variety of topics related to system modeling and design of wind turbines and plants. Following the workshop, 2 days of tutorials were held at NREL, showcasing software developed at Sandia National Laboratories, the National Aeronautics and Space Administration's Glenn Laboratories, and NREL. This document provides a brief summary of the various workshop activities and includes a review of the content and evaluation results from attendees. Additional information can be found at <http://wind.nrel.gov/SystemsEngineering/Workshop2013/index.html>.

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1 Introduction

As part of the systems engineering initiative at the National Wind Technology Center (NTWC) at the National Renewable Energy Laboratory (NREL), a series of workshops are held biennially to bring together researchers and practitioners from industry, laboratories, and academia to share presentations and discuss systems engineering approaches to wind energy research, design, and development. The NWTC's wind energy systems engineering initiative focuses on the development of an analysis platform and research capabilities for integrated system modeling of wind plants. In addition, the initiative seeks to foster collaborative research and analysis to promote application of systems engineering and integrated design and research processes in the wind industry. The use of integrated design and development practices holds the potential to improve overall wind energy system performance and cost for a variety of wind energy stakeholders.

The workshop was held in Broomfield, Colorado, from January 29 to February 1, 2013. The event included a day-and-a-half workshop exploring a wide variety of topics related to system modeling and design of wind turbines and plants. Following the workshop, 2 days of tutorials were held at NREL, showcasing software developed at Sandia National Laboratories, the National Aeronautics and Space Administration's (NASA's) Glenn Laboratories, and NREL. Additional information can be found at <http://wind.nrel.gov/SystemsEngineering/Workshop2013/index.html>.

2 Objectives

The objectives of the workshop were to:

- Bring together researchers and practitioners from industry, laboratories, and academia to present and discuss the state of the art in systems engineering and integrated system modeling for wind energy
- Expose and address the current challenges that the wind industry faces that could be improved by the use of systems approaches to research, design, and development
- Provide exposure to industry practitioners for how to incorporate systems engineering methods and tools into wind energy system design and development.

2.1 Report Framework

The remainder of this document describes the workshop proceedings. First, a general description of the workshop is given, followed by a summary of each workshop session. Finally, the conclusions and common themes from the presentations, discussion sessions, and post-workshop questions are addressed in the Conclusions section. For completeness, presentations that were given at the workshop are available at

http://www.nrel.gov/wind/systems_engineering/se_workshop_2013.html.

3 Workshop Description

The focus of the 2nd NREL Wind Energy Systems Workshop was on systems engineering methods applied to wind energy research, design, and development. Sessions included a holistic look at wind system cost of energy, systems engineering methods for wind energy, integrated turbine design (from components to turbines and from turbines to plants), and overall wind plant design.

Over 140 participants from all over the world participated. They came from industry, laboratories, and academia and represented a large number of disciplinary backgrounds involving all facets of wind energy systems: from component to turbine design, plant design and operation, and even research on uncertainty analysis applied to wind turbines and plants. Two-thirds of the attendees represented the labs and academic community while roughly a third represented industry. The huge increase in participation as compared to the first workshop of around 40 participants demonstrated the growing importance of systems engineering and systems approaches to wind energy research, design, and development.

Overall, the workshop covered a breadth of topics. The session on wind energy system cost from turbines to plants laid a nice groundwork for the workshop by describing the types of metrics that are useful in calculating the cost of energy. Another session covered why a systems engineering approach is needed for wind energy. The next session presented approaches for optimizing rotors and blades. The second day started with dialogue regarding the cost of energy from a wind plant level, and the next session discussed the uncertainties in this type of analysis. The session on Systems Engineering Application to Industry Wind Turbine Design showcased how some of the largest original equipment manufacturers (OEMs) incorporate the design methods that had been discussed. The talks on wind plant layout and optimization were helpful and it was interesting to view in relation to a systems engineering approach. One comment made by an attendee during the workshop summarized this concept perfectly: “With all of the complexities discussed on the individual components, single turbine, and wind plant, the goal to incorporate all of these elements is going to be a challenge.”



Figure 1. Paul Veers, chief engineer of the NWTC, addresses the workshop attendees for some closing remarks at the end of the second day of the workshop (*Photo by Katherine Dykes*)

Most of the workshop participants were from the United States, whereas several were from Europe—Italy, Denmark, Germany, and Portugal—and Asia—India, South Korea, and Japan. Between January 17 and February 5, 2013, 309 unique visitors accessed the Systems Engineering Workshop Web page. Figure 2 reflects the geographic variation in the type of users that accessed the site. Most are based in the United States (275 unique visitors) and Colorado (168 unique visitors), but many came from international locations in Europe and elsewhere.

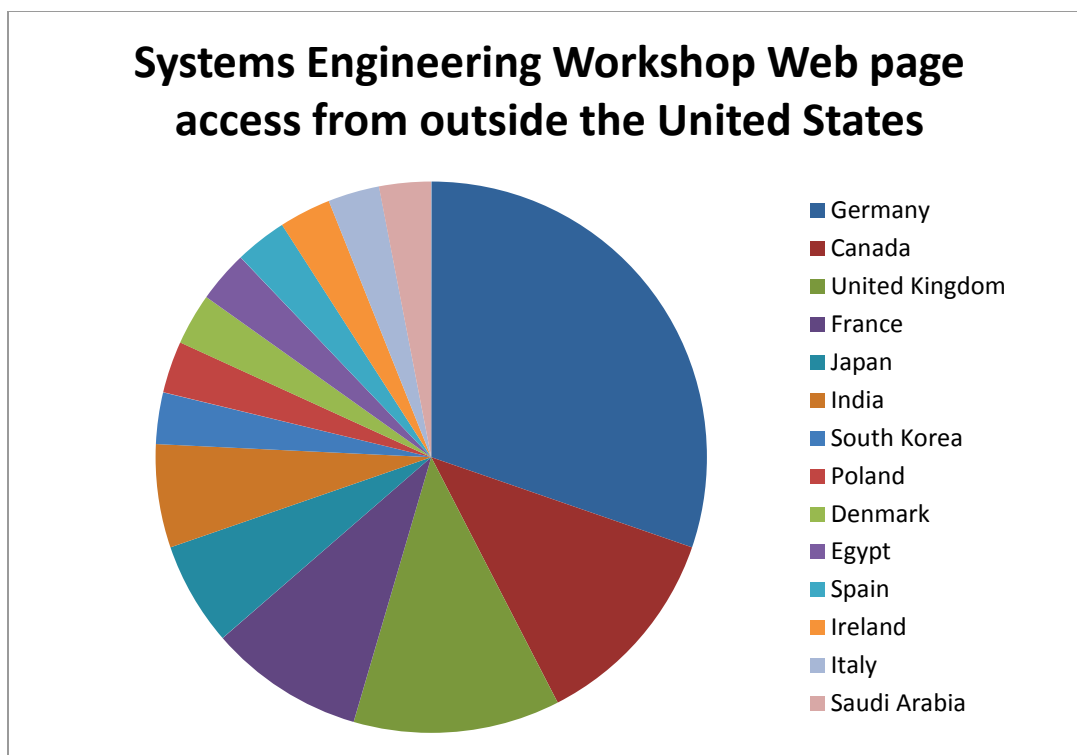


Figure 2. Access of Systems Engineering Workshop Web page from outside the United States

The follow-on sessions were also well attended. Forty-one people participated in the Thursday tutorials and 20 participated in the Friday tutorials (which featured overviews of NREL's wind energy computer-aided engineering tools and systems engineering software).

3.1 Detailed Summary by Session

3.1.1 Overall Workshop Review

The summaries in this section are provided by the moderator and include the key takeaways. More information on each session including descriptions, abstracts, and biographies can be found in the workshop program and on the workshop Web page once the presentations are uploaded. A brief agenda is provided in Appendix A.

Opening Session: Systems Innovation in Wind Energy

The U.S. Department of Energy (DOE) is committed to reducing the levelized cost of energy (LCOE) of wind systems by fostering innovation and enhancing the speed of development through a balanced program of technology development and barrier removal. Nick Johnson provided an overview of the DOE Wind and Water Power Program (WWPP) that is supporting the accelerated development of wind energy systems, with a new emphasis on the entire wind plant as the critical focus of advancement. The NREL systems engineering effort is sponsored by the WWPP to foster their goals through the synthesis of individual technology innovations into the context of the wind plant LCOE. The importance of accurately reflecting the design requirements of each subsystem and the interactions between subsystems in the system engineering model was emphasized by Paul Veers of NREL. A subsystem example of a blade

system design effort that introduced innovation through the integration of manufacturing requirements into the aerodynamic design of blades was used to illustrate the opportunity for systems engineering on a broader scale.

Session 1: Wind Energy System costs from Turbines to Plants

There are many project planning aspects that need to be considered to optimize wind energy competitiveness. Ben Maples of NREL moderated a session that looked at overall wind system cost of energy. Eric Lantz of NREL highlighted how historical trends in wind energy capital costs have shown a decrease—up until the historic lows of the mid 2000s, at which point there is an inflection in the trend. This increase in price saw a high in 2009 and trends since then have indicated prices are continually falling. Bernard Bulder of ECN spoke about how operation and maintenance costs are substantial and great care should be taken in planning for operational expenses. To do so, the impacts of losses and induced loading from wakes must be understood. One possible solution to this may be the introduction of wind plant controls. Finally, a talk on wind project financing was given by Rajan Arora of RES Americas. The lenders look very closely at design aspects of the project with a special emphasis on turbine technology, which means all of these system-level analyses must be conducted before a project can even be financed. While evaluating the turbine, lenders look at items such as the deployment history of the turbine, any known turbine issues, the suitability of the turbine for the specific project site, and any known serial defect issues. The bottom line indicates that a single focus optimization will certainly lead to a nonoptimal system design. To get to the optimum system design, all aspects of the project must be planned and optimized as a single integrated system.

Session 2: Systems Engineering Methods Applied to Wind Energy I

As wind power matures and offshore applications become more accessible, there is a fundamental need to reduce costs across the entire project, from development to installation and operation. Larger machines have even more intricate coupling between components and disciplines, with uncertainties in the various design parameters that also need to be assessed. Relegating the design of a wind turbine to a sequential optimization of components and processes will no longer be viable, and a full systems engineering approach will need to be employed to arrive at cost-effective and competitive products in the future power market. The automation of this approach is as important as the validation of the individual modules with data from the field and cross-tool verification.

There were three speakers in this session, which was moderated by Rick Damiani from NREL. Carlo Bottasso, a professor at Politecnico di Milano, discussed needs and tools to better define and understand the effectiveness of innovations for wind turbine systems. Automated design methods, which do not replace the role of the expert designer, help explore the solution space and evaluate all the necessary trade-offs across all components. Andrew Ning, post-doctoral researcher at NREL, highlighted important aspects of optimization problems for wind turbines. His presentation focused on understanding the importance of optimization objectives and constraints, explaining how sequential aero/structural optimization would yield suboptimal results compared to fully integrated optimization. Ryan Schkoda, post-doctoral fellow at Clemson University, introduced the new Wind Turbine Drivetrain Testing Facility in Charleston, South Carolina. The test benches are complex electrical-mechanical-hydraulic-systems intended to assess performance of entire nacelle assemblies under a variety of loading conditions. To

understand the complex interaction among components, system interaction and coordination must be taken into account through a set of modular dynamic models.

Session 3: Systems Engineering Methods Applied to Wind Energy II

The third session of the day provided additional perspectives on multidisciplinary design analysis and optimization. Scott Hughes of NREL moderated a session with three speakers; however, Joaquim Martins of the University of Michigan presented both Turaj's and his own presentations. The presentation by Turaj Ashuri highlighted his PhD work in multidisciplinary optimization (MDO) for a wind turbine integrating NREL's FAST and other codes. Joaquim Martins' presentation focused on relatively new work looking at MDO for wind, drawing extensively from his experience in the aerospace sector and focusing on blade design in particular. Curran Crawford from the University of Victoria, BC, Canada, finished the session with a presentation on additional MDO work applied to integrated wind turbine aerodynamic and structural design. Overall, the session highlighted the growing activity in MDO for wind energy applications for various subsystems and overall turbine design.

Day 2 Opening Session: Reducing the Cost of Wind Energy

The second day opened in a similar spirit as the first day with a focus on big picture issues. Although the first day highlighted the DOE and NREL shift towards systems approaches to wind energy research and analysis, the second day highlighted the overall motivation of a systems approach by looking at global wind plant LCOE trends. Maureen Hand of NREL provided an overview of historical LCOE trends for a number of countries and then discussed different methods for projecting LCOE for future wind plants and technologies. She provided some background on three different approaches: learning curves, expert elicitation, and engineering-based analysis—all of which have an important role to play in assessing future potential energy costs. Continuing on with the theme of LCOE, Henk-Jan Kooijman of GE Energy discussed, from a high-level perspective, how wind energy costs may be reduced by different innovations—with particular emphasis on taking the system into account when evaluating the impact of such innovations. His talk highlighted some key technologies in the space of turbine design standards, resource assessment, and plant operations. The two presentations together laid the foundation and motivation for the rest of the day's sessions.

Session 4: Systems Engineering Methods Applied to Wind Energy III

The focus of this session, moderated by Justin Gray of NASA, was on the application of uncertainty quantification (UQ) to wind turbine and wind plant design. Gianluca Iaccarino, an assistant professor from Stanford University, demonstrated the application of UQ to high-fidelity analysis of vertical-axis wind turbines. Mike Eldred from Sandia National Laboratories presented details on how to account for both epistemic and aleatory uncertainty in the design process with the DAKOTA software. The central theme of both presentations was the large effect that uncertainty can have on the overall design of a wind power system and how that mandates the application of UQ to properly account for it. The most common, and simplest to execute, UQ technique involves a statistical sampling method with thousands (or hundreds of thousands) of samples to converge to a valid answer. This method can be extremely computationally expensive, and Eldred discussed several more advanced UQ methods that can provide answers within hundreds of function evaluations. These methods open the door for the use of UQ for design under uncertainty as an integral part of the design process.

Session 5: Systems Engineering Application to Industry Wind Turbine Design

In this session, moderated by Scott Schreck of NREL, four presentations were given by wind industry systems engineering experts. Charu Mehendale, from GE Power and Water, summarized the diverse systems engineering tools and methods used by GE, for evaluating new technologies and designing next-generation products. He noted the potential for system engineering tools at the component, turbine, and wind plant levels and emphasized that both deep technical models (such as those that calculate aerodynamic efficiency or load impacts) and market-specific economic models (which evaluate projected customer cash flow) are critical to this process. John Leahey of Vestas - American Wind Technology highlighted the advantages of concurrent engineering, including improved product quality and reduced cost, and explained how this type of engineering relates to systems engineering. He emphasized that linking assorted computer-aided engineering tools does not magically result in concurrent engineering. Rather, diverse departments and personnel need to be linked as well, which requires a new focus on organizational collaboration and communication. Eddie Mayda, from Siemens Energy Inc., spoke about the multidisciplinary, multiobjective design of wind turbine rotors, how the process has become substantially more complex, and how it must be solved faster, better, and cheaper than ever before. To meet these challenges, automated design optimization and MDO techniques have been applied at Siemens. A description of the MDO framework at Siemens was presented, including their multiobjective strategy and some recent success stories. Christopher Halse, representing Romax Technology Inc., discussed how a wind turbine drivetrain's main shaft, main bearings, gearbox, high-speed coupling, and generator need to be designed together. Methods were described for physical modeling of the drivetrain system aimed at understanding how components interact in terms of loading, misalignments, dynamic responses, and failure rates. An optimal drivetrain design was proposed, which utilizes a two-stage medium-speed gearbox, with various generator options and nacelle connection options.

Lunch Session: Offshore Energy System Design

Jim O'Sullivan's keynote address was based on the oil and gas perspective to convey experience from the industry that may be applicable to offshore wind systems. The presentation was full of energy and kept the audience's attention, highlighting how things are done in the oil patch and hard lessons learned that can be avoided in the offshore wind industry. O'Sullivan, Vice President of Technip North America, kept referring to how the industry needs to change to a more inclusive model by thinking outside the box. Economics require creative thinking to make offshore wind commercially viable and O'Sullivan confirmed that this is already being done. A key point from this session was the fact that developing offshore wind energy is about three times the cost as developing onshore.

Section 6: Wind Plant Design and Optimization I

This session, moderated by Pat Moriarty of NREL, had speakers from three industry sectors: manufacturer Phillipe Giguere from GE, researcher Matt Churchfield from NREL, and consultant/due diligence Jake Frye from DNV Keema. Each speaker gave his perspective on wind plant development and operation. Phillipe Giguere's talk focused on the importance of international design standards and structural loading of turbines. When GE consults on a wind plant layout, they ensure that standards are being met while optimizing energy capture at the same time. Turbine control settings can also be adjusted to increase energy capture after installation. Matt Churchfield talked about the importance of wake modeling when optimizing a layout. New models are needed, although current high-fidelity models are not necessarily more

accurate than lower fidelity ones. More data for validation is needed. Jake Frye provided a consultant's perspective of checking both the manufacturers and wind plant developers' designs and assumptions. Turbines are often placed in locations close to their design margins and uncertainty plays an important role in the process. Reductions in uncertainty have the potential to reduce the cost of energy in a number of ways.

Section 7: Wind Plant Design and Optimization II

This session, which was moderated by Ryan King of NREL, presented perspectives on layout optimization from developers, OEMs, and third-party engineers. Matt Filippelli, lead engineer at AWS Truepower, presented on the design and validation of AWS Truepower's openWind tool, and in particular discussed the available wake models, including a deep array wake model and optimization techniques that included balance-of-station costs. Scott Haynes, senior meteorologist at Iberdrola Renewables, discussed wind plant layout design from the developer's perspective and emphasized the iterative process and lengthy timescales inherent to wind plant development. Haynes examined the Federal Aviation Administration filings database for commonalities in plant layout and found the crosswind spacing was increasing yearly, whereas downwind spacing remained constant at about 1 mile between rows. These patterns suggest that landownership boundaries along township-section-range borders are driving layout design rather than wind resource. Matthew Lynn from GLGH also presented a case study demonstrating the spatial constraints that must be observed in wind plant design. In addition, he discussed challenges in modeling stable atmospheric conditions and offered research results that showed that computational fluid dynamics simulations of stable atmospheric conditions were in better agreement with observations than a simple linear windflow WAsP run. The question-and-answer period featured a discussion that juxtaposed the constraints and optimization of land-based and offshore wind plant development. In response to questions about wake modeling and research priorities, the panel felt that improving flow modeling over complex terrain was a higher priority than improving existing wake models.

Section 8: Integrated Wind Turbine and Plant Modeling

Peter Graf, of the NREL Computational Sciences Center, moderated this session, which focused on a set of approaches for integrated wind turbine and plant modeling. In the first talk, Katherine Dykes, senior engineer at NREL, spoke about the NWTC's efforts in developing a new software tool for the research, design, and development of wind energy systems. This tool—specifically focused on integrating engineering and cost-based analysis—will: represent a full wind plant, allow interchangeable models of varying fidelity, and support a wide variety of analysis. A summary of the first full year of development highlighted the overall goals, software design, a new set of engineering and cost models, and the integration of these models into several initial cost-of-energy studies. The second speaker, Frederik Zahle, from Denmark Technical University (DTU) Wind Energy, spoke about the Light Rotor Project, which focuses on new, more integrative design strategies. Zahle focused specifically on the design of a 10-MW reference turbine, a case involving the collaboration of aerodynamic, aeroelastic, and structural experts. The third talk in the session was by Pierre-Elouan Réthoré, also of DTU. Réthoré focused on integrated design tools for wind plants from two separate projects. The first project is concerned with creating a multifidelity framework for optimizing land-based and offshore wind farms. The second involves mesoscale wake effects, studying the effects of entire wind plants on neighboring wind plants. These talks represent the next generation of highly integrated, multiscale, multiphysics, multifidelity wind plant analysis and design tools.

4 Conclusion

Overall, the workshop covered a breadth of topics and did a successful job of showcasing methodologies in systems engineering that have been applied to wind energy research studies as well as those used in industry practice. Although a lot of work has been done to leverage systems engineering methods such as MDO and UQ in wind energy research, far fewer applications of such approaches are used in industry practice, yet several excellent exceptions were presented.

Generally, integrating practices across the wind industry is difficult, given the number of organizations and the large technological complexity involved; however, the potential for improving system performance and cost was demonstrated by many of the presentations. The conference brought the challenges of realizing the potential gains from integrated system design and development to the forefront. In addition, it laid the foundation for bringing industry stakeholders together to take on that challenge, thereby realizing wind energy systems that embody systems engineering practices for overall improved system performance and cost.

Appendix A

Short Agenda

The second NREL Wind Energy Systems Engineering Workshop took place on January 29 and 30, 2013. The first workshop in January 2010 successfully garnered interest in this important topic among participants from industry, the national laboratories, and academia. In the last few years, the interest in systems engineering and techno-economic modeling of wind energy systems has grown substantially. As a result, NREL created the latest 2-day workshop to showcase research and development activity in these areas and provide plenty of opportunity for discussion about potential future developments and collaborations. Follow-on meetings on January 31, 2013, and February 1, 2013, featured software tutorials and smaller group meetings for discussion. The following agendas outline the workshop activities from January 29 to February 1, 2013.

Table A1. First Day Agenda of Workshop

| Tuesday, January, 29, 2013 | |
|----------------------------|---|
| 11:00 a.m. to 1:00 p.m. | Registration open |
| 1:00 p.m. to 1:45 p.m. | Day 1 opening remarks: Mr. Nick Johnson, DOE Energy Efficiency and Renewable Energy Opening keynote address: "Systems Innovation in Wind Energy" Paul Veers, NWTC |
| 1:45 p.m. to 2:00 p.m. | Break |
| 2:00 p.m. to 3:00 p.m. | Session I: Wind Energy System Costs from Turbines to Plants Moderator: Ben Maples, NWTC Eric Lantz, NREL Strategic Energy and Analysis Center Ir. Bernard Bulder, ECN, the Netherlands Rajan Arora, RES Americas |
| 3:00 p.m. to 4:00 p.m. | Session II: Systems Engineering Methods Applied to Wind Energy I Moderator: Rick Damiani, NWTC Carlo Bottasso, Politecnico di Milano, Italy Andrew Ning, NWTC Ryan Schkoda, Clemson Wind Turbine Drivetrain Testing Facility |
| 4:00 p.m. to 4:15 p.m. | Break |
| 4:15 p.m. to 5:15 p.m. | Session III: Systems Engineering Methods Applied to Wind Energy II Moderator: Scott Hughes, NWTC Joaquim Martins, University of Michigan Curran Crawford, University of Victoria, Canada Turaj Ashuri, University of Michigan |
| 5:15 p.m. to 5:30 p.m. | Break |
| 5:30 p.m. to 7:30 p.m. | Evening reception and poster session |

Table A2. Second Day Agenda of Workshop

| Wednesday, January 30, 2013 | |
|------------------------------------|--|
| 8:00 a.m. to 8:30 a.m. | Registration and continental breakfast |
| 8:30 a.m. to 9:30 a.m. | Day 2 opening remarks: Maureen Hand, NREL Strategic Energy and Analysis Center Opening keynote address: “Reducing the cost of wind energy” Henk-Jan Kooijman, GE Energy |
| 9:30 a.m. to 10:15 a.m. | Session IV: Systems Engineering Methods Applied to Wind Energy III Moderator: Justin Gray, NASA Gianluca Iaccarino, Stanford University Mike Eldred, Sandia National Laboratories |
| 10:15 a.m. to 10:30 a.m. | Break |
| 10:30 a.m. to 12:00 p.m. | Session V: Systems Engineering Application to Industry Wind Turbine Design Moderator: Scott Schreck, NWTC Christopher Halse, Romax Technology Eddie Mayda, Siemens Energy Inc. John Leahey, Vestas – American Wind Technology, Inc. Charu Mehendale, GE Global Research |
| 12:00 p.m. to 1:30 p.m. | Lunch Keynote address: “Offshore Energy System Design” Jim O’Sullivan, Technip |
| 1:30 p.m. to 1:45 p.m. | Break |
| 1:45 p.m. to 2:45 p.m. | Session VI: Wind Plant Design and Optimization I Moderator: Pat Moriarty, NWTC Philippe Giguere, GE Energy Matt Churchfield, NWTC Jake Frye, DNV KEMA Energy & Sustainability |
| 2:45 p.m. to 3:00 p.m. | Break |
| 3:00 p.m. to 4:00 p.m. | Session VII: Wind Plant Design and Optimization II Moderator: Ryan King, NWTC Matt Filippelli, AWS Truepower Scott Haynes, Iberdrola Renewables Matthew Lynn, GL Garrad Hassan |
| 4:00 p.m. to 5:00 p.m. | Session VIII: Integrated Wind Turbine and Plant Modeling Moderator: Peter Graf, NREL Computational Sciences Center Katherine Dykes, NWTC Frederik Zahle, DTU Wind Energy, Denmark Pierre-Elouan Réthoré, DTU Wind Energy, Denmark |
| 5:00 p.m. to 5:15 p.m. | Closing remarks Paul Veers, NWTC |