RFI DE-FOA-0001932: Pathways to Success for Next-Generation Supersized Wind Turbine Blades

DATE:	May 8, 2018
SUBJECT:	Request for Information (RFI)

Description

The Wind Energy Technologies Office (WETO) is issuing a Request for Information (RFI) to gain public input regarding the key challenges associated with the manufacturing and deployment of larger next-generation blades for land-based wind turbines. Information sought under this RFI is intended to assist WETO in analyzing the costs and benefits of various pathways to achieve larger wind turbine blades, which are currently constrained by transportation logistics over existing road and rail infrastructure. Potential pathways include onsite blade manufacturing or assembly, transportation and logistics innovations, and hybrid approaches. The RFI further solicits input on specific areas where further federal research and development would best be applied to have a high impact on enabling supersized blades for the next generation of cost-competitive wind energy.

Background

WETO operates within the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE). WETO's mission is to lead the nation's efforts to research and develop innovative technologies, lower the costs and accelerate the development of wind power. To find more information about WETO within EERE, please visit wind.energy.gov.

To maximize potential future cost reductions in wind technology, wind power plants will require substantially larger turbine blades to achieve increased energy production, greater capacity factors, and higher plant efficiencies, particularly at sites with low to moderate wind speeds. However, current U.S. transportation limitations, manufacturing and assembly methods, and materials all impart limitations into the design of land-based blades. Certain physical constraints within the land-based transportation system result in blade designs and dimensions that are not fully optimized for performance and, as blade lengths increase, these transportation and handling limits have an increased influence on the blade design. This ultimately will present a growing, material impediment to lowering the cost of wind energy.

Offshore wind turbine blades are not anticipated to face the same logistical challenges from the transportation and handling constraints facing blades for land-based turbines as offshore components are not projected to be transported over land to the project deployment site and instead will have local on-site manufacturing. To date, this has allowed blade root diameters to increase, blade chord dimensions to expand, and overall lengths of 80–90 meters (m) for offshore wind turbine blades. Without the land-based handling constraints, "supersized" blade designs will able to regain some improvements in aerodynamic efficiency because blade shape can be aero-optimized. In addition, expanding the blade dimensions can result in a structurally more efficient design, such that increased blade lengths are achievable with more efficient structural configurations and more cost-effective distribution of mass in the overall structural design.

To date, designers of land-based wind turbine blades have been making slight compromises in aerodynamic and structural capabilities of blades to achieve the increased blade lengths that have enabled wind energy to become a leading low-cost energy source. At the same time, transportation companies have continued innovating methods and equipment for hauling longer blades, thus delaying the need for more radical blade innovation. However, further expansion of land-based wind energy in the United States necessitates new thinking in the design, manufacture, and transport of supersized blades.

Over the past 10–20 years, there have been significant advances in material science, blade design, new manufacturing techniques, and wind industry experience with novel blade configurations intended to mitigate certain transportation limitations. In addition, transportation and power plant construction equipment and techniques have also evolved as the scale of wind turbines increased and the industry acquired significant deployment experience. Past studies of wind turbine transportation logistics identified various hard and soft break points in turbine sizes. However, given the industry's experience base, ongoing commercial initiatives, and new technology advances, EERE seeks to understand specific areas where further federal research and development would best be applied to have a high impact on enabling supersized blades for the next generation of cost-competitive wind energy.

March 2018 Workshop

The WETO convened the Pathways to Success for Supersized Wind Turbine Blades Workshop (the Workshop) on March 6-7, 2018, in Washington DC. The Workshop was the first step in a project studying various new alternatives related to blade manufacturing and transportation, and field assembly of supersized blades too large to be transported in traditional ways over the existing road and rail network. The project seeks to identify specific research and development opportunities EERE could pursue to address technical barriers or implementation challenges faced by the U.S. wind energy industry to achieve continued rotor scaling and consequent decreases in the levelized cost of energy (LCOE).

The Workshop began with a plenary session, which was intended to inform the participants of the overall workshop structure and objectives, and to provide background on the current industry status, projections for future deployment of wind energy, and benefits to the wind industry and the U.S. as a whole if technologies could enable cost-effective manufacture and transport of supersized blades. The overall objective of the plenary session was to provide background and context within which to frame the dialogue in the following group pathway discussions.

Following the plenary session, the remainder of the two-day workshop featured three group-discussion sessions, with each session focusing on a specific "pathway" to enabling LCOE reductions for rotor blades of increasing size; the three pathways were identified as "transportation solutions," "on-site manufacturing," and "hybrid and alternative solutions."

The transportation solutions pathway session focused on current and future innovations within the transportation sector that could enable cost-effective movement of thousands of full-sized blades up to 100 m long (and even larger) to various regions across the U.S.. Discussions acknowledged continual advancements in over-land transport (e.g., truck and rail) that have so far allowed cost-effective transport of blades up to lengths of 60+ m. Dimensional constraints for over-land transportation of blades with increasing dimensions were discussed. Factors included non-negotiable constraints such as rail tunnels and snow-sheds; and partially-avoidable constraints such as road overpasses and permitting rules for road transport, including variances between permissible hauling equipment in Europe and the U.S., as well as state-to-state variances within the U.S.. This session also introduced a new type of heavy-lift aircraft as an alternative to over-land transport.

The on-site manufacturing pathway focused on ideas where raw materials are brought to a project site, a temporary manufacturing facility is established, and entire blades are manufactured on site. Factors considered in these discussions included proximity of the temporary facility to the final wind projects(s), size of projects(s), duration of temporary factory presence, lead-time for erection and commissioning of the factory, process validation for initial blades, lead-time requirements for blade production, workforce training, balance between local and travelling workforce, quality control, factory utility requirements, environmental impact, permitting, and community acceptance.

Finally, the hybrid and alternative solutions pathway focused on different combinations of on-site manufacturing, on-site assembly, off-site manufacturing, and transportation to identify potential ideas from further investigation. One of the key solutions discussed was segmented blades assembled on site. While transportation feasibility is a clear benefit, segmented or modular blades may incur a combination of down-side factors such as increased weight, assembly costs, quality-control challenges, and maintenance of jointed connections.

The Workshop sessions offered significant insights into the challenges and potential enabling technologies for supersized wind turbine blades. Discussion highlights and take-aways for the three pathways can be found in further detail in the "2018 Workshop Summary Report: Creating Pathways to Success for Supersized Wind Turbine Blades" (Workshop Report). , attached as Appendix A.

Purpose

The purpose of this RFI is to solicit feedback and input from industry, academia, research laboratories, government agencies, and other stakeholders on the issues and challenges associated with increased scaling of next-generation wind turbine blades. Specifically, WETO is interested in information regarding on-site blade manufacturing (or assembly), transportation of supersized blades, and hybrid solutions that may involve a combination of innovative transportation and on-site manufacturing/assembly methodologies. EERE is interested in RFI responses that provide supplemental insights to the "2018 Workshop Summary Report: Creating Pathways to Success for Supersized Wind Turbine Blades" (Appendix A). **This is solely a request for information and NOT a Funding Opportunity Announcement (FOA). EERE is not accepting applications.**

Disclaimer and Important Notes

This RFI is NOT a Funding Opportunity Announcement (FOA); therefore, EERE is not accepting applications.

Any information obtained as a result of this RFI is intended to be used by the Government on a non-attribution basis for planning and strategy development; this RFI does not constitute a formal solicitation for proposals or abstracts. Your response to this notice will be treated as information only. EERE will review and consider all responses in its formulation of program strategies for the identified materials of interest that are the subject of this request. EERE will not provide reimbursement for costs incurred in responding to this RFI. Respondents are advised that EERE is under no obligation to acknowledge receipt of the information received or provide feedback to respondents with respect to any information submitted under this RFI. Responses to this RFI do not bind EERE to any further actions related to this topic.

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Because information received in response to this RFI may be used to structure future programs and/or otherwise be made available to the public, **respondents are strongly advised to NOT include any information in their responses that might be considered business sensitive, proprietary, or otherwise confidential.** If, however, a respondent chooses to submit business sensitive, proprietary, or otherwise confidential information, it must be clearly and conspicuously marked as such in the response.

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Request for Information Categories and Questions

Category 1 - Market Demand: EERE requests information from stakeholders regarding the market demand to manufacture and deploy larger next-generation blades for land-based wind turbines.

1) What is your opinion regarding the industry need for super-sized wind turbine blades (blades > 62m and >100m in length, > 4.3m chord/root dimensions)? What are the current commercial drivers compelling continued blade and rotor scale increases and is there an upper commercial limit? If transportation-related physical limits for land-based wind turbine blades were mitigated, are there other considerations that would limit continued turbine scale growth?
2) What is the time urgency associated with finding solutions to enable cost-effective blade growth? Is this a problem now, or 2, 5, or 10 years out? If industry does not see this as an immediate need, when will the industry need a cost-effective solution to the challenge of super-sized wind turbine blades?
3) What are additional key benefits/advantages associated with the continued scaling of land-based wind turbine blades, beyond those specified in the "2018 Workshop Summary Report": Creating Pathways to Success for Supersized Wind Turbine Blades (Attachment A)
4) What are the supplemental key challenges/barriers associated with continued scaling of land-based wind turbine blades, beyond those specified in the Workshop Report (Attachment A)?
5) What are the opportunities and the innovative areas for which further strategic R&D investments by EERE would be most beneficial as they pertain to larger blades for land-based wind turbines?

Category 2 – Transportation Solutions: EERE/WETO requests information from stakeholders regarding transportation solutions and the exploration of new/innovative options for handling and transporting very large blades from conventional manufacturing facilities to wind energy project sites. We also seek information and input to better define the envelope of current costs and capabilities and estimates on future costs and capabilities.

1) What are the additional key challenges/barriers associated with transportation of super-sized blades (blades >62m and >100m in length, > 4.3m chord/root), beyond those specified in the 2018 Workshop SummaryReport (Attachment A)

2) What innovative ideas are either in use or soon to be in use, for handling blades sized to comply with current physical constraints for transportation? How much longer can blades be and still successfully navigate the land-based infrastructure using road and/or rail techniques?
3) Considering existing ground-based transport technology, what additional changes in transportation are possible to move blades of 70m, 80m, 90m and 100m+? How much additional transportation capability exists within the system? To what extent is the system limited by infrastructure, transportation technology, or rules and regulations?
4) Help us bound the range of current blade-related transportation costs by providing anonymized values for recent blade transportation efforts by providing the following (on a per project basis):
    a. Total number of blades shipped
    b. Blade length and mass
    c. Approximate haul distance (from factory to project site)
    d. Primary transport mode (if both road and rail were used, split response by each mode)
    e. Total transport costs – try to account for all handling, permitting, escort services, overtime, fees, special infrastructure adaptation and reclamation, etc.

    You do not need to identify project, manufacturer, or other details. As an alternative, you could offer transportation cost ranges from recent work using $/loaded mile or $/kg/loaded mile metrics; noting the mode and total number of blades transported.
5) Based on your experience and familiarity with recent blade transportation efforts, what would be the estimated increase in costs to ship the same number of longer blades over the same routes for which you are familiar? How might these estimates change based on blade lengths of 70m, 80m 90m and 100m+ (assuming blade chord and root dimensions are unchanged and within infrastructure limits)? Identify any hard limits on blade length and the reason. Identify any step-wise cost increases and the reason (i.e. major infrastructure constraint mitigation).
6) Identify state or federal rules that influence the ability to transport longer blades (assuming the blade chord and root dimensions are within infrastructure limits). What size blades could be transported if certain existing rules were updated?
7) How much investment in an advanced fleet of road or rail equipment is needed to move a few thousand blades per year that are ~65m and larger? What are the logistics industry's R&D investments needed to develop advanced transportation equipment designs?

8) Beyond innovation in transportation equipment, what are other areas for improvement that could facilitate movement of longer blades through the existing infrastructure? Consider ideas such as infrastructure constraint modeling and mapping, route planning software, more real-time traffic information, etc. Estimate the impact of these other areas on facilitating the ability to move very large blades.
9) What are the key opportunities and the innovative areas for which further strategic R&D Investments by EERE would advance transportation-based solutions for supersized wind turbine blades?
10) Please provide comments on both the technical and economic feasibility of proposed transportation solutions for supersized wind turbine blades, including the time scale for achieving commercial viability of innovative solutions.
11) If one could completely re-imagine the design, materials, manufacturing, and assembly of super-sized wind turbine blades, what specific innovations and R&D activities in transportation methods will enable this departure from conventional blades, beyond those specified in the Workshop Report (Attachment A)?

Category 3 – On-Site Manufacturing: EERE/WETO requests information from stakeholders regarding the potential to use on-site manufacturing, as it relates to full-scale blade production either at a project site or within close proximity, to minimize or eliminate long-haul transport on public roads and highways. For the purpose of answering the questions that follow, please focus on the opportunities and challenges associated with complete blade production on-site. Issues related to assembly of segmented blades should be addressed under Category 4 questions.

1) If one can completely re-imagine the design, materials, manufacturing, and assembly of super-sized wind turbine blades, what specific innovations and R&D activities are necessary to enable on-site manufacturing, beyond those specified in the Workshop Report (Attachment A)?
2) Please provide comments on both the technical and economic feasibility of using on-site manufacturing to produce supersized wind turbine blades, including the time scale for achieving commercial viability of innovative solutions.
3) What are the key challenges/barriers associated with on-site manufacturing of supersized blades (blades >62m and >100m, > 4.3m chord/root)?
4) How would complete on-site blade manufacturing need to differ from existing off-site manufacturing? Identify any current innovative manufacturing ideas that could be scaled to manufacture very large wind turbine blades considering only raw materials and moderately sized sub-components are shipped to the project site. Identify any manufacturing processes that show promise of achieving a 24-hour blade manufacturing cycle.

5) Discuss benefits and impacts on the project development process considering the possibility that future projects could include a temporary (~1–2 years in production) on-site blade manufacturing facility. Comment on the degree to which on-site manufacturing is considered a benefit or hindrance in the project development process. Comment on the degree to which on-site manufacturing, including the financial commitment to construction of a temporary blade manufacturing facility (roughly 6 to 12 months in advance of turbine construction), is viewed as a benefit or hindrance.
6) Which materials have favorable properties (high stiffness-to-weight ratio, high fatigue resistance, low mass, and low cost) for consideration in automated or additive manufacturing processes? Comment on the range of available thermoplastics, thermosets, fibers, or other materials from which blades could be manufactured, but are not used today. Which materials show promise in high fatigue/low-cost applications where additional R&D, material qualification, and material development could be successful?
7) Comment on the value of EERE investment in blade-specific manufacturing automation techniques and ability/interest of industry to participate.
8) Offer your comments on prioritization and likely impact associated with EERE investment in the following topics related to on-site manufacturing:
   a. Improvements in blade-specific manufacturing automation (equipment, speed, costs)
   b. Development of advanced materials and material qualification for blades
   c. Development of advanced process qualification (thermowelding, additive manufacturing, etc.)
9) What are the opportunities and the innovative areas for which further strategic R&D Investments by EERE would advance on-site manufacturing of supersized wind turbine blades?

Category 4 – Hybrid Solutions: EERE/WETO requests information from stakeholders regarding the application of hybrid solutions, i.e. combinations of innovative transportation and on-site manufacturing, or assembly, such as modular or segmented blades.

1) What are the key challenges and barriers associated with hybrid solutions for supersized blades (blades >62m and >100m, > 4.3m chord/root) that involve combinations of innovative transportation and on-site manufacturing, beyond those specified in the Workshop Report (Attachment A)?

2) Based on your opinion or studies, what combinations of approaches listed above would achieve cost-effective deployment of supersized blades? What combinations should be considered that could achieve a LCOE?
3) What are the opportunities and the innovative areas for which further strategic R&D Investments by EERE would be most beneficial as they pertain to hybrid solutions for the manufacturing/assembly/transport of supersized wind turbine blades?
4) Please provide comments on both the technical and economic feasibility of hybrid solutions to produce and transport supersized wind turbine blades, including the time scale for achieving commercial viability of the innovative solutions.
5) What magnitude of transportation cost savings (versus transport of monolithic blades) would you expect to be associated with the following blade segmentation options:
   a. Two-piece blade with blade joint at roughly mid-span
   b. Three-piece blade with a blade joint at mid-span and a chord extender near the root
   c. Multi-piece blade with numerous smaller blade elements transportable in non-oversized load configurations

   Provide your information as a percentage change or estimated costs per mile.
6) What magnitude of assembly cost increases versus manufacturing of monolithic blades (including quality control) would you expect to be associated with the following blade segmentation options?
   a. Two-piece blade with blade joint at roughly mid-span
   b. Three-piece blade with a blade joint at mid-span and a chord extender near the root.
   c. Multi-piece blade with numerous smaller blade elements transportable in none-oversized load configurations

   Provide your information as a percentage change or incremental additional costs per blade.
7) Comment on your opinion of the wind industry acceptance of bonded joints and bolted connections in the context of risk tolerance, quality control, inspections, and maintenance. Would you prefer bonded joints with less future operations and maintenance requirements or would you prefer bolted connections with increased inspection needs but with the ability to reverse/repair? (Bolted connections are reversible, have initially simpler quality control, and require future inspection and maintenance. Bonded connections are irreversible, have higher initial QC requirements; but have limited to no future maintenance.)

8) Based on your familiarity with current segmented blades in commercial applications, comment on the following topics:
   a. Demonstrated benefits
   b. Commercial feasibility
   c. Technical challenges
   d. What would make them more compelling commercially?
9) If one can completely re-imagine the design, materials, manufacturing, and assembly of super-sized wind turbine blades, what innovations in hybrid solutions will enable this departure from conventional blades?

Request for Information Response Guidelines

Responses to this RFI must be submitted electronically to WindEnergyRFI@ee.doe.gov no later than **5:00pm (ET) on June 11, 2018**. Responses must be provided as attachments to an email. It is recommended that attachments with file sizes exceeding 25MB be compressed (i.e., zipped) to ensure message delivery. Responses must be provided as an attachment to the email, and no more than 10 pages in length, 12 point font, 1 inch margins. Only electronic responses will be accepted. Additional electronic appendices, attachments or links are acceptable.

Please identify your answers by responding to a specific question or topic if applicable. Respondents may answer as many or as few questions as they wish.

EERE will not respond to individual submissions or publish publicly a compendium of responses. A response to this RFI will not be viewed as a binding commitment to develop or pursue the project or ideas discussed.

Respondents are requested to provide the following information at the start of their response to this RFI:

- Company / institution name;
- Company / institution contact;
- Contact's address, phone number, and e-mail address.

APPENDIX A: 2018 Workshop Summary Report: Creating Pathways to Success for Supersized Wind Turbine Blades

CREATING PATHWAYS TO SUCCESS FOR SUPERSIZED WIND TURBINE BLADES

2018 Workshop Summary Report

Lawrence Berkeley National Laboratory

Document No.: 10080081-HOU-R-01
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Task and objective:
This report presents the results of analysis conducted by DNV GL on behalf of Lawrence Berkeley National Laboratory.

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A	20 April 2018	Initial Draft	D. Griffin	K. Smith	K. Smith
B	27 April 2018	Revised Draft	D. Griffin	K. Smith	K. Smith
C	01 May 2018	Final	D. Griffin	K. Smith	K. Smith

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Appendices

List of abbreviations

Abbreviation	Meaning
AEP	Annual Energy Production
DNV GL	DNV KEMA Renewables, Inc.
DOE	U.S. Department of Energy
EERE	Federal Energy Management Program
FAA	Federal Aviation Administration
LCOE	Levelized cost of energy
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
PTC	Production Tax Credit
R&D	Research, development, and deployment
RFI	Request for Information
WETO	Wind Energy Technologies Office

Acknowledgments

The U.S. Department of Energy would like to acknowledge the support provided by the organizations represented on the workshop planning committee in developing the workshop process and sessions. The preparation of this workshop report was coordinated with assistance from DNV GL. The report content is based on the workshop session discussions, session descriptions taken from the workshop notes, and other notes recorded by the workshop facilitation team. The Pathways to Success for Supersized Wind Turbine Blades Workshop was sponsored by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. The workshop was hosted at the Kimpton Hotel Palomar in Washington, D.C. Per DOE instructions, the Workshop was conducted in compliance with the Information Quality Act.

EXECUTIVE SUMMARY

Workshop overview

On March 6-7, 2018, the U.S. Department of Energy (DOE) office of Energy Efficiency and Renewable Energy (EERE) conducted a workshop on Pathways to Success for Supersized Wind Turbine Blades. The workshop was held at the Kimpton Hotel Palomar in Washington DC. Approximately 50 experts and industry stakeholders came together, including manufacturers, transportation specialists, project developers, operators, engineering firms, consultants, and university researchers. Technical experts from the national laboratories and the Wind Energy Technologies Office were also present to engage in discussions about solving the challenges faced by supersized wind turbine blades.

The workshop participants were charged with evaluating the current status of wind turbine blade design, manufacture, transportation, erection, and operation; identifying constraints to cost-effective application of current technologies and methods for blades of increasing size; and discussing needs and opportunities for research, development, and deployment (R&D) in areas of materials, manufacturing, structural configuration, and transportation. The workshop was one step within a larger initiative to identify specific R&D opportunities the DOE could pursue to address technical barriers or implementation challenges faced by the U.S. wind energy industry to achieve continued decreases in the levelized cost of energy (LCOE).

The workshop began with a plenary session. Valerie Reed, Acting Director, Wind Energy Technologies Office (WETO) began by welcoming participants and providing perspective into DOE's higher level interests. Among her topics, she emphasized the importance of enabling wind energy to continue on the trajectory of lowering LCOE since it enables multiple energy options and a diverse energy supply mix for the nation. Patrick Gillman, Modeling and Analysis Program Manager, WETO introduced the workshop agenda, explained DOE's objectives for both the workshop and overall project, and introduced DNV GL as the workshop facilitator and overall principal investigator for DOE on the project. Mike Derby, Technology Program Manager, WETO provided context and background for attendees regarding the drivers for continued wind turbine growth and efforts DOE has been leading. Eric Lantz, Modeling and Analysis Program Manager and Johney Green, Associate Lab Director for Mechanical and Thermal Engineering Sciences at the National Renewable Energy Laboratory (NREL) presented their analysis explaining the market potential if the wind industry is able to achieve further reductions in LCOE and increase turbine sizes. Dan Shreve, Partner, MAKE Consulting, provided market trend information and a discussion of the competitive landscape, both from a global and U.S. market perspective. Dayton Griffin, Senior Principal Engineer, DNV GL, and Steve Nolet, Principal Engineer and Senior Director of Innovation and Technology, TPI Composites, Inc., provided attendees information about current industry experience with blades in the field and manufacturing. Mr. Griffin provided a primer on engineering trade-offs in blade designs that are being made to accommodate existing transportation constraints and the related impacts on turbine performance. Mr. Nolet provided the blade manufacturer's perspective and offered some insight into manufacturing metrics requiring attention to ensure potential innovations are economically competitive.

Following the plenary session, the remainder of the two-day workshop featured three group-discussion sessions, with each session focusing on a specific "pathway" to enabling LCOE reductions for rotor blades of increasing size. Kevin Smith, Director Asset Operation and Management Services at DNV GL, introduced the three pathways as "on-site manufacture," "transport," and "hybrid and alternative," which included various options involving central manufacturing of sub-elements followed by on-site assembly. Each of the pathway group discussions was opened with a short presentation from one or more invited speakers. DNV GL facilitated the group discussions and ensured that each included diverse technologies and options, as well as balanced input from stakeholder groups and individuals.

Presentations to open the group discussion for the on-site manufacturing pathway were provided by Scott Carron, NREL, and David Champa, Additive Manufacturing, Ingersoll Machine Tools. Mr. Carron presented a preliminary analysis of on-site blade manufacturing that will be made available for further assessment in the project. Mr. Champa provided insight into machine and tooling developments in additive manufacturing and noted the need for a larger industry roadmap for developing advanced tooling, materials, and processes starting with smaller blade elements then moving to the entire blade.

Presentations to open the group discussion for the transportation pathway were provided by Clay Gambill, Director BNSF Logistics, and Dr. Grant Cool, Chief Operating Officer, Hybrid HE. Mr. Gambill described various methods and innovations transportation companies have been able to achieve using rail and truck modes. Adjustments to blade mounts on rail cars enabling slight blade articulation without blade bending to navigate turns in rail yards has been beneficial to facilitate transport of blades up to 60 m in length. Further information about the economic parameters, train lengths, route selection, and constraint analysis was provided to better inform attendees about the challenges longer blades pose for rail transport. Dr. Cool presented information about Lockheed Martin's LMH-1 hybrid airships. The LMH-1 and related airships in the series is a hybrid aircraft that combines buoyancy, aerodynamic lift, powered propulsion, and a hover-craft type landing skirt. The aircraft's purpose is to provide heavy lift cargo capabilities to remote areas and to provide another general cargo transportation option that eliminates cross-modal handling.

The group discussion on the hybrid and alternative pathway was opened by a presentation from Daniel Hynum, Technical Leader, Wind Advanced Technology, General Electric (GE). Mr. Hynum described some history of segmented and field-assembled wind turbine blades. There have been many segmented blade paths attempted, yet barriers to gaining market acceptance have included competition from transportation innovations, added weight, cost, and quality-considerations for on-site assembly.

The final working session of the workshop, led by Mr. Gillman of WETO, was a group discussion of where within the three pathways considered DOE investment in R&D could have the greatest positive impact. Discussions also included consideration of what capabilities DOE could offer to help enable industry-driven solutions.

Following these sessions, DNV GL provided a short recap of the workshop findings, expert recommended priorities, and next steps in the larger project. Mr. Gillman then closed the meeting.

Major outcomes

Participation among the workshop attendees was considered highly productive. Experts and stakeholders were engaged throughout the sessions and offered significant insights into the challenges and potential enabling technologies for supersized blades. Discussion highlights and take-aways for the three pathways were as follows.

On-site manufacturing pathway

- On-site manufacturing from raw materials to full scale blades was perceived as lowest option in terms of technical and commercial feasibility, with significant challenges including infrastructure requirements, permitting (especially if wet chemistry is involved), set-up time, training of local workforce, and quality control/assurance.

- Alternative material and process technologies could potentially improve the cost-effectiveness of this approach; however, significant advances in automation, additive manufacturing, and fatigue resistance materials would be needed to better enable on-site manufacturing from raw materials and any materials/process advancements could be applied in offsite or hybrid/modular blades.
- Locating "on-site" manufacturing in a local community where industrial land maybe available was mentioned as a potential mitigant for seeking approvals for manufacturing on private land. Local transportation of the blades to the site would still be required, thus not completely eliminating the transportation challenges.

Transportation pathway

- Logistical constraints to ground-based transportation appear to have few absolutes, as it was pointed out that to date the transportation/logistics experts have continued to innovate in ways that have avoided the necessity for segmented/modular blades or on-site manufacturing.
- Although no hard limit on blade length transport by road and rail was clearly identified, it was observed that fewer and fewer route options become viable with blades longer than currently available. The system could move one 100 m blade with sufficient planning and costs; however, moving thousands of blades at this scale over long distances was considered untenable.
- Regulations for over-road transport vary by state and are in some cases inconsistent with federal rules. Some transportation solutions being used outside of the U.S. may not be allowed here under current regulations. Harmonization of permitting regulations could reduce barriers to cost-effective transport of large blades.
- Heavy-lift airships appear to have the capacity and performance needed to transport blades up to 100 m in length, but business case for the development and deployment of this approach is not clear.

Hybrid and alternative pathway

- Options discussed included 2-piece, 3-piece, and "modular" (multi-piece) configurations on a continuum of increasing transportation benefits balanced by increasing cost and complexity related to on-site assembly.
- Some workshop participants from transportation companies expressed their opinion that blade elements of 47 m to 52 m long were an economic sweet spot for road and rail transport.
- The technology for splitting and connecting blades is available now, but the business case has not been sufficiently compelling due to competitive transportation solutions (to date). However, when considering the transportation concerns of blades of 70 m to 100 m long, the business case for segmented blades may improve.
- Attendees were reminded of the current manufacturing trends where solutions need to avoid the cubic mass growth and that costs per kg have been continuously decreasing. It was hard to envision segmented blades not having a weight penalty while also incurring additional on-site assembly costs. Transportation costs would be reduced and blade design could be aero-optimized to improve performance, but analysis is needed to determine the degree of impact on LCOE.

The next steps for this project are:

- Disseminate the workshop summary (this report) to the public

- Produce a public Request for Information (RFI) to solicit further input to this project
- Conduct modeling and analysis (led by DNV GL), which will include:
  - Consideration of inputs obtained in workshop and RFI responses
  - Evaluation of potential benefits, challenges, and opportunities for enabling technologies
  - Quantitative assessments based on selected scenarios for U.S. wind energy projects
  - LCOE analyses for selected scenarios
  - Recommendations concerning DOE R&D funding priorities to realize significant LCOE impact

1 INTRODUCTION

The Wind Energy Technologies Office within the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), convened the Pathways to Success for Supersized Wind Turbine Blades Workshop on March 6−7, 2018, in Washington, D.C. The workshop was one step within a larger initiative to identify specific research and development (R&D) opportunities DOE could pursue to address technical barriers or implementation challenges faced by the U.S. wind energy industry to achieve continued decreases in the levelized cost of energy (LCOE).

The workshop was designed as the first step in a stakeholder engagement and Request for Information (RFI) effort to seek input from the wind energy industry about potential technology pathways to be explored that enable continued growth of larger wind turbine blades. DOE's Wind Energy Technologies Office (WETO) has initiated this project under its Big Adaptive Rotor initiative to study various new alternatives related to blade manufacturing, transportation, and field assembly of supersized blades.

Over the past 10−20 years, there have been significant advances in material science, blade design, various new manufacturing techniques, and wind industry experience with novel blade configurations intended to mitigate certain transportation limitations. In addition, transportation and power plant construction equipment and techniques have evolved as the scale of wind turbines increased and the industry acquired significant deployment experience. Past studies of wind turbine transportation logistics (WindPACT 2001) identified various hard and soft break points in turbine sizes. However, given the industry's experience base, ongoing commercial initiatives, and new technology advances, DOE is seeking to understand specific areas in which further federal R&D would best be applied to have a high impact on enabling supersized blades for the next generation of cost-competitive wind energy.

The workshop brought together a small, experienced group of 40–50 professionals representing industry stakeholders, such as manufacturers, transportation specialists, project developers, operators, engineering firms, consultants, and university researchers. Technical experts from the national laboratories and WETO were also present to engage in deep discussions about solving the challenges faced by supersized wind turbine blades.

2 WORKSHOP ORGANIZATION

The DOE began the workshop effort by assembling a workshop planning team that included members from select national laboratories and two consulting firms. The team was tasked with developing the workshop process and agenda, identifying presenters for select sessions, identifying experts and industry contacts to the DOE for invitation to the workshop, and developing preparatory materials for the workshop. Workshop planning and implementation efforts were conducted in January and February 2018.

The workshop was structured around the following activities:

- Presentations about the latest national laboratory and industry research on the opportunities and potential impacts associated with continued upscaling of turbines and related blades.
- Attendees sharing their perspectives with other experts on the strengths and weaknesses of potential pathways to achieving ultra-large blades, including advanced transportation and logistics solutions, on-site manufacturing options, and hybrid solutions, such as segmented and modular blades designed for on-site assembly.

- Attendees providing their viewpoints on what the highest value areas are for DOE R&D investment to address challenges identified in the workshop sessions.

Workshop participants focused on documenting ideas, concepts, and information needed for further study. They did not judge, evaluate, rank, down-select ideas, or otherwise push toward group consensus to not violate the Federal Advisory Committee Act, which governs how federal agencies can solicit input on the direction of future programs. Facilitators and DOE monitored the sessions and did not see a need to correct workshop content or discussions. No small group break-out sessions were held; thus, all participants were able to hear the information presented and associated discussion among attendees.

The workshop planning team roster is shown in Appendix A, and the workshop agenda is shown in Appendix B. Preparatory materials developed by the workshop planning team consisted of the pre-reading document included in Appendix C.

2.1 Participants

Workshop planning team developed a list of potential attendees who were then issued workshop invitations. The 50 registrants represented tooling manufacturers, blade manufacturers, wind turbine manufacturers, material suppliers, owner/operators, construction companies, transportation companies, engineering design firms, market consulting firms, university researchers, DOE staff, and staff from national laboratories. Among attendees, representatives from Germany and the Netherlands were present. The list of registrants can be found in Appendix D.

2.2 Workshop products

The workshop resulted in two primary products:

- Presentations by panel members, invited speakers, and facilitators on selected topics setting the stage for the Pathways discussions or guidance for attendees to manage and frame discussions.
- This workshop report to be used by the DOE to conduct the upcoming Request for Information where further input from industry stakeholders who could not attend the workshop will be solicited.

3 OPEN PLENARY

The workshop began with a plenary session, which was intended to inform the participants of the overall workshop structure and objectives, as well as to provide background on the current industry status, projections for future deployment of wind energy, and benefits to the wind industry and the United States as a whole if technologies could enable cost-effective manufacture and transport of supersized blades. The overall objective of the plenary session was to provide background and context within which to frame the dialogue in the following group pathway discussions that followed.

Valerie Reed, Acting Director of WETO, opened the workshop by welcoming participants and providing perspective into DOE’s higher-level interests. Among her topics, she emphasized the importance of enabling wind energy to continue on the trajectory of lowering LCOE because it enables multiple energy options and a diverse energy supply mix for the nation. The energy landscape is highly competitive and will continue to remain competitive with the low electricity prices and energy efficiency offered by wind, solar photovoltaics, and natural gas. Options provide opportunities for new technology innovations. Seeking creative alternatives to enable significantly larger wind turbine blades in a cost-effective manner is critical with further growth of wind energy in the United States.

Patrick Gilman, Manager of WETO's Modeling and Analysis Program, introduced the workshop agenda, explained DOE's objectives for both the workshop and the overall project, outlined the current challenges and opportunities associated with supersized blades for land-based wind projects, and introduced DNV GL as the workshop facilitator and overall principal investigator for DOE on the project. All attendees introduced themselves so that everyone was aware of who was present during the sessions.

Mike Derby, Technology Program Manager of WETO, provided context and background for attendees regarding the drivers for continued wind turbine growth and efforts DOE has been leading. He noted that although wind energy technology has seen significant reductions in LCOE since 2000, the rate of generating capacity growth of land-based wind turbines and related blade lengths in the United States has tapered in recent years because of transportation-related challenges. Taller wind turbines with larger rotors expand the areas within the United States where price-competitive wind energy can be generated; provided that the transportation challenges are addressed to enable placement of supersized wind turbine blades on-site. He reminded the attendees about example R&D efforts relevant to the workshop topic, such as three-dimensional printing blade molds tested at the National Renewable Energy Laboratory (NREL) with plans to fly blades manufactured from the molds at Sandia National Laboratories' Scaled Wind Farm Technology facility; modular concrete towers and spiral-welded steel towers as examples of on-site manufacturing; and efforts made to advance modular blades incorporating spaceframe technology pursued by Wetzel Engineering. Derby presented a summary of the Atmosphere to Electrons research initiative and how rotor and control advances could enable improved energy capture and wake effect manipulation.

Eric Lantz, Modeling and Analysis Program Manager, and Johney Green, Associate Lab Director for Mechanical and Thermal Engineering Sciences at NREL presented their analysis explaining the market potential if the wind industry is able to achieve further reductions in LCOE and increase turbine sizes. The U.S. wind industry has been able to achieve a ~40% reduction in LCOE over the past 10 years as a result of increased turbine size, greater energy capture, and reduced equipment costs. Turbine size continues to be an important path for lower LCOE to access stronger winds at higher elevations and to enable installation in regions of the United States that do not presently have a significant wind energy installation capacity. The Great Lakes, Southeast, and mountain regions in particular would significantly benefit from larger turbine sizes in ~2030 and beyond. However, LCOE must decrease further, on the order of 50%, to enable continued expansion of wind generation and to compete against other low-cost technologies. If achievable, the additional U.S. market is estimated at about $1−$2 trillion.

Among the many enabling technical advances that the wind industry should consider to achieve larger blades and larger turbines, NREL noted there are significant changes in manufacturing happening at the moment and the pace of manufacturing change is increasing. In comparison to historic industrial periods, we are now in "Industry 4.0" where many ideas are being merged such as additive manufacturing, advanced materials, data science, and various methods of automation. Reexamination of the entire product cycle maybe needed based on new opportunities. Failure to think creatively, embrace change, or ignore advances in other industries could be detrimental for the wind industry. Therefore, it is important that the industry evaluate strategies such as manufacturing blades on site, evaluate all forms of transportation alternatives, and continue to investigate hybrid solutions where smaller blade components are shipped to a site and assembled.

Dan Shreve, Partner, MAKE Consulting, provided market trend information and a discussion of the competitive landscape, both from a global and U.S. market perspective. Further, the effects of competitive bidding, various subsidies, and recent tariffs on market prices that wind energy projects are expected to meet were presented. Price and performance gains for wind have been dramatic; however, the curves are flattening as certain limits in turbine size and the transportation system are being experienced. The wind industry also has a significant market challenge in 2020 as production-tax-credit-driven installations drop, and load growth is estimated to remain flat. Offshore wind deployment in the United States around this period may provide a buffer, but the scale is not expected to be as big as what land-based opportunities could be. The original equipment manufacturers (OEMs) and supply chain are highly focused on execution in the near term, (through 2020) and do not have sufficient R&D efforts to explore and solve many challenges related to supersized land-based wind turbines. MAKE outlined various trends in current blade supply and manufacturing and included a look at historic efforts related to modular blades and their results in the marketplace. As part of the discussions, it was noted that transportation innovations have been able to address the current blade sizes such that modular blades have not been a lower-cost alternative to date. It was mentioned that, if not for transportation limitations, blade length and shape would be significantly different and land-based wind turbine blades would be similar to blades currently used offshore.

Dayton Griffin, Senior Principal Engineer, DNV GL, and Steve Nolet, Principal Engineer and Senior Director of Innovation and Technology, TPI Composites, Inc., provided attendees information about current industry experience with blades in the field and manufacturing. Mr. Griffin provided a primer on engineering trade-offs in blade designs that are being made to accommodate existing transportation constraints and the related impacts on turbine performance. Relieving blade designs from transportation constraints would enable better aerodynamically optimized blade shapes consisting of larger maximum chord dimensions, more blade pre-curve, longer blade lengths, and expanded root diameters. In addition, DNV GL's experience from the field is showing about half of blade structural failures are attributed to inconsistencies in blade manufacturing quality processes. Other leading issues include edgewise vibrations, lightning damage, and hail/severe weather related strikes. Therefore, it is important that any blade manufacturing innovations implemented to achieve longer blades must also advance or enable improved manufacturing quality and consistency and address other issues noted here.

Mr. Nolet provided the blade manufacturer's perspective and offered some insight into important manufacturing metrics that we need to monitor to ensure potential innovations are economically competitive. Mr. Nolet noted that the total cost/kg of finished goods has continued to trend downward even though blade sizes have continued to grow. In terms of scalability, there is no hard limit to the blade lengths envisioned using the current resin-infusion methods. However, existing factory infrastructure and related gantry crane capacity to lift and mate blade molds is becoming a concern. He reminded attendees about the square-cube relationship of blade mass as a function of length with an exponent greater than 2. Blade mass is growing quicker than annual energy production (AEP) gains which innovation needs to consider and reduce the rate of mass growth, if possible. Numerous opportunities for expanded use of carbon fiber and pultruded materials still exist and should be considered. He noted that we already can build supersized blades, as evidenced by the blade dimensions currently utilized offshore, where transportation constraints are largely removed. Finally, limits in capacity of current blade testing facilities in the U.S. must be addressed.

4 PATHWAY GROUP DISCUSSIONS

Following the plenary session, the remainder of the two-day workshop featured three group-discussion sessions, with each session focusing on a specific “pathway” to enabling LCOE reductions for rotor blades of increasing size. Kevin Smith, Director AOM Services, DNV GL, introduced the three pathways as on-site manufacture, transport, and hybrid and alternative, which included various options involving central manufacturing of sub-elements followed by on-site assembly. Each of the pathway group discussions was opened with a short presentation from one or more invited speakers. DNV GL facilitated the group discussions and ensured that each included diverse technologies and options, as well as balanced input from stakeholder groups and individuals.

In the group discussion sessions, workshop participants went deep into identifying ideas, options, and key information needs to understand and evaluate different innovative solutions. The agenda included the following three separate sessions to stay focused on each session topic:

- On-site Manufacturing Pathway – Focused on ideas where raw materials are brought to a project site, a temporary manufacturing facility is established, and entire blades are manufactured on site.
- Transportation Pathway – Discussed current and future innovations within the transportation sector that could enable cost effective movement of thousands of full sized blades up to 100 m long to various regions across the U.S.
- Hybrid Solutions Pathway – Focused on different combinations of on-site manufacturing, on-site assembly, off-site manufacturing, and transportation to identify potential ideas from further investigation.

To ensure that different stakeholder groups were able to present their perspectives on a given topic, the facilitators actively sought information by calling on different groups. We also sought to capture information (or potential sources of information) on a range of factors to better understand the innovation alternatives, such as technical maturity, commercial maturity, breakpoints or known limits, impacts on product quality, impacts to cost of energy, energy required to produce/transport, and life cycle environmental impacts. The following summary highlights some topics raised in the group discussions.

4.1 On-site manufacturing pathway session

The on-site manufacturing pathway focused on ideas where raw materials are brought to a project site, a temporary manufacturing facility is established, and entire blades are manufactured on-site. Factors considered in these discussions included proximity of the temporary factory to the final wind projects(s), size of projects(s), duration of temporary factory presence, lead-time for erection and commissioning of factory, process validation for initial articles, lead-time requirements for blade production, workforce training, balance between local and travelling workforce, quality control, factory utility requirements, environmental impact, permitting, and community acceptance.

4.1.1 Discussion initiating speakers

Scott Carron (NREL) presented a preliminary analysis of on-site blade manufacturing. Three main variables were considered: plant mobilization (i.e., nonrecurring costs), transportation, and remote labor. Blade manufacturing cycle time was adjusted from 24 hours to 36 hours to accommodate the assumption that field manufacturing reduced efficiency. Adjustments for incorporating emerging material technology, such as thermoplastics or thermosets, were investigated. The initial findings indicated that economic breakpoints might exist in the range of 70-m to 80-m blades, but further analysis is needed.

David Champa (Ingersoll) provided insight into machine and tooling developments in additive manufacturing and noted the need for a broader industry roadmap for developing advanced tooling, materials, and processes starting with smaller blade elements and then moving to the entire blade. Current efforts to use additive manufacturing to build blade molds by DOE's Oak Ridge National Laboratory is a good beginning, but further applications are not clear at this time. Among other topics, Mr. Champa explained the importance of improving and innovating on extruders, which can apply materials unique to wind turbine blades that operate at much higher application rates than methods that are currently available. A rough target on the order of 500 pounds per hour was mentioned, which is at least one order of magnitude higher than current extruder application rates.

Discussion highlights and takeaways are summarized in the following sections.

4.1.2 Opportunities

- The primary opportunity identified was in reducing the distance and complexity of transportation route from "on-site" factory to project location.
- Developers stated they could quantify how many replacement sets were needed so the facility would not have to return to the site, thereby mitigating replacement concerns.
- Benefits to the local economy are possible as the workforce would likely be a combination of traveling staff with higher-level skills and experience, and workers hired and trained locally for lower-level skills. However, this benefit would likely be medium-term (1-3 years) for specific communities, as the factories are expected to be temporary.
- The closest examples to on-site blade manufacturing are concrete batch plants, cured and placed pipe deployed in sewer lines, and spiral welding steel tower sections for wind turbines.

4.1.3 Challenges

- On-site manufacturing from raw materials to full-scale blades was perceived as an option. Alternative material and process technologies could potentially improve the cost effectiveness of this approach; however, significant advances in automation, additive manufacturing, and fatigue-resistant materials would be needed to better enable on-site manufacturing from raw materials.
- Obtaining local land owner and local jurisdiction approvals to site and permit a temporary manufacturing facility was noted as a significant barrier. Siting and approvals for a regular wind project are currently challenging, but adding a temporary manufacturing facility was noted as an additional hurdle that may be too significant to overcome in the project development process. Given the wet chemical processes used in blade manufacturing, or other potential alternatives, air emissions were also identified as a challenge to permitting and operation.
- An on-site manufacturing facility would place demands on sourcing adequate utilities, such as electrical power, water, and sewer/waste water. The remote wind project locations would intensify these challenges.
- The logistics and lead time needed to set up an on-site manufacturing structure, verify manufacturing quality/consistence with production tests, and perform production runs such that sufficient blades are available in time for overall project construction was estimated to be considerable—potentially on the order of at least 6−12 months.

- Current additive manufacturing costs per pound were noted as being potentially significantly higher than current blade material cost per pound and a significant business case would be needed to overcome the gap for new alternatives. Additive manufacturing would need to eliminate certain process steps, enable engineering safety factors, and achieve other improvements in blade performance to be cost competitive.
- Manual labor used in current blade manufacturing ranges from 40% to 60% of the costs (and these costs are highly sensitive to market and processes fluctuations), yet the current methods achieve very high mass application rates into the molds. Current additive manufacturing mass application rates were considered much too low, therefore, new, emerging alternatives would need to be explored/examined.

4.1.4 Enabling factors

- Locating "on-site" manufacturing in a local community where industrial land may be available was mentioned as a potential limitation for seeking approvals for manufacturing on private land. Local transportation of the blades to the site would still be required, thus not completely eliminating the transportation challenges.
- Bringing segmented blade molds to a site and assembling 80-m to 100-m blade molds was mentioned as plausible. Envisioning a facility large enough to utilize multiple sets of blade molds to enable manufacturing of multiple blades was potentially challenging. Moving away from these long, one-piece molds would be important, but no current processes have been explored in sufficient detail to overcome this barrier.
- Avoiding wet chemistry and use of thermoplastics or thermosets that are stored dry was noted as a possible enabling factor.
- The discussion included alternative manufacturing concepts (beyond current blade in mold type methodology). Ideas included vertical additive manufacturing versus horizontal methods (and their feasibility); multi-headed additive manufacturing tooling; and large-scale machines (like a tunnel boring machine) wherein multiple processes are being performed simultaneously.
- It was noted that any advances that enable on-site manufacturing would likely benefit off-site manufacturing as well and maybe to a higher degree (yet transportation issues would still be a problem).

4.2 Transportation pathway sessions

The transportation pathway session focused on current and future innovations within the transportation sector that could enable cost-effective movement of thousands of full-sized blades up to 100 m long to various regions across the United States. Discussions acknowledged continual advancements in over-land transport (e.g., truck and rail) that have so far allowed cost-effective transport of blades of up to 60 m long. Dimensional constraints for over-land transportation of blades with increasing dimensions were discussed. Factors included non-negotiable constraints, such as rail tunnels and snow sheds, partially avoidable constraints, such as road overpasses and permitting rules for road transport, including variances between permissible hauling equipment in Europe and the U.S., as well as state-to-state variances within the U.S. This session also included heavy-lift aircraft as an alternative to over-land transport.

4.2.1 Discussion Initiating Speakers

Clay Gambill, Director, BNSF Logistics, opened the session describing various methods and innovations transportation companies have utilized using rail and truck modes. Adjustments have been made to blade mounts on rail cars enabling slight blade articulation without blade bending to navigate turns in rail yards. This approach has allowed the transport of up to 60-m blades. Further information about the economic parameters, train lengths, route selection, and constraint analysis was provided to better inform attendees about the challenges longer blades pose for rail transport. In addition to length, blade chord and precurve prove to be challenging for rail. Discussion of limited and controlled blade bending to achieve certain turns was discussed and some limited tests have been performed. Reaction forces from the blade into the rails, causing wheels to elevate on the track, were noted as a concern. Road transport has expected limits and concerns were discussed. However, the concept of using trailers with only one point of contact (whereby the blade root is anchored to the trailer on an articulating support that can pitch and turn to maneuver the blade around objects) was mentioned because it is used in China and other parts of the world. Apparently, United States transport regulations do not currently allow only one point of contact, thus this technique is not available for use on public roads but could be used within a project site. Also, using the blade as part of the trailer is a potential enabler, but new load cases in blade design would be needed and OEMs would need to gain confidence that this technique is repeatable in a safe manner that avoids blade damage. State-specific load permitting and variable local escort support from police continues to pose challenges and will not likely change. As blade length grows, fewer routes will be able to accommodate road and rail transport, thus delivery costs are expected to rise as extra efforts would be needed to deliver hundreds of blades.

Dr. Grant Cool, Chief Operating Officer, Hybrid HE, presented information about Lockheed Martin's LMH-1 Hybrid Airships. The LMH-1 and related airships in the series are hybrid aircraft that combine buoyancy, aerodynamic lift, powered propulsion, and a hover-craft type landing skirt. The aircraft's purpose is to provide heavy-lift cargo capabilities to remote areas as well as another general cargo transportation option that eliminates cross-modal handling. Lockheed Martin has built and flown a scaled prototype that is 80% through Federal Aviation Administration certification for their first model (LMH-1). The first commercial LMH-1 will fly in 2019 and orders are in place for delivery in 2020. The aircraft has been under development for years and four wind turbine manufacturers (among other industries) have worked with Lockheed Martin to understand the capabilities needed to mitigate transportation logistics for various wind turbine components. Unlike past efforts to utilize airships for cargo transport, Lockheed Martin has been able to move through the design, development, and certification stages, which indicates a viable business plan and strategy. This was further reinforced by Lockheed Martin's spending approximately $1 billion on the certification process.

Discussion highlights and take-aways are summarized in the following sections.

4.2.2 Opportunities (ground-based transport)

Although no hard limit on blade length transport by road and rail was clearly noted, it was observed that fewer and fewer route options become viable with blades longer than those that are currently available. Current transport systems could move one 100 m blade with sufficient planning and costs; however, moving thousands of blades at this scale over long distances was considered untenable.

4.2.3 Challenges (ground-based transport)

- Variances between federal and state, as well as state-to-state variance in permitting regulations adds significant cost and complications to transport planning and execution.

- • Current costs to transport blades by road and rail were estimated to range between $15 and $30/mile. Costs to move much larger blades would potentially be significantly higher, indicating that we are close to an inflection point in road and rail transport costs. To enable more cost-effective road and rail transport of larger blades, the use of segmented blades would need to be evaluated such that lower costs/mile could be achieved by moving multiple smaller blade elements. (See Section 4.3 for more information.)

4.2.4 Enabling factors (ground-based transport)

- Road and rail logistics companies noted that more coordination between blade designers and logistics experts could yield some additional capabilities within the current ground transportation systems. Three-dimensional constraints modeling, better articulating support systems to reposition the blade during transport, re-evaluation of blade support points, and additional load cases where limited blade flex and/or using the blade as part of the trailer were some examples for collaboration.
- Harmonization of permitting regulations across transportation routes could improve feasibility and cost of transportation, particularly in the case of routes crossing multiple states. The possibility of designated transportation “corridors” with simplified/harmonized regulations was discussed.

4.2.5 Opportunities (airships)

- The current LMH-1 airship is too small to accommodate a large-scale wind turbine blade; however, designs are in place for LMH-2 and LMH-3 airships that would be capable of carrying one or multiple blades. LMH-2 was estimated to have a load capacity of 90 tons and the LMH-3 load capacity was estimated at about 500 tons. These aircraft are approximately available in 2022 and 2025, respectively.
- The LMH-1 aims to alleviate truck transport into remote areas (for relatively standard-sized loads). The LMH-2 is oriented to move larger objects at a cost competitive with rail transport. The LMH-3 is oriented at marine-scale transport of numerous cargo containers and other oversized or extremely heavy objects at marine cost points.
- Storage, handling, and aircraft performance still requires investigation and demonstration, but based on current understanding, blade sizes and masses up to 100 m appear well within the airship cargo dimensions and load capacities. Multiple blades per airship may be possible with the LMH-3.
- Final production costs at scale are confidential, but aircraft prices were indicated as relatively low in comparison to current commercial air cargo jets and airship vessel fabrication, which use well-understood technologies. The initial price of the LMH-1 is estimated at $40 million per aircraft. The LMH-3 price was indicated at approximately $200 million. For comparison, the list price for a Boeing 777 ranges between $250 and $350 million.
- Transport cost per mile was estimated by Lockheed Martin as on the order of $.25 to $.50/ton/loaded mile. Translated to a 40-ton, 100-m blade, this would indicate costs of $10 to $20 per loaded mile, which is competitive and potentially lower than current blade transport costs.
- There were various questions and further discussion about the commercial viability, time to market, safety, helium supply, and costs associated with airships related to moving wind turbine blades. No obvious barriers were noted.
- Other details about flight paths, altitude, speed, landing areas, maintenance, weather condition envelopes, ground crews, etc. were discussed and no obvious barriers were noted.
- Transport speeds were on par with rail, road, and marine.

4.2.6 Challenges (airships)

- The biggest challenge associated with airships has been developing and proving a viable business case along with the time and capital needed to achieve certification. Given where Lockheed Martin is at in the certification process, commercial opportunities within the next few years are now realistic. The information presented indicates that airships could be viewed as viable, competitive innovations for further study to enable supersized blades.
- Takeoff and landing will require a clear and relatively flat space of up to five airship lengths in radius. Takeoff will require nonzero winds to provide lift assistance. Landing is possible in nonzero wind conditions but is improved with nonzero winds.

4.2.7 Enabling factors (airships)

- With coordination between blade designs and airship configuration and operations, it seems conceivable that larger blade chord, more precurve, and larger root dimensions could be achieved and transported with airships.
- • Given asymmetric blade mass distribution, securing blade root ends within or under the aircraft using an engineered harness or racking structure would need to be evaluated.

4.3 Hybrid pathway session

The hybrid and alternative solutions pathway focused on different combinations of on-site manufacturing, on-site assembly, off-site manufacturing, and transportation to identify potential ideas that could be explored with further investigation. While it is clear that segmentation minimizes transportation costs, the trade-offs are higher costs associated with higher weight, increased assembly costs, quality-control challenges, and maintenance of jointed connections.

4.3.1 Discussion initiating speaker

Daniel Hynum, Technical Leader, Wind Advanced Technology, GE, presented the opening session that described some history of segmented and field-assembled wind turbine blades. There have been many segmented blade paths attempted, yet barriers to gaining market acceptance and competition from transportation innovations has curtailed segmented blades. Fundamentally, joints within blades (regardless of whether they are bonded or mechanically secured) result in more blade mass and costs, also requiring other support structure elements in the turbine. Field operations are required to assemble the joints and ongoing maintenance may be required (depending on the fastener method used). There were a couple of paths for hybrid construction noted, two-piece blades, three-piece blades, and multiple blade elements. Two-piece blades with a transverse joint are viewed as a logical next progression step that addresses certain aspects of blade length. Three-piece blades would consist of a transverse joint to address length and a nonstructural chord segment to address blade width. Multiple element blades could incorporate wide-ranging ideas, from spaceframe structures to different prefabricated elements like spars, shear webs, and shells shipped to the site and assembled or “manufactured” into a complete blade. Each option trades different aspects of blade design, manufacturing, and logistics; no optimum combination is apparent based on experience to date.

Discussion highlights and take-aways are summarized in the following sections.

4.3.2 Opportunities

- Transportation companies expressed their opinion that blade elements of 47 m to 52 m long were a sweet spot for road and rail transport.
- The technology for splitting and connecting blades is available now, but the business case has not been sufficiently compelling due to competitive transportation solutions (to date). However, when considering the transportation concerns of blades of 70 m to 100 m long, the business case for segmented blades may be stronger.
- Field assembly of bonded or mechanical joints was viewed as sufficiently technically mature given that various types of blade repairs are currently handled in the field and methods would be similar.
- As long as OEMs and blade manufacturers are able to obtain design certifications of segmented blades, Owner/Operators did not see a significant barrier to acceptance of segmented blades.
- Modular blades offer potential for transportation benefits beyond that possible for 2-piece or 3-piece assemblies; however, economies realized in production and transportation of parts would need to be sufficient to offset the cost, complexity and potential added maintenance for assembled blades.

4.3.3 Challenges

Attendees were reminded of the current manufacturing trends where solutions need to avoid the cubic mass growth and that costs per kg have been continuously decreasing. It was hard to envision segmented blades not having a weight penalty while also incurring additional on-site assembly costs. Transportation costs would be reduced and blade design could be aero-optimized to improve performance, but analysis is needed to determine the degree of impact on LCOE.

4.3.4 Enabling factors

- There were various discussions about which location on the blade would be most beneficial for transverse joints and no clear opinions emerged. Some thought mechanical joints tend to perform better closer to the root and maybe bonded joints could perform better mid-span or further outboard.
- Early deployment experience indicates moderate confidence that technology risks of segmented blades could be overcome.
- As more experience with field assembly of segmented blades is acquired, some noted that a follow-on step could be limited on-site manufacturing of blade components like a D-spar, provided material and automatic manufacturing advances are achieved.
- Testing of subscale blades with alternative materials and features, such as bolted/bonded connections, is needed.

5 FUTURE DOE FOCUS DISCUSSION

The final session of the workshop, facilitated by Patrick Gilman of WETO, was a group discussion of where within the three pathways considered DOE investment in R&D could have the greatest positive impact. Discussions also included consideration of what capabilities DOE could offer to help enable industry-driven solutions. The session was introduced by suggesting various categories of DOE engagement such as convening, early-stage R&D, analysis, testing, and validation/demonstration. Administration priorities, budget and timeframe were identified as potential constraints to DOE impact.

Attendee feedback, including recommendations for DOE engagement and priorities, is summarized below according to the engagement categories listed above.

5.1 Convening

- Standardization in transportation should consider:
  - Coordination among stakeholders (required).
  - Potential for federal/state cooperation to facilitate permitting and harmonize rules for transport of large wind turbine components (particularly in current 3- to 7-year period in which cutting federal regulatory red tape is a focus of the administration).
  - Obtaining fundamental costs underlying research strategy so that transportation-related cost elements are accurately reflected in analyses of on-site manufacture and assembled blades.
- Continued coordination and hosting of meetings should involve:
  - Getting competitors and diverse stakeholders together.
  - Breaking down “silos” and facilitating synergies amongst stakeholders.

5.2 Early-Stage R&D

- Continued investment in national laboratories as part of the need to combine the ability to innovate and commercialize materials and manufacturing technologies.
- Determine the significance of incubator projects that can be grown or acquired for commercialization pending demonstrated value.

5.3 Analyses

- Analytic scenarios need to realistically evaluate large reductions in LCOE, including;
  - Predicted advancements in material and manufacturing technologies, costs, performance
  - Evolving trends for wind project asset management, including re-powering and life extension
  - Transportation regulations and potential for reducing regulatory cost barriers
  - Implications of new tax laws
  - Economic evaluation of LCOE impact from segmented blades, onsite manufacturing and/or transportation alternatives with increasing fidelity
  - Evaluation of material and process advancement (e.g. thermoplastics and additive manufacturing) in conventional offsite manufacturing, not only for onsite manufacturing or modular blades
  - Establish publicly-available cost/performance metrics for materials and processes to facilitate assessment of innovations and potential for cost-effective implementation

5.4 Testing, Validation / Demonstration

- Testing of materials and bonded and bolted connections

- Testing of subscale blades with alternative materials and features, such as bolted/bonded connections
- Demonstration of new material/process combinations, including process technologies that can reach scale (i.e., kilogram per hour of material placement) needed for large blade fabrication
- Potential shift from "safe life" to "damage-tolerant" design philosophy, with drone-based inspections, structural health monitoring, or other technologies used to reduce needed design margins and/or reduce requirements concerning fatigue performance of materials
- DOE review/coordination of in-house testing by OEMs and/or companies innovating materials in processes to facilitate industry acceptance and path to commercialization
- Value of DOE's ability to provide support from the early stage through full-scale demonstration

6 CLOSING AND NEXT STEPS

The workshop was closed by Mr. Gillman with a brief recap and outline of the next steps, which included:

- The development and public dissemination of the workshop summary (this report)
- A public RFI to solicit further input to this project
- Modeling and analysis to be led by DNV GL, with:
    - Consideration of inputs obtained in workshop and RFI responses
    - Evaluation of potential benefits, challenges, and opportunities for enabling technologies
    - Quantitative assessments based on selected scenarios for U.S. wind energy projects
    - LCOE analyses for selected scenarios
    - Recommendations concerning DOE R&D funding priorities to realize significant LCOE impact

7 WORKSHOP SUMMARY

A workshop on Pathways to Success for Supersized Wind Turbine Blades was conducted by the U.S. Department of Energy's (DOE's) office of Energy Efficiency and Renewable Energy (EERE) at the Kimpton Hotel Palomar in Washington D.C., on March 6-7, 2018. Approximately 40−50 experts and industry stakeholders came together for the event, including manufacturers, transportation specialists, project developers, operators, engineering firms, consultants, and university researchers. Technical experts from the national laboratories and WETO were also present to engage in discussions about solving the challenges faced by supersized wind turbine blades.

The workshop attendees participated in evaluating the current status of wind turbine blade design, manufacture, transportation, erection and operation, identifying constraints to cost-effective application of current technologies and methods for blades of increasing size, and discussing needs and opportunities for research, development and deployment of materials, manufacturing, structural configuration, and transportation. The workshop was one step within a larger initiative to identify specific R&D opportunities DOE could pursue to address technical barriers or implementation challenges faced by the U.S. wind energy industry to achieve continued decreases in LCOE.

Following a plenary session, the 2-day workshop featured three group discussion sessions, with each session focusing on a specific "pathway" to enabling LCOE reductions for rotor blades of increasing size. The three pathways considered were "on-site manufacture," "transport," and "hybrid and alternative," which included various options involving central manufacturing of sub-elements following on-site assembly. Each of the pathway group discussions was opened with a short presentation from one or more invited speakers, followed by an open discussion with balanced input from stakeholder groups and individuals.

Participation among the workshop attendees was considered highly productive. Experts and stakeholders were engaged throughout the sessions and offered significant insights into the challenges and potential enabling technologies for supersized blades. Discussion highlights and take-aways for the three pathways were as follows:

7.1 On-site manufacturing pathway

- On-site manufacturing has significant challenges including infrastructure requirements, permitting (especially if wet chemistry is involved), setup time, training of local workforce, and quality control/assurance.
- Alternative material and process technologies could potentially improve the cost effectiveness of this approach; however, significant advances in automation, additive manufacturing, and fatigue-resistant materials would be needed to better enable on-site manufacturing from raw materials and any materials/process advancements could be applied in offsite or hybrid/modular blades.
- Locating on-site manufacturing in a local community where industrial land may be available was mentioned as a potential limitation for projects seeking approvals for manufacturing on private land. Local transportation of the blades to the site would still be required, thus not completely eliminating the transportation challenges.

7.2 Transportation pathway

- Logistical constraints to ground-based transportation appear to have few absolutes, as it was pointed out that transportation/logistics experts (to date) have continued to innovate in ways that have avoided the necessity for segmented/modular blades or on-site manufacturing.
- Although no hard limit on blade length transport by road and rail was clearly identified, it was observed that fewer and fewer route options become viable with blades longer than those that are currently available. The system could move one 100-m blade with sufficient planning and costs; however, moving thousands of blades at this scale over long distances was considered untenable.
- Regulations for over-road transport vary by state and are, in some cases, inconsistent with federal rules. Some transportation solutions being used outside of the United States may not be allowed in the country under current regulations. Harmonization of permitting regulations could reduce barriers to cost-effective transport of large blades.
- Heavy-lift airships appear to have the capacity and performance needed to transport blades up to 100 m in length.

7.3 Hybrid and alternative pathway

- Options discussed included 2-piece, 3-piece, and “modular” (multi-piece) configurations on a continuum of increasing transportation benefits balanced by increasing cost and complexity related to onsite assembly.

- Transportation companies expressed their opinion that blade elements of 47m to 52m long were an economic sweet spot for road and rail transport.
- The technology for splitting and connecting blades is available now, but the business case has not been sufficiently compelling due to competitive transportation solutions (to date). However, when considering the transportation concerns of blades of 70m to 100m long, the business case for segmented blades may improve.
- Attendees were reminded of the current manufacturing trends in which solutions need to avoid the cubic mass growth and that costs per kilogram have been continuously decreasing. It was difficult to envision segmented blades not having a weight penalty while also incurring additional on-site assembly costs. Transportation costs would be reduced and blade design could be aero-optimized to improve performance, but analysis is needed to determine the degree of impact on LCOE.

7.4 Next steps

The next steps for this project include the following:

- The development and public dissemination of the workshop summary (current report)
- A public Request for Information (RFI) to solicit further input to this project
- Modeling and analysis to be led by DNV GL, with
    - Consideration of inputs obtained in workshop and RFI responses
    - Evaluation of potential benefits, challenges, and opportunities for enabling technologies
    - Quantitative assessments based on selected scenarios for U.S. wind energy projects
    - LCOE analyses for selected scenarios
    - Recommendations concerning DOE R&D funding priorities to realize significant LCOE impact

APPENDIX A – WORKSHOP PLANNING TEAM ROSTER

Name	Affiliation
Alexsandra Lemke	U.S. Department of Energy Wind Energy Technologies Office
Patrick Gilman	U.S. Department of Energy, Wind Energy Technologies Office
Ben Murray	U.S. Department of Energy, Wind Energy Technologies Office
Richard Tusing	U.S. Department of Energy, Wind Energy Technologies Office
Mike Derby	U.S. Department of Energy, Wind Energy Technologies Office
Dayton Griffin	DNV GL
Jennifer States	DNV GL
Kevin Smith	DNV GL
Ryan Wiser	Lawrence Berkeley National Laboratory

APPENDIX B – WORKSHOP AGENDA

Creating Pathways to Success for Supersized Wind Turbine Blades

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

MARCH 6–7, 2017 • KIMPTON HOTEL PALOMAR, PHILLIPS BALLROOM • 2121 P STREET, WASHINGTON, D.C.

Monday, March 5, 2018	
6:00 p.m.	**No-Host Happy Hour, Urbana Restaurant, Kimpton Hotel Palomar**

Tuesday, March 6, 2018	
8:00 a.m.–8:30 a.m.	**Networking Breakfast and Registration | Phillips Ballroom**
8:30 a.m.–8:40 a.m.	**Welcome & Introduction** *Speaker:* Valerie Reed | Acting Director, Wind Energy Technologies Office (WETO)
8:40 a.m.–8:50 a.m.	**Ground Rules and Agenda Review** *Speaker:* Patrick Gilman | Modeling and Analysis Program Manager, WETO
8:50 a.m.–9:00 a.m.	**Attendee Introductions** *Facilitators:* Kevin Smith and Dayton Griffin, DNV GL
9:00 a.m.–9:30 a.m.	**Background, Challenge, and Approach** *Speaker:* Mike Derby | Technology Program Manager, WETO • Why supersized rotors are critical to future cost reductions and what inhibits them today • DOE's Big Adaptive Rotor Initiative • DOE's unique role and capabilities • How this workshop and follow-on analysis will seed DOE's future investments
9:30 a.m.–10:15 a.m.	**Framing the Prize** *Speakers:* Eric Lantz | Modeling and Analysis Program Manager, NREL; Johney Green | Associate Laboratory Director for Mechanical and Thermal Engineering Sciences • What is the benefit of overcoming the challenges to continued blade scaling and what are the technology pathways we could follow to get there?
10:15 a.m.–11:00 a.m.	**Market Trends: Pushing Performance and Lowering Landed Cost of Wind Blades** *Speaker:* Dan Shreve | Partner, MAKE Consulting • Land constraints and auction systems are driving European wind turbine supply toward 65+ meter blade adoption. • In the post-PTC environment, the United States must follow suit, with more aggressive product development. • Innovative airfoil design, advanced material adoption, and a radical rethink of production processes could all revolutionize blade performance and landed cost.

11:00 a.m.–11:15 a.m.	**Networking Break**
11:15 a.m.–11:45 a.m.	**Blade Performance and Quality Trends** *Speaker:* Dayton Griffin | Senior Principal Engineer, DNV GL • Updates based on field experience, including trends affecting aerodynamic and structural performance (e.g., leading-edge erosion, lightning protection, and edgewise vibration) • Blade-related effects on operation and maintenance (cost and reliability) • Current and evolving manufacturing quality methods.
11:45 a.m.–12:15 p.m.	**Current State of the Blade Supply Industry** *Speaker:* Steve Nolet | Principal Engineer, TPI Composites • Current challenges and limitations given the cost effectiveness of current technology • Current industry trajectories—solutions currently on the way.
12:15 p.m.–1:00 p.m.	**Lunch | Urbana Restaurant | Kimpton Hotel Palomar**
1:00 p.m.– 1:45 p.m.	**Three Solution "Pathways" on a Continuum** *Speaker:* Kevin Smith | Director AOM Services, DNV GL • Potential "On-Site Manufacturing" Enablers • Potential "Transport" Enablers • Potential "Hybrid and Alternative" Enablers; novel solutions with partial offsite central manufacturing and shipment to site.
1:45 p.m.– 2:30 p.m.	**On-Site Manufacturing Pathways—Kickoff Presentation** *Speaker:* David Champa | Additive Manufacturing, Ingersoll Machine Tools
2:30 p.m.– 4:30 p.m.	**On-Site Manufacturing Pathways—Group Discussion** *Facilitators:* Kevin Smith and Dayton Griffin, DNV GL
4:30 p.m.–5:00 p.m.	**Wrap Up** *Speaker:* Patrick Gilman | Modeling and Analysis Program Manager, WETO
5:00 p.m.	**No-Host Networking Reception |Hotel Lobby, Urbana Restaurant**

Wednesday, March 7, 2018	
8:30 a.m.– 9:00 a.m.	**Welcome, Day One Recap** *Speaker:* Patrick Gilman | Modeling and Analysis Program Manager, WETO
9:00 a.m.– 9:45 a.m.	**Transportation Pathways—Kickoff Presentation** *Speaker:* Clay Gambill | Director, BNSF Logistics; Dr. Grant Cool | Chief Operating Officer, Hybrid HE
9:45 a.m.–11:45 a.m.	**Transportation Pathways—Group Discussion** *Facilitators:* Kevin Smith and Dayton Griffin, DNV GL
11:45 a.m.– 12:45 p.m.	**Lunch | Urbana Restaurant | Kimpton Hotel Palomar**
12:45 p.m.– 1:30 p.m.	**Hybrid and Alternative Pathways—Kickoff Presentation** *Speaker:* Daniel Hynum | Technical Leader, Wind Advanced Technology, GE
1:30 p.m.– 3:30 p.m.	**Hybrid Solutions—Group Discussion** *Facilitators:* Kevin Smith and Dayton Griffin, DNV GL
3:30 p.m.– 3:45 p.m.	**Break**

3:45 p.m.– 4:30 p.m.	**Future DOE Focus—Group Discussion** *Facilitator:* Patrick Gilman | Modeling and Analysis Program Manager, WETO • Where within these pathways could DOE's investment in R&D be most beneficial? • What capabilities can DOE bring to bear to help enable industry-driven solutions?
4:30 p.m.–5:00 p.m.	**Workshop Recap** *Speakers:* Kevin Smith and Dayton Griffin, DNV GL • Recap of workshop findings, expert recommended priorities, and next steps
5:00 p.m.	**Meeting Close** *Speaker:* Patrick Gilman | Modeling and Analysis Program Manager, WETO

APPENDIX C – PRE-READING DOCUMENT

CREATING PATHWAYS TO SUCCESS FOR SUPERSIZED WIND TURBINE BLADES

Pre-Read for March 6 & 7 Workshop

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Thank you for your interest and upcoming attendance at the U.S. Department of Energy's (DOE's) Wind Energy Technologies Office workshop, "Creating Pathways to Success for Supersized Wind Turbine Blades." We have prepared the following pre-reading material to accompany the workshop agenda and provide attendees some additional information about the overall project, workshop objective, expectations for attendee involvement, and post-workshop project activities.

PROJECT INTRODUCTION AND BACKGROUND

To maximize potential future cost reductions in wind technology, wind power plants will require substantially larger turbine blades to achieve increased energy production, greater capacity factors, and higher plant efficiencies, particularly at sites with low to moderate wind speeds. However, current U.S. transportation limitations, manufacturing and assembly methods, and materials all impart limitations into the design of blades deployed onshore. Certain physical constraints within the land-based transportation system result in blade designs and dimensions that are not fully optimized for performance and, as blade lengths increase, these transportation and handling limits have an increased influence on the blade design and ultimately present an impediment to lowering the cost of energy.

We know that offshore blades have been freed of their land-based transportation and handling constraints. This has beneficial results in allowing blade root diameters to increase, blade chord dimensions to expand and overall lengths being pushed out to 80–90 meters. Without the land-based handling constraints, "supersized" blade designs will able to regain some improvements in aerodynamic efficiency because blade shape can be aero-optimized. In addition, expanding the blade dimensions can result in a structurally more efficient design, such that increased blade lengths are achievable with more efficient structural configurations and more cost-effective distribution of mass in the overall structural design.

To date, designers of onshore wind turbine blades have been artfully making slight compromises in aerodynamic and structural capabilities of blades to achieve the increased blade lengths that have enabled wind energy to become a leading low-cost energy source. However, further progress of land-based wind energy in the United States necessitates new thinking in design, manufacturing, and transport of supersized blades.

DOE's Wind Energy Technologies Office has initiated this project to study various new alternatives related to blade manufacturing, transportation, and field assembly of supersized blades. Over the past 10–20 years, there have been significant advances in material science, blade design, various new manufacturing techniques, and wind industry experience with novel blade configurations intended to mitigate certain transportation limitations. In addition, transportation and power plant construction equipment and techniques have also evolved as the scale of wind turbines increased and the industry acquired significant deployment experience. Past studies of wind turbine transportation logistics (WindPACT, 2001) identified various hard and soft break points in turbine sizes. However, given the industry's experience base, ongoing commercial initiatives, and new technology advances, DOE is seeking to understand specific areas where further federal research and development would best be applied to have a high impact on enabling supersized blades for the next generation of cost-competitive wind energy.

At a high level, the DOE project will entail the following approach:

1. Engage key industry and research stakeholders in a workshop to capture current knowledge of innovative solutions, technical and/or economic barriers, manufacturing trends, time horizons, and other information available regarding on-site and offsite blade manufacturing, blade design changes, transportation solutions, and cranes.
2. Document blade dimensions necessary to achieve blade lengths up to 100 m corresponding to land-based turbines generating capacities of 5 MW per turbine or more. Refine and/or confirm current knowledge of transportation dimension and mass constraints common in areas of the United States Establish alternative blade dimensions achievable if transportation barriers are mitigated or removed and the resulting impact of turbine performance and cost of energy (COE).
3. Via a public Request for Information, investigate and capture information on on-site blade manufacturing (or assembly), offsite blade manufacturing, and transportation innovations being investigated and/or implemented by major OEMs and their key suppliers. In addition to technical methodology, information documented would attempt to include time to market, technology maturity, expected quality versus industry quality, production rates, manufacturing costs, and impacts on future O&M.
4. Capture current information on land, sea, and air transportation technologies and new developments related to moving thousands of wind turbine blades in the most cost-effective manner possible. Confirm understanding of physical transportation limits. In addition, assess crane requirements necessary to erect larger turbines with higher hub heights and longer blades as established in the turbine scaling effort.
5. Establish a technology evaluation rubric methodology and a hypothetical wind project development scenario to evaluate performance and cost of energy impacts. The project team will model selected combinations of manufacturing, transportation, and assembly approaches to quantify the range of potential LCOE improvement.
6. Analyze results to determine areas of opportunity and gaps for which further strategic R&D investment by DOE would be most beneficial in unlocking significant COE reductions not currently accessible to industry, and/or enabling industry efforts to advance faster. Deliver presentation of results for DOE and industry stakeholders to enable strategic discussions and decisions.

INTRODUCTION TO WORKSHOP

The workshop will be held in Washington, D.C., at the Kimpton Hotel Palomar from March 6–7, 2018, and will bring together a small, experienced group of 40–50 professionals representing industry stakeholders such as manufacturers, transportation specialists, project developers, and operators. Technical experts from the national laboratories and the Wind Energy Technologies Office will also be present to engage in deep discussion about solving the challenges we face as an industry today.

WHAT IS THE PURPOSE OF THE WORKSHOP?

The goal of this workshop is to facilitate an exchange of information and facts and to solicit and obtain your individual feedback to identify the most promising wind energy technology research pathways to overcome current transportation constraints to supersized blades, including required innovations, areas where industry advancements are occurring, and gaps where federal research and development investment may be needed to overcome these challenges.

WHAT TOPICS WILL BE COVERED?

The workshop is focused on identifying and documenting ideas for further consideration in the overall project related to:

- **On-site Manufacturing**—full-scale blade manufacturing at a project site or within close proximity to minimize or eliminate long-haul transport on public roads and highways.
- **Transportation Solutions**—new/innovative options for handling very large blades transported from conventional manufacturing facilities to wind energy projects. Identify ideas for handling blades sized to comply with current physical constraints and ideas for handling blades that exceed current physical constraints. Handling and transport ideas need to be cost-effectively scaled to move 10,000+ blades per year over long distances and variable terrain.
- **Hybrid Solutions**—combinations of transportation and on-site manufacturing or assembly. Optimizing cost-effective capabilities of different approaches, and what combination should be considered that could achieve a lower COE.

We expect to discuss and document key information about various enabling technologies that need further evaluation in the project. Example topics include (but are not limited to): additive manufacturing in a wide variety of forms; robotic manufacturing; modular blades; advanced materials, including thermoplastics; modified transportation equipment; and advances in airships for cargo.

WHAT SHOULD WE EXPECT TO DO DURING THE WORKSHOP?

- Hear about the latest national laboratory and industry research on the opportunities and potential impacts associated with continued scaling of turbine blades.
- Offer insight into and share perspectives with other experts on the strengths and weaknesses of potential pathways to achieve ultra-large blades, including advanced transportation and logistics solutions, on-site manufacturing options, and hybrid solutions, such as segmented and modular blades designed for on-site assembly.
- Provide your viewpoint on what the highest value areas are for DOE research and development investment.

WHAT ARE THE GROUND RULES FOR THE WORKSHOP?

During the workshop, we will be focused on documenting ideas, concepts, and information needed for further study. Although we may feel inclined to judge, evaluate, rank or down-select ideas, or otherwise push toward group consensus, it is important that we avoid such discussions so that we don't violate the Federal Advisory Committee Act, which governs how federal agencies can solicit input on the direction of future programs. Facilitators and DOE will help monitor the sessions and will advise if our discussions are trending in a direction that requires correction.

PATHWAY GROUP DISCUSSIONS

DNV GL's team will facilitate the group discussion sessions where we will go deep into identifying options and key information needs to understand and evaluate different innovative solutions. We will have three separate sessions on the agenda and will seek to stay focused on the session topic. To help make sure different stakeholder groups have their perspectives on a given topic heard, the facilitators will actively seek information by calling on different groups. We will also seek to capture information (or potential sources of information) on a range of factors to better understand the innovation alternatives, such as technical maturity, commercial maturity, breakpoints or known limits, impacts on product quality, impacts to COE, and energy required to produce.

APPENDIX D – WORKSHOP REGISTRANTS

Name	Affiliation
Santhosh K Chandrabalan	3M Renewable Energy Division
Chris King	BNSF Logistics
Clay Gambill	BNSF Logistics
Dayton Griffin	DNV GL
Jennifer States	DNV GL
Kevin Smith	DNV GL
Phillip Westerby	EDP Renewables
Tom Perley	Envision Energy
Florian Sayer	Fraunhofer
Daniel Hynum	GE Renewable Energy
Patrick Fullenkamp	GLWN, Global Wind Network
Neil Gupta	Green Dynamics
Dr. Grant Cool	Hybrid Enterprises
David Champa	Ingersoll Machine Tools
Ryan Wiser	Lawrence Berkeley National Laboratory
Mark Bolinger	Lawrence Berkeley National Laboratory
Aaron Barr	MAKE Consulting
Dan Shreve	MAKE Consulting
Doug Cairns	Montana State University
Brian Smith	National Renewable Energy Laboratory
Daniel Laird	National Renewable Energy Laboratory
Eric Lantz	National Renewable Energy Laboratory
Johney Green	National Renewable Energy Laboratory
Scott Carron	National Renewable Energy Laboratory
Dan Brake	NextEra Energy, Inc.
Jeffrey Hammitt	NextEra Energy, Inc.
Bob Norris	Oak Ridge National Laboratory
Brian Post	Oak Ridge National Laboratory
Dominic Lee	Oak Ridge National Laboratory
Dr. Tim Unruh	Office of Energy Efficiency and Renewable Energy | U.S. Department of Energy
Dinesh Barway	Piasecki Aircraft Corp

Name	Affiliation
Darren Ellam	Pontis Engineering
Brian Naughton	Sandia National Laboratories
Josh Paquette	Sandia National Laboratories
Thomas Rice	Sandia National Laboratories
Jacques Nader	SIEMENS Gamesa
Steve Nolet	TPI Composites, Inc.
Alexsandra Lemke	U.S. Department of Energy Wind Energy Technologies Office
Liz Hartman	U.S. Department of Energy, Wind Energy Technologies Office
Ben Murray	U.S. Department of Energy, Wind Energy Technologies Office
Michael Hahn	U.S. Department of Energy, Wind Energy Technologies Office
Mike Derby	U.S. Department of Energy, Wind Energy Technologies Office
Patrick Gilman	U.S. Department of Energy, Wind Energy Technologies Office
Valerie Reed	U.S. Department of Energy, Wind Energy Technologies Office

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Combining leading technical and operational expertise, risk methodology and in-depth industry knowledge, we empower our customers' decisions and actions with trust and confidence. We continuously invest in research and collaborative innovation to provide customers and society with operational and technological foresight. Operating in more than 100 countries, our professionals are dedicated to helping customers make the world safer, smarter and greener.