SUPERSIZED WIND TURBINE BLADE STUDY

R&D Pathways for Supersized Wind Turbine Blades

Lawrence Berkeley National Laboratory

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[1] Effective 27 August 2018, DNV KEMA Renewables, Inc. was merged into DNV GL Energy USA, Inc.

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Abbreviation	Meaning
AEP	Annual Energy Production
ATS	Anderson Trucking Service, Inc.
BNSFL	BNSF Logistics – a Berkshire Hathaway Company
BoP	Balance of Plant
C&I	Commercial & Industrial
$C_{P,max}$	Maximum Power Coefficient
dBA	Decibels
DNV GL	DNV GL Energy USA, Inc.
DOE	Department of Energy
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IRS	Internal Revenue Service
L	Blade length
L_b	Baseline blade length
LCOE	Levelized Cost of Energy
LTA	Lighter than air
LWST	Low Wind Speed Turbine
MWST	Moderate Wind Speed Turbine
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
PTC	Production Tax Credit
R&D	Research and Development
RFI	Request-for-Information
TSR	Tip Speed Ratio
TSR_D	Design Tip Speed Ratio
U.S.	United States
VG	Vortex Generator

EXECUTIVE SUMMARY

The challenge

Over the past decade, the U.S. wind energy industry has achieved significant improvements in energy production and cost efficiency driven in part by increased turbine, blade, and tower size. However, the industry is fast approaching a logistical cost and capability ceiling as turbine components become too large for existing U.S. infrastructure and transportation options to accommodate. Developing and operating a wind project is a complex optimization process that necessitates numerous trade-offs between turbine size, costs, project location, proximity to people, environmental impacts, component delivery, access to sufficient wind resource, local employment, and many other topics. As turbine component sizes increase, logistical constraints add to this challenge and can either reduce the number of developable sites or elevate costs, creating additional variables to optimize or making potential sites economically uncompetitive. Finding new solutions to logistical challenges associated with ever-larger components can enable the industry to achieve optimal wind levelized cost of energy (LCOE) options in every U.S. region.

Introduction

Lawrence Berkeley National Laboratory retained DNV GL Energy USA, Inc. ("DNV GL") to study the key challenges associated with manufacturing and deploying next generation, increasingly larger, land-based wind turbine blades. This study includes quantitative analyses exploring the costs and benefits of three potential pathways to enable use of wind turbine blades that are too large to be transported using traditional methods on existing road and rail infrastructure. The three innovation pathways considered in this study are: innovative transportation, segmented (hybrid) blades, and on-site manufacturing. Analysis of these pathways is intended to ultimately identify unique, high-value research and development (R&D) the U.S. Department of Energy (DOE) could undertake to enable use of "supersized" blades. We performed the analysis by extending current technologies beyond their business-as-usual trajectories to seek insights into areas where R&D could accelerate technology shifts, however, we did not endeavor to identify a full suite of truly disruptive innovations or paradigm shifting science. This study is also not intended, nor should it be interpreted as selecting a "best" or "preferred" innovation pathway. The study focuses on wind turbine blades and is not a detailed study of alternative wind turbine design or an optimization study intended to close specific knowledge gaps.

In 2018, DOE initiated the Big Adaptive Rotor project, which seeks to identify rotor technologies and turbine design configurations needed to enable the next generation of high capacity factor wind plants. This supersized wind turbine blade study is a task of the Big Adaptive Rotor project and will serve to inform the design parameters and research directions for the project.

Specific elements of this study scope include:

- Workshop to solicit project input, conducted 6-7 March 2018 in Washington DC [1]
- Public Request-for-Information (RFI), issued 8 May 2018
- Development of bounding assumptions and modeling scenarios
- Development of turbine system models for increasing turbine/rotor sizes

- Modeling of blade dimensions, cost, weight, and power performance for various sizes and design/manufacturing options
- Development of cost data and logistical breakpoints for various transportation methods, on-site manufacturing, and hybrid scenarios
- Modeling of LCOE for selected scenarios
- Development of recommendations concerning DOE R&D funding priorities to realize supersized blades and significant LCOE impact

Land-based transportation infrastructure, primarily road and rail networks, has been used exclusively to enable off-site factory manufacturing of all wind turbine components with economically competitive transportation and delivery logistics. As wind turbine components and blades have increased in size over the past 30 years, the transportation industry has developed various innovative solutions to manipulate these oversized and overweight loads across the nation. Thus far, wind turbine scale increases combined with the related transportation and delivery costs, have been able to achieve declining LCOE. However, achieving the next generation of supersized turbines (necessary to both unlock lower energy costs and expand wind energy development potential) requires further R&D to address new challenges of scale, manufacturing, and delivery.

Today, the transportation industry and local infrastructure are handling large-scale wind turbines with the following broad dimensions:

- Rotor diameters: up to 134 m
- Blade lengths: up to 67 m
- Hub heights: up to or even beyond 100 m (consisting of multiple steel tube sections of ~20 m long)
- Drive train system: up to 3-4 MW

Turbines of this size are primarily being deployed across the central U.S. where existing road and rail networks are more capable of conveying oversized components. Transportation of current large-scale turbines through the northeastern U.S. and Rocky Mountain regions has been increasingly difficult both technically and economically due to physical constraints associated with older infrastructure and mountainous terrain features, respectively. It is common for components in these regions to enter via a regional port to reduce overland transportation distances.

The ability of transportation solutions to deliver blades larger than 65 m is of growing concern. There are efforts underway to plan delivery of blades in the 70 m+ range; however, the routing and equipment is increasingly specialized and added costs are being incurred for new or modified trailers, road modifications, increased road closures, police escort requirements, etc. Therefore, the industry is now at a logistical cost and capability ceiling in terms of feasible blade length for transport, with approximately 75 m as the perceived limit without more aggressive innovations.

Analysis approach

The core approach of this study is a quantitative evaluation of the manufacture, transport, and erection of land-based wind turbines for blade lengths ranging from 65 m to 115 m. Detailed system-level cost modeling was performed for the baseline (65-m blade) wind turbine; subsequent analysis for larger turbines focused on the cost to manufacture, transport, and install blades in the range of 75 m to 115 m, with impact on LCOE as the primary metric.

As constraints exist to cost-effective scaling of current conventional manufacturing and transportation technologies within this size range, alternatives were identified and evaluated. These alternatives are designated as "Pathways," with three major categories identified for evaluation in this study:

1. Innovative transportation: Continued scaling-up of current manufacturing approach – monolithic blades with two scenario variants;

   - Dimensional constraints of the blades as needed to facilitate long-haul transportation by truck or rail. Blade width and height are constrained due to significant barriers such as overpass and tunnel clearances with innovations including limited and controlled blade bending to enable increasing component lengths.
   - Blade dimensions unconstrained with nonconventional transportation such as lighter-than-air (LTA) hybrid airships.

2. Hybrid solutions (segmented blades): These include segmented or modular blades, with major components within dimensional constraints that are manufactured with conventional methods and assembled on-site.
3. On-site manufacturing: Development of temporary or short-term factories in close proximity to wind turbine projects so that long-haul transportation from factory is avoided.

Any of these three pathways may be enabled by alternative manufacturing and materials technologies. Examples include additive manufacturing, thermoplastic blade skins, and low-cost carbon fibers.

Given the topic of supersized blades, transportation cost is a critical variable in quantifying any cost impacts or comparing alternative approaches for blade assembly or manufacturing that may be achieved under different pathways. In many alternative solutions, avoiding (or minimizing) transportation costs is a key objective, therefore the magnitude of transportation costs become part of the "budget" available to alternative scenarios. Transportation costs are also highly sensitive to the point of origin, destination, and selected route.

For this study, a series of assumptions and hypothetical facilities were developed to enable the analysis. These assumptions were intended to reflect both current industry characteristics and future development opportunities if supersized land-based turbines are realized. Results of the analysis are highly sensitive to the assumptions and our work is intended to be adaptable to enable analytical updates as market conditions change. Thus, the report intentionally endeavors to be transparent in all calculations. Figure ES-1 illustrates the hypothetical configuration of the manufacturing facilities and project locations used in this study.

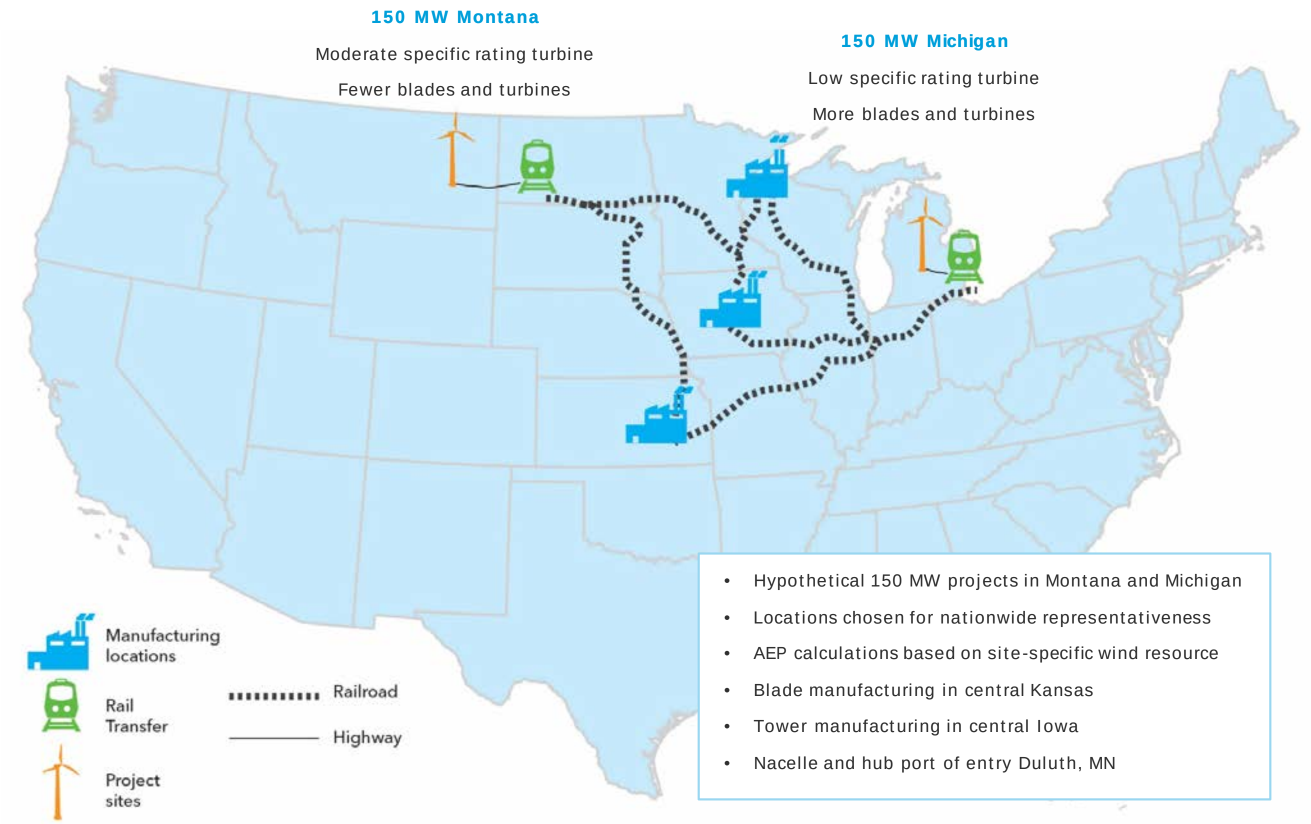

Figure ES-1 Hypothetical configuration of the manufacturing facilities and project locations

DNV GL identified and modeled two classes of wind turbines to represent current and possible near-future industry practice for optimizing turbine design to site conditions. These include a "Low Wind Speed" turbine (LWST) and a "Moderate Wind Speed" turbine (MWST) with specific power of approximately 150 W/m^2 and 225 W/m^2, respectively. These characteristics are roughly aligned with current and potential near-future competitive turbines in the U.S. market and correspond to International Electrotechnical Commission (IEC) design classification of III and II, respectively. The primary turbine blade, rotor, tower, and site wind speed parameters are given in Table ES-1. LWSTs (specific power of ~150 W/m^2) are assumed to be used at the hypothetical Michigan site, and MWSTs (specific power of ~225 W/m^2) are assumed to be used at the hypothetical Montana site. For a given rotor size, the blade designs between the LWST and MWST are unchanged; only the generator rating is modified to achieve the specific power target.

While this approach was selected as a simplification for the purposes of this study, DNV GL considers it to also be a reasonably good approximation of industry trends. Blades intended for higher-wind sites will typically have structural design dominated by peak load cases, whereas lower specific-power turbines designed for lower wind-speed sites may be more influenced by fatigue loading due to the use of relatively longer blades.

Table ES-1 Primary rotor/turbine configuration parameters

Turbine ID	Blade Length (m)	Turbine quantity	Rotor Diameter (m)	Tower Height (m)	Specific Rating (W/m^2)	Generator Size: (MW)	Average Wind Speed at Hub (m/s)
Baseline	65	71 (MI) 46 (MT)	134	100	150 (MI) 225 (MT)	2.10 (MI) 3.25 (MT)	7.21 (MI) 7.95 (MT)
WTG-75	75	54 (MI) 35 (MT)	154	110	150 (MI) 225 (MT)	2.75 (MI) 4.25 (MT)	7.38 (MI) 8.12 (MT)
WTG-95	95	33 (MI) 22 (MT)	194	130	150 (MI) 225 (MT)	4.50 (MI) 6.75 (MT)	7.69 (MI) 8.42 (MT)
WTG-115	115	23 (MI) 15 (MT)	234	150	150 (MI) 225 (MT)	6.50 (MI) 9.75 (MT)	7.92 (MI) 8.65 (MT)

DNV GL performed detailed blade structural and cost modeling to derive blade-specific estimates for use in this study. Table ES-2 provides a summary of the estimated weight and cost for both monolithic and modular (segmented) blades produced in a traditional off-site factory. The weight and cost adders for modular blade components range from about 11.5% to 14.5% of the monolithic 75 m and 115 m blades, respectively.

Table ES-2 Summary weight and cost for off-site monolithic and modular blades

Blade Length (m)	Radius (m)	Monolithic		Spanwise Joint		Root Cuff		Segmented Blade	
		Mass (kg)	Cost	Mass (kg)	Cost	Mass (kg)	Cost	Mass (kg)	Cost
65	67	18,640	$194,788	N/A	N/A	N/A	N/A	N/A	N/A
75	77	25,314	$264,531	2,905	$30,252	N/A	N/A	28,219	$294,783
95	97	42,071	$439,638	4,828	$50,277	370	$4,479	47,268	$494,394
115	117	63,546	$664,059	7,292	$75,942	1,857	$20,827	72,695	$760,828

Blade-specific LCOE was then calculated for the Baseline turbine using the Total Cost of Delivered Blade, Turbine Annual Energy Production (AEP), blade specific operations and maintenance (O&M) cost, and fixed charge rate (7.9%). Then, holding the Baseline blade-specific LCOE as a constant and adjusting for scaled manufactured blade costs and AEP for each of the study turbines, a “Total Cost of Delivered Blade Target” was derived for the 75 m, 95 m, and 115 m blades. In calculating this Target, impacts of taller hub heights, larger swept area, and increased wind speeds associated with larger wind turbines are accounted for in the AEP for each turbine.

The Target represents the threshold or “budget” for pathways to compete. Pathways that result in Total Delivered Blade Costs that are more or less expensive than the Target value will influence the blade’s contribution to overall system LCOE accordingly. Pathways equal to the Target have no impact on system level LCOE but may still enable LCOE improvements in other turbine systems.

Figure ES-2 presents the calculated Total Cost of Delivered Blade Targets for each of the project locations. The cost target in Michigan is greater than in Montana due to older infrastructure, increased number of local jurisdictions to travel through, and other transportation costs in the Great Lakes region being slightly more expensive than similar costs in Montana.

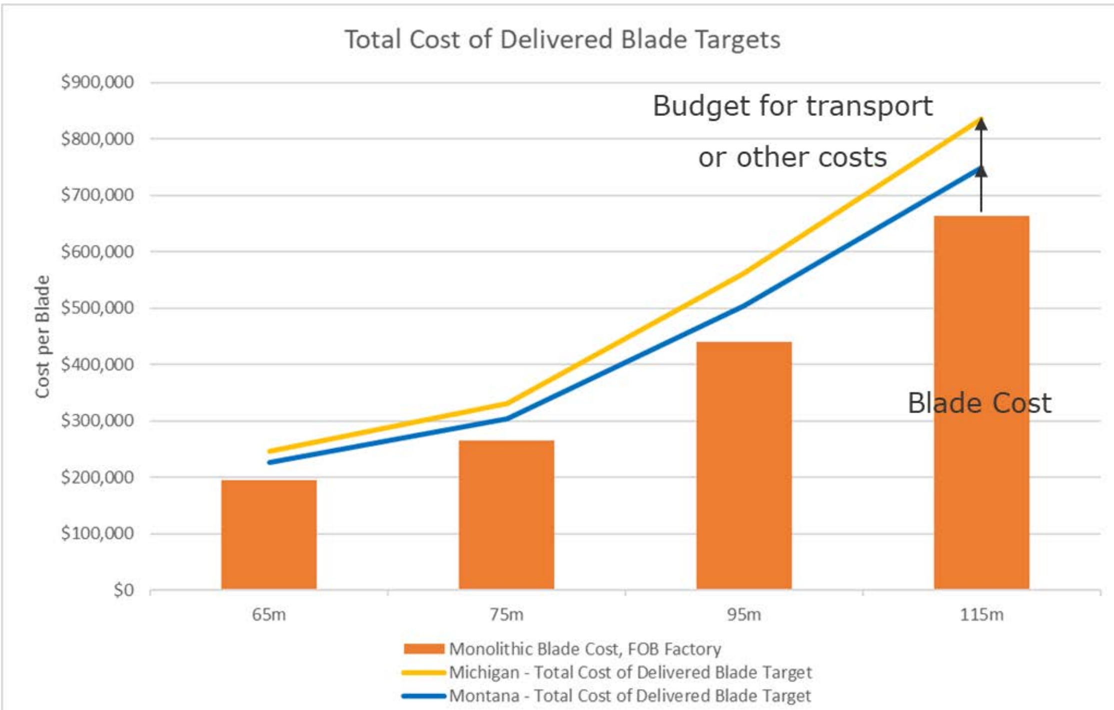

Figure ES-2 Calculated total cost of delivered blade targets

Key findings

Figure ES-3 and Figure ES-4 summarize our estimates of the total costs of delivered blades by innovation pathway at the hypothetical projects in Michigan and Montana, respectively. The target values indicated on these figures correspond to the point at which total delivered blade costs have no impact on increasing or decreasing the system LCOE. Values below the target indicate an opportunity to help lower system LCOE, whereas values exceeding the target indicate upward pressure on system LCOE.

Figure ES-5 and Figure ES-6 summarize the percent impact on system LCOE for each of the innovation pathways at the hypothetical projects in Michigan and Montana, respectively. The impact on system LCOE accounts for total costs of delivered blades (Figures ES-3 and ES-4), plus includes AEP performance variations, O&M cost differences, and fixed charge rate effects. Whether increases in system LCOE caused by supersized blades are acceptable depends on opportunities to achieve cost savings in other turbine sub-systems. Similarly, achieving a neutral impact on system LCOE can be acceptable, provided it does not come at a cost of increases in other parts of the turbine. Thus, integrating these results into a more holistic study of supersized wind turbines is recommended.

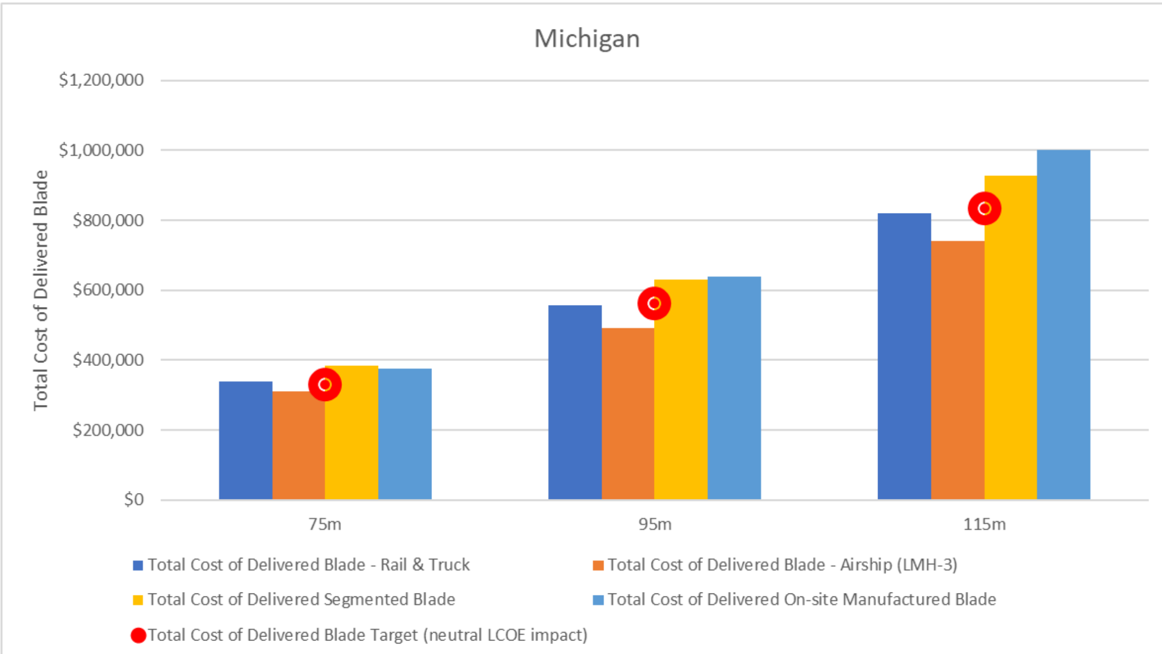

Figure ES-3 Innovation Pathway summary – Total cost of delivered blades, Michigan

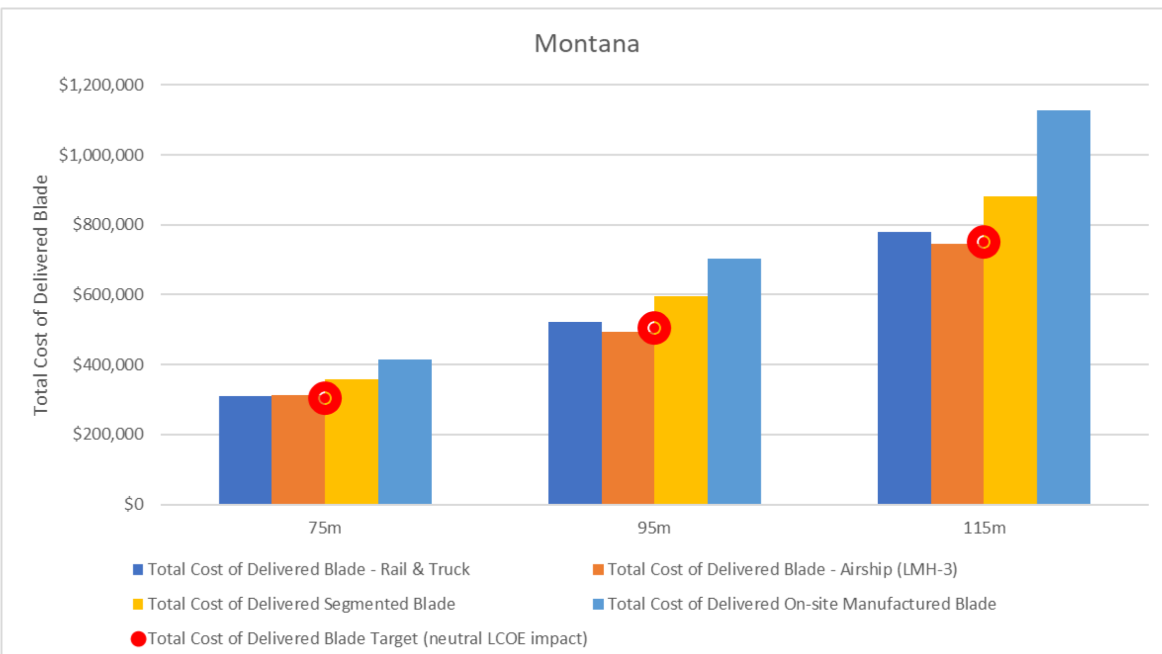

Figure ES-4 Innovation Pathway summary – Total cost of delivered blades, Montana

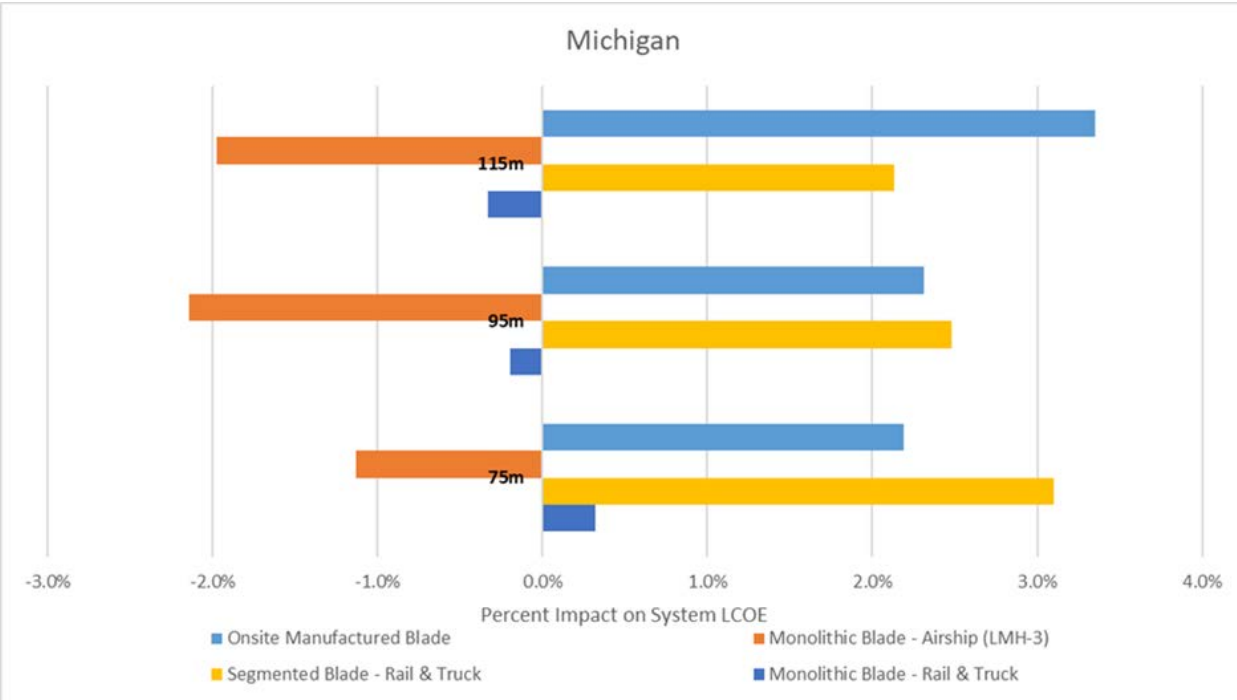

Figure ES-5 Innovation Pathway summary – Impact on system LCOE, Michigan

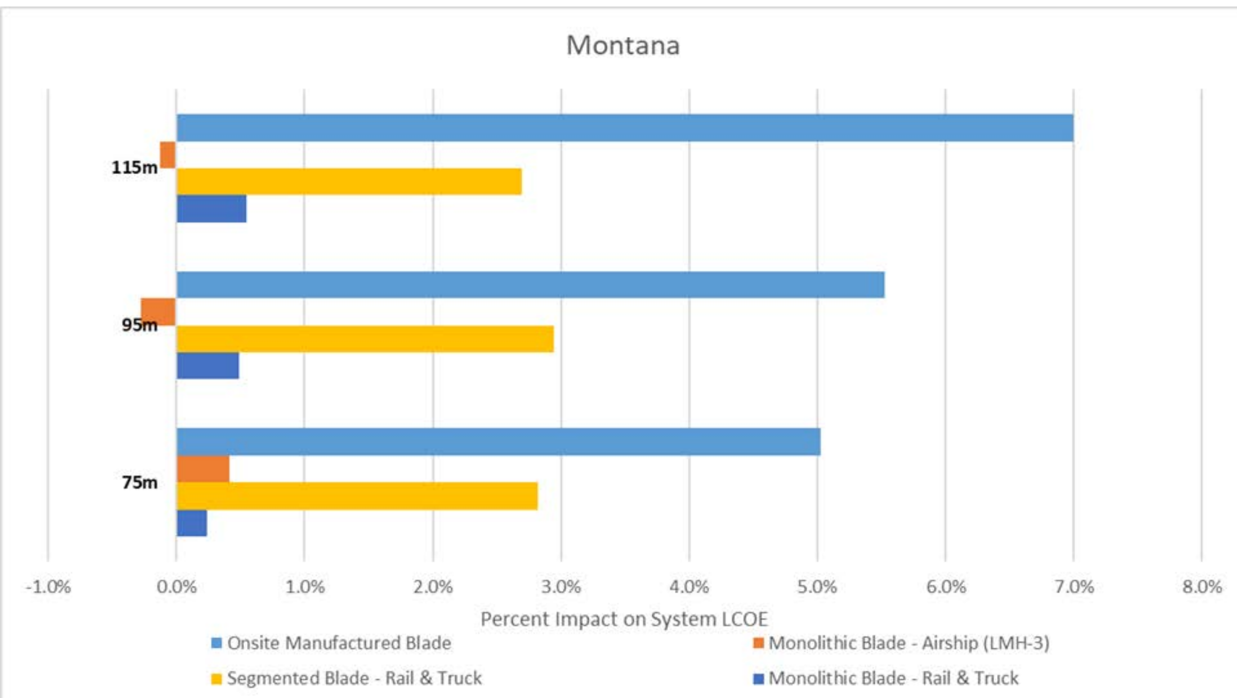

Figure ES-6 Innovation Pathway summary – Impact on system LCOE, Montana

Based on our analysis and the values summarized in Figure ES-3 through Figure ES-6, opportunities for supersized blades where blade-specific costs and performance contributed to a neutral or reduced overall system LCOE appear possible with use of LTA hybrid airships or controlled blade bending in rail transport. In other innovation pathways studied, blade-specific costs and performance contributed to increases in system LCOE indicating a broader, more systemic approach beyond just blades or different project site assumptions may be necessary to achieve lower system level LCOE.

LTA hybrid airships, under our assumptions, were identified as having potential for blade-specific costs and performance able to lower system LCOE at both project sites, ranging from -2.1% to 0.4% depending on the site and blade length. LTA hybrid airships, if certified and commercialized, have potential to enable nationwide deployment of supersized blades and wind turbines in a cost competitive manner. Although there are active commercial efforts to bring this technology to market, there is significant uncertainty in the timing and cost of this innovation option. Monitoring developments of this technology and seeking areas of collaboration to improve market development for wind energy (and other applications) is recommended due to the potential for its enabling effects for supersized turbines.

Currently, blade flexing during transport is not allowed because this loading method has not been established in the blade design and transport infrastructure has not been developed to enable it. R&D that enables limited and controlled blade bending in rail transport plus specialized road trailers appears able to achieve a neutral impact on system LCOE, ranging from -0.3% to +0.5%. However, there are geographic limitations on where controlled blade bending could be viable, thus this area of innovation may not have the nation-wide impact needed to achieve deployment of supersized wind turbines in regions where they are most applicable. This approach could theoretically take advantage of the designed flexibility characteristics inherent in wind turbine blades, provided these loads can be accounted for in the blade design as well as the rail and road transport infrastructure. This innovation area offers an opportunity for additional study of blades, the rail system and trailers, and related infrastructure to further assess the viability, management of reaction loads caused by bending, and impact on blade fatigue life expectancy.

Segmented blades and on-site manufacturing pathways were found to increase system LCOE contribution, thus requiring greater savings in other turbine systems to achieve continued overall system LCOE reductions. Segmented blades offer features that other pathways are not currently able to provide, such as the ability to enable supersized blade deployment across the entire U.S. and blade joint solutions that are under active investigation and early deployment by major original equipment manufacturers. Other areas of innovation studied are further from market readiness. Additionally, there are likely opportunities to refine and optimize segmented blades to drive costs closer to a neutral LCOE impact, which for some regions, may be sufficient for wind deployment to be economically competitive. Segmented blades might become an optional feature available to the market along with monolithic blades and site-specific analysis would determine which option is most feasible and economically competitive.

Based on current labor-intensive blade manufacturing processes and methods, on-site (mobile) blade manufacturing faces economic challenges driven mainly by low tool/equipment utilization caused by time spent relocating and commissioning a mobile plant and elevated costs of local labor for hiring, training, plant commissioning, and first article manufacturing. These and other costs incurred each time the mobile plant is deployed represent significant challenges for any method of on-site blade manufacturing.

The simplified analysis we present to study on-site manufacturing is useful to illustrate certain observations and challenges that additional R&D into this topic should seek to address. The largest contributors to the incremental cost of on-site manufacturing correspond to high one-time (i.e., non-recurring) expenses for factory set-up, worker training, and plant commissioning. In addition, tool and equipment utilization have the largest impact on (recurring) production costs. Regardless of the new manufacturing techniques developed in the future, control and reduction of these factors are key to improving the viability of any on-site manufacturing process.

We offer the following observations as guidance for future R&D into any on-site manufacturing techniques:

- A highly automated machine process that significantly reduces labor and training costs will have increased sensitivity to tooling utilization. Thus, automated processes with high tooling costs will demand close to 24/7 utilization to avoid increasing production costs. Achieving very high machinery utilization and relocating from project to project with efficiency to avoid lengthy periods of zero production will be important.
- Decreasing reliance on local unskilled labor would reduce or eliminate training costs but would likely demand higher wages and other benefits to attract a skilled labor force willing to relocate on a regular basis. Wind plant construction today relies heavily on traveling teams of highly skilled workers, thus it can be done. Using a traveling workforce may put pressure on gaining local acceptance of the temporary on-site factory. The lack of local jobs could become an additional challenge in the project development process.
- It's a moving target. Manufacturing innovations that can improve the viability of on-site manufacturing will likely have an increased impact in off-site factories due to higher tool utilization in off-site factories.

Clearly our analysis did not account for all issues and challenges that on-site manufacturing would need to address. In our opinion, the outstanding issues and challenges would likely add to the cost of on-site manufacturing and it is possible that many project locations would not have suitable utilities, services, or the ability to gain environmental and local approvals. Comments from Owner/Operators during the stakeholder workshop noted that inclusion of on-site manufacturing into the already complex project development process adds uncertainty and could put development of an entire project at risk.

As illustrated in Figure ES-7, additive manufacturing technologies (3-D printing) have three parameters that future R&D needs to focus on to help advance this technology. Current additive manufacturing utilizes low stiffness materials not well suited for structural blade elements. Material deposition rates for the largest industrial equipment are far below current manual labor methods. Finally, the finished cost of a structure that combines material, labor and tool utilization needs to compete with off-site manufacturing production costs. For current additive manufacturing methods, the combination of needing more material (due to low stiffness) and slow deposition rates would compound to increase delivered blade costs and result in heavier blades (with corresponding related negative implications in other turbine sub-systems).

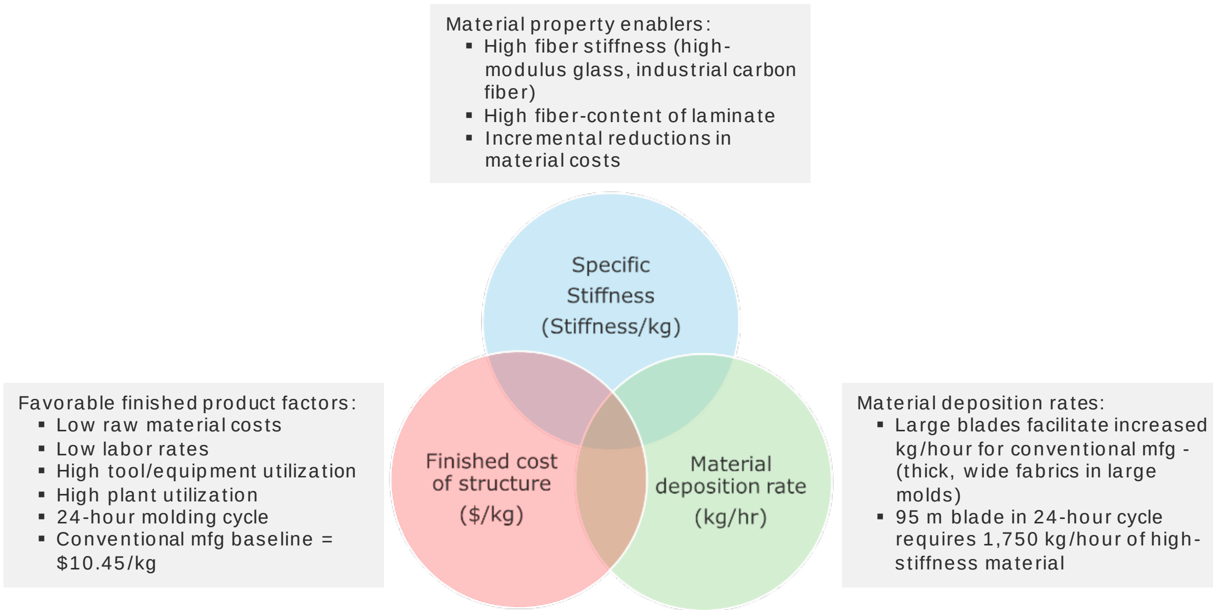

Figure ES-7 Additive manufacturing trilemma elements

Figure ES-8 summarizes the results of our pathway assessment in terms of impact on LCOE, our current opinion of commercial readiness, and geographic breadth each pathway could offer.

Blade Manufacturing, Design, and Transport Pathways	Percent Impact on Wind Project Levelized Costs from Blades Alone [%]						Commercial Readiness			Geographic Breadth
Location	Michigan site			Montana site						
Blade length	75 m	95 m	115 m	75 m	95 m	115 m	75 m	95 m	115 m	all lengths
Innovative rail/truck transport; centralized traditional manufacturing	+0.3	-0.2	-0.3	+0.2	+0.5	+0.5	●	◖	◖	◖
Airship transport; centralized traditional manufacturing	-1.1	-2.1	-2.0	+0.4	-0.3	-0.1	○	○	○	●
Segmented blades with on-site assembly; centralized manufacturing; rail/truck transport	+3.1	+2.5	+2.1	+2.8	+2.9	+2.7	●	◖	◖	●
On-site manufacturing of full monolithic blade	+2.2	+2.3	+3.3	+5.0	+5.5	+7.0	○	○	○	◖

Key:

Commercial Readiness:	Geographic Breadth:
● = Commercially ready today ◖ = Commercially ready in ~5 years ○ = Not commercially ready or readiness uncertain	● = Deployable Nationwide ◖ = Deployment limited to central & southern U.S.; mountains, and east coast unlikely

Figure ES-8 Pathway assessment summary

Conclusions

Based on the pathway analysis and findings, our industry understanding, and familiarity with U.S. DOE national laboratory core competence, we identified a number of high value R&D topics that could be pursued to enable development of supersized blades. It is important to note that many R&D topics are viewed as having benefits that could be applied to support some or all of the pathways studied. As mentioned previously, this project is not intended to “select a pathway”, thus high-value R&D topics are ones that have a significant impact across multiple pathways and leverage areas where U.S. DOE has strong competence, unique facilities, capacity to take high risks, and a long-term view.

Figure ES-9 presents DNV GL’s identification of R&D topics that could enable supersized blades. We cross-reference these topics to each innovation pathway and indicate our judgement on the degree of impact a given R&D topic would have on enabling or addressing challenges in a given pathway. The pathways are ordered in terms of potential impact for lowering LCOE. Finally, we apply our judgement on DOE laboratories’ ability to impact and advance the given R&D topic.

	R&D Pathway Enabling			
R&D Topic	1. Innovative transportation	2. Hybrid solutions (segmented blades)	3. On-site manufacturing	Core DOE Lab competence
Aerodynamic design (lift-enhancing)	✓✓✓	✓✓	✓	✓✓
Rotor configuration options (e.g., downwind)	✓✓	✓	✓	✓✓✓
Advanced aeroelastic modeling (dynamic stability, deflections)	✓✓✓	✓✓	✓✓	✓✓✓
Advanced controls / sensor technologies	✓✓✓	✓✓✓	✓✓	✓✓✓
Blade leading-edge erosion	✓✓✓	✓✓	✓✓	✓
Blade / rotor aeroacoustics	✓✓✓	✓✓✓	✓✓	✓✓
High-stiffness / low-cost materials (e.g., industrial carbon fiber)	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Structural joint technology		✓✓✓		✓
Thermoplastic materials (mechanical properties)	✓	✓✓✓	✓✓	✓
Thermoplastic materials (fabrication and joining)	✓	✓✓✓	✓✓	✓
Robotic fabrication (including additive manufacturing)	✓✓	✓✓	✓✓✓	✓✓
High-capacity airship development	✓✓✓			

LCOE Opportunity: High ⟷ Low

Key:	
✓✓✓	Strong impact
✓✓	Moderate impact
✓	Low impact

Figure ES-9 R&D topics to enable supersized blades

ACKNOWLEDGEMENTS

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1 INTRODUCTION

Lawrence Berkeley National Laboratory retained DNV GL Energy USA, Inc. ("DNV GL") to study the key challenges associated with manufacturing and deploying next generation, increasingly larger, land-based wind turbine blades. This study includes quantitative analyses exploring the costs and benefits of three potential pathways to enable use of wind turbine blades that are too large to be transported using traditional methods on existing road and rail infrastructure. The three innovation pathways considered in this study are: innovative transportation, segmented (hybrid) blades, and on-site manufacturing. Analysis of these pathways is intended to ultimately identify unique, high-value research and development (R&D) the U.S. Department of Energy (DOE) could undertake to enable use of "supersized" blades. This study is not intended, nor should it be interpreted as selecting a "best" or "preferred" innovation pathway. The study focuses on wind turbine blades and is not a detailed study of alternative wind turbine design or an optimization study intended to close specific knowledge gaps.

This project provides supplemental information for use in DOE's Big Adaptive Rotor project, led by Sandia National Laboratory. The Big Adaptive Rotor project is a detailed study of alternative wind turbine designs and systems. This report presents the results of DNV GL's analyses and recommendations; it does not necessarily represent the opinions of the U.S. DOE or consensus among various national laboratories.

1.1 Objective and scope of study

The primary objective of this study is to develop insights and recommendations into areas where further federal R&D would have the greatest impact on enabling supersized blades for the next generation of cost-competitive wind energy. Specific elements of this study scope include:

- Workshop to solicit project input, conducted 6-7 March 2018 in Washington DC [1]
- Public Request-for-Information (RFI), issued 8 May 2018
- Development of bounding assumptions and modeling scenarios
- Development of turbine system models for selected turbine/rotor sizes
- Modeling of blade dimensions, cost, weight, and power performance for various sizes and design/manufacturing options
- Development of cost data and logistical breakpoints for various transportation, on-site manufacturing, and hybrid scenarios
- Modeling of levelized cost of energy (LCOE) for selected scenarios
- Development of recommendations concerning DOE R&D funding priorities to realize supersized blades and significant LCOE impact

1.2 Report organization

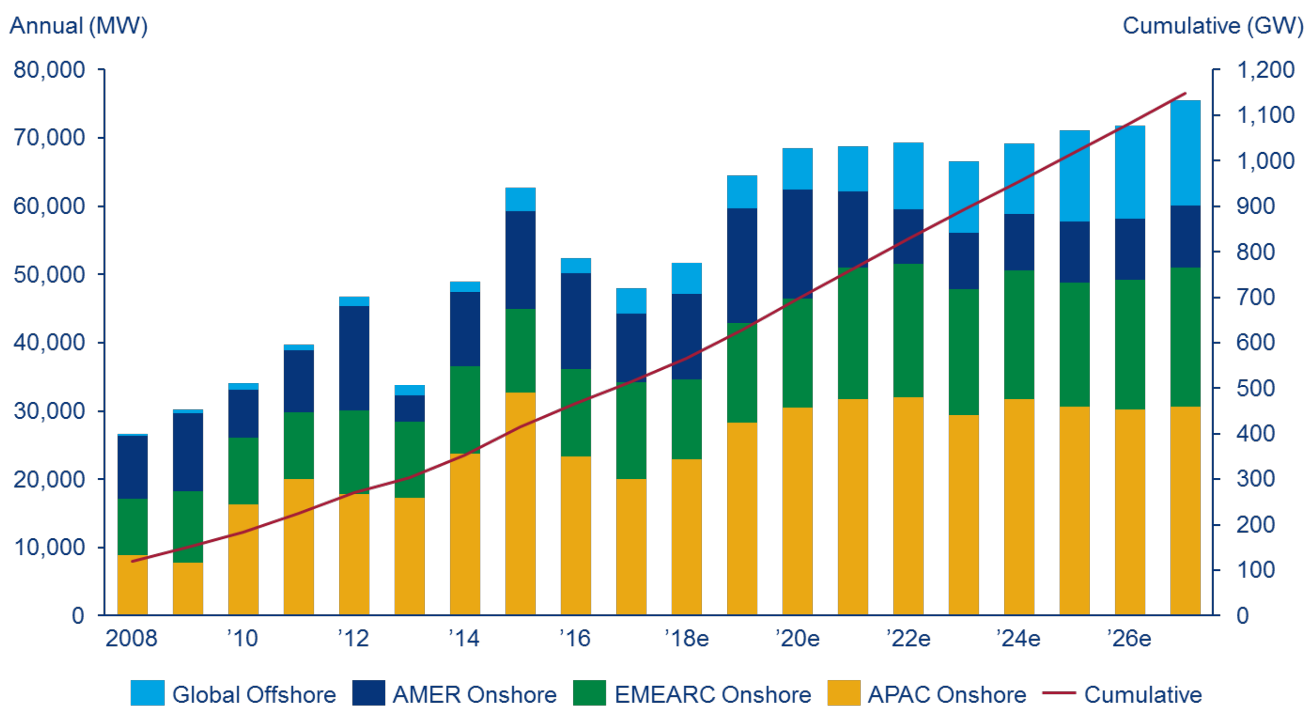
Section 2 provides background on the current blade market and scaling trends including barriers and constraints. Section 3 describes the study approach. Section 4 describes the modeling assumptions and scenarios used in this study. Sections 5 through 7 take a deeper look at blade aerodynamic modeling, blade structural and cost modeling, and blade manufacturing and transportation considerations, respectively. Section 8 presents a detailed analysis of each potential pathway. Section 9 presents DNV GL's observations and conclusions and Section 10 presents DNV GL's recommendations for potential DOE R&D into this topic.

2 BACKGROUND

2.1 Market trends

The global wind energy market has experienced significant growth over the past decade, driven by the increasing cost-competitiveness of wind energy and policy momentum to de-carbonize electricity supply. Figure 2-1 illustrates the rapid growth in global wind power installations, and Wood Mackenzie's outlook for the next 5 years.

The U.S. market has experienced multiple demand peaks and valleys, following decades of one- and two-year extensions of the Production Tax Credit (PTC) that has kept the U.S. wind industry in a state of continuous flux. The latest extension of the PTC in 2015 and a subsequent 2016 Internal Revenue Service (IRS) guidance brought unprecedented clarity to the wind development pipeline. U.S. wind developers now have four years to complete projects once PTC-qualified and enjoy a multi-year phase-out window that gives developers certainty about the terms of their tax treatment for projects grid-connected as late as 2023.

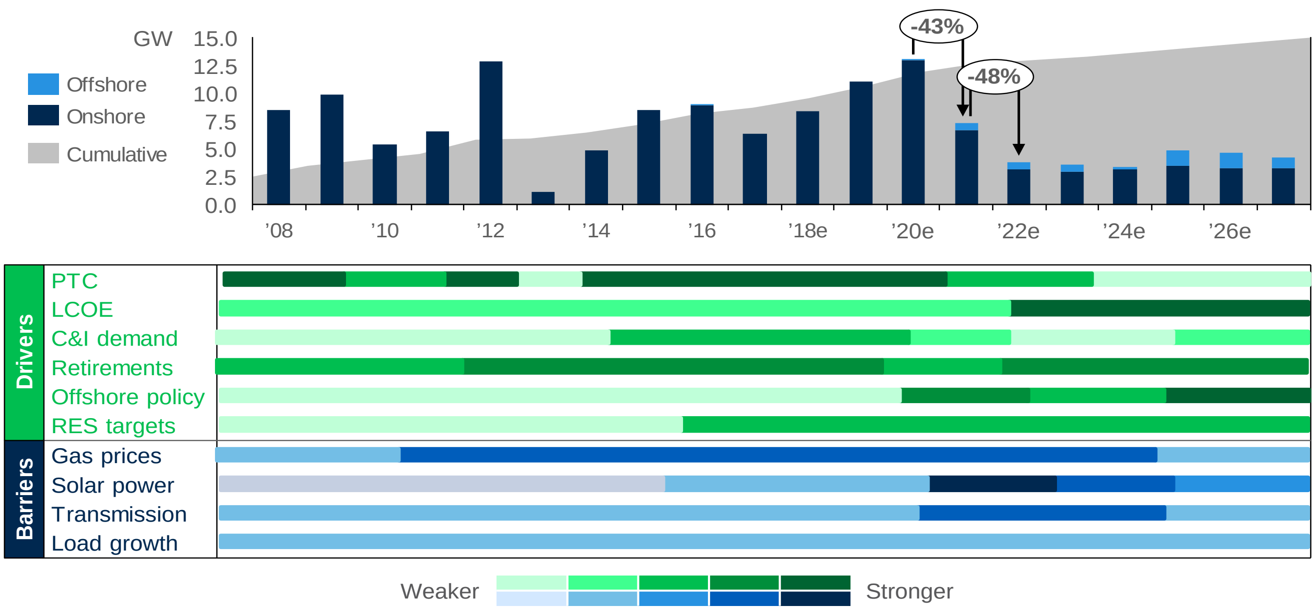


Note: Based on Q4 2018 Market Outlook Update (MOU)
Source: Wood Mackenzie

Figure 2-1 Global wind energy market

As illustrated in Figure 2-1 above, Wood Mackenzie forecasts that 2020 will be a record year for the U.S. wind energy industry, with nearly 12 gigawatts (GW) installed in the last year of full-value PTC, prior to the phase-out of the incentive. Annual wind installation volumes will begin to decline as the phase-out begins, though projects built in 2021 with access to the 80% PTC will remain cost-competitive with solar photovoltaic (PV) and gas capacity in several states.

Figure 2-2 illustrates the drivers and barriers to future wind energy development within the U.S. Drivers influencing wind capacity installations in the forecast period include state-level policies focused on carbon reduction, sustained interest from the commercial and industrial (C&I) sector, and increasing cost-competitiveness of wind power. Primary barriers to wind deployment after 2020 include plummeting costs of solar PV power, limited electricity demand growth, and sustained low natural gas prices.



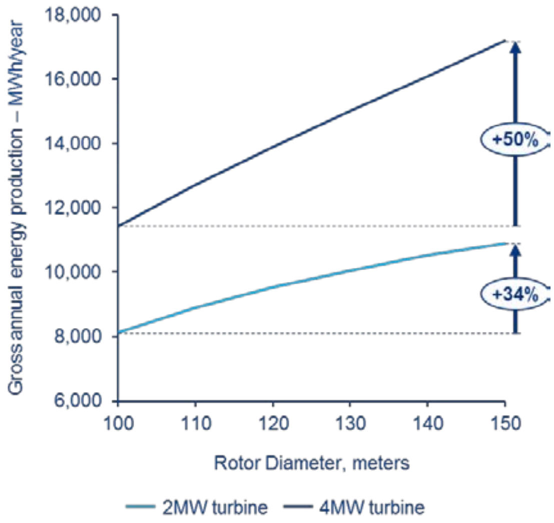
Note: The gradient bars for underlying key drivers and barriers illustrate the approximate time when each driver/barrier will influence the wind power outlook. "Retirements" refers to fossil fuel-fired power capacity retirements.
Based on 2018 Q4 Market Outlook Update (MOU)
Source: Wood Mackenzie

Figure 2-2 U.S. wind power outlook with key underlying drivers and barriers, 2018e to 2027e

Annual capacity installation volumes are expected to stabilize at an average of 4.7 GW/year from 2024 to 2027. Wind costs will continue to fall due to technology improvements, whereas wholesale electricity prices are expected to rise. This will cause utility and C&I interest in wind energy to rebound, especially in concert with continued and perhaps expanded state and federal policy measures to support renewable energy.

2.1.1 LCOE trends related to rotor size

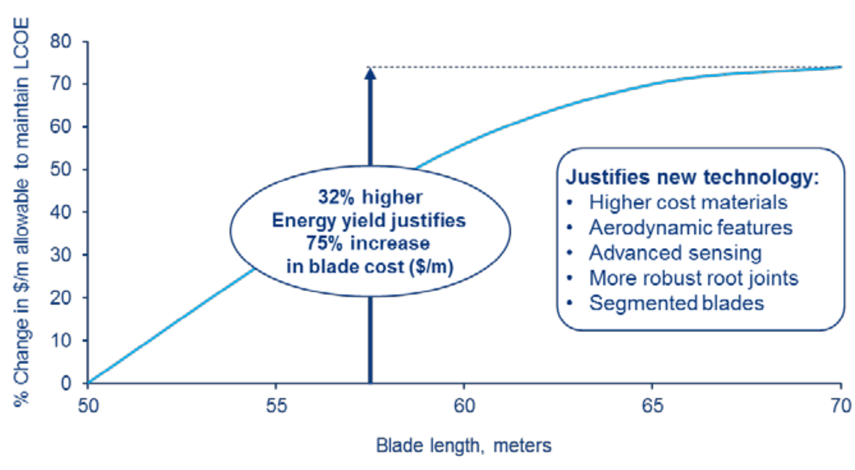
Wind energy LCOE has dropped substantially due to many factors, including a maturing supply base, intense global competition among wind turbine manufacturers, improved reliability, and technology improvements. The largest single driver of LCOE gains has been increased energy capture due to longer and more efficient blades. Figure 2-3 illustrates the effect that increasing blade length has on energy production—the most important factor for LCOE improvement.



Note: Gross energy production of scaled power curves.
Hub height wind speed maintained at 7.5 m/s
Source: Wood Mackenzie

Figure 2-3 Energy production impact of blade length

Figure 2-4 illustrates that while longer blades add cost, the cost per meter can be significantly higher for longer blades and still present a net benefit to the LCOE. This dynamic encourages investment in research and developing in blade technology to improve efficiency, reduce loading, and optimize performance.



Note: 2.5 MW turbine capacity maintained constant on 90 m tower
Non-blade costs scaled up at 10% per 10 m of blade length increase, including BOP
Source: Wood Mackenzie

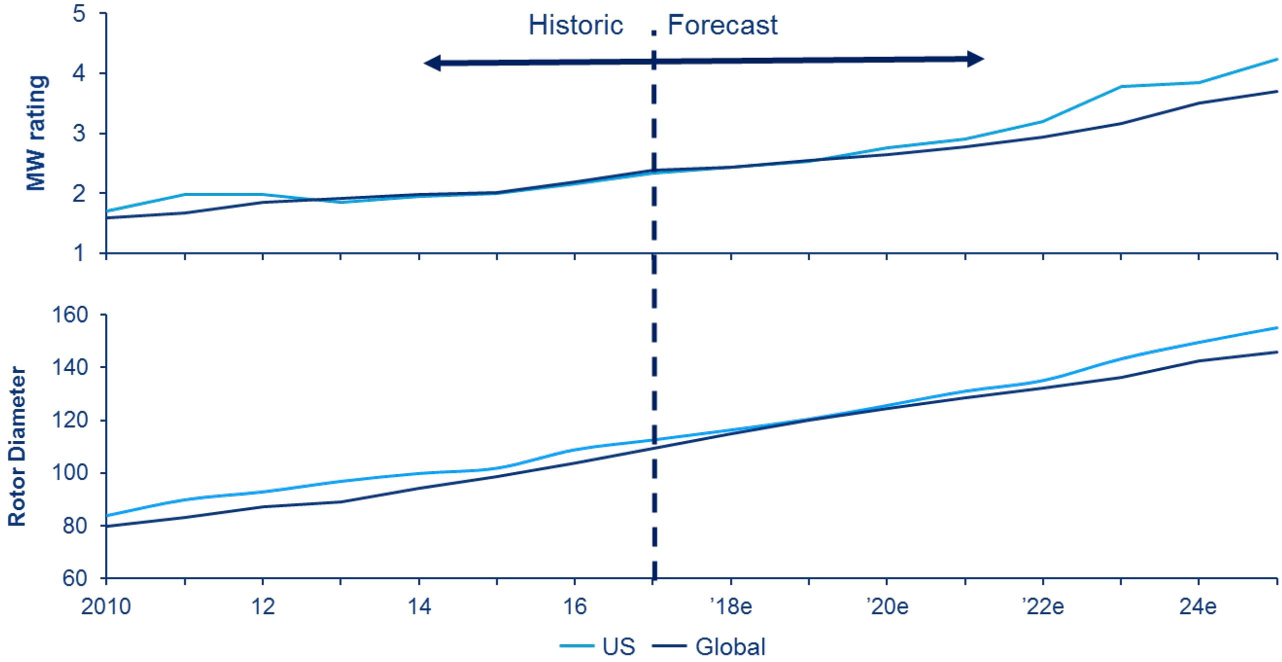
Figure 2-4 LCOE sensitivity of longer blades

2.2 Scaling trends

2.2.1 Turbine size trends

The rating size of turbines continues to escalate quickly in all global markets. Figure 2-5 shows that this growth accelerated in 2017, both in the U.S. and globally, due to increasing wind plant developer preferences for larger megawatt (MW) ratings. As the latest generation of 3-5 MW land-based turbines become more common, the supply chain has experienced significant economies of scale, leading to an overall reduction in the capital expense for these large turbines. Beyond the improved cost position of the wind turbines, larger turbines provide LCOE benefits in other areas as well. Larger turbines provide economies of scale in balance of plant (BoP) expense, as fewer turbines are required to meet farm-level MW ratings, and this results in fewer foundations and simpler roads and electrical collection networks. Larger turbines are also expected to yield significant operations and maintenance (O&M) savings, as fewer on-site technicians are needed at a wind farm with fewer turbines. While the expense related to component replacement is higher for larger turbines, primarily due to larger component sizes, the reliability of this equipment is generally expected to improve as the latest generation of turbines incorporate design and quality improvements.

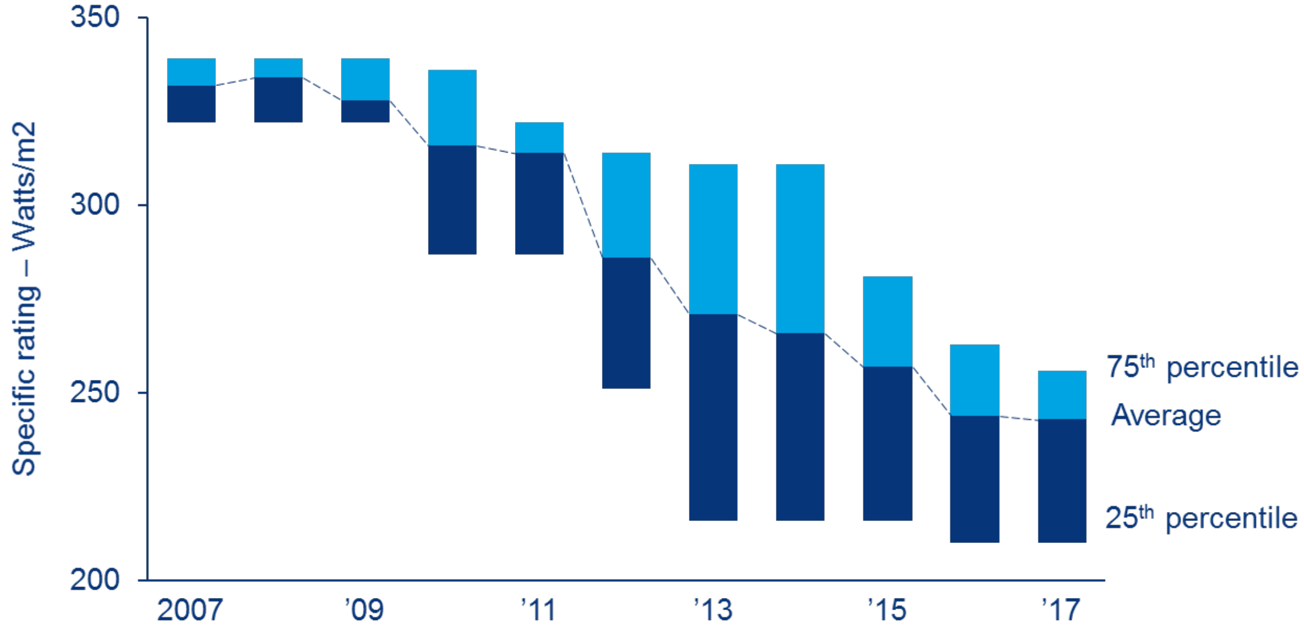
Rotor sizes across all markets are also expected to grow rapidly, as shown in Figure 2-5. Many of the massive 140 m+ rotors have been originally developed for European land-constrained markets, but adoption of these large rotors is quickly spreading to other regions, like the U.S., Latin America, and Asia. Energy production gains and prevalence of low-wind speed resource areas are prompting this rapid deployment of massive rotors to global markets.



Note: Average values shown including both Onshore and Offshore
Forecast accounts for future product deployments and demand
Source: Wood Mackenzie

Figure 2-5 Growth in wind turbine size

Energy production is closely linked to the specific rating of the turbine, measured in the nominal power divided by the rotor swept area (Watts/meter-squared). A lower specific rating will yield a higher capacity factor and energy production within a given wind turbine size range and wind regime. Specific power has also seen a continued evolution, as shown in Figure 2-6, indicating that growth in rotor swept area is outpacing the growth in turbine ratings.



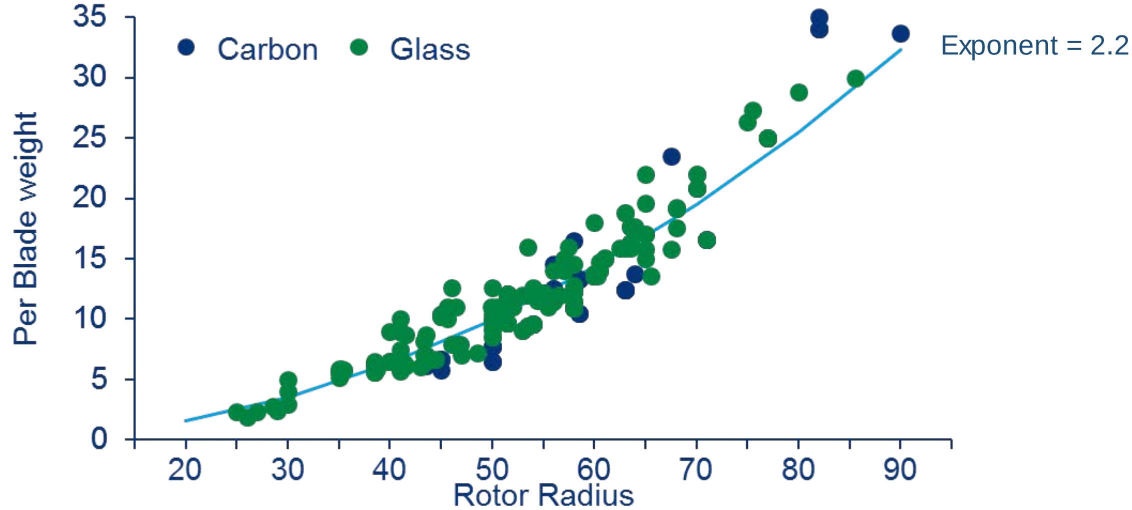
Note: Percentiles are given according to turbine count
Source: Wood Mackenzie

Figure 2-6 Evolution in specific power – U.S.

2.2.2 Blade scaling trends (power-production, weight, and cost)

The potential power generated by a wind turbine is proportional to the square of the blade length, or the "swept area" of the rotor. Basic engineering principles suggest that the volume and weight of a blade should be proportional to the cube of the blade length, if the blade were scaled on a self-similar basis. This "square-cube law" has often been referenced within the wind energy industry to forecast an end to the progressive march toward larger turbines, because the weight and cost of the rotor blades would be growing much faster than the available power, and any LCOE improvements would be dependent on offsetting benefits realized in other parts of the wind turbine generator (WTG) system. While "square-cube law" is the common terminology, the true scaling relationship would be even less-favorable if the blades did follow the cubic scaling relationship. This is because the square relationship on power is only realized if the rated power of the WTG system scales up with area. If the rated power is constrained (as in the case of larger blades on a given WTG without increasing the rated power), the benefit is only realized at wind speeds below rated power.

As blade lengths have continued to grow in the global wind energy market, the mass of the blades has not grown at a cubic rate. Turbine designers and blade manufacturers have innovated around the "square-cube law" to limit the growth of blade weight to approximately an exponent of 2.2, as illustrated in Figure 2-7.



Note: Based on Q2 2018 Market Outlook Update
Source: Wood Mackenzie

Figure 2-7 Blade weight scaling trends

This deviation from the “square-cube law” is due to several technical advancements. Material use improvements are the most significant factor, including the increased utilization of carbon fiber and high modulus glass fiber as an alternative to traditional fiberglass, as well as material forms that reduced the amount of plastic resin relative to the load-carrying fibers.

Blade aerodynamic design is also evolving quickly. New airfoil families have been developed, improving aerodynamic lift with thicker airfoils (increasing thickness-to-chord ratio) resulting in more slender blades (i.e., reducing chord dimensions). Many new blade designs are utilizing slender blades that reduce blade weight and loading while optimizing energy production. Flatback blade root airfoils are now being used by most original equipment manufacturers (OEM) as a means to reduce the maximum chord dimension and associated weight without significant sacrifice to aerodynamic performance. Adoption of aeroelastically tailored blades with a swept profile is also increasing as a means to passively reduce loading through twist-bend coupling during turbine operation. Most of the latest generation of blades also incorporate a variety of aerodynamic add-ons, including vortex generators (VG), trailing edge serrations, gurney flaps, and other features in order to maximize rotor efficiency without a significant cost and weight penalty.

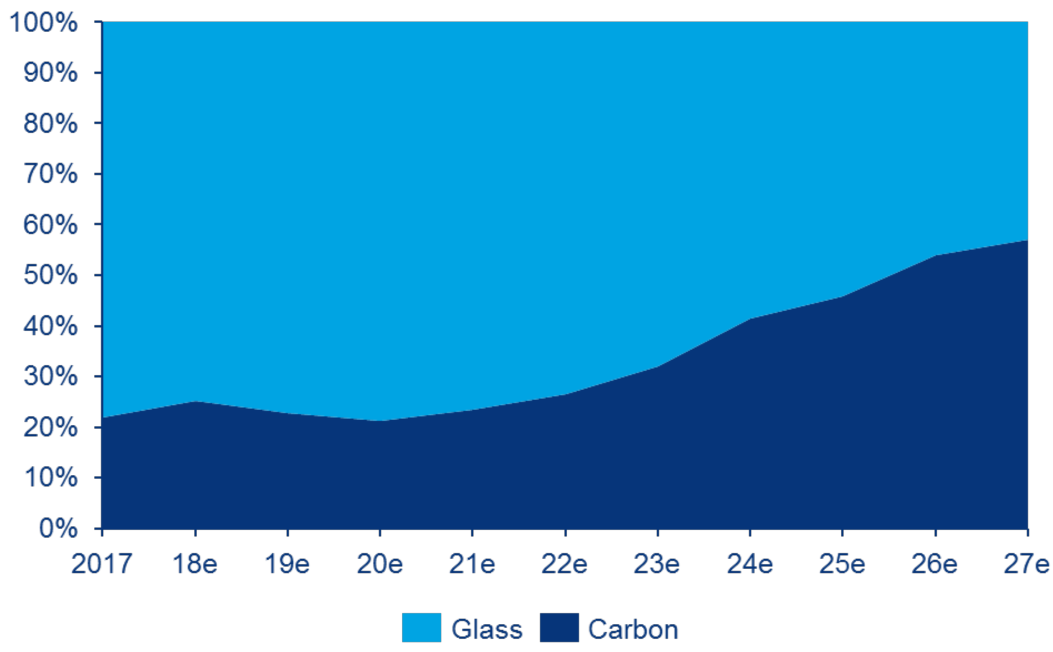
Evolutionary improvements to manufacturing and design practices are also helping to reduce the weight of longer blades. The wind energy industry has seen increased adoption of pultruded composites to improve fiber alignment and improve manufacturing tolerance. Widespread transition away from balsa wood core material and toward engineered foam does not have a significant impact on the weight profile of the blade but improves the manufacturing tolerance and provides greater precision on the resin uptake during the infusion process. Similarly, increased automation systems being used for material delivery and deposition during the blade manufacturing process are helping to reduce manufacturing deviations and design tolerances.

Figure 2-8 illustrates the trend in material use for wind turbine blades. Where carbon fibers are used in large blades, they are typically used only in the main load-carrying “spar caps.” The remaining structural elements such as skins and shear webs are constructed from fiberglass laminate, including sandwich style panels with balsa or foam core as discussed above. The transition from fiberglass to carbon spar caps represents a significant decrease in weight and increase in stiffness due to the high stiffness-to-weight properties of carbon fibers. It also represents a significant increase in cost-per-weight of the carbon portion of the structure, and by extension to the cost-per-weight of the entire finished structure. As such, it can be misleading to combine trends for all-fiberglass blades and those with carbon fiber spars.

For all-fiberglass blades, there has been a slow but steady trend toward reduced cost-per-weight of finished blade structure. Primary drivers for this trend include:

- Incremental increases in stiffness of fibers with material costs constrained by economies of scale and process engineering
- Reductions in labor required relative to material weight being handled, as fabric size and thickness increase to match larger mold dimensions
- Optimization of manufacturing plant utilization, with 24/7 or 24/6 production schedules common
- Increased use of automated manufacturing processes

Specific data for blade manufacturing costs is not readily available as it embodies valuable intellectual property of the manufacturers. Based on information in the National Renewable Energy Laboratory (NREL) blade cost model, and calibration from discussions with manufacturers contributing to the present study, a cost of $10.45/kg is considered a representative value for all-fiberglass blades. This value is for the final finished part, including profit margin, at the factory location.



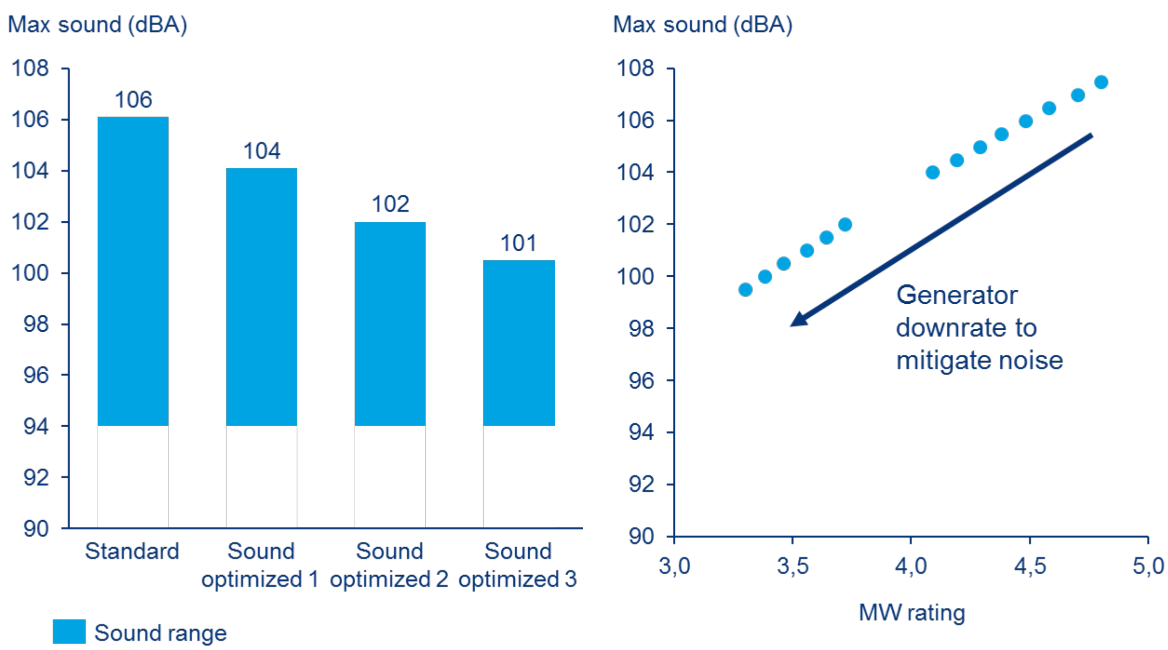
Note: Global installations, including both onshore and offshore
Source: Wood Mackenzie

Figure 2-8 Material use trends in wind blades

2.2.3 Market barriers for longer blades

Increased blade length has obvious benefits for power production and LCOE, but other factors present significant barriers to longer blades. As discussed earlier, there may be a significant weight penalty as blades increase in length, thereby also increasing costs. Moreover, as discussed in the following sections, transportation and logistical challenges and costs increase as blade length grows. Both of these challenges are analyzed in this report. Even beyond these two challenges, however, longer blades also impose possible noise concerns, increased O&M costs, and regulatory hurdles that are not assessed in this study.

More specifically, as turbine blades have grown larger, tip speeds have increased. Higher tip speeds have a beneficial impact on turbine aerodynamic efficiency, but also generate higher noise emissions. Aeroacoustic sound power level, measured in decibels (dBA), generally increases exponentially with blade tip speed, as much of the noise is generated from tip vortex shedding and trailing edge noise. Blade designers have innovated around this barrier by optimizing blade fine pitch control to limit tip noise, while also introducing lower-noise tips and serrated trailing edges, as shown in Figure 2-9.

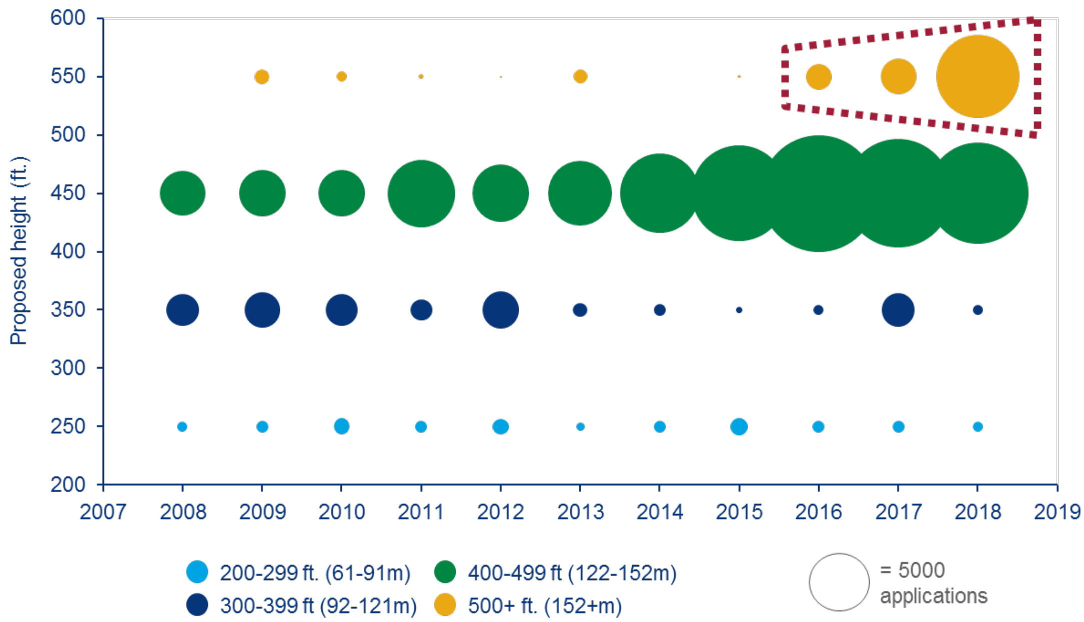


Note: Indicative sound optimized ranges shown
Source: Wood Mackenzie

Figure 2-9 Noise emissions improvements management strategies

Higher tip speeds from longer blades also impose more damage to the blade leading edge over the lifecycle. Leading edge erosion is caused by rain, dust and insects present within the incoming wind stream and is exacerbated by higher blade tip speeds. Erosion has emerged as a significant O&M concern within the wind energy industry, as unchecked erosion can lead to a significant decrease in aerodynamic performance and can ultimately result in catastrophic blade damage. Longer blades also impose higher loads on critical load-bearing components, including pitch bearings and drivetrains, and can result in higher O&M expenses to repair or replace these capital components.

Longer blades also impose other regulatory hurdles, including tip height constraints. In the U.S., the Federal Aviation Administration requires an exclusion to any structures higher than 152 m (500 ft), which has limited the adoption of taller towers and longer blades in the U.S. market. However, as the cost effectiveness of larger turbines has continued to be proven, more wind energy developers have filed for tip heights in excess of 152 m, as shown in Figure 2-10.



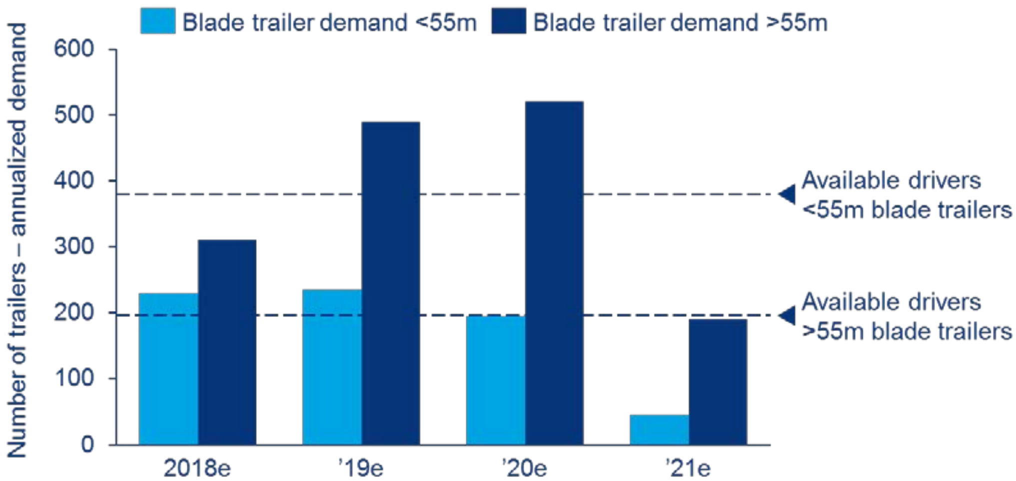
Note: Applications filed through November 2018
Source: Wood Mackenzie

Figure 2-10 FAA wind turbine permits over 152 m (500 ft)

2.3 U.S. wind turbine blade transportation market

Wind turbine blades represent a highly specialized class of freight that faces multiple logistical constraints, including dimensional constraints and capacity constraints. Dimensional constraints are imposed on the maximum chord in order to be transportable under bridges, around turns and through complex terrain. Additionally, for over-the-road shipping, the maximum rear overhang of a blade is limited to 30 feet in many states, requiring much longer trailers to be built or modified to accommodate the next generation of blades. For rail shipping, there are dimensional limitations on the curvature of blades, in order to allow blades to navigate around curves in the rail network and be contained across multiple standard rail cars.

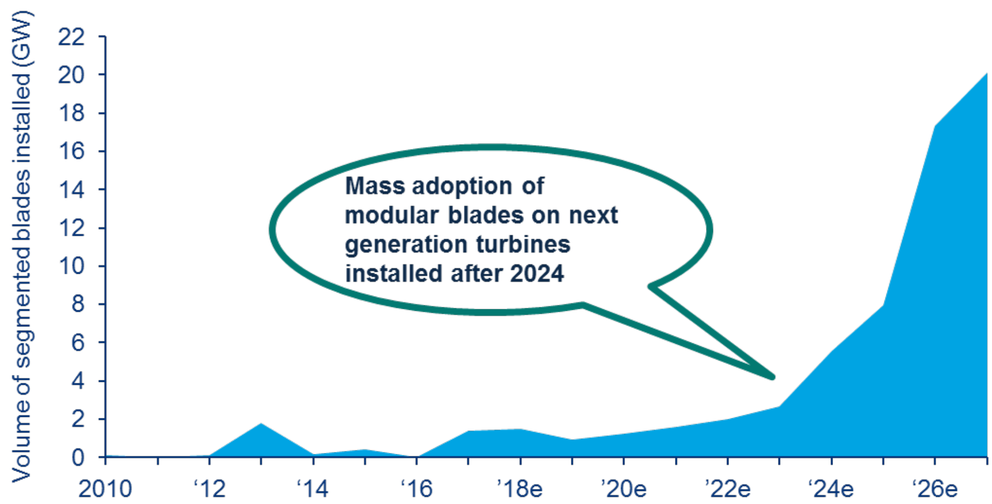
For over-the-road transport, wind turbine blades require specialized trailers and highly trained drivers. A significant capacity of blade trailers has been deployed to the U.S. market to serve the needs of wind turbine blade logistics, but the overwhelming majority of these trailers are intended for blades shorter than 55 m. Longer blades are in increasing demand (see Figure 2-10), but require more specialized equipment and drivers that are in very short supply. With the pending drop in market activity within the U.S., due to expiration of the PTC, few trailer manufacturers are willing to invest in new equipment with prospects of much lower volumes.



Note: Trailer capacity annualized to account for install demand and typical utilization rates
Source: Wood Mackenzie

Figure 2-11 U.S. blade logistics capacity

Multiple solutions exist to avoid the logistics constraints imposed by longer blades. Segmented blades that ship in separate pieces present a solution to the logistics constraint but add weight and cost to the blade and require expensive on-site assembly that is prone to quality concerns. Segmented blades have primarily been deployed in Europe so far and in limited quantities, but Wood Mackenzie expects significant growth in the deployment of segmented blades in the coming years, as shown in Figure 2-12. Other solutions to longer blades that have not yet been deployed include aerial transportation, mobile factories, and alternative approaches to segmented blades.



Note: Segmented blade volumes estimated based on identified technology development at major OEMs

Source: Wood Mackenzie

Figure 2-12 Global segmented blade volumes

2.4 Blade-specific transportation logistics

Information on the industry status for transportation of wind turbine components was obtained through numerous sources. Notable contributions include information provided by BNSF Logistics (BNSFL), Anderson Trucking Service, Inc. (ATS), other participants in the industry workshop [1], NREL studies [2], [3], and market data and insights from Wood Mackenzie and DNV GL.

Land-based transportation infrastructure, primarily road and rail networks, have been used exclusively to enable off-site manufacturing of all wind turbine components with economically competitive transportation and delivery logistics. As wind turbine components and blades have increased in size over the past 30 years, the transportation industry has developed various innovations and solutions to manipulate these oversized and overweight loads across the nation. Thus far, wind turbine scale increases combined with the related transportation and delivery costs, have been able to achieve declining LCOE. However, achieving the next generation of supersized turbines (necessary to unlock both lower energy costs and expand wind energy development potential) requires further R&D to address new challenges of scale, manufacturing, and delivery.

Today, the transportation industry and local infrastructure are handling wind turbines with the following broad dimensions:

- Rotor diameters: up to 134 m
- Blade lengths: up to 67 m
- Hub heights: up to 100 m (consisting of multiple steel tube sections of ~20 m long)
- Drive train system: up to 3 MW

Turbines of this size are primarily being deployed across the central U.S. where existing road and rail networks are more capable of conveying oversized components. Transportation of current large-scale turbines through the Northeast and Rocky Mountain regions has been increasingly difficult both technically and economically due to physical constraints associated with older infrastructure and mountainous terrain features, respectively. It is common for components in these regions to enter via a regional port to reduce overland transport distances.

Physical infrastructure constraints that impact load size are highly dependent on the manufacturing origin, project location, available transport routes, and local regulatory jurisdictions through which the component must pass. There are few absolutes, but feedback from experienced transportation companies identified two key constraints for blades: root diameter and maximum chord, as illustrated in Figure 2-13). More specifically, as described in Section 4.1.3, constraints of key blade dimensions for ground transport were established as:

- Blade root diameter limit: 4.5 m
- Blade chord limit: 4.75 m

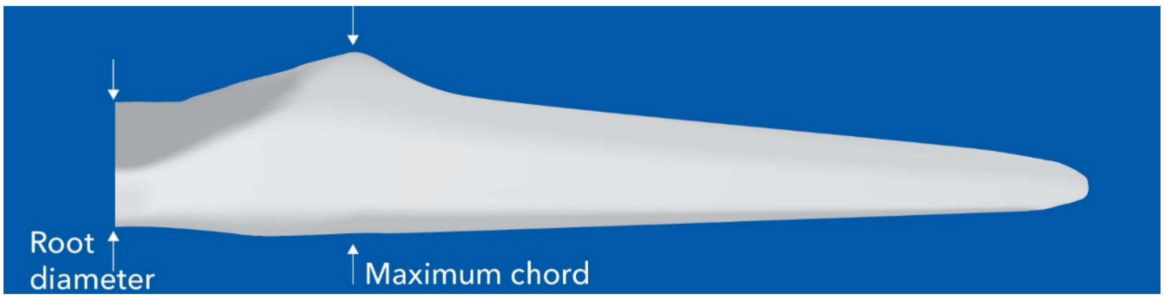


Figure 2-13 Key physical constraints for blade transport (not to scale)

These two constraints correspond to various parts of the road and rail network—bridges, tunnels, tight-radii turns, and rock walls that are immovable (or unavoidable) and not large enough to enable blade passage. Often, OEMs utilize blade designs with dimensions smaller than these values to help maximize regions where product deployment is possible.

Over the decades, blade length has posed less of a challenge than root diameter and chord width because innovations in transportation equipment, combined with increased industry experience has resulted in refined equipment and techniques to maneuver long blades. The relatively light weight of wind turbine blades has also enabled new transport fixtures and trailer designs. Thus far, blades have been handled to avoid any bending, rotation, and road shock. For transport on public roads, federal regulations require at least two points of support along the blade, with the rear support needing to be within 30 ft of the blade tip. This regulatory requirement prohibits trailer innovation that allows blades to be pitched and articulated to avoid objects. In addition, blades are designed to accommodate transport loads caused by the need for transport saddles in the outer third of the blade. There is slightly more material in the blade at the transport saddle location. Figure 2-14 through Figure 2-16 picture ground transportation, rail transportation, and a pitched transport variation disallowed by the above noted 30-ft rule.

Source: Shutterstock

Figure 2-14 Ground transportation of blade

Source: BNSFL

Figure 2-15 Rail transportation of blades

Source: Dacotrans with Goldhofer FTV

Figure 2-16 Truck / trailer configuration not allowed on public roads in U.S. due to regulations

The ability of transportation solutions to deliver blades longer than 65 m is of growing concern. Efforts are underway to plan delivery of blades in the 70 m+ range; however, the routing and equipment is increasingly specialized and added costs are being incurred for new trailers, road modifications, increased road closures, etc. Therefore, the industry is now at a logistical cost and capability ceiling in terms of feasible blade length for transport, with approximately 75 m as the perceived limit without more aggressive innovations.

3 STUDY APPROACH

The core approach of this study is a quantitative evaluation of the manufacture, transport, and erection of land-based wind turbines with blade lengths ranging from 65 m to 115 m. Detailed system-level cost modeling was performed for the baseline (65-m blade) wind turbine; subsequent analysis for larger turbines focused on the cost to manufacture, transport, and install blades in the range of 75 m to 115 m, with impact on LCOE as the primary metric.

3.1 Enabling pathways

As constraints exist to cost-effective scaling of current conventional manufacturing and transportation technologies within this size range, alternatives were identified and evaluated. These alternatives are designated as “Pathways,” with three major categories identified for evaluation in this study:

1. Innovative transportation: Continued scaling-up of current manufacturing approach – monolithic blades with two scenario variants:
   - Dimensional constraints of the blades as needed to facilitate long-haul transportation by truck or rail. Blade width and height are constrained due to significant barriers such as overpass and tunnel clearances with innovations to enable increasing component lengths
   - Blade dimensions unconstrained with nonconventional transportation such as LTA airships
2. Hybrid solutions (segmented blades): These include segmented or modular blades, with major components manufactured as current conventional approach within dimensional constraints with on-site assembly.
3. On-site manufacturing: Development of temporary or short-term factories in close proximity to wind turbine projects so that long-haul transportation from factory is avoided.

Any of these three pathways may be enabled by alternative manufacturing and materials technologies. Examples include additive manufacturing, thermoplastic blade skins, and low-cost carbon fibers.

3.2 Modeling approach

This study was executed to focus analysis on key factors and pathways that enable a complete blade to be positioned at a turbine pad (within a hypothetical wind project) and ready for inclusion in the wind turbine assembly process. To explore different pathways related to enabling supersized blades, we chose not to perform a study of costs and logistics related to all wind turbine components (nacelles, towers, hubs, drive train, balance of station, etc.). In addition, we acknowledge that optimization of blade design, assumptions, and logistics techniques within each pathway is an area where further R&D effort could be considered. This project focused on studying alternatives across the pathways to identify high value R&D opportunities; however, optimizing each scenario studied was beyond the current scope of inquiry. Optimization of a solution within a given pathway can be performed as part of future research.

Primary parameters for modeling and analysis used in this study are the total cost of a delivered blade and the blade contribution to system LCOE. Items included in these parameters are:

1. Cost of a manufactured blade

2. Transportation and handling costs incurred to move blades (or blade segments) from manufacturing origin to a turbine pad location
3. For segmented blades, in addition to items 1 and 2, costs include assembling blade segments on the ground at the turbine pad, prior to rotor assembly (rotor assembly is considered part of turbine assembly and therefore not included in this study of blade pathways).
4. For on-site manufacturing, includes costs for mobilizing, assembly, commissioning, and demobilizing a temporary on-site blade factory; blade production costs from the on-site factory; and short haul blade transport costs between the factory and turbine pad location.

For each pathway, the total cost of a delivered blade was estimated, combined with annual energy production, blade specific O&M costs, and fixed charge rate assumptions to calculate the blade contribution to overall system LCOE. These outputs helped to form the basis for identifying promising solutions within pathways, and by extension R&D needs and opportunities to leverage future DOE investments.

3.2.1 Modeling details

To the extent practical, pathways have been quantitatively evaluated in this study. Analytical tools and modeling approaches are summarized here and documented in greater detail in the following report sections. Tools applied for various study elements are:

- Blade aerodynamic shapes and power performance evaluated using:
  - Baseline 65 m blade similar to land-based turbine model developed under IEA Task 37 project, with some exceptions [4]
  - PROPID code (UIUC, Selig) for initial aerodynamic design using airfoils from Delft University (same as IEA Task 37)
  - WT_PERF (NREL) used to analyze aerodynamic performance for larger blades, with and without dimensional constraints
  - Spreadsheet-based calculations for power curves and annual energy production (AEP)
    - Developed AEP calculations for blades with and without root diameter and chord dimensional constraints needed for ground-based transportation
    - Unconstrained blade designs were used for segmented blades, on-site manufactured blades, and transport options where constraints were not applicable
- Blade weight and costs developed using:
  - Baseline weight scaled from IEA Task 37 blade
  - Scaling exponent of $R^{2.2}$ as discussed in Section 6.2
  - Manufacturing costs for major structural elements evaluated using NREL Wind Blade Manufacturing Cost spreadsheet model (NREL, Berry)
  - Added cost and weight for segmented/modular blades developed by DNV GL engineering estimates
- Transportation costs
  - DNV GL utilized cost estimates from transportation companies active in the wind industry.

- O&M costs
  - For segmented blades, DNV GL developed an O&M costs estimate adder to account for an assumed increase in number of inspections to verify the blade joint during operations.
- On-site manufacturing costs estimated by DNV GL
  - Manufacturing elements from NREL cost model
  - Manufacturing facility scale from TPI Sandia reports [5],[6] and DNV GL experience
  - Temporary facility building costs from RSMeans
  - Labor costs from NREL cost model with DNV GL experience adjustment
- LCOE calculated using Microsoft Excel
  - Blade costs modeled using NREL model (see above)
  - AEP derived from blade aerodynamic design noted above
  - Operating costs from DNV GL model
  - Fixed charge rate for LCOE based on U.S. DOE guidance (7.9%)

4 MODELING ASSUMPTIONS AND SCENARIOS

4.1 Manufacturing and transportation

Transportation cost is a critical variable in quantifying potential cost impacts or comparing alternative approaches for supersized blade assembly or manufacturing that may be achieved under different pathways. In many alternative solutions, avoiding (or minimizing) transportation costs is a key objective, therefore the magnitude of transportation costs become part of the "budget" available to alternative scenarios. Transportation costs are highly sensitive to the point of origin, destination, and selected route. For this study, a series of assumptions and hypothetical facilities were developed to enable the analysis. These assumptions were intended to reflect both the current industry characteristics and future development opportunities if supersized land-based turbines are realized. Figure 4-1 illustrates the hypothetical configuration of the manufacturing facilities and project locations used in this study. As part of establishing the baseline LCOE calculation, transportation costs for nacelles, towers, and blades for the Baseline (65 m) wind turbine were developed using the facility map in Figure 4-1. The following sub-sections outline core assumptions made in developing the analysis. Additional details regarding how these assumptions are used and impacts on the analysis are presented throughout the other analysis sections of this report.

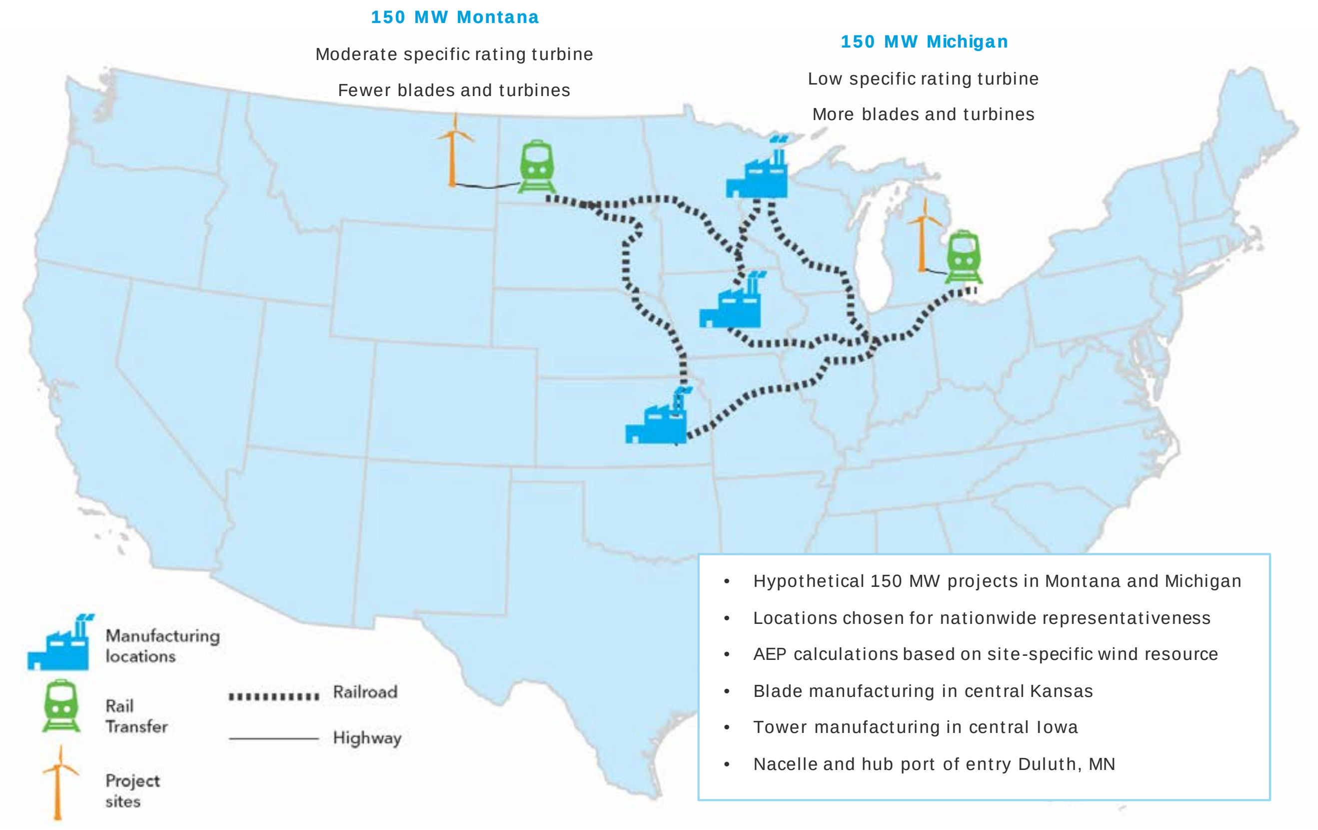


Figure 4-1 Hypothetical configuration of the manufacturing facilities and project locations

4.1.1 Off-site blade manufacturing plant assumptions

The following assumptions were made regarding off-site blade manufacturing:

- Hypothetical pre-existing blade manufacturing facility is in Kansas. Approximate geographic location for transportation cost calculating purposes was centered on Osage, Lyon, and Chase counties.
- Blade manufacturing plant is built with full rail and road access.

4.1.2 Project development location assumptions

The following assumptions were made regarding the project development locations:

- Two wind projects of 150 MW each, one in Central Michigan, the other in Eastern Montana.
- Central Michigan location has wind speeds consistent with lower wind resource sites across the U.S. and typically would utilize a Low Wind Speed Turbine (LWST).
- Eastern Montana project location has wind speeds consistent with moderate wind resource sites across the U.S. and typically would utilize a Moderate Wind Speed Turbine (MWST).
- For purposes of transportation cost estimating, the Central Michigan project location is the center of Gratiot County, and the Eastern Montana project location is the center of McCone and Garfield counties.

4.1.3 Transportation assumptions

The following assumptions were made regarding transportation:

- Blades can be loaded at the factory directly onto truck, rail, or alternative transport.
- At the project site, blades can be delivered directly to turbine pad location.
- Ground-based transportation is the primary mode with both truck and rail evaluated.
- Alternative transport option (i.e., LTA airship) was considered for blades not transportable by truck and rail.
- Obtained industry estimates for total transportation costs of truck, rail, and airship – from off-site factory to turbine pad, including all handling, mode transfers, permitting, escorts, etc.
- OEM has transportation fixtures built and available to facilitate proper handling.
- Wind industry and market opportunities are sufficiently robust such that transport industry invests in new trucks, trailers or rail cars, and blade fixtures needed to accommodate supersized blades.
- Feasible routes are available, and all permit approvals are obtained.
- No costs for infrastructure upgrades or modifications to enable transport are included.
- Blade transportation rate of five complete turbines are delivered per week to each project site and there is a continuous flow of blades to project site (as opposed to intermittent flow).
- For 95 m and 115 m blades, controlled flexing can be performed during rail transport

4.1.3.1 Ground-based transport (rail/truck) assumptions

- Sufficient rail cars and blade fixtures are available to assemble complete trains for efficient transport.
- Rail transfer facility is located ~50 to 100 miles from the project site and rail cost will have an additional cost of short haul trucking added to move blades to project site.

- Existing/suitable rail-to-truck transfer location is already available (and does not need to be built). Rail costs include labor and crane equipment needed at transfer site – but does not include costs to develop/build the transfer site.
- Constraints of key blade dimensions for ground-based transport were established as:
  - Blade root diameter limit is 4.5 m.
  - Blade chord limit is 4.75 m.

4.1.3.2 LTA airship transport assumptions

- Utilized publicly available information regarding Lockheed Martin's LMH-1 and related prototype P-791; information shared by Lockheed Martin at the Workshop; and additional input from the company to develop blade transport scenarios and estimates utilizing their conceptual LMH-2 and LMH-3 aircraft.
- The aircraft are commercially available in the marketplace, fully certified, and all approvals for operation are obtained. The aircraft have sufficient market applications outside the wind industry such that they have diverse applications within the transportation industry and are viewed as an additional transport mode.
- One aircraft is utilized continuously to transport blades from off-site factory to the landing/staging area at project location.
- Blades are secured within cargo hold (as opposed to external loading with slings or other devices) such that flight paths and operation in limited visibility conditions are not restrictive.
- A proper and sufficiently sized staging/landing area is present at off-site blade factory and project site. Landing area at project site is located within ~5 miles of turbine pad locations.
- Ground based off-loading equipment and "micro haul" transport to final turbine pads is added to airship delivery costs.
- Truck transport costs for "micro haul" of blade from landing area to turbine pad is estimated as 25% of short-haul truck costs. In this case "micro haul" means on-site delivery of blades from the landing pad to the turbine pad, estimated as ~5- to 10-mile trip.
- Hypothetical wind project construction requires about 4 to 6 months and blade delivery occurs in a focused period to maximize airship utilization.
- Spring to early fall season performance window.
- LMH-2 craft and cargo hold are sized to accommodate one blade; LMH-3 can accommodate up to three blades.

4.1.4 On-site manufacturing assumptions

- On-site manufacturing method is similar to current blade-in-mold techniques.
- Project site has available water, power, wastewater, gas/propane to enable operation of temporary factory.
- Land owner and community acceptance of a temporary factory is achieved.
- Land lease costs are comparable to project land royalty payments.
- Environmental and building permits are approved and presence of on-site factory does not prevent wind project development.
- Sufficient space is available within proximity to project for building the temporary factory (within ~5 miles of turbine pad locations – same for airship staging/landing)

- Truck transport costs for “micro haul” of blade from factory to turbine pad is estimated as 25% of short haul truck costs.
- Labor force is composed of 15% skilled travelling workers; 85% locally trained workers.
- There are enough local people that are either available to work or willing to leave existing jobs to work in temporary blade plant.
- Serial blade production begins prior to project construction and there is no impact on wind plant construction schedule.
- Blade production cost elements (per NREL cost model).
- One example full scale blade article is produced for training and to demonstrate plant commissioning (blade is not installed on turbine).
- Local workers require 10-week training period plus time for plant commissioning.
- Production quality is same as achieved in off-site factories.
- On-site factory can achieve same production efficiencies and rates as off-site serial production.
- The temporary factory can be mobilized and assembled in a 3-month period.
- Plant commissioning, worker training, and first manufactured article can be performed in a 3-month period.

4.1.5 Segmented blade assumptions

- Blade segment transport
  - Same ground transportation assumptions as previously noted for truck and rail
- Blade assembly
  - Added field crew plus two support cranes to assemble segmented blades
  - 5-person work crew prepares, assembles, and checks one blade per 4 hours
  - Mechanical joints are used
  - Segmented blade assembly process has appropriate jig and support equipment to facilitate efficient assembly and alignment
  - Process is similar to effort for making blade/hub connection
  - Blades are assembled on ground before overall rotor and turbine assembly is performed
- O&M estimate
  - Mechanically joined segments will be inspected annually
  - Contracted specialists are brought to site to perform blade inspections
  - Inspections are internal to blade
  - No crane is needed to perform O&M inspections
  - No change in blade reliability due to presence of blade segments
  - Blade segment inspections are an extension to the annual scheduled service - primarily extending time needed to perform turbine inspections
  - Work crews have any special tooling or joint inspection equipment
  - Work crew utilizes 3 technicians
  - 1.5 turbines are inspected per day for blades with one segment
  - 1 turbine is inspected per day for blades with two segments

4.2 Turbine and rotor configurations

DNV GL identified and modeled two classes of wind turbines to represent current and possible near future industry practice for optimizing turbine design to site conditions. These include LWST and MWST (as defined in section 4.1.2) with specific power of approximately 150 W/m^2 and 225 W/m^2, respectively. These characteristics are generally aligned with competitive turbines in the U.S. market and/or anticipated within the coming years and correspond to IEC design classification of III and II, respectively. For a given rotor size, the blade designs between the LWST and MWST are unchanged; only the generator rating is modified to achieve the specific power target.

The primary turbine blade, rotor, tower, and site wind speed parameters are given in Table 4-1. As noted above, for a given rotor size, the blade designs between the LWST and MWST are unchanged, only the generator rating is changed. While this approach was selected as a simplification for the purposes of this study, DNV GL considers it to also be a reasonably good approximation of industry trends. Blades intended for higher-wind sites will typically have structural design dominated by peak load cases, whereas specific power designs intended for lower wind speed sites may be more influenced by fatigue loading due to relatively longer blades in comparison to nameplate rated capacity.

For the purpose of this analysis, we assume the lower wind-speed site in Michigan uses LWSTs, with a specific power rating of approximately 150 W/m^2. The moderate wind-speed site in Montana, on the other hand, is assumed to use MWSTs with specific power of approximately 225 W/m^2. Analysis of turbines with longer blades deployed at each site therefore also assumes growth in turbine nameplate capacity (and hub heights) to maintain specific power at these specified levels, and to ensure adequate ground clearance.

The wind speed data in Table 4-1 represent the hypothetical project locations in Central Michigan (LWST) and Eastern Montana (MWST), respectively. Hourly wind speed data were provided by NREL at various heights above ground for the specified project locations. DNV GL calculated annual averages and vertical shear values to derive the values in Table 4-1. Similarly, NREL provided hourly data for temperature and pressure at 100 m above ground for these locations. From these data, DNV GL calculated annual average air density values of 1.202 and 1.121 kg/m^3, respectively, for the Michigan and Montana project locations.

Table 4-1 Primary rotor/turbine configuration parameters

Turbine ID	Blade Length (m)	Turbine Quantity	Rotor Diameter (m)	Tower Height (m)	Specific Rating (W/m^2)	Generator Size (MW)	Average Wind Speed at Hub (m/s)
Baseline	65	71 (MI) 46 (MT)	134	100	150 (MI) 225 (MT)	2.10 (MI) 3.25 (MT)	7.21 (MI) 7.95 (MT)
WTG-75	75	54 (MI) 35 (MT)	154	110	150 (MI) 225 (MT)	2.75 (MI) 4.25 (MT)	7.38 (MI) 8.12 (MT)
WTG-95	95	33 (MI) 22 (MT)	194	130	150 (MI) 225 (MT)	4.50 (MI) 6.75 (MT)	7.69 (MI) 8.42 (MT)
WTG-115	115	23 (MI) 15 (MT)	234	150	150 (MI) 225 (MT)	6.50 (MI) 9.75 (MT)	7.92 (MI) 8.65 (MT)

5 BLADE AERODYMNAMIC MODELING

5.1 Baseline blade aerodynamic design

The aerodynamic design for the 65 m baseline blade was developed using the PROPID code developed by Dr. Michael Selig at the University of Illinois, Urbana-Champaign. Based on previous blade design projects, DNV GL selected the DU-series of airfoils developed by the University of Delft blade for radial positions from the root to 75% span. The 18% thick NACA 64(3)-618 airfoil was used from 75% span to the blade tip.

PROPID is an inverse-design code whereby a user can develop blade aerodynamic designs with near-optimal aerodynamic performance while varying structural characteristics (i.e., chord and thickness) by modifications in design lift coefficient and tip-speed ratio. The use of PROPID for performing blade parametric studies is discussed in detail in Reference [7].

The inverse-design feature of PROPID allows for a combination of free design variables and constraints. The primary free variables used in this study at each blade radial position were chord and twist, and the corresponding constraints were local lift coefficient and axial induction factor. PROPID iterates free variables until the specified constraints are simultaneously met at each radial position. A blade with near-optimal aerodynamic performance will result from a target lift coefficient (C_L) value near maximum lift-over-drag ($L/D_{,max}$) and an axial induction factor of 1/3. The location of airfoils and “target” lift distribution used for the current study aerodynamic designs is given in Table 5-1. As these conditions are the targets for near-optimal performance, the term “design lift” will also be used.

Table 5-1 Airfoil and target lift distribution

Airfoil Family C_L Distribution			
Station #	**Airfoil**	**r/R**	**C_L at $L/D_{,max}$**
1	Cylinder	0.050	n/a
2	DU00-W-401	0.150	n/a
3	DU00-W-350	0.250	1.10
4	DU97-W-300	0.350	1.25
5	DU91-W2-250	0.450	1.25
6	DU93-W-210	0.550	1.20
7	Hybrid	0.650	1.10
8	NACA 64(3)-618	0.750	1.00
8	NACA 64(3)-618	0.850	1.00
9	NACA 64(3)-618	0.950	1.00

(Note: r/R = position on rotor (r) as a fraction of total rotor radius (R))

Per Actuator Disk Theory, for a rotor with a given number of blades, maximum efficiency (power extraction) will be realized for a specific product of lift times chord (C_L * c). Hence, chord dimensions may be constrained while maintaining efficiency as design lift values are increased. For a given airfoil, design lift must be selected at a value that can be realized both in the smooth condition typical of analyses and wind tunnel testing, as well as the condition for as-built blades in service conditions. Although modern wind turbine airfoils, including the Delft DU-series, have been designed for relative roughness insensitivity, these effects are of practical importance in the aerodynamic performance of commercial wind turbine blades. Realizing favorable design lift values can be particularly challenging for the very thick airfoils that are used for structural efficiency at inboard radial locations. Vortex generators (VG) or other aerodynamic devices are frequently used to improve robustness of lift, especially at inboard radial locations.

Another key variable related to chord dimensions is the tip speed ratio at which optimal performance is realized ("design tip speed ratio", TSR_D). This is the tip speed ratio corresponding to maximum power coefficient ($C_{P,max}$), and would be maintained as constant during the variable-speed range of turbine operation. Optimal rotor and turbine system design includes trade-offs that involve annual average wind speed, specific power, maximum tip speed, air density, rotor solidity and TSR_D. As rotors have been trending to increasingly-large blades, reduced specific power and solidity, there has been a corresponding trend to rotor designs with increasing TSR_D and maximum tip speed.

DNV GL has included these industry trends in the aerodynamic blade designed used for the current study. Design lift and rotor speed are powerful variables for controlling blade chord dimensions, and these sensitivities have been exploited to facilitate transportation of the current generation of large blades. While historically (circa 2000), TSR_D values of 7.5 and tip speeds in the range of 65-75 m/s were not uncommon, current turbines typically have TSR_D in the range of 8.5 to 9.5, and maximum tip speeds of 80 m/s and above. Due to noise considerations, offshore turbines have been leading the trend toward increasing rotor speeds, but land-based turbines have been trending close behind.

Figure 5-1 shows chord distributions for near-optimal blades generated by PROPID for varying values of TSR_D. For visual clarity of planform difference, the plot has approximately 2:1 aspect ratio for chordwise versus spanwise dimensions. Sensitivity of solidity to TSR_D is clearly seen with reduced chord dimensions for increased tip speed ratio.

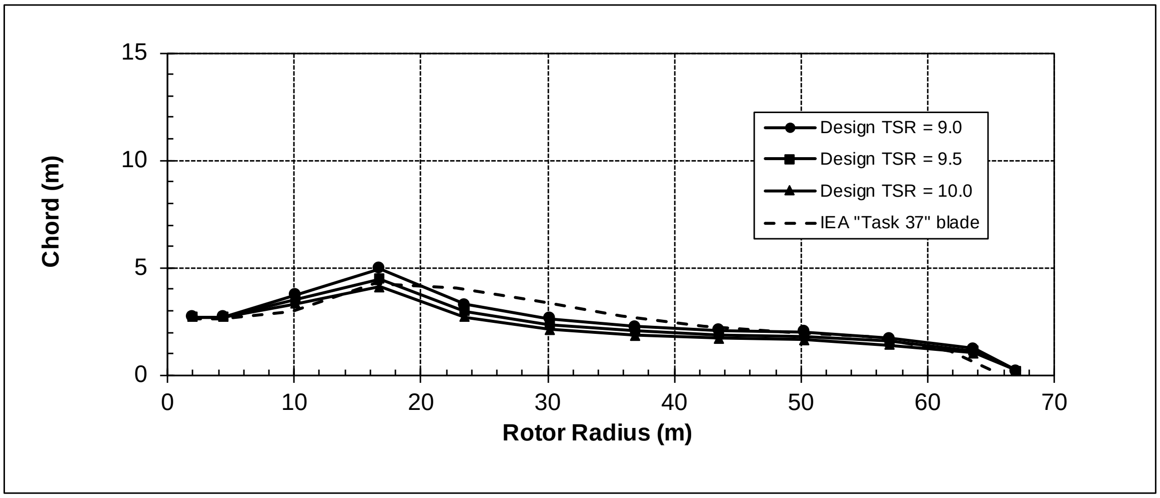


Figure 5-1 Planforms for near-optimal designs at varying TSR_D

Figure 5-1 also shows the chord dimensions for the IEA Task 37 blade. In the outer span, the chord dimensions are similar to those for the PROPID case with TSR_D = 10.0. The IEA blade has higher solidity in the mid-span region than all PROPID cases. The IEA maximum chord dimension falls between PROPID TSR_D = 9.5 and 10.0, though shifted outboard modestly. Overall, the IEA blade has the appearance of being designed for slightly higher TSR_D and/or lower lift values than the more-slender PROPID blades, but with maximum chord dimensions constrained for transportation and an overall smoother shape characteristic of actual commercial designs.

For the purposes of the present study, DNV GL selected the PROPID aerodynamic design corresponding to TSR_D = 10.0 to define major dimensions for manufacturing and transportation. This value of design tip-speed ratio is only modestly higher than typical for commercial blades in the upper-end of the current size range and reflects expectations that designers will continue toward increased TSR_D as one approach to constraining dimensions for transport logistics. While it is recognized that commercial blades will have additional smoothing of planform shape, that level of design detail has not been included in this study, as the primary purpose is to characterize major dimensions for modeling of power performance, manufacturing, and transportation.

For each aerodynamic configuration in this study, WT_PERF analyses were performed to develop C_P-TSR curves. Power curves were then generated using a spreadsheet calculation. Power curve and AEP calculations are described further in Section 5.3 below.

5.2 Scaling of aerodynamic designs

Aerodynamic shapes for larger blades were generally derived using "self-similar" scaling of the 65 m baseline. As noted in Section 3.1, two variants of aerodynamic shape were considered: with and without constraints on maximum chord and root diameter dimensions. Generally, "transportation constrained" blades could grow in length but with height and width constrained to allow long-haul transportation by truck or rail. "Unconstrained" blades were scaled in all dimensions and were assumed to represent pathways such as on-site manufacturing, modular blades, or airship transportation. Based on a literature review and inputs from transportation experts, a chord dimension limit of 4.75 m and root diameter limit of 4.5 m was established for this study.

Pre-curve dimensions were derived based on the IEA Task 37 blade and scaled using a self-similar approach for larger blades. It should be noted that pre-curve dimensions are a significant factor for the feasibility and cost of long-haul truck and rail transport. Optimization of cost-effective transportation for large blades is expected to include significant trade-offs between pre-curve, blade stiffness, nacelle tilt, overhang, and tower diameter in efforts to simultaneously meet constraints relative to transportation and blade tip-tower clearance. However, such trade-offs were beyond the scope of the current study.

As part of the initial aerodynamic design effort, the effect of constrained chord dimensions on aerodynamic performance was evaluated for blade lengths ranging from 65 m to 115 m and TSR_D values between 9.0 and 10.0. The results are characterized in terms of rotor peak power coefficient in Table 5-2, where $C_{P,U}$ denotes unconstrained dimensions, $C_{P,C}$ is constrained chord dimensions, and ΔC_P reflects the reduction in efficiency due to the constraint. Where $C_{P,C}$ is blank, the dimensional constraint limits were not reached in the scaled shape.

As would be expected from Figure 5-1, blades with TSR_D = 9.0 reach dimensional constraint limits earlier than blades with higher TSR_D values and have larger losses in aerodynamic efficiency due to the corresponding constraints. For the blades with TSR_D = 10.0, dimensional constraints are first encountered for the 95 m blade, and aerodynamic efficiency loss is a modest 0.64% even at 115 m blade length. Note that these calculations were performed using aerodynamic inputs representative of airfoils in smooth condition. For actual operation, losses would be expected to modestly increase in proportion to loss of airfoil lift due to roughness or other as-built / in-service effects.

Table 5-2 Effect of dimensional constraint as blades scale in length

Blade	**Design TSR = 10.0**			**Design TSR = 9.5**			**Design TSR = 9.0**		
Length (m)	**$C_{P,U}$**	**$C_{P,C}$**	**Δ CP**	**$C_{P,U}$**	**$C_{P,C}$**	**Δ CP**	**$C_{P,U}$**	**$C_{P,C}$**	**Δ CP**
65	0.5047	-	-	0.5044	-	-	0.5035	0.5035	0.00%
75	0.5048	-	-	0.5046	0.5045	0.02%	0.5036	0.5033	0.06%
95	0.5056	0.5049	0.14%	0.5052	0.5035	0.34%	0.5042	0.5015	0.54%
115	0.5044	0.5012	0.64%	0.5041	0.4990	1.02%	0.5042	0.4975	1.35%

As noted above, based on dimensional and aerodynamic analyses, TSR_D = 10.0 was selected for scaling of blade geometry from 65 to 115 m. Planform and side-views for blades ranging from 65 to 115 are shown in Figure 5-2 through Figure 5-9. Where relevant (95 m and 115 m blade), the planform views show both unconstrained and constrained dimensions. In all figures, the axes have been adjusted an approximate aspect ratio of 2:1 between chord and length dimensions.

The plots below represent the major dimensions for assessing transportation of monolithic and segmented blade variants.

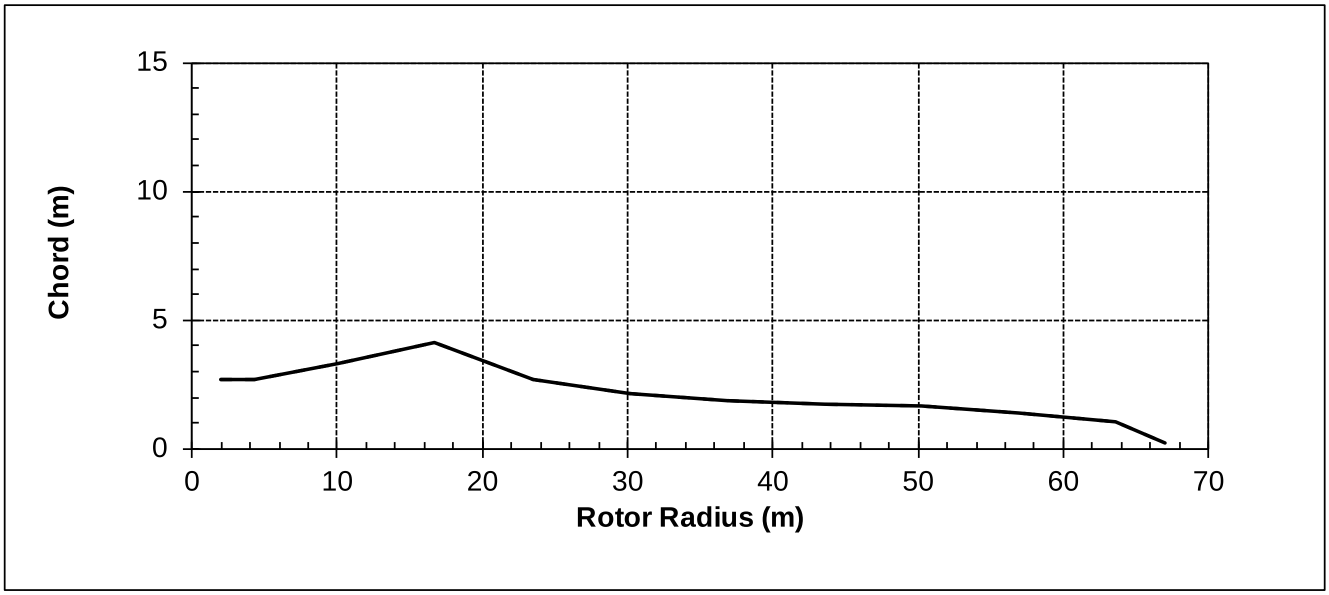


Figure 5-2 Planform for 65 m baseline blade

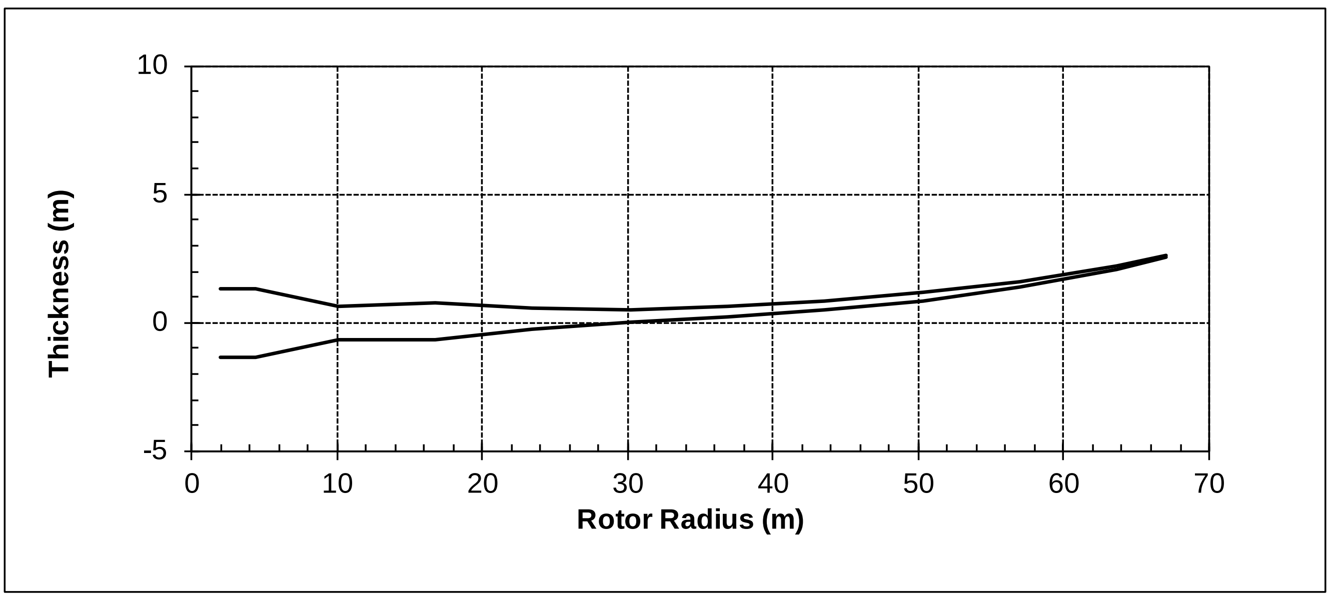


Figure 5-3 Side-view for 65 m baseline blade

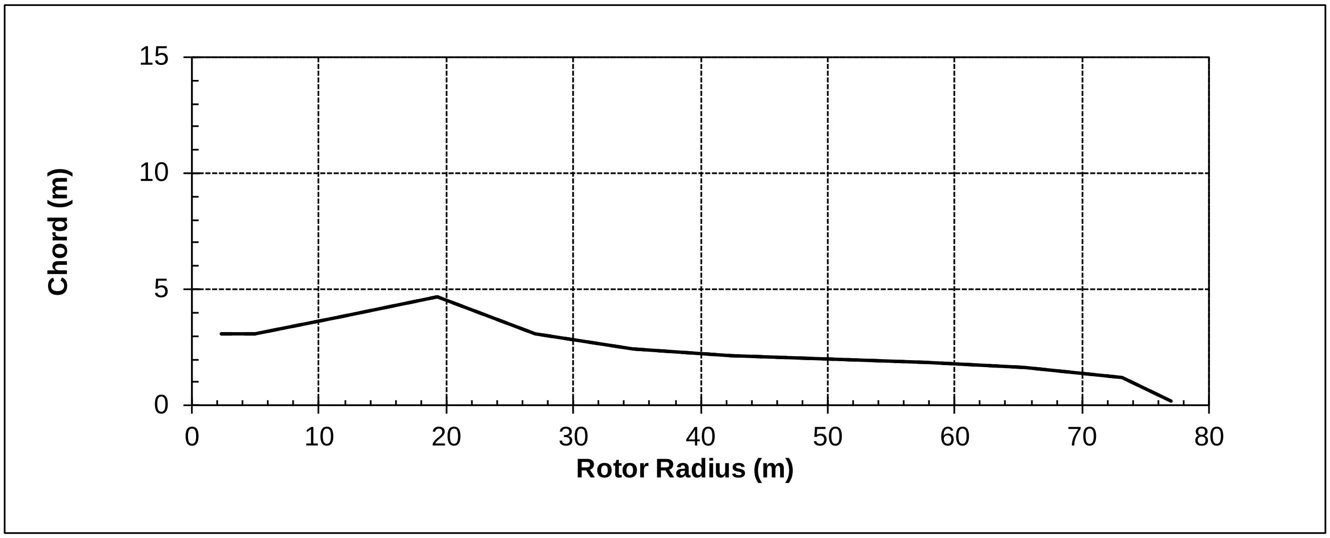


Figure 5-4 Planform for 75 m blade

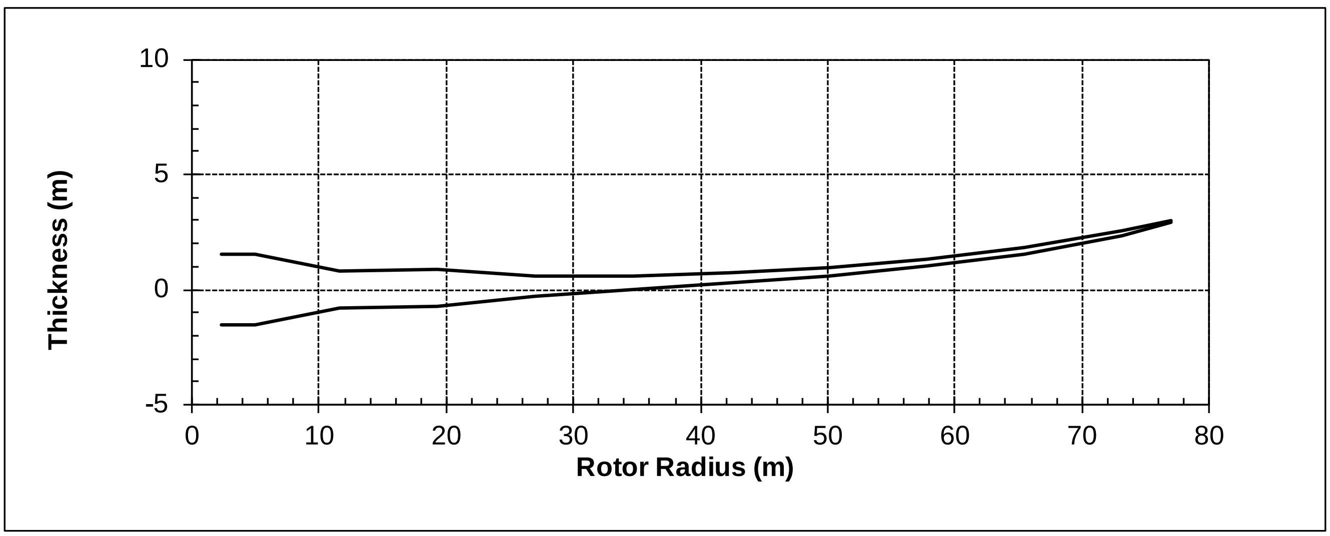


Figure 5-5 Side-view for 75 m blade

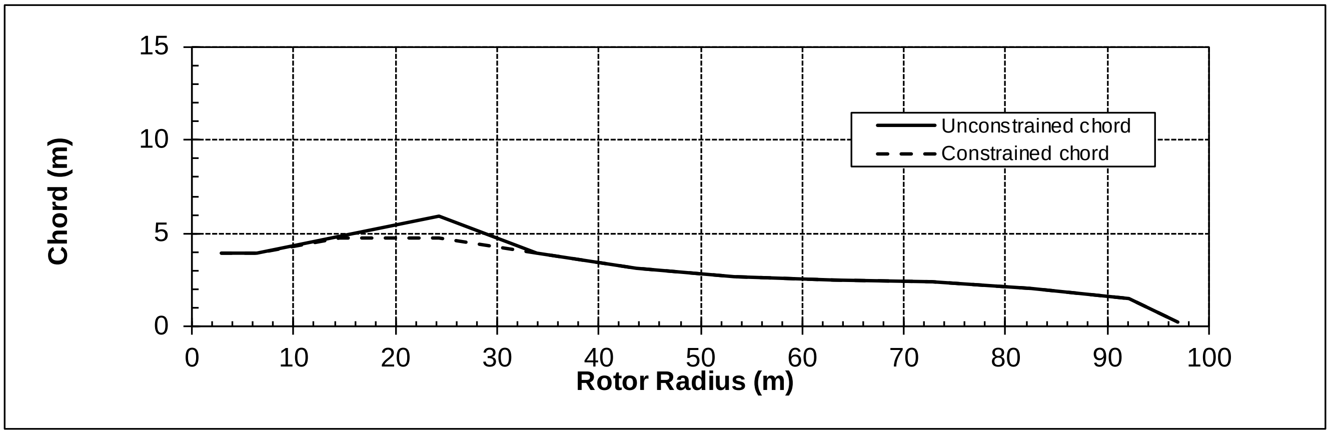


Figure 5-6 Planform for 95 m blade

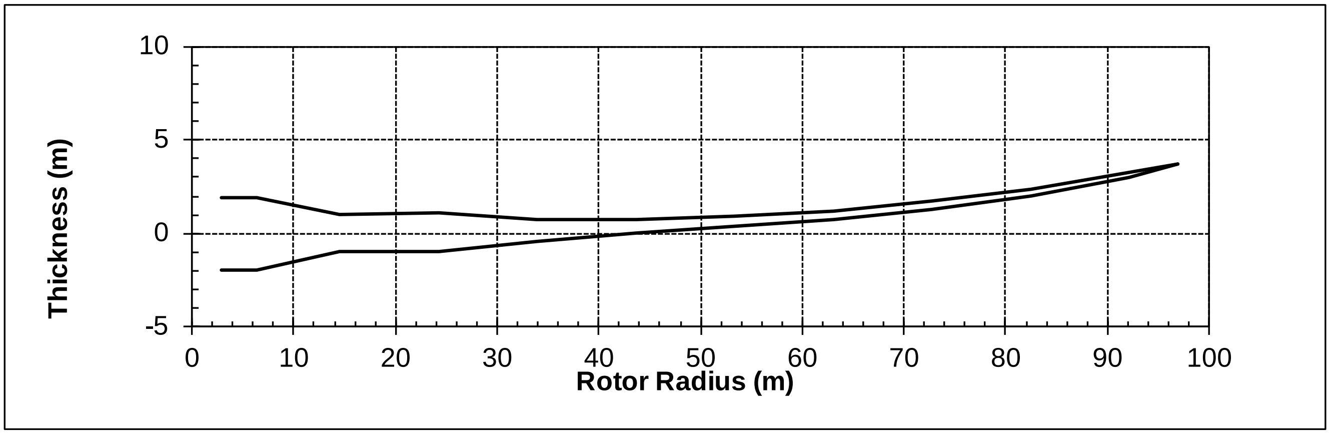


Figure 5-7 Side-view for 95 m blade

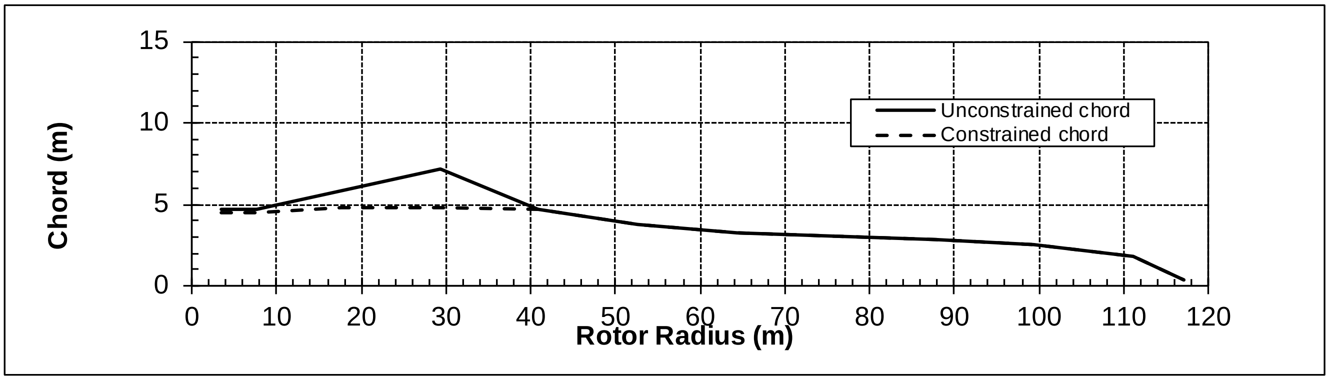


Figure 5-8 Planform for 115 m blade

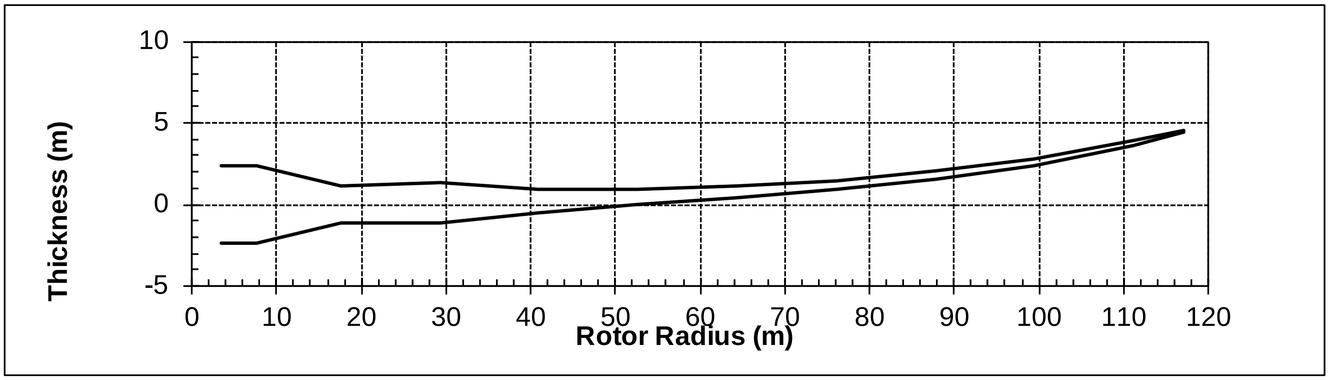


Figure 5-9 Side-view for 115 m blade

5.3 AEP calculations

As introduced above, WT_PERF analyses were performed to develop C_P-TSR curves for all aerodynamic configurations. Rotor power was adjusted to system electrical power using the drivetrain efficiency model used in WindPACT Studies [8]. Rotor speed distributions were calculated based on a maximum tip speed of 90 m/s and an assumed speed range of 1.6:1. For the purposes of this study, turbulence/control effects at the transition to rated power were ignored. AEP was calculated for corresponding hub-height annual average wind speed assuming a Weibull distribution with k = 2. Typical losses were applied to account for availability, soiling, wakes, turbine performance, environmental, and curtailments derived from DNV GL's experience accumulating to 20%.

Operational parameters and power curve for the 65 m blade at the Montana (MWST) site are shown in Figure 5-10 and Figure 5-11. The figures illustrate that rated wind speed is approximately 10 m/s, and that the maximum rotor speed (i.e., maximum tip speed) is reached below rated power resulting in a modest extent of "Region 2B" operation.

Table 5-3 shows the AEP results for all rotor configurations and locations. Annual average wind speeds are as shown in Table 4-1 earlier, including the effect of wind shear with increasing tower height. The AEP values in Table 5-3 show that the AEP losses for constrained chord dimensions are low, with the most significant loss being 0.25%. This is partly due to the relatively high value of TSR_D = 10.0. The dimensions of chord constraint, and the corresponding magnitude of AEP losses due to those constraints, would increase with decreasing values of TSR_D.

An analytical comparison of data in Table 4-1 and Table 5-3 reveals that for the rotor configurations in this study, the AEP benefits from wind speed increases due to higher tower heights is constrained. This is explained by the low specific-power values of these rotors. As an example, for the Central Michigan (LWST) location, average wind speed increases from 7.21 m/s for the 65 m blade (100 m hub height) to 7.92 m/s for the 115 m blade (150 m hub height). Since available energy scales as the cube of wind speed, this represents a 32.5% increase in the theoretically-available energy. However, with a specific rating of 150 W/m^2, the turbine reaches rated power at a wind speed of 8.5 m/s, and the additional energy above this wind speed is not realized. In part as a result, only about 31% of the theoretical energy benefit is captured (i.e., net AEP benefit is about 10% rather than theoretically-available 32.5%).

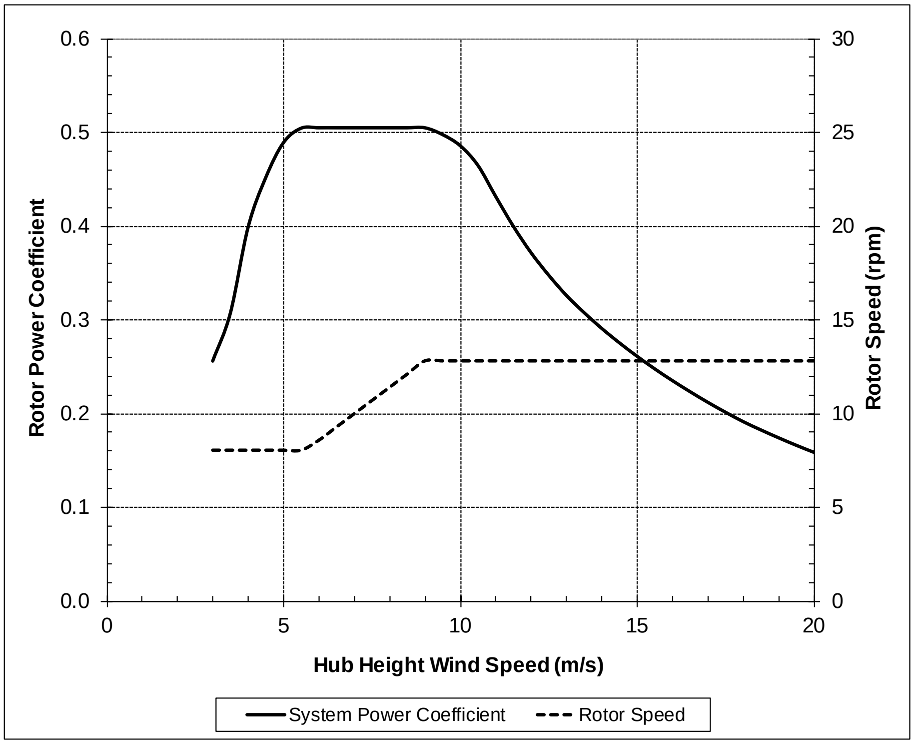


Figure 5-10 Rotor efficiency and speed for baseline 65 m blade (Montana site)

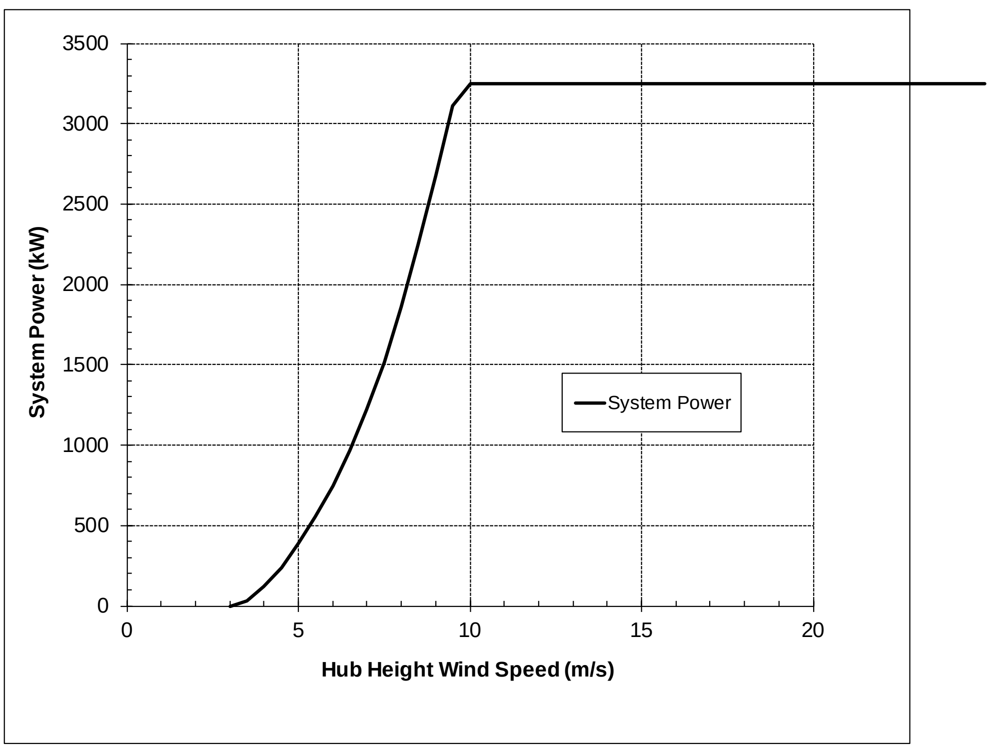


Figure 5-11 Power curve for baseline 65 m blade (Montana site)

Table 5-3 AEP results for all rotor configurations and project locations

Blade Length (m)	Site	Net AEP (MWh)		Net Capacity Factor (%)		Δ Constraint
		Unconstrained	Constrained	Unconstrained	Constrained	
65	Montana	11,737	NA	41%	NA	-
	Michigan	8,194	NA	45%	NA	-
75	Montana	15,812	NA	42%	NA	-
	Michigan	11,058	NA	46%	NA	-
95	Montana	26,178	26,163	44.3%	44.2%	-0.06%
	Michigan	18,683	18,675	47.4%	47.4%	-0.04%
115	Montana	38,984	38,887	45.6%	45.5%	-0.25%
	Michigan	27,807	27,752	48.8%	48.7%	-0.20%

6 BLADE STRUCTURAL AND COST MODELING

6.1 Baseline blade weight and cost modeling

The 65 m baseline weight of 18,640 kg was derived from the IEA Task 37 blade adjusted to 65 m using $R^{2.2}$ scaling. A very similar weight was derived independently from the NREL blade cost and weight spreadsheet (Ref. Derek Berry) using the following steps:

1) The laminate schedule for the NREL 61.5 m blade was analyzed to determine the mass corresponding to the root build-up for the modeled T-bolt connection.
2) A 35% reduction factor was applied as estimated adjustment for an embedded-stud root connection to better reflect state-of-the-art for large blades
3) The resulting 61.5 blade mass was scaled to 65 m using $R^{2.2}$ relationship

This process resulted in a modeled weight of 18,713 kg, which is within 0.4% of the scaled IEA Task 37 blade and also agrees very well with industry weight trends for fiberglass-spar blades of this size.

Specific data for blade manufacturing costs is not readily available as it embodies valuable intellectual property of the manufacturers. Approximate cost estimates for major structural elements (e.g., spar cap, skins, root connections) were derived from the NREL cost spreadsheet. Major cost categories include materials, labor (unskilled and skilled), labor overhead, tooling and equipment, land and buildings, and profit margin. The NREL spreadsheet cost model as received by DNV GL resulted in a unit cost of $12.87kg for the final finished part, including profit margin, at the factory location. Based on discussions with manufacturers contributing to this study, the NREL model unit cost was considered to be high for the current industry. Based on industry guidance, DNV GL adjusted the costs to $10.45/kg as a representative value for all-fiberglass blades. This value is not intended to reflect actual costs of any specific manufacturer, but is within the current range of expected industry norms.

As noted above, the scaling exponent has been established as $R^{2.2}$ for blades from 65 m to 115 m. A lower exponent could be concluded from the complete data set of blades between 40 and 70 m; however, the lower exponent would reflect a shift toward increased use of carbon fiber in blades in the 60 m to 70 m range. The scaling in the current study will not directly include a shift of the materials in the primary load-carrying structure (e.g., fiberglass to carbon fiber spars). This assumption is made to simplify the cost modeling, and to avoid obscuring sensitivities to the primary variables of manufacturing and transportation approaches outlined in Section 3.2 earlier.

6.2 Off-site blade manufacturing

The scaling of blades for off-site production applied the following variants:

- Monolithic blades, where conventional off-site manufacturing could produce blades dimensionally constrained by road/rail transportation limits, or alternatively could produce blades that are unconstrained in their design due to assumed airship transport.
- Modular or segmented blades which are produced in a conventional off-site location such that individual components are within road/rail transportation limits. The main components (i.e.,

monolithic equivalent) are derived using $R^{2.2}$ scaling, but with weight and cost adders due to joints and assembly in developing delivered blade costs.

6.2.1 Off-site monolithic blade weight and cost

As noted above, the scaling exponent has been established as $R^{2.2}$ for blades from 65 m to 115 m. A lower exponent could be concluded from the complete data set of blades between 40 and 70 m; however, the lower-exponent would reflect a shift toward increased use of carbon fiber in blades in the 60 m to 70 m range. The scaling in the current study will not directly include a shift of materials in primary load-carrying structure (e.g., fiberglass to carbon fiber spars). This assumption is made to simplify the cost modeling, and to avoid obscuring sensitivities to the primary variables of manufacturing and transportation approaches outlined in Section 3.2 above.

However, the scaling exponent of $R^{2.2}$ does assume significant ongoing engineering of materials, and blade and turbine design, to stay far below the self-similar cubic relationship. It is expected that realization of the $R^{2.2}$ relationship for blades between 65 m and 115 m will include further advances in aerodynamic design (primarily in improving aerodynamic lift for increasingly-thick airfoil sections), further development of fibers with increased modulus (e.g., intermediate and high-modulus glass fiber), material forms and processes that increase fiber volume content of laminate, and advancement of load-mitigating controls strategies at the WTG system, among other measures.

Based on inputs from manufacturers contributing to this study, DNV GL applied a constant unit cost of $10.45/kg for off-site monolithic blades. This assumes all-fiberglass designs, though with potential increase in fiber modulus as noted above. Maintaining this constant value assumes a neutral balance of upside and downside cost drivers as the blades were scaled to larger sizes. Upside factors include potential cost increases for additional use of intermediate and high-modulus fibers, wage growth, and potential need for increased height of buildings and overhead cranes. Factors allowing downside cost opportunity include reduced headcount-per-kg of material as fabrics being placed in molds increase in width and thickness, increased use of preformed materials, and continual value-engineering of processes, including automation.

Summary results of weight and cost for off-site production of monolithic blades is presented in Section 6.2.2 below.

6.2.2 Modular (segmented) blades

Two variants of modular blades were modeled:

- 2-piece blade with a spanwise joint where chord and root diameter were within road/rail dimensional constraints (75 m blade).
- 3-piece blades with a spanwise joint and an additional chordwise “cuff” to restore chord dimensions that exceeded road/rail dimensional constraints.

In both cases, the final assembled blades were dimensionally the same as the corresponding monolithic unconstrained version. Main components (i.e., monolithic equivalent) of modular blades were derived using $R^{2.2}$ scaling, but with weight and cost adders due to joints. Assembly costs were also added as discussed in Section 8.2, along with transportation costs to develop total delivered blade costs.

Characteristic dimensions and the estimated weight of sub-components were developed for all blade variants. Two basic approaches were considered for spanwise joints. One was to locate the joint near mid-span, so that each of the two parts was close to the minimum length practical. The other was to locate the joint in the vicinity of 60 to 70 m, near the limit of current transportation feasibility. In every case, the design bending loads would decrease with increasing spanwise position, but the inherent structural efficiency of the connection (due to cross-sectional shape) would decrease as well.

There would be numerous parameters involved in the optimization of spanwise joint location, and the most cost-effective solution might depend on the blade length specific distribution of bending load, structural shape of the blade, and intended shipping methods and route. A complete parametric evaluation of these options was beyond the scope of the current study, and the near mid-span option was selected for the analyses. It should be noted that the difference between these two fundamental approaches is most significant for the 75 m blade and diminishes for larger blades as the mid-span length of the 115 m blades approaches that of current large commercial blades.

The locations of joints for modular blades are shown schematically in Figure 6-1 through Figure 6-3. Major dimensions for the subcomponents are given in Table 6-1, where “part 1” and “part 2” are the inboard and outboard portions, respectively, for the spanwise joint and “part 3” is the chord extension, or “root cuff.”

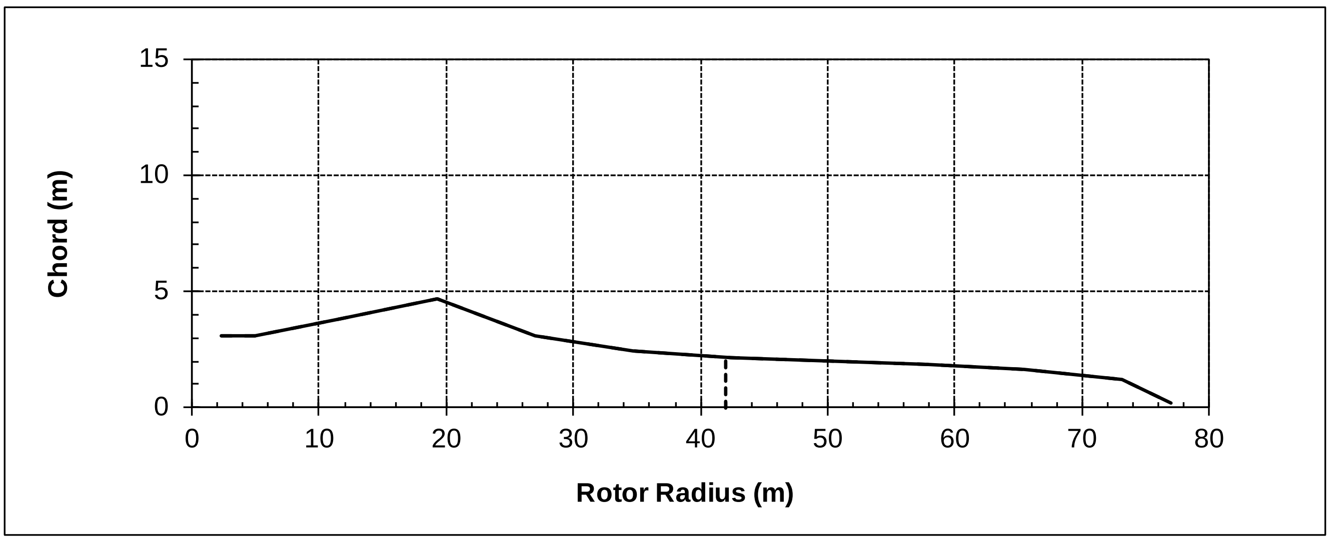


Figure 6-1 Spanwise joint location for 75 m blade

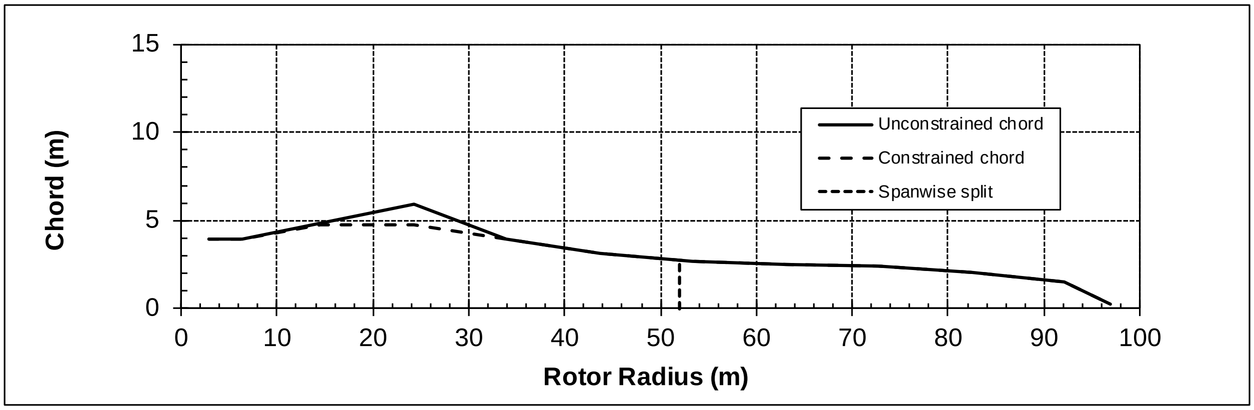


Figure 6-2 Spanwise and chordwise joint locations for 95 m blade

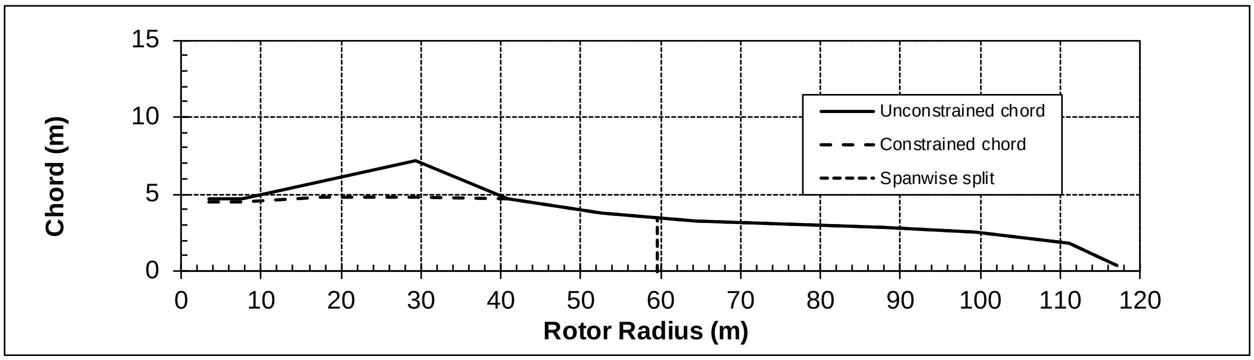


Figure 6-3 Spanwise and chordwise joint locations for 115 m blade

Table 6-1 Major dimensions for all modular blade variants

Blade (m)	Part	Length (m)	Max. Width (m)	Max. Chord (m)	Prebend (m)	Mass (tonne)	Notes
75	1	40.0	3.10	4.71	0.49	16.45	Inboard seg mass 65% of total
	2	35.0	0.45	2.14	2.49	8.86	Outboard seg mass 35% of total
95	1	50.0	3.91	4.75	0.59	41.28	Inboard seg mass 65% of total
	2	45.0	0.59	2.74	3.16	22.23	Outboard seg mass 35% of total
	3	20.0	0.52	1.19	0.00	4.00	Root cuff mass WAG for shipping est.
115	1	57.5	4.50	4.75	0.63	41.28	Inboard seg mass 65% of total
	2	57.5	0.79	3.44	3.87	22.23	Outboard seg mass 35% of total
	3	35.0	0.63	2.41	0.00	7.00	Root cuff mass WAG for shipping est.

Note: Maximum width for Part 1 is root diameter. Other parts are maximum thickness.

Detailed modeling of the spanwise joint and root cuff was performed for the baseline 65 m case, then scaled for larger blades. The connection weight and cost were estimated using the following steps:

1) The root connection (laminate build-up and hardware) were isolated in the NREL 61.5 m cost model
2) A 35% reduction factor was applied to laminate build-up as estimated shift from T-bolt to embedded stud style connection
3) The total resulting blade mass (including adjusted root build-up) was scaled up to 65 m and checked against IEA Task 37 blade and industry commercial trend-line
4) The mid-span joint was estimated based on bending loads and dimensional characteristics of local blade cross-section:
    a. Based on evaluation of DNV GL loads database, the peak flapwise bending moment was estimated to be 20% of the flapwise bending moment.
    b. Using the available geometry, a bolt pattern was estimated and evaluated.
    c. Mid-span joint parameters were iterated in an attempt to match peak bolt stress (mid-span bolt stress equal to peak for root connection).
    d. Laminate build-up was estimated to match final joint configuration.
    e. Cost for laminate part estimated as $10.45/kg.
    f. Bolt hardware weight and cost estimated by direct calculation.
5) Cost and weight for the root cuff were calculated based on skin weight from NREL 61.5 m laminate schedule, scaled as $R^{2.2}$ for larger blade lengths, with estimated factors to account for fastener connections. Fastener hardware weight and cost was estimated directly based on assumed joint configuration. While there is significant uncertainty in these estimates, the root cuff weight and cost represent a small contribution to overall weight and cost for the modular blades.

Due to geometric constraints such as available locations for connection laminate and required bolt spacing, the predicted bolt stresses for the final mid-span joint configuration were estimated as 129% of the peak root connection bolt stress. While this suggests a non-conservative result, there is significant uncertainty in the initial root connection build-up estimation. The mid-span joint was also evaluated based on ratios of approximated engineering parameters, rather than a detailed design or optimization process, so the result was considered as a reasonable approximation for the purposes of this study.

For the 65 m blade case, the final estimated mid-span root connection consisted of 36 M30 bolts (18 each blade shell), and a laminate build-up with weight approximately 26% of the root connection. Due to reduced structural efficiency at mid-span, this is greater than the bending load ratio (20% of root bending load), but only modestly, indicating that the estimate is at least reasonable. However, whereas the root laminate build-up is one-sided (with a steel pitch bearing/hub assembly on the other side), the mid-span bolted connection would require a laminate build-up on both the inboard and outboard parts. As a result, the total joint laminate build-up was estimated to be about 52% of the root build-up.

Table 6-2 provides a summary of estimated weight and cost for both monolithic and modular blades produced in a traditional off-site factory. The weight and cost adders for modular blade components range from about 11.5% to 14.5% of the monolithic blade, respectively, for 75 m and 115 m blades. Assembly costs for modular blades are accounted for in Section 8.2.

Table 6-2 Summary weight and cost for off-site monolithic and modular blades

Blade (m)	Radius (m)	Monolithic		Spanwise Joint		Root Cuff		Segmented Blade	
		Mass (kg)	Cost	Mass (kg)	Cost	Mass (kg)	Cost	Mass (kg)	Cost
65	67	18,640	$194,788	N/A	N/A	N/A	N/A	N/A	N/A
75	77	25,314	$264,531	2,905	$30,252	N/A	N/A	28,219	$294,783
95	97	42,071	$439,638	4,828	$50,277	370	$4,479	47,268	$494,394
115	117	63,546	$664,059	7,292	$75,942	1,857	$20,827	72,695	$760,828

6.3 On-site monolithic blade manufacturing

6.3.1 On-site manufacturing assumptions

The following assumptions were applied to estimate the cost for on-site manufacturing:

- On-site manufacturing method is similar to current conventional blade-in-mold techniques.
- Blade weights are the same as conventional off-site production.
- Project site has available water, power, wastewater, gas/propane to enable operation of temporary factory.
- Land owner and community acceptance of a temporary factory is achieved.
- Environmental and building permits are approved and presence of on-site factory does not prevent wind project development.
- Sufficient space is available within proximity to project for building the temporary factory (within ~5 miles of turbine pad locations – same for airship staging/landing).
- Truck transport costs for “micro haul” of blade from factory to turbine pad is estimated as 25% of short haul truck costs.
- Labor force composed of 15% skilled travelling workers; 85% locally trained workers.
- Serial blade production begins prior to project construction and there is no impact on wind plant construction schedule.
- One example full scale blade article is produced for training and to demonstrate plant commissioning (blade is not installed on turbine).
- Local workers require 10-week training period plus time for plant commissioning.
- Production quality is same as achieved in off-site factories.
- After start-up period the on-site factory can achieve the same production efficiencies and rates as off-site serial production.

Note that many of these assumptions may be considered optimistic, particularly those involving availability of suitable land/building space with available utilities within 5 miles of turbine pads along with community acceptance, environmental impact assessment/approval for hazardous materials, and other permitting. DNV GL acknowledges that many assumptions used to study on-site manufacturing have significant impacts on the wind project development process, land owner acceptance, local community acceptance, and regulatory approval/compliance requirements. Resolving these challenges is outside the project scope, but they do add an additional layer of complexity to executing on-site manufacturing that needs careful consideration and further investigation.

6.3.2 65 m baseline blade estimate

DNV GL analyses initially focused on manufacturing the Baseline 65 m blade to identify and estimate elements where on-site manufacturing deviates from off-site manufacturing. Utilizing the NREL blade model, key variables were isolated and extrapolated to develop estimates of the cost adders for on-site manufacturing of 75 m, 95 m, and 115 m blades.

For the Baseline 65 m off-site blade plant, the following operations and labor parameters are established:

- Two production lines operate with three work shifts per day
- Blade mold cycles are completed every 24 hours
- 540 workers are needed to operate the blade factory on a continuous basis
    - 85% are considered unskilled labor trained to perform specific tasks ($28/hr fully burdened)
    - 15% are considered skilled labor with a 25% premium in wage rate ($35/hr fully burdened)

Translating these parameters to an on-site manufacturing scenario, DNV GL assumed:

- No change in production lines, mold cycling or total labor force
- Added 20% cost to skilled labor wage as incentive for traveling with mobile factory
- Local/regional labor market around the wind project can supply sufficient number of unskilled workers to be trained

The cost implications of on-site manufacturing are identified in two categories, recurring costs, and non-recurring costs. Recurring costs correspond to costs generated once serial blade manufacturing begins. These serial manufacturing costs are assumed to not differ between wind project sites at which on-site manufacturing is performed. Non-recurring costs correspond to one-time costs incurred each time the on-site manufacturing plant is positioned at a wind project. These correspond to costs that cannot be avoided when relocating the manufacturing facility and costs that cannot be shared across multiple plant deployments.

6.3.2.1 Recurring cost adders

Utilizing the baseline off-site blade manufacturing cost of $10.45/kg as the reference for recurring costs, the NREL blade model establishes the following fractional contributions:

- Labor fraction = 30%
- Materials fraction = 35%
- Tooling utilization = 7%

Other fractional elements into the blade manufacturing costs exist (cost of capital, utilities, building/facility maintenance, overhead, profit) but are assumed to have secondary effects on blade costs when evaluating on-site versus off-site manufacturing.

Accounting for the on-site labor cost changes noted above, DNV GL calculated a 3.6% increase in on-site labor costs over off-site. Considering the labor fraction of 30%, the net increase in baseline blade recurring cost is $0.11 per kg.

The fundamental price of materials used in the blade are assumed to remain unchanged with on-site manufacturing, however, delivery costs of the materials is assumed to increase due to shipping and handling to maintain the on-site manufacturing process. For conventional off-site manufacturing, some level of supply-chain optimization is typical, such as material sub-suppliers situating manufacturing or chemical processing plants adjacent to blade manufacturing plants to minimize transportation, storage, and delivery costs. DNV GL estimated that supply chain inefficiencies related to adding field delivery of blade materials, chemicals, and process materials would add 15% to the material costs of the blade. Accounting for the material fraction of 35%, the net increase in baseline blade cost is $0.55 per kg.

Tool utilization is a manufacturing metric that corresponds to the degree of operating efficiency which the entire manufacturing process achieves. It represents the percentage of time the equipment, facility and process are in production, thus maximizing the distribution of investment costs of the equipment, facility, and process over as much product as possible. Broadly speaking, off-site blade manufacturing facilities are in production about 85% to 95% of the time which effectively distributes tooling, equipment, and facility costs down to 7% of the blade production cost.

For on-site manufacturing, all the tooling, molds, process equipment, facility costs, etc. are comparable in magnitude for off-site manufacturing. However, DNV GL estimates that the utilization rate of this equipment would be 50% lower than achieved off-site. Under optimistic scenarios, we assume the on-site factory could produce all the blades for the 150 MW project in a 6-month serial production period. However, we assume a 3-month period is needed to deliver and build the on-site factory. An additional 3-month period is needed to commission the factory, train local workers, and produce a “first article” to demonstrate that all equipment, processes, and workers can meet manufacturing quality and production thresholds. Our 50% reduction in tool utilization (corresponding to a 100% increase in tooling costs) is due to the process equipment, tooling, molds, and facility costs not in serial production for 6 months of the year. Accounting for the tooling utilization fraction of 7%, the net increase in baseline blade cost is $0.73 per kg. DNV GL considers the utilization factor to be optimistic, as it does not explicitly include time for decommissioning of the factory, disassembly of tooling and equipment and preparation for shipment to the next on-site factory location.

The combination of these factors result in a 13.3% increase in recurring costs for on-site blade manufacturing over off-site manufacturing, with a resulting $11.84/kg rate.

6.3.2.2 Non-recurring cost adders

DNV GL elected to simplify the analysis of non-recurring costs to focus on three of the largest likely contributors: training the local unskilled labor force, factory construction, and “first article” production. DNV GL assumes that these activities are executed with quality and high efficiency, that a quality and engaged workforce is available, and that local landowners and authorities having jurisdiction (AHJs) over approvals support the facility.

DNV GL estimated the local unskilled workforce would require ~10 weeks of training and plant commissioning performed by the traveling skilled staff. Given the total headcount of 540 people, a blended hourly rate of $30.10 and 40-hour work weeks, the resulting non-recurring labor cost is $6.5 million. The underlying assumptions for training of local labor force are considered optimistic, and do not explicitly include the costs of advertising for local employees, human resource functions of interviewing and hiring, and inevitable attrition of local employees during the training and production periods.

Construction related costs that are incurred each time the on-site factory is deployed were estimated as follows:

- Metal factory building, concrete foundation, overhead structural cranes, laydown yard, and parking area $1.73M for 5,195 m^2 facility ($332.80/$m^2$)
- Plumbing, wiring, interior walls, fixtures, finishing, utilities: $500k
- Install, align, calibrate, major production equipment: $500k
- Environmental, building, OSHA permitting/approvals: $200k
- Total factory cost = $2.93M

DNV GL assumed the factory is required to produce one blade, as part of plant commissioning, worker training, and demonstration of quality control. It is assumed these first articles would not be installed on a wind turbine, thus their production costs are accounted for as a non-recurring cost. Due to ramp-up of related to processes and training, DNV GL approximated the cost of this article as 1.25 times the recurring cost of the blade, or $389.5k.

In total, the combined non-recurring cost assumed for the Baseline blade is $9.82M. The primary contribution to estimated non-recurring costs is the training of a local workforce, followed by the planning and construction of the facility itself. Relative to these two cost elements, the costs for production of a first-article are modest.

6.3.3 75 m, 95 m, and 115 m on-site blade manufacturing

DNV GL developed on-site blade manufacturing costs by applying the following scaling assumptions to parameters previously presented in the calculation of the Baseline 65 m blades. The scaling assumptions are based on DNV GL project team opinion and experience as well as guidance from a review of previous Sandia/TPI studies [5], [6], but are not grounded in detailed research. The following scaling assumptions were applied to account for factors related to producing larger blades.

- Labor workforce headcount: scales at ½ blade length (L) due to assumed labor efficiencies as blade size grows.
- Factory area:
  - scales at length over baseline length squared $(L/L_b)^2$ for change from 65 m to 75m blades
  - factory area for 95 m blade is same size as for 75 m blade as 95 m production is reduced from two to one production lines
  - 115 m blade factory also operates with only one line, so scales up from 95 m case using L/L_b^2
- Overhead structural space: scales at L due to increasing building height requirements for overhead cranes to manipulate molds and blades
- Plumbing, wiring, interior walls, fixtures, finishing, utilities: scales with factory area
- Installation, alignment, and calibration of major production equipment: scales with factory area
- Laydown yard, parking, other paved areas: 50% of factory area at cost of $5/sq ft
- Environmental, AHJ approvals: no change with factory size
- First article production cost: 1.25 * blade mass * recurring production costs

Table 6-3 summarizes the estimated non-recurring costs associated with each deployment of the on-site blade factory, as adjusted with the scaling factors presented above. The costs are further translated into cost per blade, based on the blade counts at the Montana and Michigan project locations.

Table 6-3 Summary of non-recurring costs associated with on-site blade manufacturing factory

Blade Length (m) =	75	95	115
Headcount =	581	664	747
Labor cost for training/commissioning =	$6,995,240	$7,994,560	$8,993,880
Factory & first article non-recurring =	$4,197,255	$4,294,904	$6,343,659
First article production cost =	$374,756	$622,826	$940,758
Total (non-recurring) costs =	$11,567,251	$12,912,291	$16,278,297
Montana non-recurring cost adder/blade =	$110,164	$195,641	$361,740
Michigan non-recurring cost adder/blade =	$71,403	$130,427	$235,917

Recurring costs for blade production correspond to the blade mass multiplied by the adjusted on-site blade production cost of $11.84/kg. Figure 6-4 presents a summary of the blade cost adder combined with the original cost of an off-site manufactured blade.

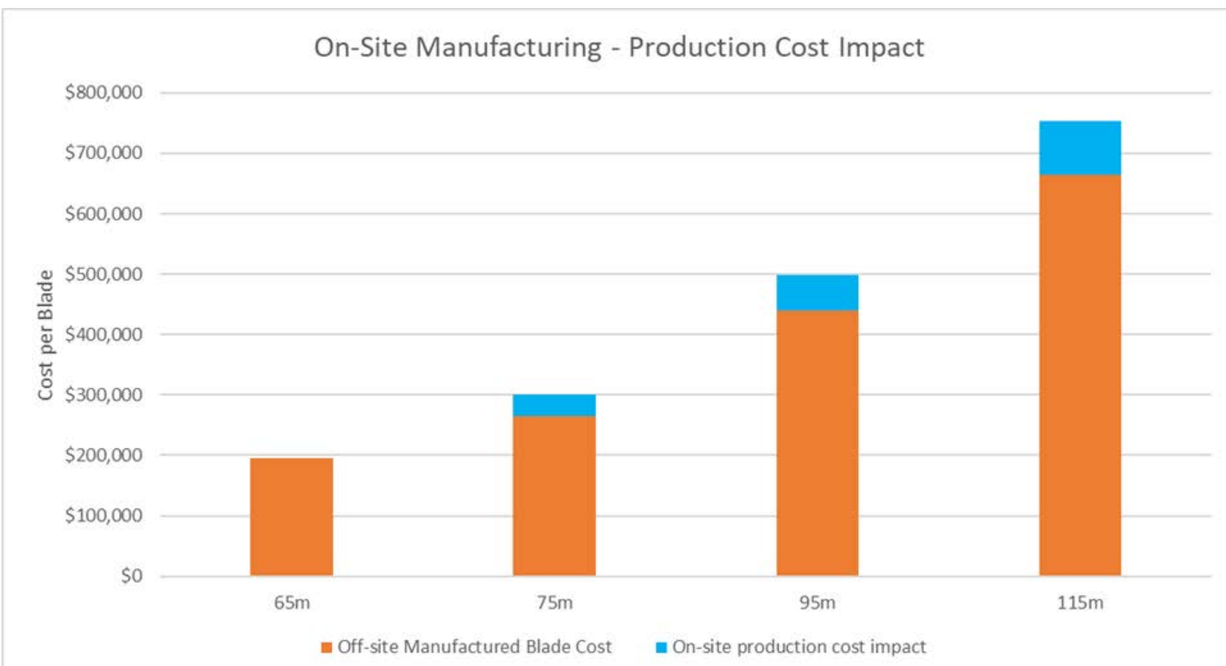


Figure 6-4 Blade production costs for on-site manufacturing (excludes one-time, non-recurring factory costs and transport costs to pad location)

7 BLADE MANUFACTURING AND TRANSPORT COST TARGETS

7.1 Off-site manufactured blade costs

Based on current blade manufacturing methods, off-site manufacturing costs estimated at $10.45/kg and the scaled blade masses presented in Section 6, the costs of finished blades at the off-site factory are calculated and presented in Figure 7-1. Based on trends to date, LCOE reductions are being achieved with the blade mass scaling rate of $R^{2.2}$. The off-site manufactured blade costs also provide the target for which production costs from on-site manufacturing and other alternatives shall compete to contribute to overall turbine LCOE reductions, though transportation costs must be added to reflect a more-complete cost comparison.

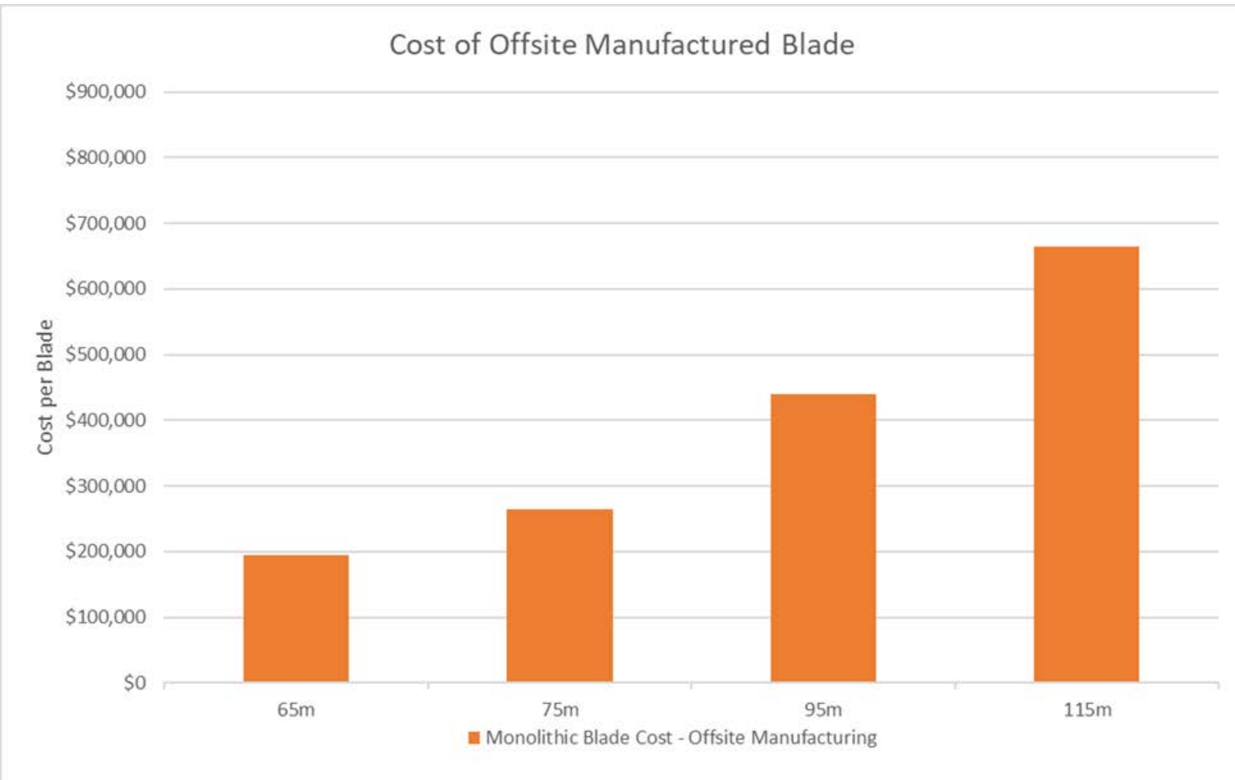


Figure 7-1 Estimated cost of off-site manufactured blades

7.2 Total cost of delivered blade targets

Isolating on the Baseline 65 m blade, transportation and handling costs were estimated by industry partners for blades manufactured in Kansas and delivered by truck and rail to the hypothetical project locations in Eastern Montana and Central Michigan. At the time of this work, industry partners reported that they were actively preparing estimates for delivery of blades with very similar characteristics as our Baseline blade to projects under development and construction in the general areas of our hypothetical projects. Therefore, the transportation costs for the 65 m blade were viewed as highly representative of current market conditions.

Transportation costs for the 65 m blade were estimated as shown in Table 7-1.

Table 7-1 Estimated transportation costs for 65 m blade

65 m blade transport costs ($/Blade)	Montana	Michigan
Long-haul truck	$40,085	$52,330
Rail + short-haul truck	$31,574	$51,775

Note: The lower value of rail + short-haul truck was used in the analysis. Includes costs to transfer from rail to truck.

Blade specific LCOE was then calculated for the Baseline turbine using the Total Cost of Delivered Blade (considering off-site manufacturing costs shown in Figure 7-1, and the lower-cost rail and short-haul truck transport costs shown in Table 7-1), Turbine AEP, blade-specific O&M cost, and fixed charge rate (7.9%). (See Appendix A for summary of LCOE calculation methodology.)

Then, holding the Baseline blade-specific LCOE as a constant and adjusting for the AEP for each of the larger study turbines, a "Total Cost of Delivered Blade Target" was derived for the 75 m, 95 m, and 115 m blades. In calculating this Target, impacts of taller hub heights, larger swept area, and increased wind speeds associated with larger wind turbines are accounted for in the AEP for each turbine. Moreover, using the scaled manufactured blade costs shown in Figure 7-1, we can split the "Total Cost of Delivered Blade Target" into two components: blade costs and budget for transportation and other costs.

This Total Cost of Delivered Blade Target represents the threshold or "budget" for pathways to compete. Pathways that result in Total Delivered Blade Costs more or less expensive than the Target value will influence the blade's contribution to overall system LCOE accordingly. Pathways equal to the Target have no impact on system level LCOE but may still enable LCOE improvements in other turbine systems.

Figure 7-2 presents the calculated Total Cost of Delivered Blade Targets for each of the project locations. The cost target in Michigan is greater than in Montana due to older infrastructure, increased number of local jurisdictions to travel through, and other transportation costs in the Great Lakes region being slightly more expensive than similar costs in Montana.

An unexpected finding in this process was that although the transportation cost element (for neutral LCOE impact) to transport supersized blades increases with blade and turbine size, the transportation cost element as a percentage of total delivered blade cost decreases slightly with increasing size.

To illustrate this point further, for Montana, the transportation cost element increases 172% from $31,574 to $85,941 per blade for the 65 m and 115 m blades, respectively. For Michigan, the transportation cost element increases 230% from $51,775 to $171,008 per blade for the 65 m and 115 m blades, respectively. However, as a percentage of the total delivered blade cost target, the transportation cost element is 22% to 20% of the total target for Michigan and 14% to 11% of the total target for Montana.

Upon closer analysis, we note that blade costs are increasing at $R^{2.2}$ while annual energy production is increasing at a slightly lower rate of $R^{2.1}$. Therefore, blade costs are increasing at a faster rate than energy capture, resulting in less "budget" available for transporting blades to the site. The low specific ratings of the turbines combined with wind shear and selected hub heights are contributing to this effect because the turbines achieve rated power at lower wind speeds, thus limiting their expected AEP gain.

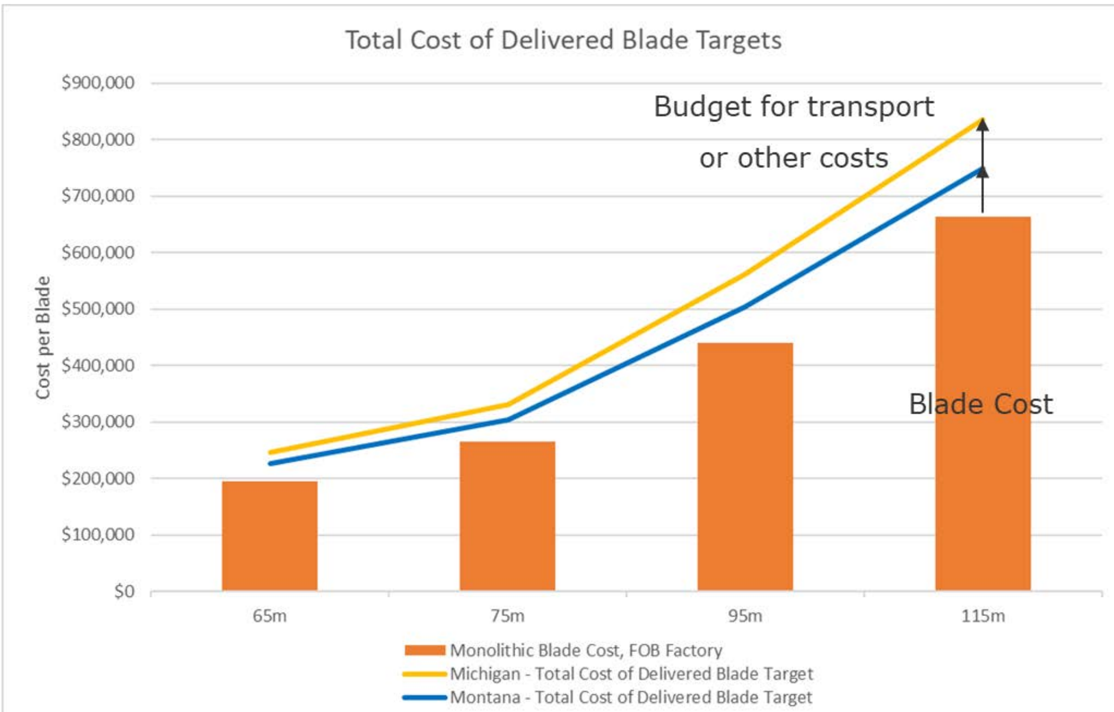


Figure 7-2 Calculated total cost of delivered blade targets

8 PATHWAY ANALYSIS AND FINDINGS

8.1 Innovative transportation pathway

Although physical constraints related to road and rail infrastructure will continue to challenge the feasibility of ground-based transportation of supersized blades, innovation opportunities remain within the transportation sector. The challenge with achieving transportation innovations is related to market scale and timing needed to spur investment in new trailers, rail cars, or other equipment. Both “Constrained” and “Unconstrained” monolithic blade configurations were evaluated to determine transport feasibility, costs, and areas of innovation that could enable supersized blades.

8.1.1 Truck and rail findings

Figure 8-1 and Figure 8-2 summarize the transportation cost estimates developed for truck and rail delivery of monolithic blades to the Montana and Michigan project locations, respectively. As noted earlier, these estimates derive in large measure from wind industry rail and road transport experts. Blue bars indicate the transportation portion of the total cost of delivered blade target values previously described in Section 7. Values exceeding the blue bars will increase the system-level LCOE, while values lower than the blue bars will contribute to decreases in system-level LCOE.

The truck and rail findings apply to blades with chord and root dimensions at or within the design constraints. Blades with unconstrained chord and root dimensions were not transportable by truck or rail.

8.1.1.1 Transporting 65 m monolithic blades

Transportation of 65 m blades by rail and truck was deemed feasible to both project locations. This finding is consistent with current market and industry capabilities. While 65 m blades are transportable over wide geographic regions across the central U.S., some route constraints over the Rocky Mountains and along the East Coast would add to logistic costs and could limit delivery to certain project locations.

As illustrated in Figure 8-1 and Figure 8-2, long haul truck costs for 65 m blades are slightly more expensive than the combination of rail plus short haul trucking. Rail can offer transport cost efficiency, avoidance of long escorts, and reduced local jurisdiction permitting costs.

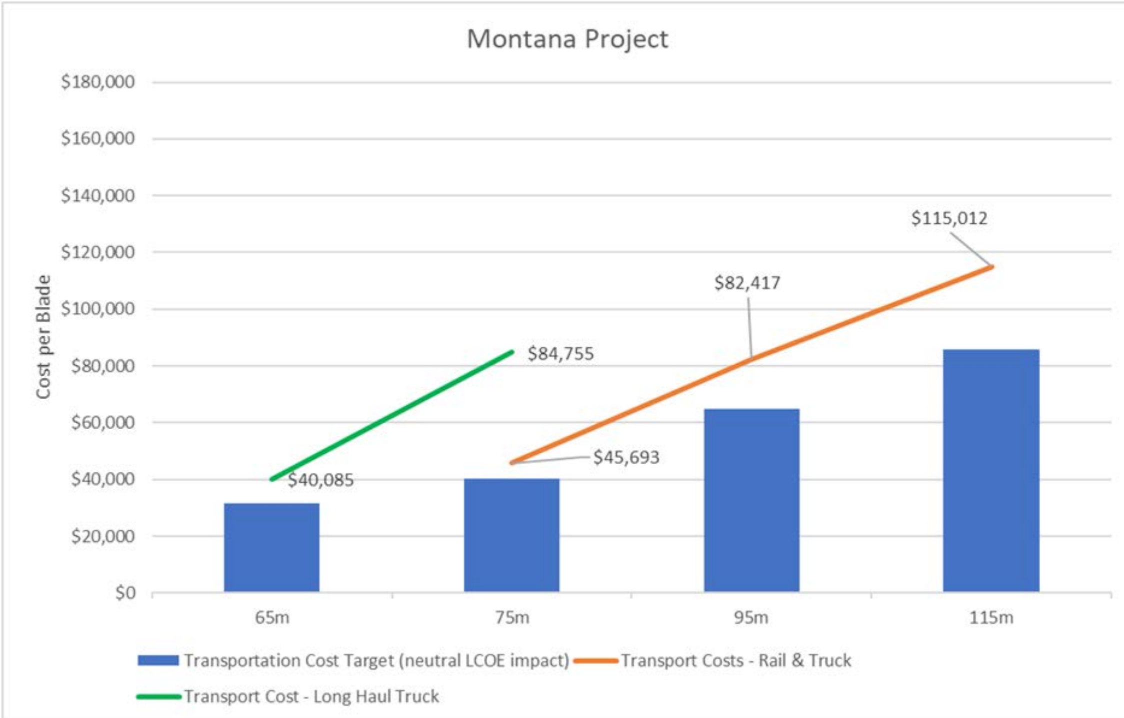


Figure 8-1 Monolithic blade, truck and rail transportation costs – Montana Project

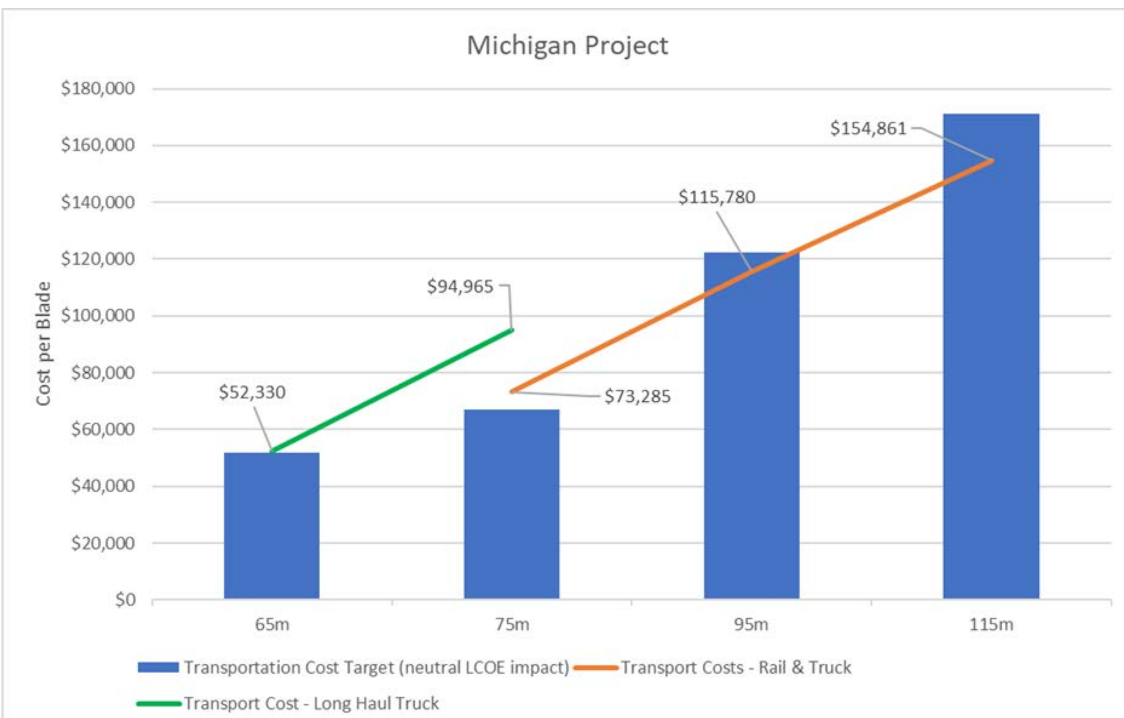


Figure 8-2 Monolithic blade, truck and rail transportation costs – Michigan Project

8.1.1.2 Transporting 75 m monolithic blades

The 75 m blades were deemed very challenging for both truck and rail, but they were found to be at the high-end limit of feasibility and within a size that trailer and rail-car modifications could be made by industry to enable delivery. Significant infrastructure constraints and costs must be managed and are apparent in the cost estimates shown in Figure 8-1 and Figure 8-2. Both long haul truck and rail transportation costs for the 75 m blades were found to exceed the transportation cost target for neutral impact on system LCOE. These findings appear to reinforce the challenge that although it may be possible to deliver 75 m blades, the economics result in upward pressure on system LCOE if considering blade costs alone. Although delivery was deemed possible for the hypothetical wind projects of this study, the geographic areas of the U.S. where delivery of 75 m blades could be performed is reduced versus 65 m blades resulting in more project locations at risk to receive 75 m blades. Generally, the 75 m blade could serve the central U.S., but transport across the Rocky Mountains or through the Eastern U.S. was deemed less likely.

8.1.1.3 Truck and trailer findings – 75 m monolithic blades

Long haul truck costs were 42% to 110% greater than the transportation cost target, depending on the project destination, translating to a 1.4% to 2.0% increase of system level LCOE.

Further items to note:

- Long haul trucking requires special trailers for road transport that do not exist at this time – but industry is already working on new trailers intended to accommodate 70-75 m blades. It was noted by industry partners that the transport industry is currently studying blades to 74 m.
- Long-haul route options for 75 m blades across the U.S. will be significantly constrained (versus long-haul routes for 65 m blades) due to local infrastructure constraints that will prohibit transport. Additional haul distances will be incurred to navigate around infrastructure constraints. Routes in the central U.S. will likely be more conducive; however, long-haul transport within the East Coast and across the Rocky Mountains will not be feasible due to physical constraints.
- Increased local concerns, state permitting issues, route escorts, and related costs add to the potential impediments for 75 m blades.
- 75 m blades appear to be the upper limit of the long-haul truck/trailer feasible range.

8.1.1.4 Rail transport findings – 75 m monolithic blades

Rail costs were 9% to 13% greater than the transportation cost target, translating to a 0.2% and 0.3% increase in system LCOE.

- Rail costs presented herein include transfer costs from rail to truck and short haul trucking to the project site.
- Three rail cars per blade were estimated with blades oriented tip to root
- Pricing was based on “full unit” trains – meaning all blades for the project are transported in one train and no blades are left over that require long haul truck/trailer delivery.
- 75 m blades are at the limit of the rail infrastructure clearance capabilities.

Short-haul trucking associated with rail delivery (50 to 100 miles on local roads within one state for example) for 75 m blades was viewed as feasible – yet still highly dependent on the project location and actual local infrastructure. For purposes of this study, short-haul routes from rail transfer location to final project location were considered feasible – but may require local infrastructure modification to enable.

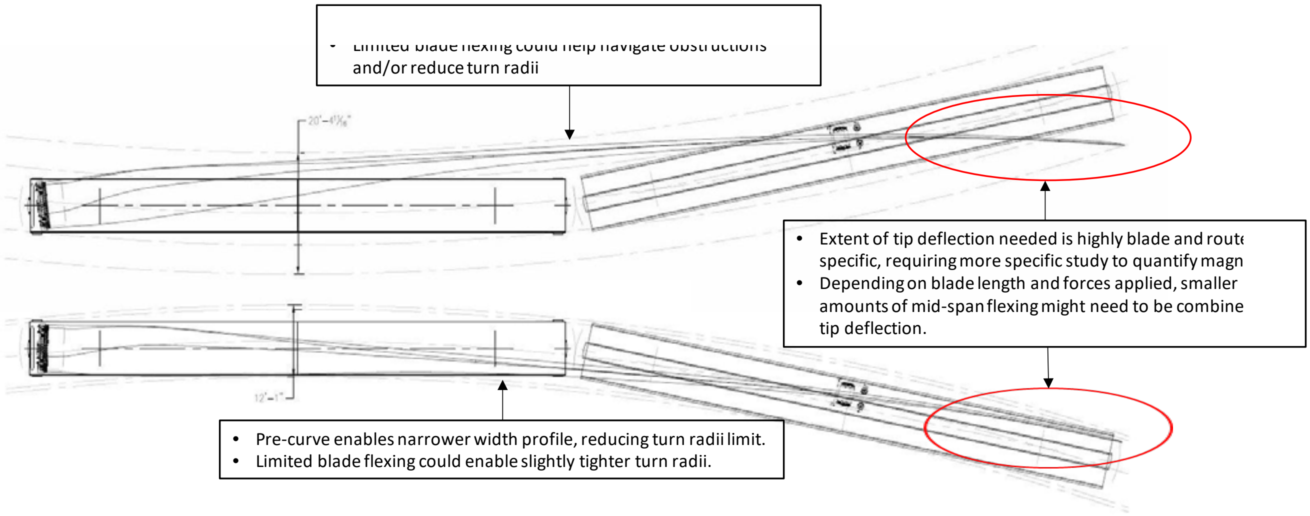
8.1.1.5 Transporting 95 m and 115 m monolithic blades

95 m and 115 m blades with unconstrained chord and root dimensions were deemed not feasible for truck or rail transport under any circumstances due to infrastructure clearance issues that cannot be mitigated. Even with chord and root dimensional constraints, long haul trucking of 95 m and 115 m blades was found to be infeasible due to significant infrastructure constraints, no viable route options, excessive infrastructure improvements, large number of blades to transport, and inability to secure local approvals, among other challenges. Therefore, no long-haul truck costs are indicated in Figure 8-1 and Figure 8-2.

Based on feedback from transportation industry partners, a future innovation for monolithic blades that enables limited and controlled flexing of the blade during rail transport to clear infrastructure hazards could enable rail movement of 95 m and 115 m constrained blades. Preliminary attempts of this concept have been made, but not thoroughly investigated. Blade design, safety standards, and OEM requirements do not currently allow blade flexing to enable transport. Significant research and engineering work would be required to incorporate controlled flexing into the blade design and transportation process; however, this represents an example of the type of innovation that could be investigated further. Advances in real time load and position sensors could be utilized to monitor blade deflection when required. Reactive forces (countering blade flex) on the rail cars, track and subgrade would also require investigation, yet these concepts appear to be within current engineering capability to understand, investigate, and develop solutions.

For study purposes, controlled blade flexing was assumed to enable rail transport of dimensionally constrained blades and is the basis for the cost estimates shown in Figure 8-1 and Figure 8-2. Without blade flexing, rail transport of monolithic 95 m and 115 m blades is not possible.

Figure 8-3 illustrates the challenge associated with blade flexing for rail transport. The objective for blade flexing would be to result in a temporary blade profile similar to that of the 75 m blade to navigate past obstructions or constraints. Based on the pre-curve dimensions shown in Section 5, tip deflections for the 95 m and 115 m blades would need to be on the order of ~1 to 2.5 m, respectively to achieve a profile similar to the 75 m blade. For comparison, under normal operation, blade tips can deflect up to 15% to 20% of blade length. For the 95 m blade, this operational deflection is on the order of 14 m to 19 m. For the 115 m blade, this operational deflection is on the order of 17 m to 23 m. Thus, the amount of blade flex needed for transport is within the range of capability. Finally, the specific amount of deflection necessary is highly dependent on the transportation route and blade design, thus there are no finite limits to be documented.



Source: BNSFL

Figure 8-3 Illustration of challenge associated with blade flexing for rail transport

We did not include an adjustment to the blade mass and cost that might be needed to accommodate blade flex in transport. In addition, we also assumed the trucking industry would be able to develop a truck and trailer solution sufficient to perform short hauls (50 – 100 miles) of 95 m and 115 m constrained blades. It was assumed that short-haul truck routes could be developed between the rail transfer yard and project development site and coordination within one state and a few local jurisdictions would be manageable. Admittedly, these assumptions result in very uncertain scenarios and cost estimates. However, we find the process useful to provide some cost estimates for comparison purposes and to identify potential areas of further research and development.

8.1.1.6 Constrained blade transport findings – 95 m and 115 m

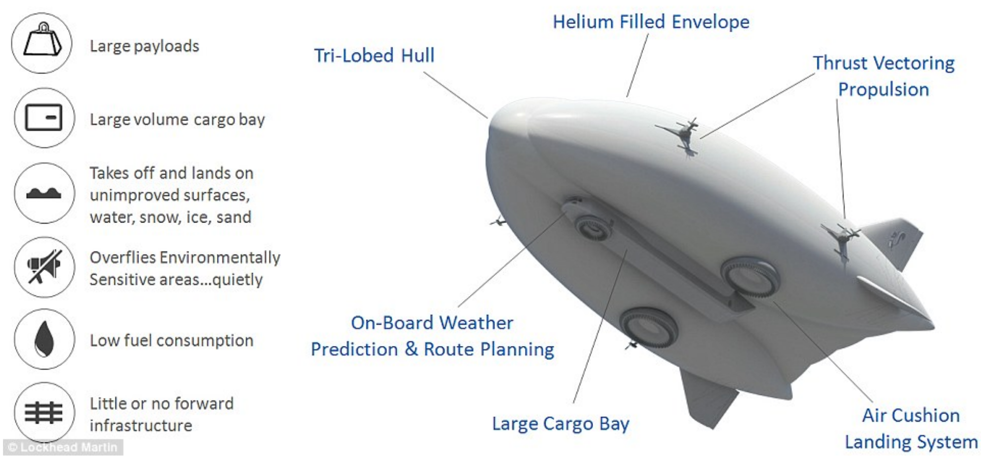
As indicated in Figure 8-1, delivery costs via rail for the Montana project location were 27% and 34% greater than the transportation cost target for 95 m and 115 m blades, respectively. This translates into a 0.5% increase in system LCOE. Figure 8-2 illustrates delivery costs via rail for the Michigan project location were 5% and 9% less than the transportation cost target for 95 m and 115 m blades, respectively. This translates into a 0.2% to 0.3% decrease in system LCOE.

- Long-haul rail is only feasible if blades can be flexed while on rail cars and navigating tight turns or trackside obstacles.
- Estimates include an assumption that accommodations will be figured out to allow flexing the 95 m blade at ~45 m from the tip; and the 115 m blade to be flexed at 45 m and 75 m from the tip.
- Flexing blades to enable short-haul trucking was discussed but it was not clear if blade flex alone would help mitigate the road-based infrastructure issues. Currently, there are no known truck/trailer combinations that exist to manipulate objects 95 m or 115 m long.
- Although flexing blades may be helpful for enabling rail transport, ultimate delivery from the rail network to project location may still be insurmountable.

8.1.2 Airship transportation – 75 m, 95 m, and 115 m monolithic blades

LTA hybrid airships have been investigated as an alternative transportation mode within the logistics industry for many decades although there have been no successful commercial operations to date. In theory, airships could disrupt the cargo transportation landscape composed of water borne vessels, ground based truck and rail, and airborne fixed wing and helicopter craft. In comparison to current transportation modes, airships may offer high payload capacity, avoidance of ground-based infrastructure challenges, achieve acceptable transport speed, and have reduced fuel consumption and operating costs (among other comparison points). The latest investigation and development of airships for cargo purposes is Lockheed-Martin's "hybrid" (LMH) airship. As illustrated in

Figure 8-4, The LMH craft combines lighter-than-air (LTA) technology; a wing-like shape to provide some lift during forward motion; and air cushion landing technology from hovercrafts into one aircraft focused on heavy cargo delivery to remote areas.



Source: Hybrid Enterprises

Figure 8-4 Lockheed Martin Hybrid airship features

In 2006, Lockheed Martin built and demonstrated a pilot scale craft, P-791 (see Figure 8-5) to demonstrate the technology. This craft was 37 m long by about 11 m tall. They envision three categories of future airships:

- LMH-1: 84 m long x 22 m tall; vessel weight ~21 ton
- LMH-2: 120 m long x 32 m tall; vessel weight ~90 ton
- LMH-3: ~260 m long x ~70 m tall; vessel weight ~500 ton

Source: Hybrid Enterprises

Figure 8-5 P-791 demonstration craft

Time to market and availability for purchase of the LMH crafts is unclear. Lockheed Martin indicated that the LMH-1 may be available for purchase after 2020 and its initial expected use may be for delivery of mining and earth moving equipment into remote regions where roads do not exist or are insufficient.

As an alternative to ground-based transportation of monolithic blades, airships were included in this study as an example of further innovation in transportation logistics and to offer a potential view into disruptive technology that can enable supersized wind turbines. Capabilities and cost estimates are derived from one supplier and we are not able to independently verify the accuracy of the information.

The LMH-1 aircraft was too small to accommodate a 75 m or larger blade; therefore, our assessment focused on the LMH-2 and LMH-3 aircraft. The lifting capacity, vessel dimensions, and possible cargo hold configuration of the LMH-2 was found to accept one blade per load; whereas the LMH-3 appeared capable of accepting three blades per load. For both vessels, it was assumed that the cargo hold was modified to accept the blade root and that portions of the blade tip would extend out to the rear of the aircraft. The asymmetric blade centers of mass were found to be beneficial for loading in the airship in this manner. Loading the blades within the cargo hold as opposed to slinging beneath the aircraft was the preferred method for safety and maximizing flying conditions. The LMH-2 did not have sufficient cargo space or lift capacity to accommodate a 115 m blade.

A size comparison of the LMH-3 aircraft and 115 m blade is presented in Figure 8-6. The LMH-3 is roughly equivalent to a modern football stadium in length, whereas the playing field dimensions are roughly equivalent to the 115 m blade. Although the blade is long, its mass is relatively light (in comparison to the LMH-3's potential lift capacity), making it an object that could be conducive to airship transport. Obviously, aircraft of this scale are conceptual at this time, thus considerable challenges may exist due to the size and public acceptance. Although extremely large, the vertical takeoff and landing capabilities of the airship enables it to occupy a manageable landing/loading zone of approximately 400 m in diameter; roughly 0.5% of the area covered by the 150 MW wind power project including space between turbines and setback zones.

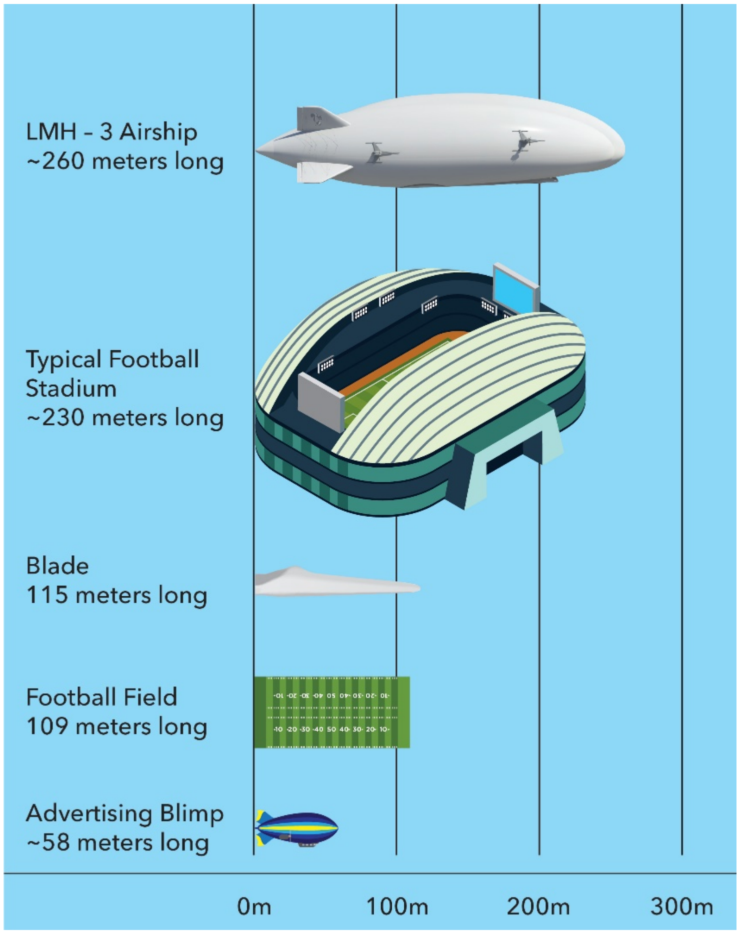


Figure 8-6 Size comparison of LMH-3 Airship, 115 m blade, and reference objects

8.1.2.1 Airship transportation findings – 75 m, 95 m, and 115 m monolithic blades

Blade transport cost estimates using airships are presented in Figure 8-7 and Figure 8-8 for Montana and Michigan, respectively. These costs include a "micro-haul" from the landing zone to turbine pad (~5 to 10 miles). Costs per blade for the LMH-2 were approximately 45% to 55% greater than the LMH-3 due to loading limitations of one blade per cargo hold in the LMH-2. Focusing on the LMH-3, cost estimates for the Montana location were 6% to 15% lower than the transportation cost target for the 95 and 115 m blades; costs were 22% higher than the cost target for the 75 m blade. For Michigan, LMH-3 cost estimates were 56% to 58% lower than the transportation cost target for the 95 and 115 m blades, and 31% lower for the 75 m blade.

These estimates consider variations in the delivered cost of blades, but do not consider the small AEP penalty associated with the dimensionally constrained blades required for traditional over-land transport. When considering both factors combined, these values translate into a 0.1% to 2.1% decrease in system LCOE for the 95 m and 115 m blade sizes.

- In the event airships of this scale achieve market presence and public acceptance, they could provide a noteworthy decrease in system LCOE. Although we did not extrapolate their potential cost benefits for other turbine elements, expanding airship usage for other turbine elements could further improve the beneficial impact on lowering system LCOE.

- Time to market and accuracy of these estimates have significant uncertainty. Airships do not offer near term opportunities for supersized turbine deployment over the next couple of years.
- There do not appear to be significant geographic limitations regarding areas of the U.S. where airships could serve, thus airships could support increased wind turbine deployment in new areas.
- Blades transported by airship would not need root and chord dimensional constraints, enabling more advanced blade shapes and designs.

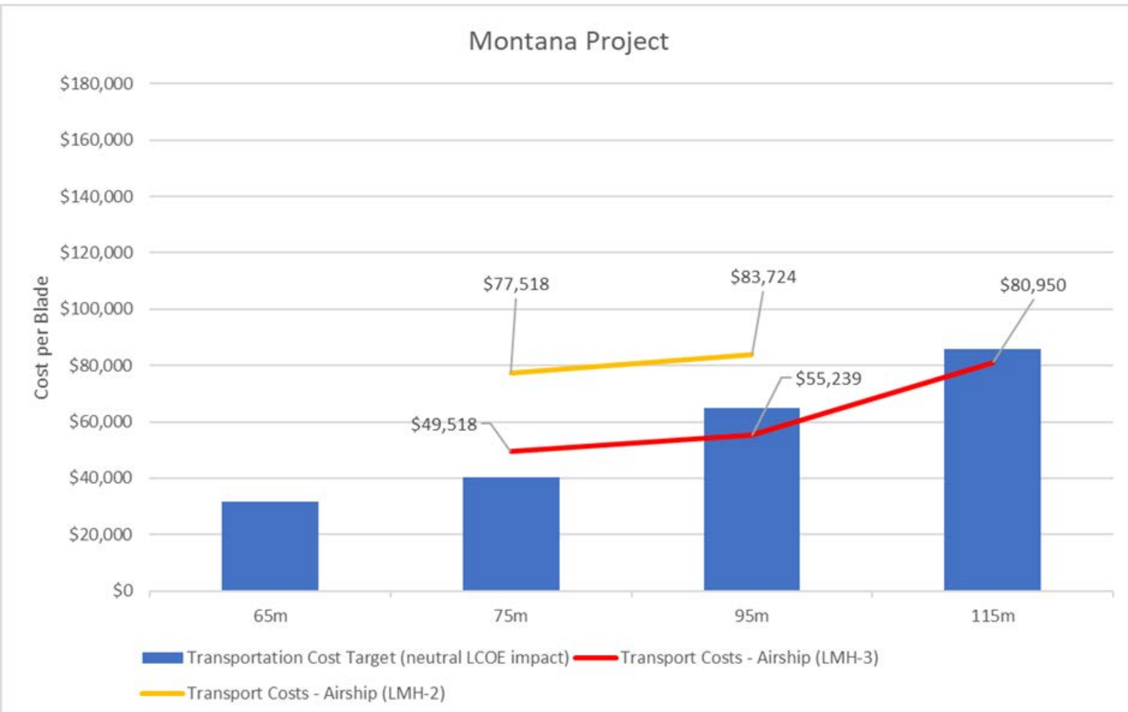


Figure 8-7 Monolithic blade, airship transportation costs – Montana Project

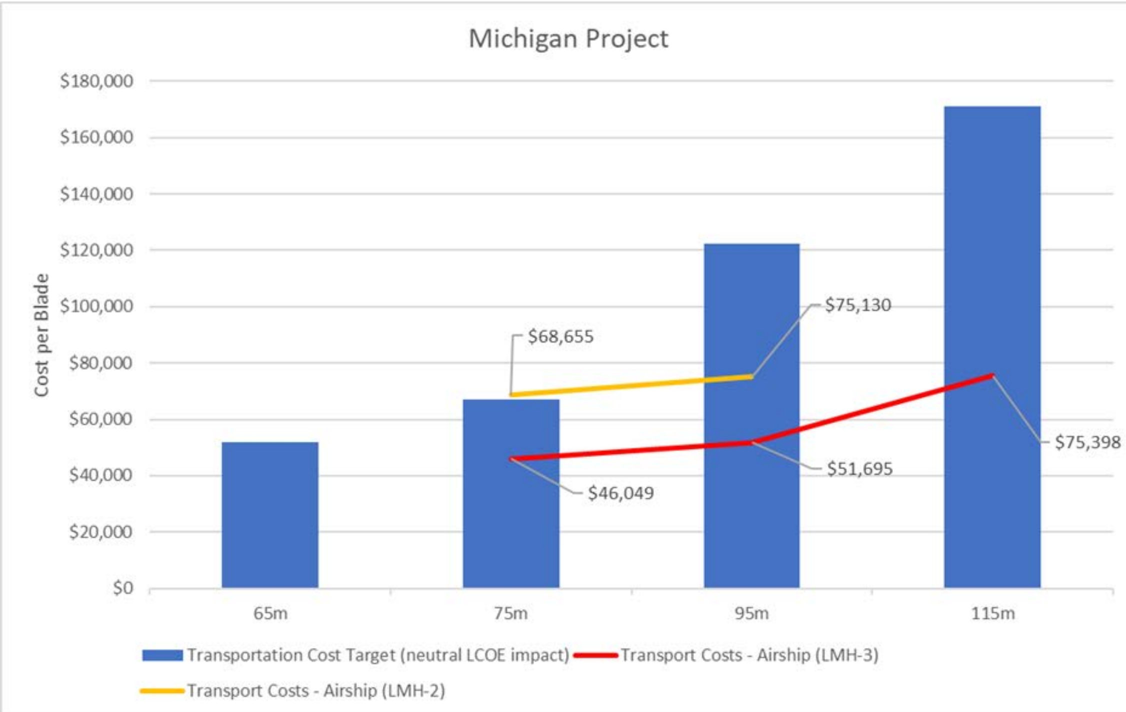


Figure 8-8 Monolithic blade, airship transportation costs – Michigan Project

8.2 Hybrid (segmented blade) pathway

Over the years, various wind turbine OEMs and technology companies have brought segmented blade concepts into the wind industry resulting in some limited field deployment experience (primarily in Europe). However, given turbine and blade sizes and project locations to date, the transportation industry has been able to achieve enough innovation to enable delivery of monolithic blades at acceptable (albeit increasing) prices in the U.S. These transportation innovations have resulted in no sustained deployment of segmented blades to date. Based on ground transportation findings in Section 8.1, it is apparent that blade sizes, transport costs, and geographic limitations are entering a range where segmented blade solutions can offer transportation feasibility for a wide range of geographic areas that may not be possible for supersized monolithic blades (even if controlled blade flexing in transport is achievable). Thus, segmented blades represent an enabling technology, with costs and impact on system LCOE as a key area for investigation.

8.2.1 Segmented blades vs. monolithic blades

There are various locations along the blade where segment joints can be located and different joint/bonding methods. This study did not seek to investigate all possible options and optimize the analysis for cost and performance. Instead we selected mechanical (bolted) joints and fasteners, mid-span joints, and chord cuffs (to resolve max chord dimensions for 95 m and 115 m blades). Current and recent industry deployments of segmented blade elements have utilized mechanical fasteners, which alleviates some uncertainties related to permanent bonding in field conditions. An annual inspection of mechanical fasteners was added to the O&M cost expectations for segmented blades, but overall long-term blade reliability assumptions remained the same as for monolithic blades. We doubt segmented blades would gain industry acceptance if long-term reliability is less than achieved by current monolithic blades.

A perception about segmented blades is their ability to avoid infrastructure constraints and mitigate excessive transportation costs while incurring modest increases in blade and field assembly costs. These cost elements (incremental blade cost adders, field assembly costs, and transportation cost changes) are highlighted in Figure 8-9 and Figure 8-10 for segmented blades delivered to Montana and Michigan, respectively. Blade costs shown in these figures correspond to the incremental cost increase from monolithic blades for the joint and associated additional support material needed in the blade to receive and transmit loads (see segmented blade design details presented in Section 6). Cost to assemble the blade elements on the ground are indicated as the “assembly cost adder”. Assembly costs for the 95 m and 115 m blades are greater than for the 75 m blade due to two joints per blade. However, assembly costs for the 95 m and 115 m segmented blades would not be significantly different.

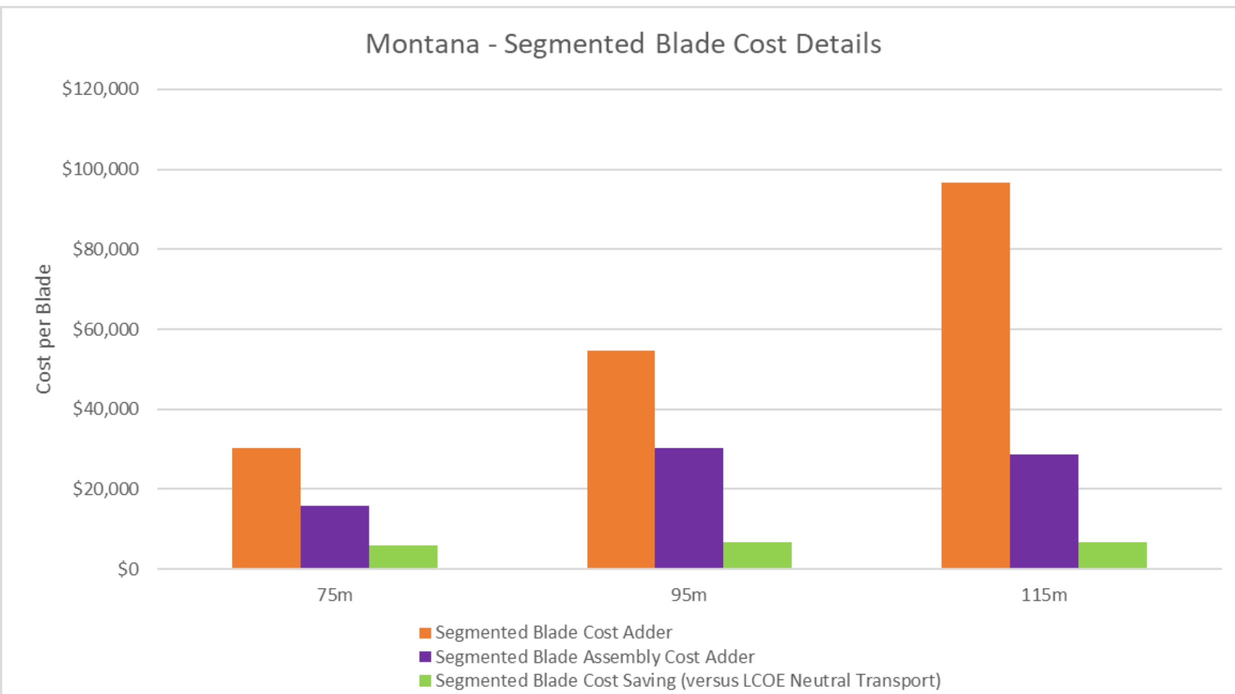


Figure 8-9 Incremental cost impacts of segmented blades – Montana

Transportation costs correspond to the lowest cost option of rail plus short-haul truck to deliver the blade segments from the factory to the project location. Transportation costs are compared against the LCOE neutral transportation cost values derived in Section 7 and illustrated in Section 8.1. Given the dimensions of the blade segments being transported, transport costs per blade segment were comparable to shipping multiple 50 to 60 m blades currently being performed by the industry. Although a modest cost savings is achieved by transporting “smaller” blade elements (meaning smaller than monolithic 75 m + blades), increasing the quantity of items (i.e., blade segments) to ship erodes the savings per blade. For low transport cost regions like Montana, transport of segmented blades results in a small cost increase (over the

LCOE neutral transport cost target). In higher transport cost regions like Michigan, transport costs can be lower than the transport cost target (see Figure 8-10). However, the magnitude of transport cost savings is relatively small compared to the cost adders of the blade and field assembly. Instead of the mid-span joint in our assumption, if the joint is positioned closer to the outer quarter or third of the blade, it would be possible to combine multiple smaller blade elements onto one rail car or truck trailer, thus achieving some additional cost savings. Under this scenario, the larger size of the remaining blade element would result in a modest transport cost increase for this element, but an overall cost savings would still be expected. This strategy may become less effective as the blades approach 115 m since the size of the blade elements become so large, they are effectively as large as current blades which are not package-able. Further optimizing segmented blade design and transport options is beyond the scope of this study, but worthy of more analysis in subsequent R&D.

One significant point is clear—segmented blades do enable transport of blade elements to assemble supersized blades on site and these elements can be sized to enable delivery across a wide geographic region of the U.S. Aside from airships, ground-based transportation innovations with controlled blade bending previously described are not likely to achieve the wide geographic deployment potential that segmented blades could achieve. However, segmented blades come with a higher total delivered blade cost as discussed in the next section.

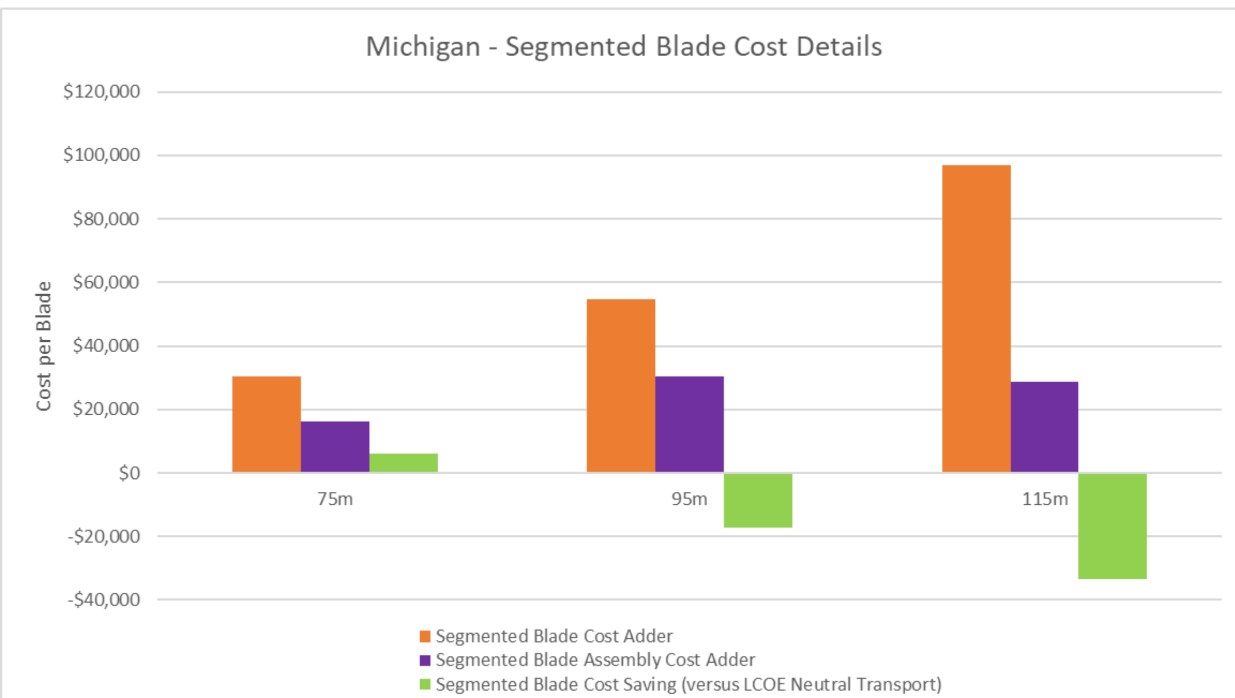


Figure 8-10 Incremental cost impacts of segmented blades – Michigan

8.2.2 Segmented blades findings

Combining the incremental cost of segmented blades summarized above, the total cost of delivered segmented blades can be calculated and compared against the target total cost of a delivered blade (previously presented in Section 7). The target cost represents the point at which delivered blade costs have a neutral (zero) impact on system LCOE. The total cost of a delivered segmented blade includes:

- Costs of blade segments
- Transport costs of segments from factory to turbine pad location
- Field costs for assembling the blade segments into a complete blade, ready for mounting onto the hub

Rotor assembly is not included.

Segmented blades utilize an unconstrained blade shape and thus have slightly greater energy capture relative to the constrained blade shapes. On the other hand, incremental O&M costs related to annual blade inspections are incurred for the segmented blades. These two considerations – AEP and O&M – are not included in the total cost of a delivered blade comparisons. However, these two additional factors are included in the LCOE comparisons that follow.

Figure 8-11 and Figure 8-12 present the total cost of delivered segmented blades for Montana and Michigan, respectively. The bars illustrate the cost components and total costs associated with segmented blades. The line illustrates the total cost of delivered blade target at which LCOE impact is neutral. At both project locations, total segmented blade costs exceeded the LCOE neutral target level by approximately 11% to 18%, depending on blade size and project location.

When also including AEP and O&M cost impacts, these costs translate into increased system level LCOE that range from 2.1% to 3.1%, depending on blade size and project location. This is a notable potential increase of system level LCOE, and places challenges on other aspects of the turbine system to increase their contributions to LCOE cost reductions. Another perspective on this finding is, unlike rail and truck transport of monolithic blades, segmented blades can enable delivery and deployment of supersize blades to wide regions of the U.S., but LCOE would increase, if no other savings in the system is achievable.

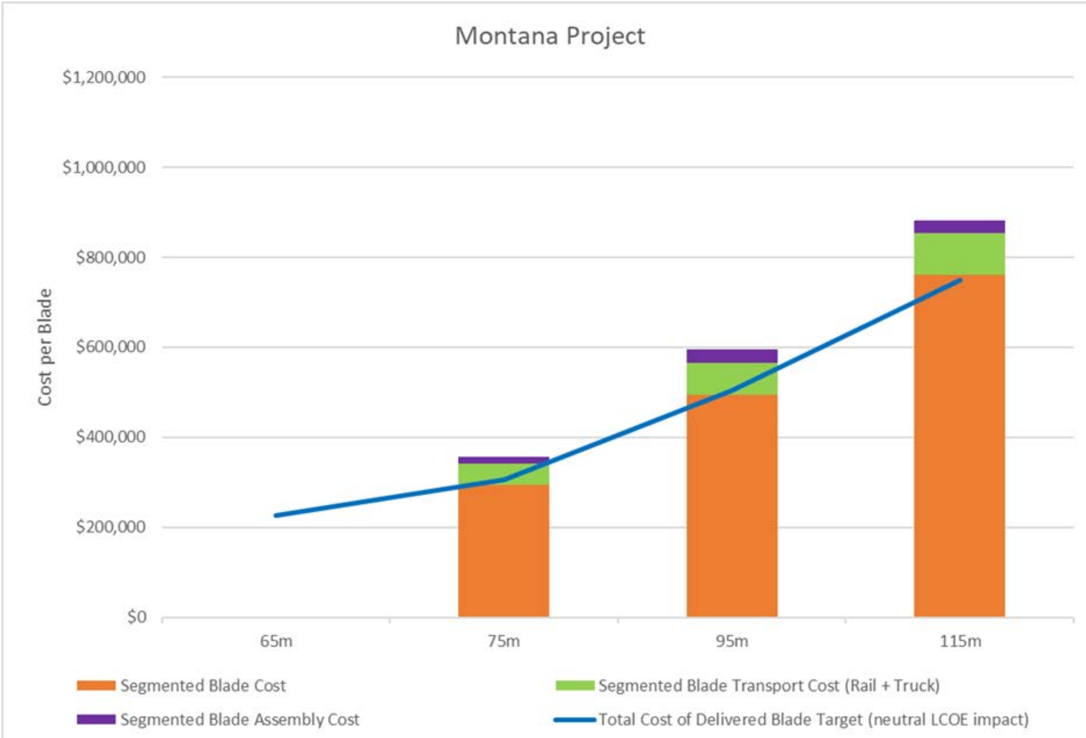


Figure 8-11 Total cost of delivered segmented blades - Montana

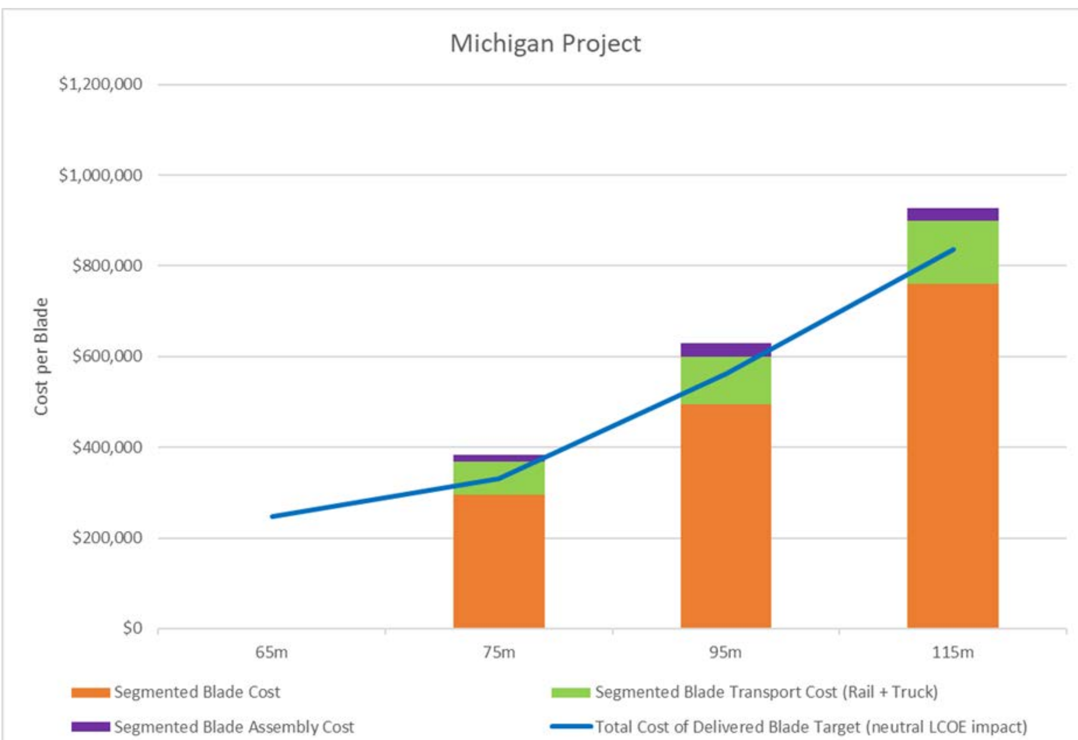


Figure 8-12 Total cost of delivered segmented blades – Michigan

8.3 On-site manufacturing pathway

Assessment of on-site (and mobile) blade manufacturing is a challenging endeavor since there is no wind industry experience and current blade manufacturing methods evolved from a traditional manufacturing approach that fundamentally assumes transportation of the product is viable and cost effective. Manufacturing innovations in other industries are accelerating due to advances in computing power, sensors & data, robotics, materials, and artificial intelligence among many other topics. Additive and subtractive manufacturing, aka “3-D printing”, has gained significant awareness in recent years by combining these innovations to enable new manufacturing techniques that either improve an existing process/product or allow creation of a new product that has not been possible with existing manufacturing techniques. These new manufacturing techniques are finding opportunities in niche applications, and may with time evolve and be increasingly utilized in wind turbine equipment manufacturing to help reduce cost and/or enable production of products that cannot be manufactured with current methods. In this pathway, we examine the concept of on-site blade manufacturing with the intent to identify topics where high value R&D could be applied along with identifying performance and cost targets that future on-site manufacturing concepts would need to consider. We do not assess the landscape of possible manufacturing technologies or try to identify specific manufacturing methods.

Specifically, based on information from the stakeholder workshop and the RFI process, we are not able to identify a new manufacturing technology or methodology that could be modelled in this project that enables full scale, on-site manufacturing of blades. Current additive manufacturing technologies are not able to utilize materials with stiffness, weight, and cost properties comparable to current blade materials; have not gained sufficient scale to achieve mass application rates (kg/hr) for competitive manufacturing time; and deployment of additive manufacturing technology for large scale products is currently limited to military, aerospace, and aviation, where market or strategic drivers are different than for wind energy. Oak Ridge National Laboratory has successfully demonstrated manufacturing of blade molds that were used to produce demonstration blades.

Instead of performing analysis to select new on-site blade manufacturing technologies, we chose a higher-level investigation into converting current “blade-in-mold” manufacturing into a mobile process performed at each wind project to “deliver” a complete supersized blade at the turbine pad. We acknowledge that converting a manufacturing process optimized for a fixed location, off-site from the wind project has the potential to inherently bias the economics and evaluation of the on-site manufacturing pathway (in comparison to other pathways in the study). However, this study is not intended to “select a pathway” but instead to identify high value R&D topics that enable supersized blades (regardless of the pathway) or topics that apply across all possible pathways. Assessment of a mobile blade factory using current blade-in-mold manufacturing is therefore useful in identifying factors, challenges, and targets that future R&D into on-site blade manufacturing should consider.

Section 4 outlined certain assumptions and methods employed in this study and for on-site manufacturing. The derivation of costs for blades produced by on-site manufacturing is summarized in Section 6.3. Finally, “Micro haul” transportation costs to move finished blades from the on-site factory to the turbine pad location are also added to the cost of an on-site manufactured blade. These are the same cost values as previously described for modeling airship delivery of blades. The resulting cost estimate is then compared with the total cost of a delivered blade target – the point at which blade specific costs have a neutral impact on system LCOE.

Combining the on-site blade production (recurring) costs, non-recurring on-site factory costs, and micro-haul transportation costs, we calculate the total cost of a delivered blade for on-site manufacturing. Figure 8-13 and Figure 8-14 (Montana and Michigan, respectively) provide a summary of the total cost to deliver a blade via on-site manufacturing compared against the target total cost of a delivered blade (neutral LCOE impact). Given the modeling scenarios and assumptions applied, on-site manufactured blades in Montana exceeded the LCOE neutral target value by approximately 34% to 49%; and on-site manufactured blades in Michigan exceeded the LCOE neutral target value by approximately 12% to 18%. The greater blade count for the Michigan project was the reason for slightly lower per blade costs. Translating these blade costs into impact on system LCOE, while also considering the modest AEP benefits from the use of unconstrained blades, we find that system LCOE would increase by 2.2% to 7%, depending on project location and blade size, with values increasing as blade size increases.

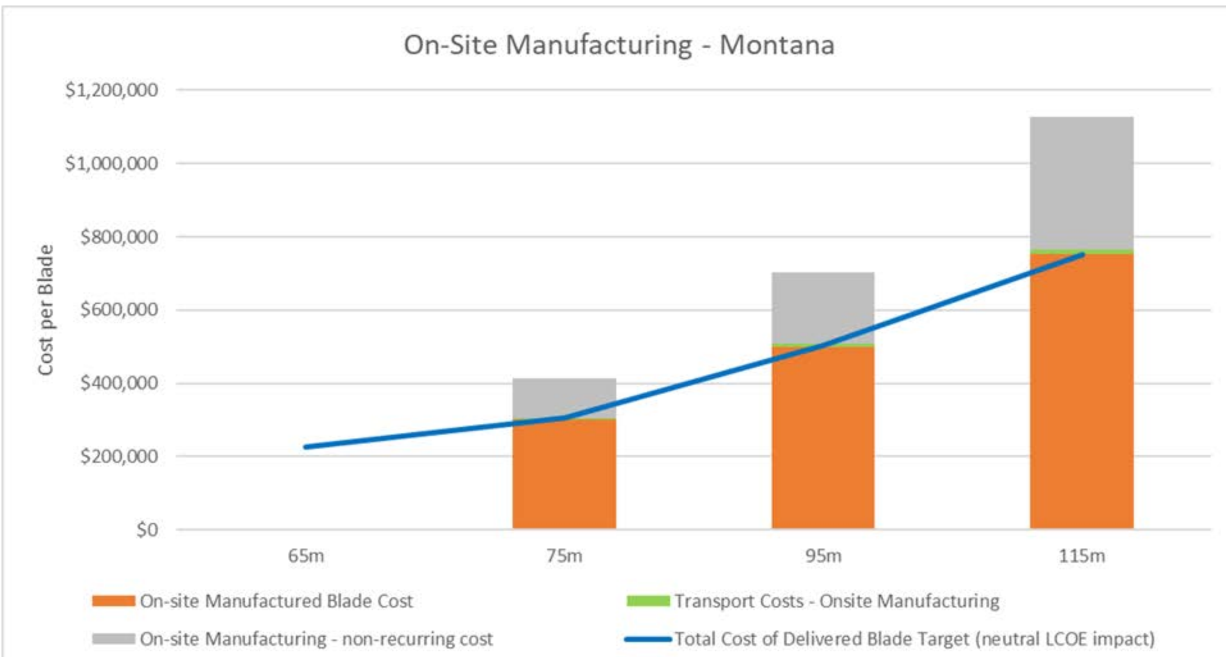


Figure 8-13 Total cost of on-site manufactured, delivered blade – Montana

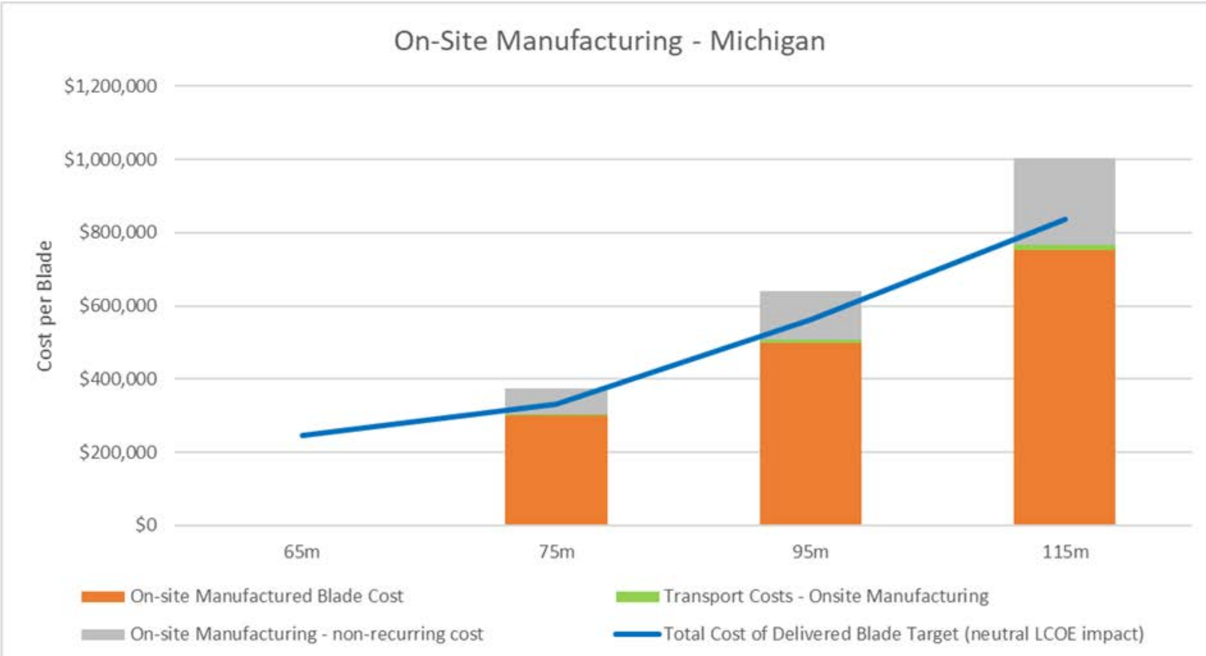


Figure 8-14 Total cost of on-site manufactured, delivered blade – Michigan

8.3.1 Observations and additive manufacturing trilemma

The simplified analysis we present to study on-site manufacturing is useful to illustrate certain observations and challenges that additional R&D into this topic should seek to address. The largest contributors to the incremental cost of on-site manufacturing correspond to high one-time expenses (i.e., non-recurring) for factory set-up, worker training, and plant commissioning. In addition, tool and equipment utilization have the largest impact on (recurring) production costs. Regardless of the new manufacturing techniques developed in the future, control and reduction of these factors are key to improving the potential viability of any on-site manufacturing process.

We offer the following observations as guidance for future R&D into any on-site manufacturing techniques:

- A highly automated machine process that significantly reduces labor and training costs will have increased the sensitivity to tooling utilization. Thus, automated processes with high tooling costs will demand close to 24/7 utilization to avoid increasing production costs. Achieving very high utilization and relocating from project to project with efficiency to avoid lengthy periods of zero production will be important.
- Decreasing reliance on local unskilled labor would reduce or eliminate training costs but would likely demand higher wages and other benefits to attract a skilled labor force willing to relocate on a regular basis. Wind plant construction today relies heavily on traveling teams of highly skilled workers, thus it can be done. Using a traveling workforce may put pressure on gaining local acceptance of the temporary on-site factory. The lack of local jobs could become an additional challenge in the project development process.

- It’s a moving target. Manufacturing innovations that can improve the viability of on-site manufacturing will have an increased impact in off-site factories due to higher tool utilization in off-site factories alone.

Clearly our analysis did not account for all issues and challenges that on-site manufacturing would need to address. In our opinion, the outstanding issues and challenges would likely add to the cost of on-site manufacturing and it’s possible that many project locations would not have suitable utilities, services, or the ability to gain environmental and local approvals. Comments from Owner/Operators during the stakeholder workshop noted that inclusion of on-site manufacturing into the already complex project development process adds uncertainty and could put development of the entire project at risk.

As illustrated in Figure 8-15, additive manufacturing technologies (3-D printing) have three parameters that future R&D needs to be focused on to help advance this technology. Current additive manufacturing utilizes low stiffness materials not well suited for structural blade elements. Deposition rates for the largest industrial equipment far below current manual labor methods. Finally, the finished cost of a structure that combines material, labor, and tool utilization needs to compete with off-site manufacturing production costs. For current additive manufacturing methods, the combination of needing more material (due to low stiffness) and slow deposition rates would compound to increase delivered blade costs and result in heavier blades (with corresponding related negative implications in other turbine sub-systems).

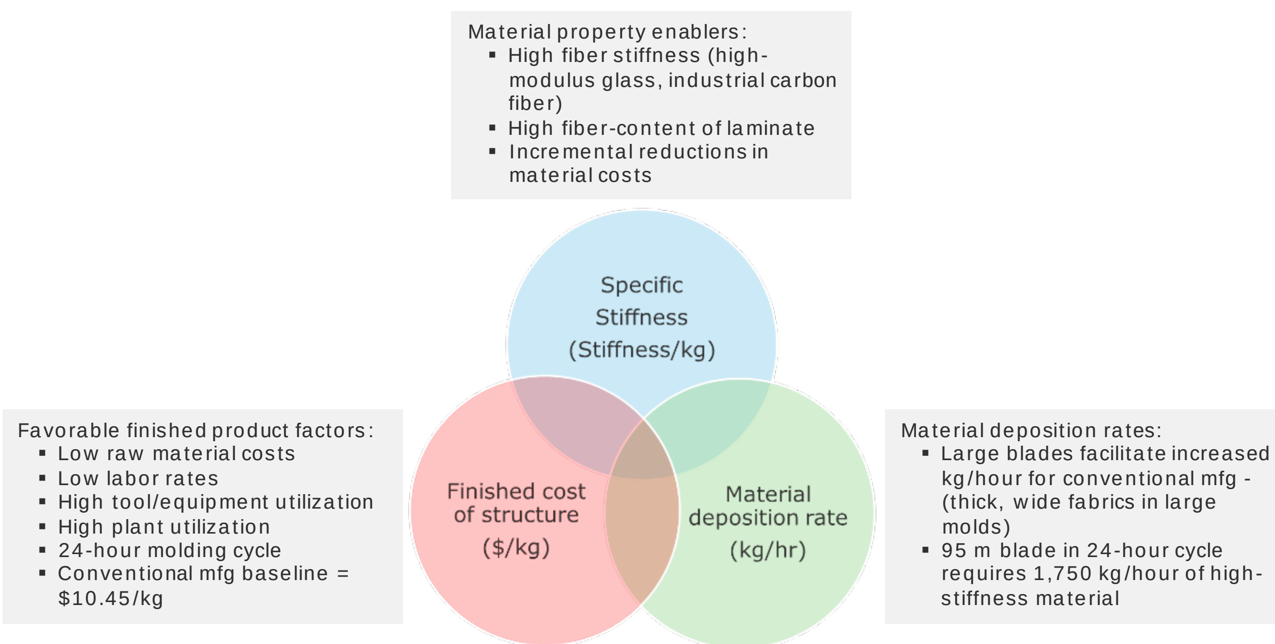


Figure 8-15 Additive manufacturing trilemma elements

9 OBSERVATIONS AND CONCLUSIONS

The goal of this project is to identify high value research and development opportunities that enable the manufacture, delivery, and installation of supersized land-based wind turbines across various regions of the U.S. to support increased deployment of low-cost wind energy. More specifically, this study focuses on logistics and manufacturing of supersized wind turbine blades due to their extreme dimensions and unique manufacturing and transportation challenges. This study is structured to investigate three innovation pathways for enabling deployment of supersized blades at various wind project development sites. The study is not intended to "select a pathway" but rather utilizes analysis of the pathways to identify high value R&D topics that could enable supersized blades or R&D topics that apply across all possible pathways. DNV GL was contracted to perform this independent study and present our observations and recommendations for consideration by various stakeholders. Although the process included multiple stakeholder engagement steps, the resulting analysis represents DNV GL's findings and does not represent consensus of the U.S. DOE, various national laboratories, industry participants, or other parties.

Figure 9-1 and Figure 9-2 summarize our estimates of the total costs of delivered blades by innovation pathway at the hypothetical projects in Michigan and Montana, respectively. The target values indicated on these figures correspond to the point at which total delivered blade costs have no impact on increasing or decreasing the system LCOE. Values below the target indicate an opportunity to help lower system LCOE, whereas values exceeding the target indicate upward pressure on system LCOE. These two figures include the cost to manufacture, transport, and/or assemble the blades, but do not consider impacts to AEP (for constrained vs. unconstrained blades) or to O&M costs (for segmented blades).

Figure 9-3 and Figure 9-4 summarize the percent impact on system LCOE for each of the innovation pathways at the hypothetical projects in Michigan and Montana, respectively. The impact on system LCOE accounts for total costs of delivered blades (Figure 9-1 and Figure 9-2), plus includes AEP performance variations, O&M cost differences, and fixed charge rate effects. Whether increases in system LCOE caused by supersized blades is acceptable depends on opportunities to achieve cost savings in other turbine sub-systems. Achieving a neutral impact on system LCOE can be acceptable, provided it doesn't come at a cost of increases in other parts of the turbine. Thus, integrating these results into a more holistic study of supersized wind turbines is recommended. For example, longer blades and greater generator capacity may result in the need for fewer turbines at a given project site, which could enable lower balance of plant costs as well as possible reductions in O&M. These potential benefits would need to be compared against other impacts of larger blades, such as the need for stronger structural support systems, pitch systems, drivetrain bearings, nacelle frame, and towers. The added structural material increases the mass and cost of these load bearing systems.

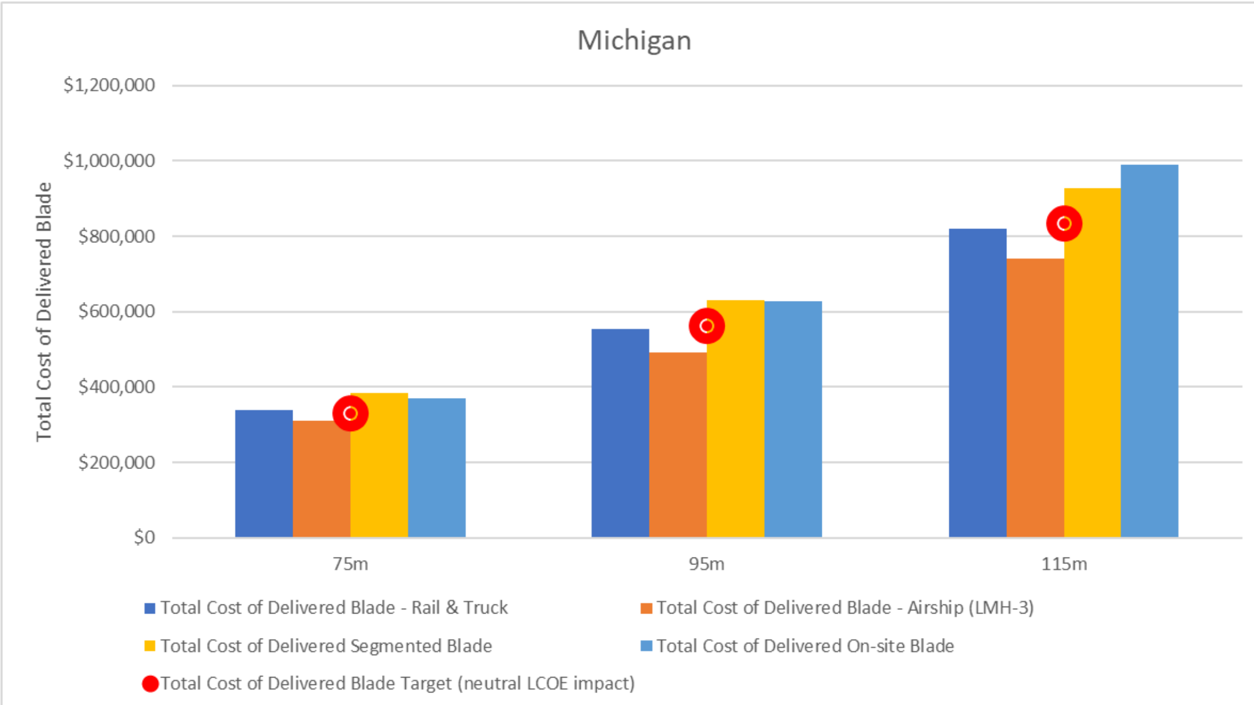


Figure 9-1 Innovation Pathway summary – Total cost of delivered blades, Michigan

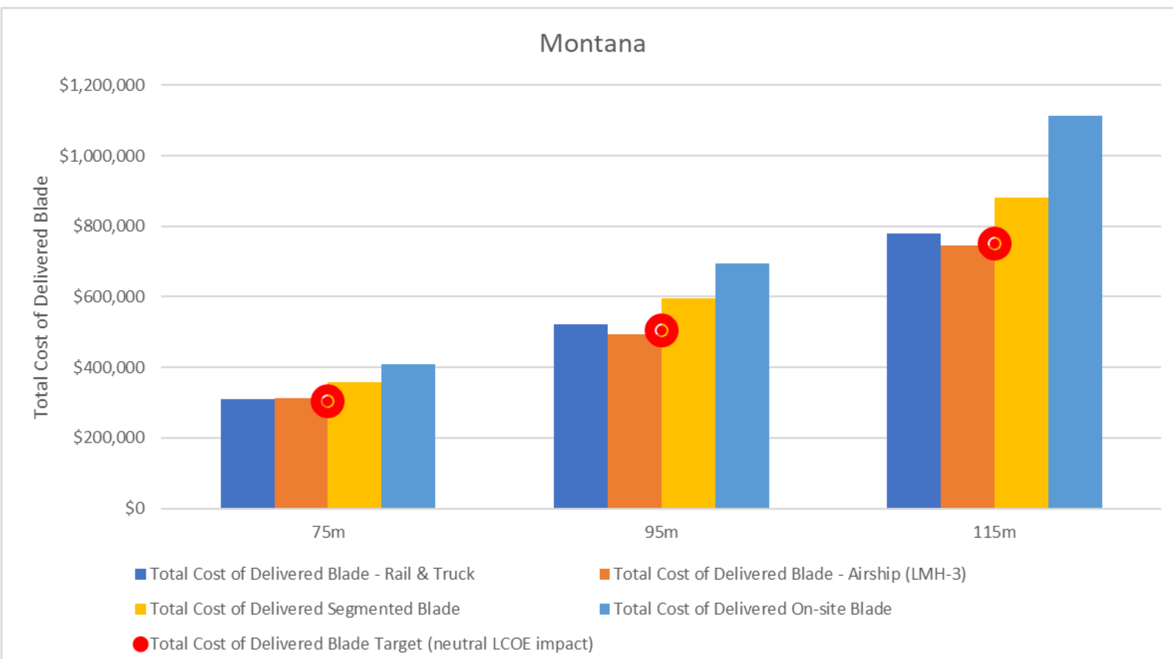


Figure 9-2 Innovation Pathway summary – Total cost of delivered blades, Montana

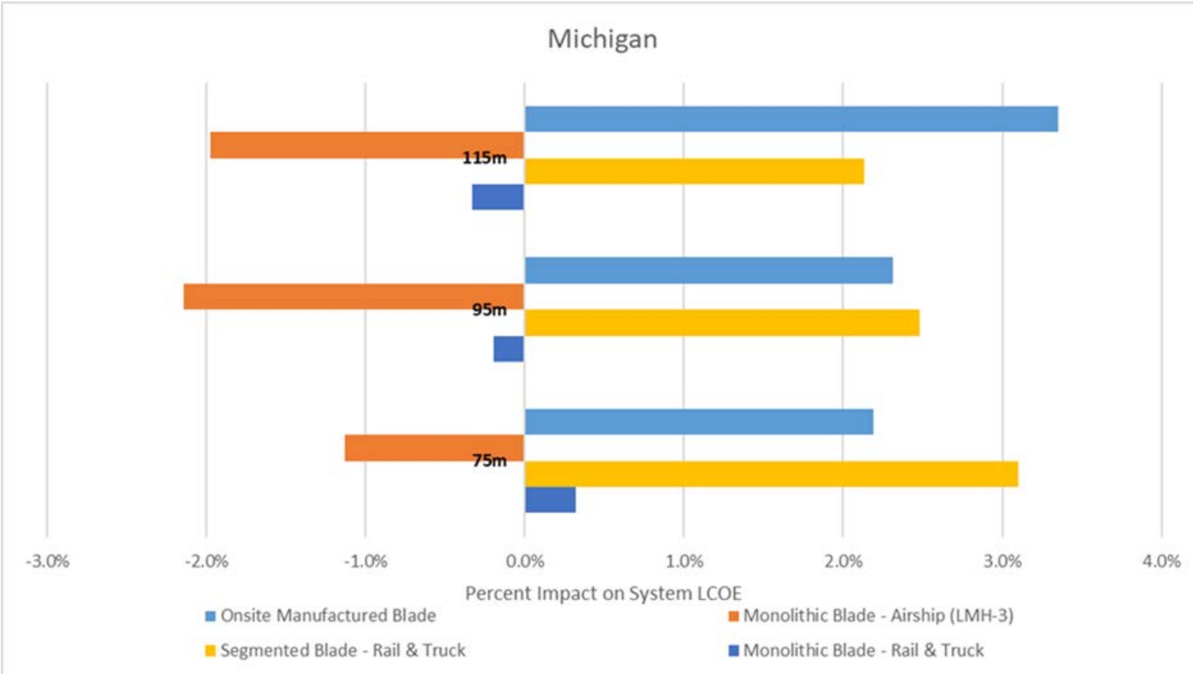


Figure 9-3 Innovation Pathway summary – Impact on system LCOE, Michigan

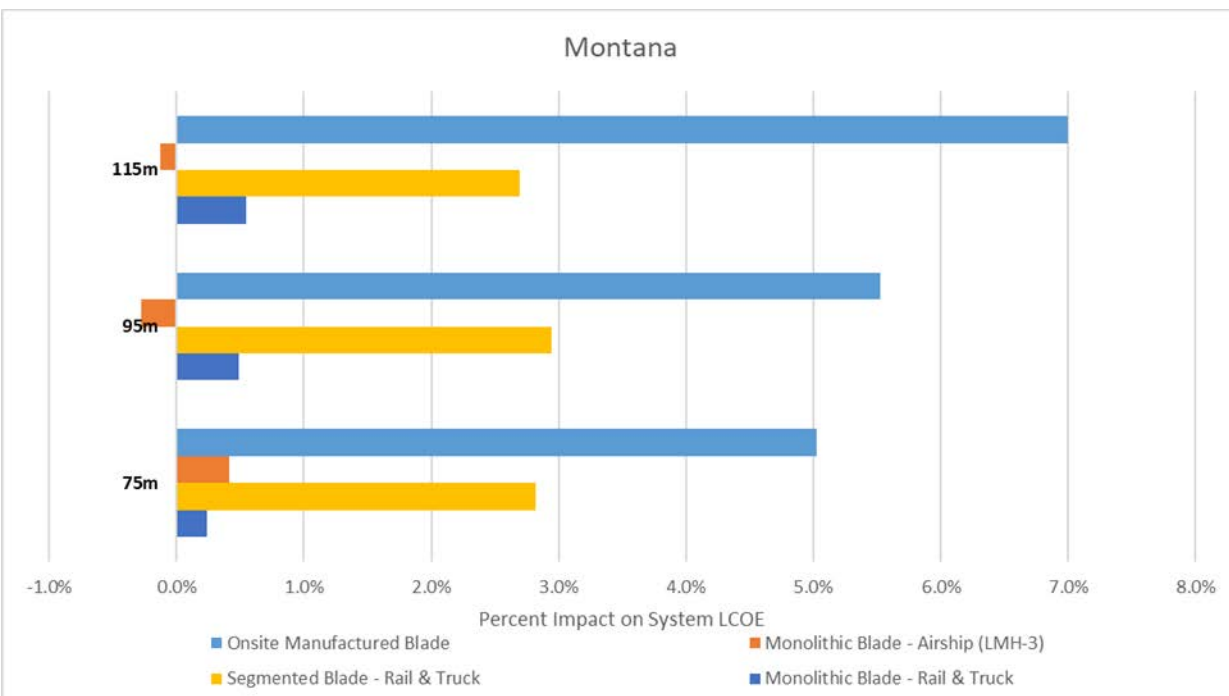


Figure 9-4 Innovation Pathway summary – Impact on system LCOE, Montana

Based on our analysis and the values summarized in Figure 9-1 through Figure 9-4, opportunities for supersized blades where blade-specific costs and performance contributed to a neutral or reduction in overall system LCOE appear possible with use of LTA hybrid airships or controlled blade bending in rail transport. In other innovation pathways studied, blade-specific costs and performance contributed to increases in system LCOE indicating a broader, more systemic approach beyond just blades or different project site assumptions may be necessary to achieve lower system level LCOE.

LTA hybrid airships, under our assumptions, were identified as having potential for blade-specific costs and performance able to lower system LCOE at both project sites, ranging between -2.1% to 0.4% depending on the site and blade length. LTA hybrid airships, if certified and commercialized, have potential to enable nationwide deployment of supersized blades and wind turbines in a cost competitive manner. Although there are active commercial efforts to bring this technology to market, there is significant uncertainty in the timing. Monitoring developments of this technology and seeking areas of collaboration to improve market development for wind energy (and many other applications) is recommended due to the potential for its enabling effects for supersized turbines.

Currently, blade flexing during transport is not allowed because this loading method has not been established in the blade design and transport infrastructure has not been developed to enable it. R&D that enables limited and controlled blade bending in rail transport plus specialized road trailers appears able to achieve a neutral impact in system LCOE, ranging between -0.3% to +0.5%. However, there are geographic limitations on where controlled blade bending could be viable, thus this area of innovation may not have the nation-wide impact needed to achieve deployment of supersized wind turbines in regions where they are most applicable. This approach could theoretically take advantage of the designed flexibility characteristics inherent in wind turbine blades, provided these loads can be accounted for in the blade design as well as the rail and road transport infrastructure. This innovation area offers an opportunity for additional study of blades, the rail system and trailers, and related infrastructure to further assess the viability, management of reaction loads caused by bending, and blade design to achieve no decrease in long-term blade life expectancy.

Segmented blades and on-site manufacturing pathways were found to increase system LCOE contribution, thus requiring greater savings in other turbine systems to achieve continued overall system LCOE reductions. Segmented blades offer features that other pathways are not currently able to provide, such as the ability to enable supersized blade deployment across the entire U.S., and blade joint solutions are under active investigation and early deployment by major OEMs. Other areas of innovation studied are further from market readiness. Additionally, there are likely opportunities to refine and optimize segmented blades to drive costs closer to a neutral LCOE impact, which for some regions, may be sufficient for wind deployment to be economically competitive. Segmented blades might become an optional feature available to the market along with monolithic blades and site-specific analysis would determine which option is most feasible and economically competitive.

Based on current labor-intensive blade manufacturing technologies currently available, on-site (mobile) blade manufacturing faces economic challenges driven mainly by low tool/equipment utilization caused by time spent relocating and commissioning a mobile plant and elevated costs of local labor for hiring, training, plant commissioning, and first article manufacturing. These and other costs incurred each time the mobile plant is deployed represent significant challenges for any method of on-site blade manufacturing.

Figure **9**-**5** summarizes the results of our pathway assessment in terms of impact on LCOE, our current opinion of commercial readiness, and geographic breadth each pathway could offer.

Blade Manufacturing, Design, and Transport Pathways	Percent Impact on Wind Project Levelized Costs from Blades Alone [%]						Commercial Readiness			Geographic Breadth
Location	Michigan site			Montana site						
Blade length	75 m	95 m	115 m	75 m	95 m	115 m	75 m	95 m	115 m	all lengths
Innovative rail/truck transport; centralized traditional manufacturing	+0.3	-0.2	-0.3	+0.2	+0.5	+0.5	●	◖	◖	◖
Airship transport; centralized traditional manufacturing	-1.1	-2.1	-2.0	+0.4	-0.3	-0.1	○	○	○	●
Segmented blades with on-site assembly; centralized manufacturing; rail/truck transport	+3.1	+2.5	+2.1	+2.8	+2.9	+2.7	●	◖	◖	●
On-site manufacturing of full monolithic blade	+2.2	+2.3	+3.3	+5.0	+5.5	+7.0	○	○	○	◖

Key:

Commercial Readiness:	Geographic Breadth:
● = Commercially ready today	● = Deployable Nationwide
◖ = Commercially ready in ~5 years	◖ = Deployment limited to central & southern U.S.; mountains, and east coast unlikely
○ = Not commercially ready or readiness uncertain	

Figure 9-5 **Pathway assessment summary**

10 RECOMENDATIONS FOR DOE R&D FUNDING PRIORITIES

Based on the pathway analysis and findings, our industry understanding, and familiarity with U.S. DOE national laboratory range of core competence, we identified a number of high value research and development topics which could be pursued to enable development of supersized blades. It's important to note that many R&D topics are viewed as having benefits that could be applied to support some or all of the pathways studied. As mentioned previously, this project is not intended to "select a pathway", thus high value R&D topics are ones that have a strong impact across multiple pathways and leverage areas where U.S. DOE has strong competence, unique facilities, capacity to take high risks, and a long-term view.

Figure 10-1 presents DNV GL's identification of R&D topics that could enable supersized blades. We cross-reference these topics to each innovation pathway and indicate our judgement on the degree of impact a given R&D topic would have on enabling or addressing challenges in a given pathway. The pathways are ordered in terms of potential impact for lowering LCOE. Finally, we apply our judgement on DOE laboratories' ability to impact and advance the given R&D topic.

	R&D Pathway Enabling			
R&D Topic	1. Innovative transportation	2. Hybrid solutions (segmented blades)	3. On-site manufacturing	Core DOE Lab competence
Aerodynamic design (lift-enhancing)	✓✓✓	✓✓	✓	✓✓
Rotor configuration options (e.g., downwind)	✓✓	✓	✓	✓✓✓
Advanced aeroelastic modeling (dynamic stability, deflections)	✓✓✓	✓✓	✓✓	✓✓✓
Advanced controls / sensor technologies	✓✓✓	✓✓✓	✓✓	✓✓✓
Blade leading-edge erosion	✓✓✓	✓✓	✓✓	✓
Blade/rotor aeroacoustics	✓✓✓	✓✓✓	✓✓	✓✓
High-stiffness / low-cost materials (e.g., industrial carbon fiber)	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Structural joint technology		✓✓✓		✓
Thermoplastic materials (mechanical properties)	✓	✓✓✓	✓✓	✓
Thermoplastic materials (fabrication and joining)	✓	✓✓✓	✓✓	✓
Robotic fabrication (including additive manufacturing)	✓✓	✓✓	✓✓✓	✓✓
High-capacity airship development	✓✓✓			

LCOE Opportunity: High ↔ Low

Key:

✓✓✓	Strong impact
✓✓	Moderate impact
✓	Low impact

Figure 10-1 R&D topics to enable supersized blades

High value R&D topics include:

- Further advances in high-stiffness/low-cost materials (e.g., industrial carbon fiber) and thermoplastics materials. Advances in materials available for blade fabrication would have significant benefits to all the possible pathways and leverages U.S. DOE core competence.
- Advanced controls / sensor technologies could be applied to monitor/enable blade bending in transport, or monitor/control segmented blade loads such that lower weight blades can be achieved, or advance automation in field manufacturing technology.

- R&D into blade/rotor aeroacoustics and leading-edge erosion can enable blades to operate at higher tip speed ratios, which has benefits on reducing the chord dimension of blades, improving their transport potential.
- Advanced aeroelastic modeling into dynamic stability and deflections also enables development of more slender blades that can result in narrower blade shape and controlled deflection during transport could be utilized.
- Pathway specific topics such as segmented blade joints and further development of airships are noted as potential high value, even though they do not impact multiple pathways and they are not considered core competency of the U.S. DOE labs. These topics do represent opportunities that if realized, could significantly enable wide scale deployment of supersized turbines across all regions of the U.S.

As requested by the U.S. DOE project leaders, we incorporated these R&D topics into specific recommended actions and categorized them as enablers of supersized blades as follows.

10.1 Enabler 1: "Go Fast", slender blades

U.S. DOE could advance R&D to develop new blades with a slenderer form that operate at higher tip speed ratios (TSR). This offers the best near-term promise for continued incremental gains down the current LCOE trajectory of larger rotors at decreasing $/MW in the range of 75 m to 90 m blades. Continue to enable long slender blades with root and chord dimensions constrained for ground transportation. In collaboration with the transportation industry, incorporate blade bending during transport into the blade design.

- U.S. DOE has strong opportunity for R&D that enables high TSR – resulting in go-fast, slender blades:
  - Industry needs help advancing technologies that enable high-lift for thick airfoils to minimize aerodynamic losses near root.
  - Aeroelastic stability issues (e.g., edgewise vibrations, flutter) are a current challenge for industry and become a bigger challenge as blades get longer and slimmer.
  - Strong opportunity exists for DOE to advance aeroelastic codes and related sensor/controls technology that are needed to design, transport, and operate long slender blades.
  - As TSR increases, leading-edge erosion and acoustic noise effects increase, and industry does not have the bandwidth to fully investigate these issues alone.
- U.S. DOE's knowledge and facilities are well suited to push further into solutions for the stiffness/deflection challenge:
  - Focus on low-cost carbon fiber, downwind rotors, advanced sensing, and controls.
  - Market dynamics and economic pressures discourage OEMs from tackling these higher risk topics.
  - National Wind Technology Center (NWTC) offers an ideal facility to deploy and test new materials, rotor configurations, sensors, and controls.
  - Scaled Wind Farm Technology facility (SWiFT) offers the ability to test blades, controls, and combined turbine system interactions in a field environment.
- High TSR enables blade height and width dimensions to stay in transport envelope:

- In collaboration with OEMs and transportation companies, R&D into controlled blade flexing in transport to mitigate blade length and maneuver around infrastructure constraints could be valuable.
- New blade design details and load cases must be developed to enable controlled blade flex in transport and de-risk the impact of controlled flexing on perceptions of long-term reliability.
- Long-haul rail appears possible up to 115 m blades, assuming controlled flexing is possible.
- Short-haul trucking is a key obstacle that requires innovation:
    - Trucking industry has knowledge and capability to move supersized blades.
    - New trailer configurations with ability to articulate (pitch) and/or flex blades are needed.
    - Regulatory change to modify requirement of load support within 30 ft (10 m) of blade tip would benefit pace of innovation.

10.2 Enabler 2: LTA Hybrid Airships

Future costs and time to market for airships remain highly speculative and information is based on input from one company. Yet, if developed at scale, cargo focused airships offer a potential path for achieving lower LCOE and facilitating wide geographic project deployment. Airship advantages increase as blade sizes and turbine populations increase.

- Allows continuation of blade cost-performance trajectory described in Enabler #1 with low risk of cost adder for transport. If LTA hybrid airships penetrate logistics market, they may be a disrupter, forcing lower costs and more innovation.
- On-site landing area (~400 m in diameter) in close proximity project can be a concern, but similar issue exists regarding space for on-site manufacturing with significantly less demands on terrain flatness, foundations, utility infrastructure, environmental impact, etc.
- R&D opportunity for DOE:
    - DOE has opportunities to explore and accelerate application of airships in partnership with industry to enable a multi-purpose vessel that meets wind industry needs.
    - Airships can benefit both land-based and offshore wind deployment and may have other applications across the energy landscape.

10.3 Enabler 3: On-site manufacturing

Based on current labor-intensive blade manufacturing technologies currently available, on-site (mobile) blade manufacturing faces economic challenges driven mainly by low tool/equipment utilization caused by time spent relocating and commissioning a mobile plant and elevated costs of local labor for hiring, training, plant commissioning, and first article manufacturing. While advances in more automated manufacturing could be achieved, these advances could also be adopted in off-site factories, resulting in a moving competitive landscape for on-site applications. The opportunity space remains for blade design and transport innovations, thus pushing need for on-site manufacturing further into the future.

- Additive manufacturing could provide benefits first in blade components less sensitive to reduced material stiffness and slow deposition rates. Examples include:
  - Blade molds to reduce cost for manufacturing blade masters and enable faster mold production to respond to shorter blade manufacturing life-cycles.
  - Pre-manufactured blade skin panels may offer a path to improve manufacturing efficiency and reduce costs.
  - DOE’s near-term impact would be to invest in demonstration technologies related to molds. Work with tool manufacturers and blade OEM partners to scale up mold manufacturing demonstrated for SWiFT blades and accelerate adoption by industry.
- DOE R&D can also demonstrate advantages and address challenges for lower stiffness skin materials:
  - Advantages include reduced sensitivity to panel buckling, enabling more flexible blades, weldability of thermoplastics, life-cycle recycling.
  - Challenges include integration with primary blade structure, fatigue properties, increased reliance of other blade elements for stiffness, aeroelastic behavior.
- DOE is in a unique position to accelerate R&D into new high-stiffness, low-cost materials as an enabler for both on-site and off-site manufacturing.

10.4 Enabler 4: Segmented blades

Without further transportation innovations, segmented blades can enable delivery of supersized blades utilizing existing transport technology and infrastructure. However, the impact of increases to system LCOE means decreases in other turbine systems must be achieved, to maintain the overall decrease in system LCOE.

- OEMs and other industry participants continue to actively investigate and strategically deploy segmented blade solutions where local market conditions are suitable. Segmented blades may be increasingly offered by OEMs as an option for select markets or regions to enable deployment of large turbines, but site-specific analysis would determine the economic viability of this solution. Due to the cost implications, segmented blades may not become the dominant blade type, but may find applications in portions of the market.
- GE recently announced segmented blades to access project sites in Germany. Gamesa & Enercon have introduced then withdrawn segmented blades from their commercial offerings over the years.

These examples indicate OEMs are able and willing to advance and deploy segmented blades when they see a competitive opportunity.

- U.S. DOE could provide support to technology developers and OEMs who are attempting new blade joint technology through partnerships for loads analysis, testing and verification. These efforts can help reduce real or perceived risks related to segmented blades.

Given that industry participants appear active and interested in developing their own segmented blade solutions, there may be stronger opportunities for U.S DOE to make unique R&D contributions in other areas.

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APPENDIX A – LCOE CALCULATION METHOD

This project utilized the levelized cost of energy calculation methodology described in *A Manual for the Economic Evaluation for Energy Efficiency and Renewable Energy Technologies* (Short et al. 1995) and included updates unique to the U.S. wind industry based on NREL's *2017 Cost of Wind Energy Review*, (Stehly et al. 2018). For wind energy, the LCOE calculation and variables are:

$$\text{LCOE} = \frac{(\text{CapEx} \times \text{FCR}) + \text{OpEx}}{(\text{AEP}_{\text{net}}/1{,}000)}$$

Where:

LCOE = levelized cost of energy ($/megawatt-hour [MWh])

FCR = fixed charge rate (%)

CapEx = capital expenditures ($/kilowatt [kW])

AEP net = net average annual energy production (MWh/megawatt [MW]/year [yr])

OpEx = operational expenditures ($/kW/yr).

For the Baseline turbine, LCOE input variables were determined as follows:

<u>FCR:</u>

- 7.9% per U.S. DOE project team guidance

<u>CapEx</u>

- Blade costs calculated by DNV GL
- Blade transportation costs based on industry partners estimates
- Turbine (less blades) costs derived from NREL's WISDEM model values recalibrated to $800/kW market reference from Wood Mackenzie
- Tower costs derived from WISDEM model
- Turbine (less blades) and tower transportation costs based on industry partner estimates
- Complete turbine, rotor and tower assembly costs derived from WISDEM model
- Balance of station costs, development costs, land costs, etc. derived from WISDEM model for 150 MW project
- Baseline total project CapEx result = $1,768/kW Michigan; $1,260/kW Montana

<u>AEP net:</u>

- DNV GL calculation based on blade design and power curves; site-specific wind speed from NREL
- Typical losses were applied to account for availability, soiling, wakes, turbine performance, environmental, and curtailments derived from DNV GL's experience accumulating to 20%.

<u>OpEx:</u>

- DNV GL calculation based on our OMCAM cost model version 2-10

- P50 20-year annual average value = $25.96/kW/yr Michigan; $18.66/kW/yr Montana and consists of turbine specific and minor balance of plant O&M costs. It does not represent total OpEx costs.
- Difference in O&M costs estimate is due to turbine and project specific factors. The Baseline turbine used for the Montana location had a higher generating capacity than Michigan, which resulted in a lower cost per kW.

The resulting system LCOE calculated for the Baseline turbine in Michigan and Montana project locations were $42.54/MWh and $32.80/MWh, respectively. We then isolated subsequent analysis on the blade specific contributions to the LCOE calculation to quantify impacts of alternative pathways to achieve supersized blades considered in this study. Blade specific LCOE as a percentage of overall system LCOE was calculated to be 17% for the Michigan project and 14% for the Montana project. These percentages were then used to extrapolate the impact of blade LCOE to system LCOE.

A.1 Segmented blade cost modification for field assembly

DNV GL utilized the NREL WISDEM model to calculate turbine and project assembly costs for the Baseline turbine model. For larger turbine models that used segmented blades, we modified the WISDEM model to account for an additional field crew and equipment needed to assemble segmented blades prior to rotor assembly. We added two small capacity support cranes needed to manipulate and stage the blade segments onto assembly fixtured/jigs to ensure alignment and enable the assembly process. Crane costs included equipment, fuel, maintenance, and an operator. We assumed a 5-person work crew, with two support cranes could assemble one mechanical (bolted) segment in four hours. We assumed the process is roughly similar to making the blade/hub bolted connection and consists of staging/preparation, installation, and alignment, installing fasteners and torque checks, and post-assembly quality assurance checks. We assumed the blade segment assembly crew would work in advance of the turbine assembly crew such that there would always be a set of assembled blades ready for turbine erection. The resulting cost estimate is ~$15,000 per segmented joint. This value was doubled for blades with two segmented joints.

A.2 OpEx cost modification for segmented blades

Given our assumption of a mechanical joint with fasteners as the method for assembling segmented blades, we developed estimates of increased blade specific O&M costs to include in LCOE analysis. We assumed internal blade joint and fastener inspections would be performed as part of annual turbine service, resulting in increased time and cost of this inspection. We assume contracted specialists perform the inspections who have specialized training and utilize specialized tools. Work is performed up tower and no need for a high capacity crane to lower the rotor or blades to the ground. Table A-1 below summarizes the assumptions and calculations to derive the incremental additional cost per turbine per year for performing blade segment inspections.

Table A-1 Incremental cost of blade segment inspections

	WTG 65 L (Baseline)	WTG 65 M (Baseline)	WTG 75 - L	WTG 75 - M	WTG 95 - L	WTG 95 - M	WTG 115 - L	WTG 115 - M
Turbine capacity (kW)	2100	3250	2750	4250	4500	6750	6500	9750
Number of turbines	71	46	54	35	33	22	23	15
Number of blades	213	138	162	105	99	66	69	45
Number of segments per blade	0	0	1	1	2	2	2	2
Total number of segments for inspection	0	0	162	105	198	132	138	90
Number of specialized technicians			3	3	3	3	3	3
Mobilization fee & per diem ($/Tech/Day)			$250	$250	$250	$250	$250	$250
Crew day rate ($90/hr & 10 hr plus per diem)			$3,450	$3,450	$3,450	$3,450	$3,450	$3,450
Inspection crew productivity (WTG/day)			1.5	1.5	1	1	1	1
# of days for inspection			36.0	23.0	33.0	22.0	23.0	15.0
Total annual blade segment inspection cost			$124,200	$79,350	$113,850	$75,900	$79,350	$51,750
Cost/WTG			$2,300	$2,267	$3,450	$3,450	$3,450	$3,450

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