



# Analysis of Transportation and Logistics Challenges Affecting the Deployment of Larger Wind Turbines: Summary of Results

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**NREL is a national laboratory of the U.S. Department of Energy  
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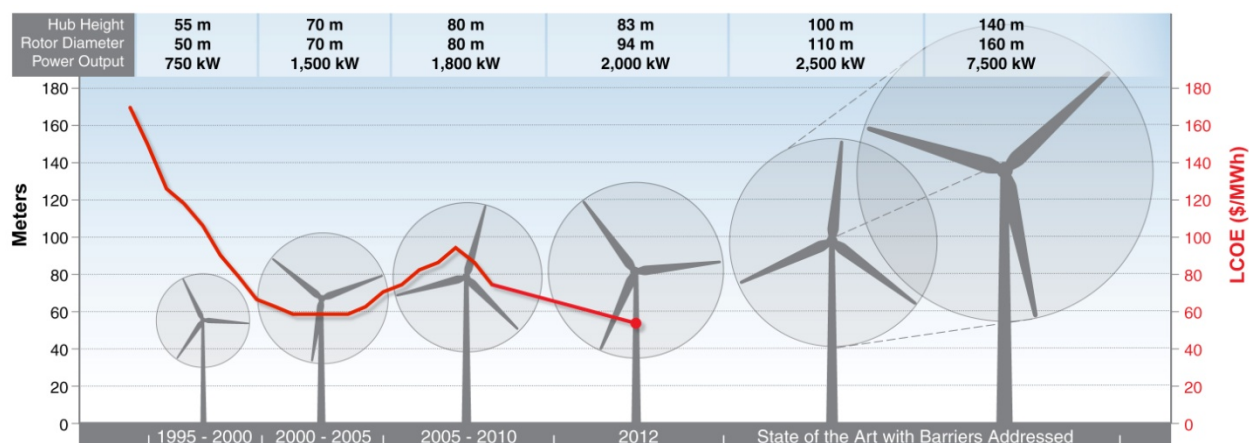
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## Project Motivation and Objectives

The average size and height of land-based wind turbines installed in the United States has increased over time as indicated in Figure 1. At the same time, the levelized cost of energy (LCOE) from wind turbines has, for the most part,<sup>1</sup> declined in part as a result of the increased economies of scale associated with larger turbines [1]. Technologies that enable larger wind turbines on taller towers create opportunities for further LCOE reductions. However, transportation and logistics challenges limit the size and tower height of land-based turbines that can be deployed in the United States. Addressing these transportation and logistics challenges will allow for deployment of larger state-of-the-art turbines, which may accelerate the development of new markets in low- and moderate-wind-speed regions in the United States and enable LCOE reduction pathways for all land-based wind turbines.

In addition, although U.S. manufacturing opportunities are not clear cut, the components required for larger wind turbines, such as the blades, can be manufactured more cost-competitively in the United States as opposed to being imported [2]. As a result, domestic content and U.S. manufacturing competitiveness may be increased by addressing challenges that limit the deployment of larger turbines.



**Figure 1. Average land-based wind turbine size and levelized cost of energy through 2012, and range of state-of-the-art turbines that could be deployed by addressing barriers**

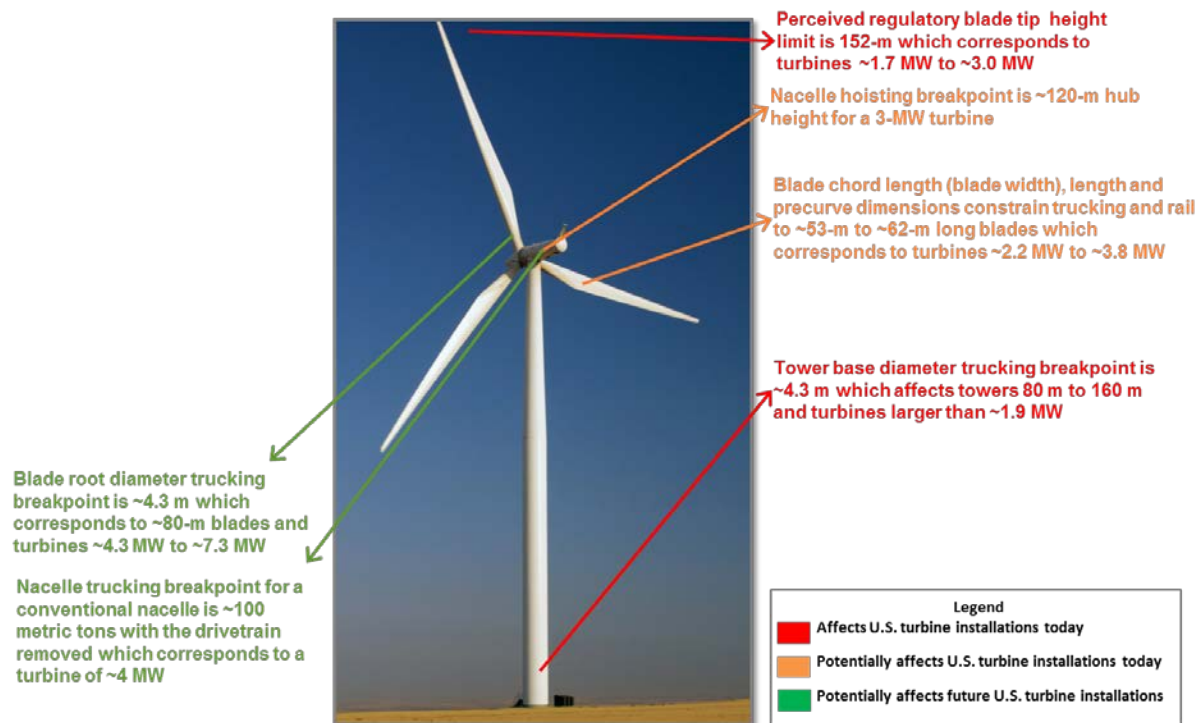
<sup>1</sup> An array of factors contributed to the temporary increase in turbine prices in the mid-2000s, including increases in raw material prices and energy prices, supply constraints, increasing OEM profitability and labor costs, and manufacturer warranty provisions.

In general, there is relatively little literature that characterizes transportation and logistics challenges and the associated effects on U.S. wind markets. The objectives of this study are to identify the transportation and logistics challenges, assess the associated impacts, and provide recommendations for strategies and specific actions to address the challenges.

## Project Approach and Summary of Results

The authors primarily relied on interviews with wind industry project developers, original equipment manufacturers, and transportation and logistics companies to obtain the information and industry perspectives needed for this study. They also reviewed published literature on trends and developments in increasing wind turbine size, logistics, and transportation issues.

The information obtained from the interviews and literature review helped identify the mass, cost, and size breakpoints (the point at which transportation and logistics costs begin to increase much more rapidly with size) for the wind turbine blades, tower, and nacelle. The breakpoints can generally be exceeded but at a substantially larger cost. The breakpoints were ranked according to their impact on current and future wind turbine installations. Figure 2 summarizes the size and mass breakpoints identified. The colors indicate the timeframe that the transportation and logistics issues affect wind plant installations. Each challenge is described in more detail in the following sections.

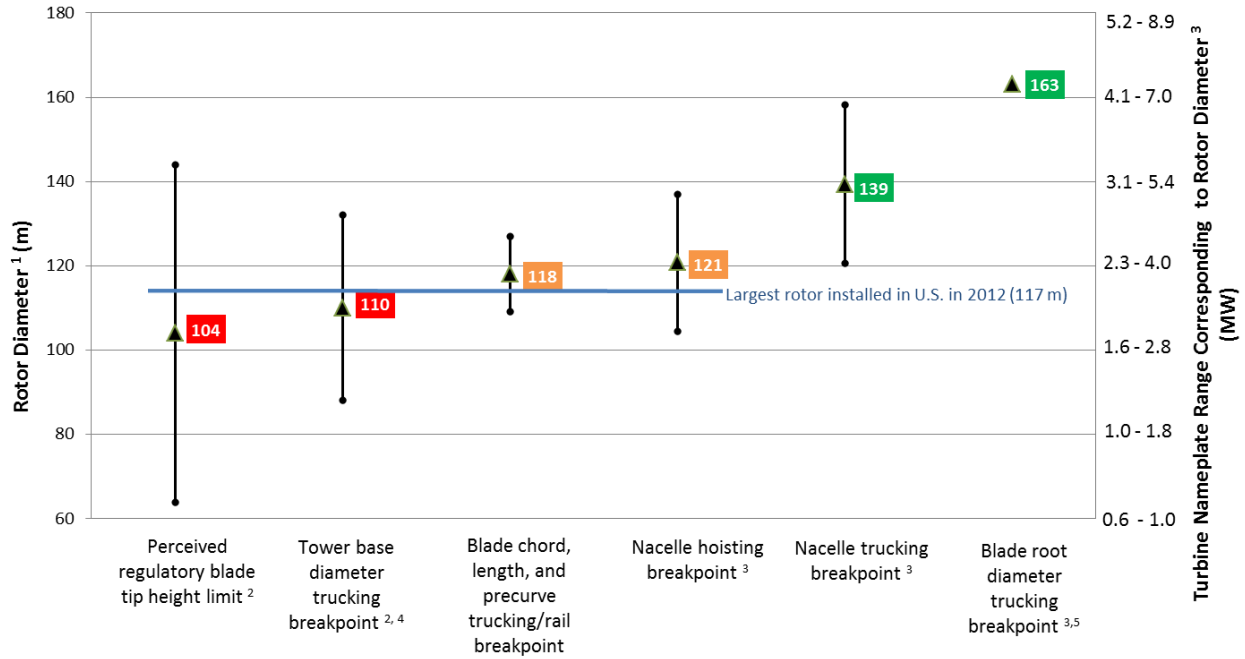


**Figure 2. Summary of the transportation and logistics breakpoints affecting U.S. land-based turbine installations**

The authors also performed analyses to: 1) identify which transportation and logistics challenges affect wind plant installations today, and 2) determine the increase in turbine size that could be achieved if the transportation and logistics challenges are solved. They considered several different metrics as the basis of these analyses, including turbine nameplate rating, blade tip height, and rotor diameter. Rotor diameter was selected as the best metric as it tends to correlate well with the masses and dimensional characteristics of the wind turbine blades, tower, and nacelle.

Figures 3 and 4 contain the results of these analyses. Figure 3 identifies which transportation and logistics challenges affect wind plant installations today. Figure 4 indicates the potential increase in turbine size (as indicated by the arrows) that could be achieved if the transportation and logistics challenges are addressed (given the assumptions listed in the footnotes).

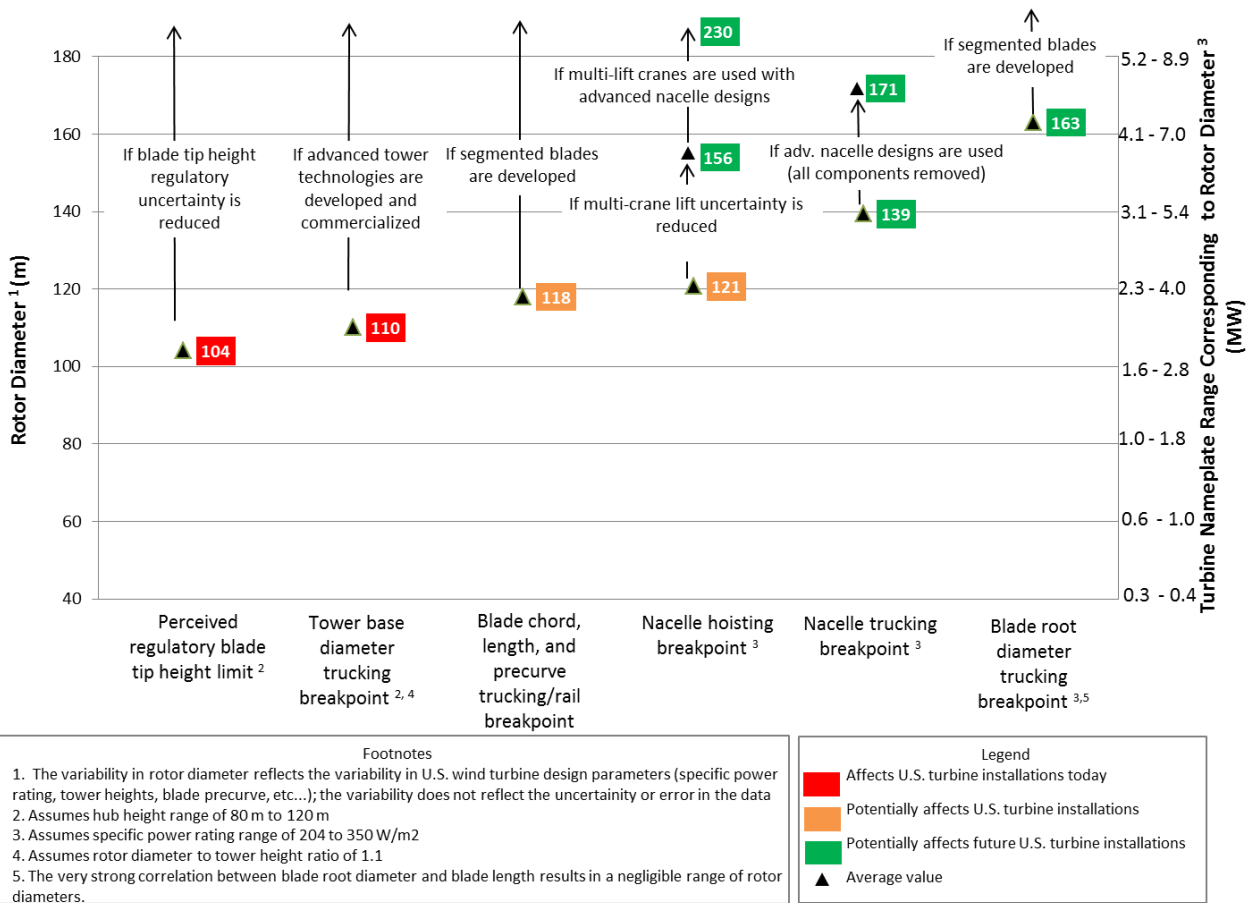
The black bars in Figure 3 represent the range of rotor diameters that could be affected by each transportation or logistic challenge considered. The magnitude of the range is caused by the variability in the different wind turbines design assumptions (for blade geometry, tower height, and specific power ratings) that are necessary to relate the transportation and logistics constraints to the rotor diameter. The numbers in the colored boxes in Figures 3 and 4 represent the average value of the range as a point of reference.



<p style="text-align: center;">Footnotes</p> <ol style="list-style-type: none"> <li>1. The variability in rotor diameter reflects the variability in U.S. wind turbine design parameters (specific power rating, tower heights, blade precurve, etc...); the variability does not reflect the uncertainty or error in the data</li> <li>2. Assumes hub height range of 80 m to 120 m</li> <li>3. Assumes specific power rating range of 204 to 350 W/m<sup>2</sup></li> <li>4. Assumes rotor diameter to tower height ratio of 1.1</li> <li>5. The very strong correlation between blade root diameter and blade length results in a negligible range of rotor diameters.</li> </ol>	<p style="text-align: center;">Legend</p> <ul style="list-style-type: none"> <li><span style="color: red;">■</span> Affects U.S. turbine installations today</li> <li><span style="color: orange;">■</span> Potentially affects U.S. turbine installations today</li> <li><span style="color: green;">■</span> Potentially affects future U.S. turbine installations</li> <li><span style="color: black;">▲</span> Average value</li> </ul>
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**Figure 3. Comparisons of selected transportation and logistics breakpoints for land-based turbines in the United States**



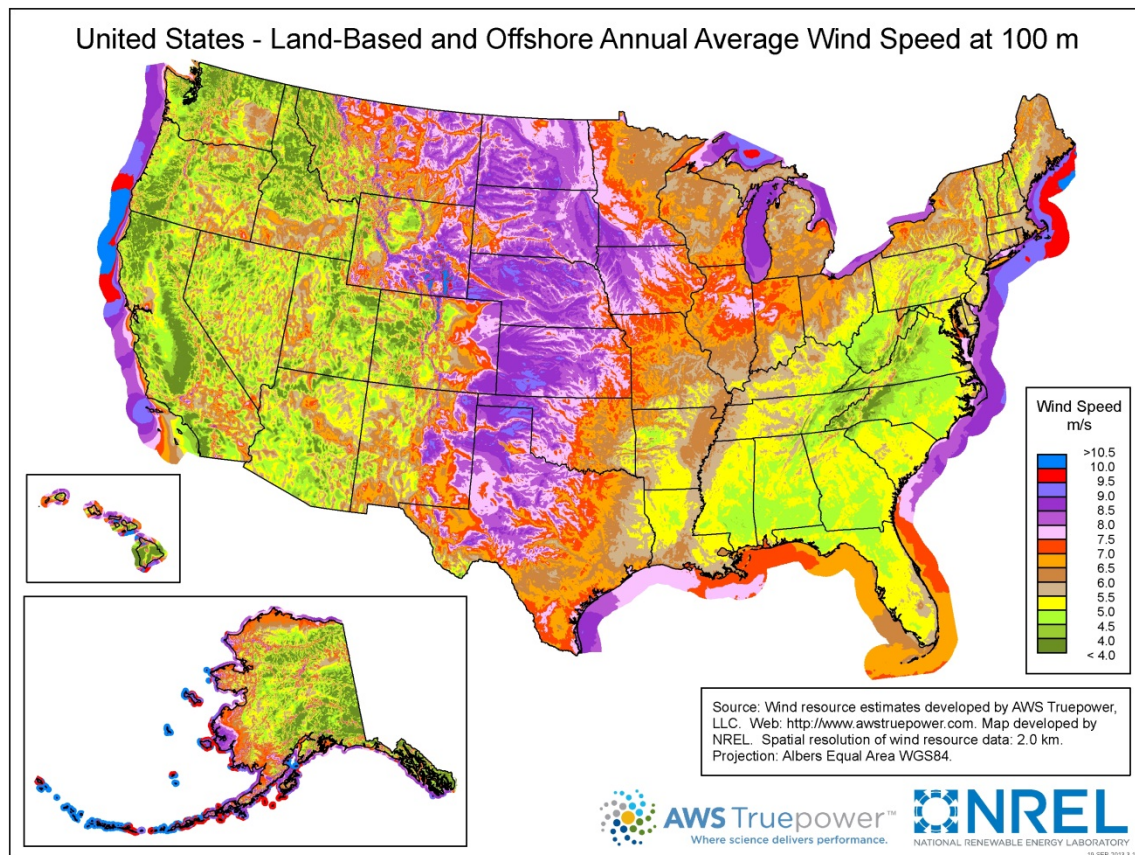


**Figure 4. The maximum size of land-based turbines that can be installed if selected transportation and logistics challenges are addressed in the United States**

## Perceived Regulatory Blade Tip Height Limit

Uncertainty regarding a perceived Federal Aviation Administration (FAA) height restriction for wind turbines has affected wind turbine manufacturer and wind plant developer willingness to develop plants and technologies with blade tip heights above 152 m (500 ft). An FAA spokesperson has stressed that although there is not a 500-ft limit, as of April 2012 it was not approving structures over 152 m until it established new rules, policy, and procedures for marking and lighting [3]. However, in late 2012, two wind plant original equipment manufacturers (OEMs) and developers indicated that they had received determinations of “no hazard” from the FAA for installations of turbines slightly taller than 500 ft. Nevertheless, NREL’s discussions with a wind turbine OEM and a developer indicated that they were unwilling to develop projects and technologies that exceed 152 m in height because of this perceived restriction.

The United States has strong wind resources that have helped make it a global leader in wind deployments. The U.S. regions with slower wind resources (see Figure 5), such as the Northeast, Southeast, and West, will benefit the most from the use of taller towers and larger rotor diameters that reach the faster winds at higher altitudes.

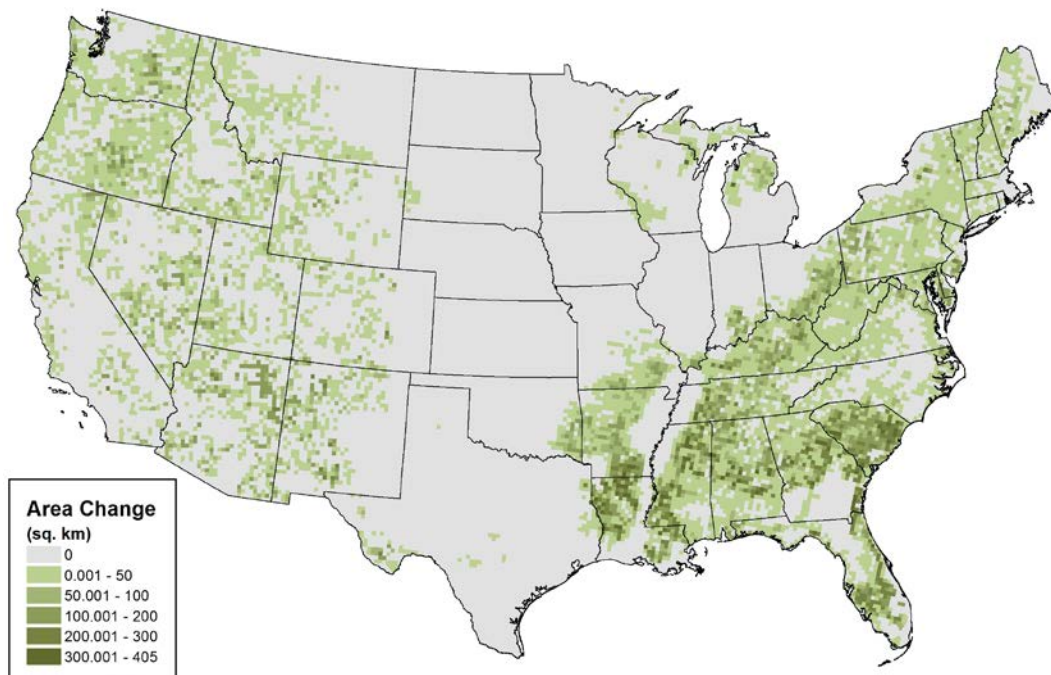


**Figure 5. United States Annual Average Wind Speed at 100 m**  
(Source: NREL and AWS Truepower)

The National Renewable Energy Laboratory (NREL) performed a preliminary analysis to estimate the possible effects of restricting turbine blade tip heights to less than 152 m [4]. The analysis calculated the increase in U.S. land area that became significantly more attractive for development by increasing the hub height of a GE 1.6-MW turbine with a 100-m diameter rotor from 96 m to 110 m (an increase in blade tip height from approximately 146 m to 160 m). The gross capacity factor (GCF) was computed for U.S. land area elements of 20 km<sup>2</sup>. Land area elements that showed increases of gross capacity factors to more than 30% were considered economically feasible for development as 30% is generally considered the minimum GCF

necessary to attain in order for a wind plant to be economically viable.<sup>2</sup> However, as wind technology advances and local power prices change, the potential of other low-wind-speed areas may also increase.

Figure 6 illustrates the new land area (in green) that crosses this 30% threshold. The map displays only the change in land area—not the land areas which already meet or exceed the 30% threshold. The land that could be “unlocked” by addressing the perceived regulatory height limit is approximately 320,000 km<sup>2</sup>—much of which is located in the east and southeast regions that tend to have slower wind resources. Theoretically, this land area equates to nearly 1,000 GW of new wind deployments if the rule of thumb of 3 MW/km<sup>2</sup> of potential wind turbine capacity is used [5].



**Figure 6. New deployable land resulting from increasing hub height from 96 m to 110 m**

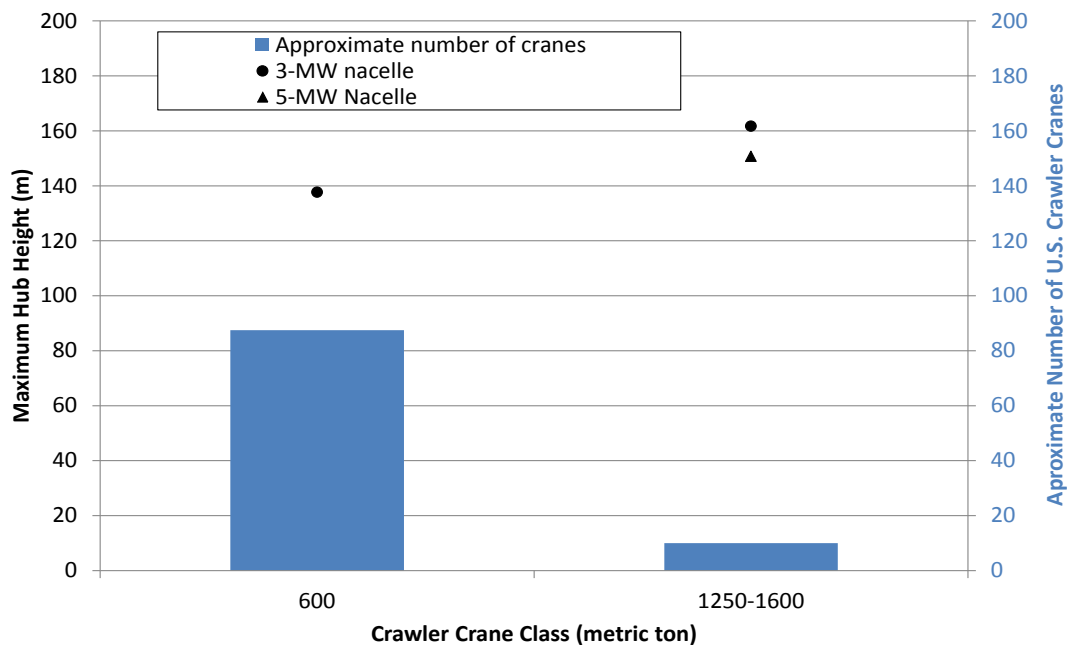
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<sup>2</sup> To compute the GCF, the long-term wind speed distribution at each wind turbine is combined with information provided by a power curve to derive the total annual energy produced at each turbine location. The gross capacity factor for a wind plant is calculated by taking this total renewable energy and dividing it by the energy that would be produced at the wind plant if all the wind turbines operated 100% of the time at their rated power (i.e. nameplate capacity). Typically, the gross capacity factor ranges from 30% to 55%, depending on both the type of turbine used, and the wind resource at the wind farm [6]. In this case, long-term adjusted hourly wind speed data was obtained from AWS Truepower at 200-m resolution and binned at 20-km resolution. The maps and statistics exclude all urban areas, bodies of water, national parks, and other protected land categories but do not include wind turbine losses that are included with the net capacity factor.

The authors recommend that wind industry stakeholders continue to work with the FAA to reduce any remaining uncertainties associated with this issue. In addition, demonstration of wind turbine installations with blade tip heights exceeding 152 m will further reduce the uncertainties.

## Nacelle Hoisting Challenge

Hoisting the nacelle onto the tower requires the largest crane capacity of all wind turbine components to install because of the lift height and mass. The masses of a 3-MW nacelle and a 5-MW nacelle are approximately 78 metric tons (t) and 130 t, respectively, without the gearbox and generator (104 t and 173 t with them installed). The availability, scheduling, and logistics of the larger crane classes (such as 1,250-t and 1,600-t crawler cranes) required to lift progressively larger wind turbine nacelles onto taller towers is increasingly challenging. Crane availability decreases drastically above the 600-t crane class (see Figure 7), thereby making it difficult to ensure that large cranes will be available for the nacelle lift. Wind turbine OEMs can take measures to reduce the nacelle mass that must be lifted onto the tower. For example, drivetrain components such as the gearbox and generator can be hoisted and installed in the nacelle after the nacelle is installed. However, such methods increase the cost and difficulty of the installation and can only reduce mass a certain extent.



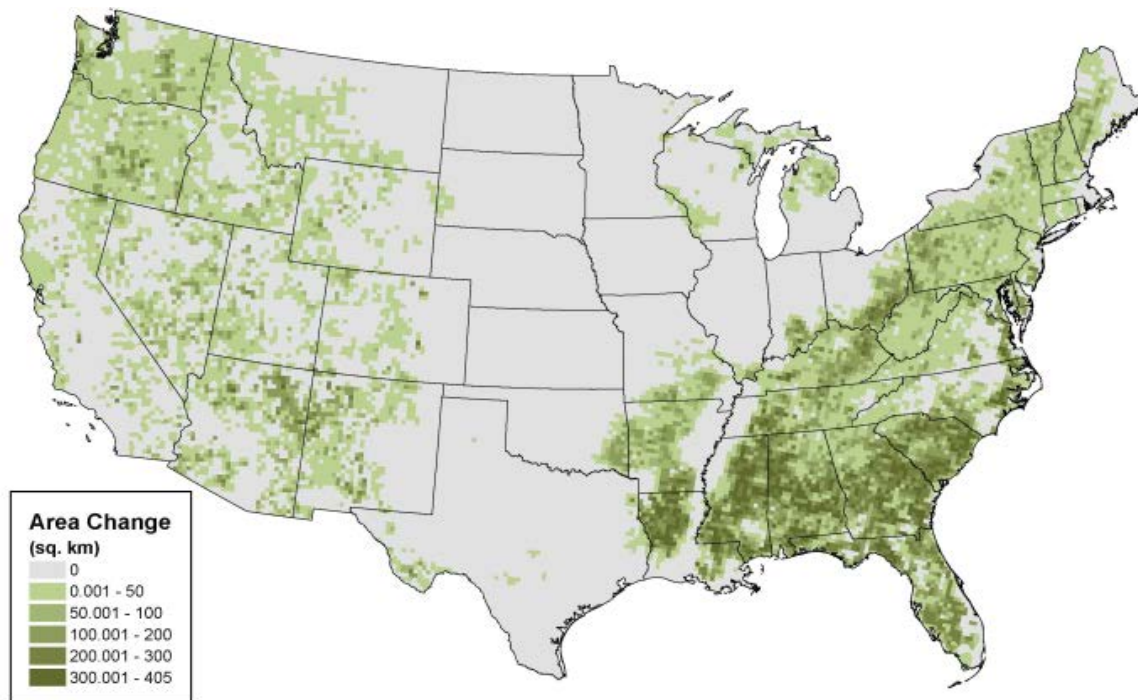
**Figure 7. Hub height that crawler cranes can hoist conventional turbine nacelles (with the gearbox and generator hoisted separately) [7] and the number of cranes estimated to be available in 2012 based on discussions with crane industry representatives**

Another challenge associated with the larger crane classes is the difficulty of transporting and maneuvering these large cranes within the wind plant, between wind plants, and in complex terrain. For example, a 1,600-t crane has a width of nearly 13 m (41 ft), which is wider than a typical two-lane interstate including shoulders. In addition, cranes of this size require more than 100 semi-tractor trailers to transport between projects making transportation difficult between wind plants.

One potential solution is to use more than one crane to hoist the nacelle onto the tower. Modern individual crane controls can be linked to reduce the risk of human error in multicrane lifts. Using two cranes simultaneously roughly doubles the capacity of a single crane and can help stabilize the lift allowing heavier nacelles or taller towers to be installed. For example, a 600-t crawler crane is projected to be unable to install a conventional 5-MW turbine even if the gearbox and generator are removed. However, two 600-t crawler cranes can be used to install a 5-MW nacelle to a hub height of approximately 130 m assuming the generator and gearbox are installed separately and that the combined crane lift capacity is derated by 25% due to the complexity of a two-crane lift.

NREL extended the preliminary analysis portrayed in Figure 6 to taller hub heights that are possible with larger cranes or dual lift installations. The maximum tower height was increased further, from 96 m to 140 m, as opposed to the 110-m hub height used for the previous analysis. In addition, NREL assumed a larger 2.4-MW commercial turbine with a 117-m rotor diameter (for both tower heights) instead of the 1.6-MW turbine to help offset the cost of the taller tower through increased production capacity. The increase in new deployable land area for the 2.4-MW turbine on a 140-m tower is roughly 614,000 km<sup>2</sup> (see Figure 8). In states such as Alabama, the unlocked land area approaches nearly 50% of the state's land area. Up to nearly 2,000 GW of new wind turbine capacity could be available in this "unlocked" area in the United States if the same 3 MW/km<sup>2</sup> rule of thumb is assumed.





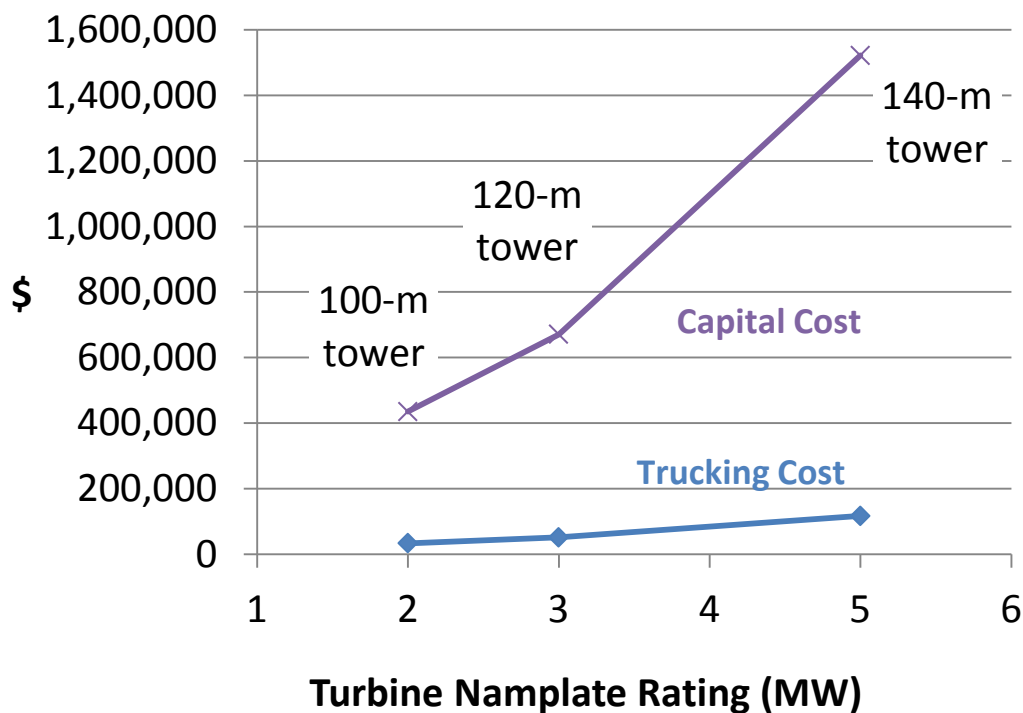
**Figure 8. New deployable land resulting from increasing hub height from 96 m to 140 m**

An obstacle to using two cranes to hoist the nacelle is the confusion between OEMs, developers, and crane operators about the reasons that dual crane lifts are not used in the United States as they are in Europe. For example, in discussions, one crane operator indicated that OEMs would not allow their turbine nacelles to be hoisted using dual crane lifts. In contrast, one OEM said the crane operators would not permit the dual crane lift. To reduce the confusion associated with dual crane lifts, the authors recommend the use of workshops and working groups to facilitate interaction among stakeholders. Demonstration projects with dual crane lifts could also be used to collect and communicate information about this potential solution.

### **Blade and Tower Transport Challenges**

The blade transportation challenge is caused by the difficulty of transporting long wide blades around turns, through narrow passages, and beneath overhead obstructions on U.S. roads and railways. Although alternate side roads can sometimes be used, the road weight limits on these side roads were cited by one industry member as limiting the effectiveness of these alternate routes. This challenge generally limits the length of blade that can be transported over roadways to between 53 m and 62 m depending on the design characteristics of the blade such as the amount of precurve and type of airfoils used.

Transporting the large diameter tower sections that are the most desirable for use in very tall towers creates a challenge similar to those associated with transporting blades. Tower sections are generally limited to 4.3 m in diameter, or, in some cases, 4.6 m if routes permit, to fit under overhead obstructions. Despite this limit, it is possible to transport conventional rolled steel tower sections to reach hub heights up to 160 m by constraining the tower diameter to 4.3 m, increasing the tower wall thickness, and shipping shorter sections that meet the weight limits of U.S. roads. However, this practice results in a rapid increase in the mass and capital cost (see Figure 9) of rolled steel towers, which makes towers tall enough to unlock new low- and moderate-speed land areas uneconomic. This increase in capital cost is of greater concern than the cost to transport the tower sections as the cost of transportation is less than 8% of the combined capital and transportation cost of the towers.



**Figure 9. Estimates of trucking cost and capital cost in 2013 for conventional tubular towers calculated assuming a 300-mile trucking distance, \$0.50/metric ton/mile, and base sections constrained to 4.3 m in diameter**

Innovative solutions for technologies that will mitigate the blade and tower transportation challenges, such as segmented blades and on-site tower manufacturing, are being explored by programs such as the Department of Energy; however, scaling up cost-effective technologies from low technology readiness levels (TRL) to commercialization will take time and require significant investment in research and development. Continued or expanded financial support for low TRL technologies, which are often developed by small and midsize companies, will help bridge the gap to commercialization of these technologies by larger companies with more substantial resources.

## Conclusions

This project identified several transportation and logistics challenges posed by the deployment of land-based wind turbines that continue to grow in size and height, assessed how they affect cost, and provided recommendations for specific actions. The tower diameter transportation constraint and perceived blade tip height limit are currently the constraints most affecting wind installations today. The authors recommend that DOE and industry continue to seek innovative technical solutions and reduce remaining regulatory uncertainties associated with these issues in the near term.

The challenges and costs associated with transporting taller towers and very long blades with wide chord lengths also affects wind plant deployments and will become more constraining as wind turbines increase in size and height. Similarly, trucking heavy nacelles and blades with larger root diameters could become challenges meriting additional attention. These challenges could be addressed with continued support for the research and development of mitigation technologies.

The problems associated with hoisting heavier nacelles onto taller towers are also affecting wind turbine installations and are expected to become increasingly important as these systems grow in scale. A number of potential solutions exist to address these problems. One potential solution is to use more than one crane to hoist the nacelle onto the tower. The authors recommend the use of workshops and working groups to facilitate interaction among stakeholders to reduce the confusion associated with dual crane lifts. Demonstration projects with dual crane lifts could also be used to collect and communicate information about this proposed approach.

Addressing these transportation and logistics challenges is expected to enable the deployment of larger wind turbines on taller towers. These larger machines can greatly expand the deployment of wind energy into low- and moderate-wind-speed regions in the United States (such as the Northeast, Southeast, and West), enable LCOE reduction pathways for all land-based wind turbines. In addition, although U.S. manufacturing opportunities are not clear cut, the components required for larger wind turbines, such as the blades, can be manufactured more cost-competitively in the United States as opposed to being imported. As a result, domestic content and U.S. manufacturing competitiveness may be increased by addressing challenges that limit the deployment of larger turbines.



## References

1. Lantz, E.; Wiser, R.; Hand, M. (2012). *IEA Wind Task 26: The Past and Future Cost of Wind Energy, Work Package 2*. pp 4-8 ; NREL Report No. TP-6A20-53510. <http://www.nrel.gov/docs/fy12osti/53510.pdf>
2. James, T.; Goodrich, A. (2014). "Supply Chain and Blade Manufacturing Considerations in the Global Wind Industry." NREL/PR-6A20-60063. Golden, CO: National Renewable Energy Laboratory. <http://www.nrel.gov/docs/fy14osti/60063.pdf>
3. Zipp, K. (2012). "To be precise, the FAA has no 500-ft limit on turbine towers," *Windpower Engineering & Development*. <http://www.windpowerengineering.com/construction/to-be-precise-the-faa-has-no-500-ft-limit-on-turbine-towers/>.
4. Roberts, J.O. (2013). *Land-Based Wind Potential Changes in the Southeastern United States* (Presentation). NREL, 16 pp.; NREL Report No. PR-5000-60381. <http://www.nrel.gov/docs/fy14osti/60381.pdf>
5. Denholm, P.; Hand, M.; Jackson, M.; Ong, S. (2009). *Land-Use Requirements of Modern Wind Power Plants in the United States*; NREL Report No. NREL/TP-6A2-45834. <http://www.nrel.gov/docs/fy12osti/53510.pdf><http://www.nrel.gov/docs/fy09osti/45834.pdf>
6. Lowenstein, J. "An Overview of Meteorological Towers and Wind Resource Assessment Studies," *Own Energy*. <http://www.ownenergy.net/blog/wind-resource-101-jason-lowenstein-phd>
7. "Terex Wind Power Crane Brochure," (2013) Brochure Reference TC-PB-E-Wind Power-06/13. [http://www.terex.com/cranes/en/idc03/groups/webcontent/@web/@cra/documents/web\\_content/ucm02\\_054906.pdf](http://www.terex.com/cranes/en/idc03/groups/webcontent/@web/@cra/documents/web_content/ucm02_054906.pdf)