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Measures for Reducing Energy Costs by Improving Design and Construction of Wind Turbine Towers

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Abstract

In today's wind energy market, there is a rising demand for both improved efficiency and power output from wind turbine systems, thereby reducing the cost per unit of wind energy. Among other alternatives, it has been shown that increasing the tower height achieves this goal by allowing turbines to operate in a more dependable wind environment and harvest wind energy more consistently. Additionally, further economic benefits can be realized through the reduction of the tower's initial cost. In this context, improved design, use of advanced materials and modularized construction can lead to significant savings in tower, transportation and land development costs. Regardless of using steel, concrete or other advanced materials, the required improvements in tower design cannot be achieved effectively without a unified specification, which does not exist in the US or elsewhere. This paper 1) identifies the standards and limit states germane for steel, concrete, and other wind turbine towers; 2) discusses how the creation of an American standard for wind turbine towers would alter the conservatism inherent in the current design practice, and therefore the overall design cost-effectiveness; and 3) addresses other options for reducing the tower costs.

1 Introduction

With the rising cost of fossil fuels and their increasingly recognized effect on the Earth's atmosphere, there is a strong movement underway, advocating the use of clean energy. Of the current alternatives, wind energy is positioned at the forefront of the renewable energy drive.

In May 2008, the Department of Energy (DOE) released a report, "20% Wind Energy by 2030", detailing a scenario in which 20% of all energy in the United States would be produced through wind energy. In order to meet the projected demand for energy consumption in the year 2030, the country would need to increase its wind energy production by 300,000 MW (U.S. Department of Energy, 2008). To accomplish this goal, continued research and development of wind turbines is necessary.

One of the major challenges identified in "20% Wind Energy by 2030" is, "…reduction in wind capital cost and improvement in turbine performance through technology advancement and improved manufacturing capabilities" (U.S. Department of Energy, 2008). While continued improvement in the durability and efficiency of the turbines themselves will aid in accomplishing this goal, it is necessary to explore other alternatives. As power production is related to the cube of the velocity, it follows that a turbine in a faster wind environment is more efficient. Due to the effects of the atmospheric boundary layer, wind velocity generally increases via a power-law distribution with height. Therefore, a logical solution to increase wind energy production is to place the turbines at increased elevations to exploit more desirable wind conditions.

The current state of practice for wind turbine tower design includes the use of tubular steel, regular strength concrete towers, and hybrid steel-concrete towers. However, the tubular steel constructed in three large segments (Figure 1.1) is more widely used in practice. While current towers satisfy the design criteria for lower hub heights, there are limitations that prevent them from being extended to greater heights.

Figure 1.1: Tubular Steel Tower (Courtesy of T. Baird, Iowa State University)

2 Current Practice

2.1 Steel Wind Turbine Towers

One of the most cited problems with steel towers is the transportation concern. For the turbines commonly deployed in current practice, 80 m (262.5 ft) tall steel towers are used, which are typically composed of three or more tube sections, stacked on top of each other. These sections are bolted or welded to form a complete tower. Since all steel is pre-manufactured in a rolling mill, it must be transported to the project site by truck or train (a typical transportation set-up can be seen in Figure 2.1). However, due to highway/bridge clearance issues, the diameter of a tube section is limited to 4.3 m (14.1 ft) (F.J. Brughuis, 2004). With this limitation, the tower height has been maximized at 80 m (262 ft), as increasing the hub height to 100 m (328 ft) requires steel tubes of diameters as high as 5.5 m (18 ft) (Lewin, 2010). As a result, the transportation limit puts a practical ceiling on hub heights, unless new construction methods requiring assembly of segmental steel sections to form the tubular sections with diameters greater than 4.3 m (18 ft) are used. Another alternative to this solution is to use higher strength steel and limit the base diameter of taller towers to 4.3 m (14.1 ft). Both of these options will increase the tower costs and make other construction materials more viable for the design of taller wind turbine towers.

Figure 2.1: Transportation of a Steel Tower (Courtesy of T. Baird, Iowa State University)

Another challenge of steel tower transportation is the distance between the manufacturing plant and the site chosen for the wind farm. The cost of the tower increases with the increasing distance to the project site, a challenge which is exacerbated by the isolated locations of tower manufacturing plants. According to a study completed by Global Energy Concepts LLC (Smith, 2000), in order to construct wind turbines within the Midwest (with South Dakota being the chosen state in the study), towers may have to be transported from as far as Texas or Louisiana. Furthermore, to meet the local demand (which is expected to grow significantly to achieve the DOE’s 20% by 2030 goal) manufactured towers may need to be imported from China, Taiwan and Korea (e.g., LaNier, 2005). Given these extreme distances and the specialized nature of tower construction, transportation constitutes a significant portion of the total cost for a wind turbine project. For a 100 m (328 ft) tower with a 3.0MW wind turbine, the transportation alone could cost as much as $200,000 (LaNier, 2005) to bring each tower to the project site. If the diameter of steel turbine towers increases beyond 4.3m (14.1 ft), this cost would drastically increase.

Wind turbines are subjected to loads that most civil engineering structures do not commonly experience. While steel is considered a light-weight building material due to its high strength, it is vulnerable to fatigue. According to the design calculations presented by LaNier (2005) and Lewin (2010), fatigue concerns govern the design of steel towers. The most important factor in fatigue is the stress range that the material will be subjected to. For a smaller stress range, a structure should be expected to be more damage resistant. Therefore, a thicker shell would see smaller stress variations, and be less susceptible to fatigue damage. Additionally, welds are susceptible to fatigue, increasing the cost of steel connections. It should also be noted that, for fatigue calculations, steel towers are designed for the 20 year life cycle of the turbine (DNV/Risø, 2002). In comparison to other civil engineering structures, this duration is very short as, for example, bridges are now designed to have 60 to 75 years of life. Consequently, it follows that if towers are designed with a material that increases the longevity of the towers, its life cycle cost could be significantly reduced.

2.2 Limit States for Design

Regardless of the material chosen for the design, all necessary limit states must be identified in order to economically and safely construct a wind turbine tower. A limit state failure can have multiple definitions, but implies that the structure has reached the limit of its usefulness. The typical limit states considered on tower design are: serviceability, strength, and fatigue. Additionally dynamic effects must be considered in design at each appropriate limit state. It is useful to note that towers constructed of different materials should be expected to have different governing limit states. Because of this, the use of alternative materials could positively affect the design life of the tower, as well as the overall cost and sustainability of the project.

2.2.1 Serviceability

In the context of towers, the limit state of serviceability refers to a limiting deflection. As there are no specifications currently in the U.S. devoted to wind turbine towers, no standardized code-based deflection limits currently exist. However, industrial chimneys have been built of concrete for years, and some provisions from this design practice could be used (LaNier, 2005). ACI 307-98 is one such specification, which includes a recommended lateral deflection limit of 1/300 of the structure height in order to “reduce effects of secondary bending moments” (ACI Committee 307, 1998). Additionally, some deflection control would be needed to allow technicians to access and service the turbine without excessive discomfort.

2.2.2 Strength

The strength limit state is typically defined to prevent structural failure. For steel, Allowable Stress Design (ASD) or Load and Resistance Factor Design (LRFD) can be used at this limit state. With ASD, sections are limited to elastic behavior and are designed for service level loads. The intent of this approach is that it will eliminate yielding and buckling failure of steel members with a predetermined factor of safety. For LRFD, factored level loads are applied and excessive yielding, fracture, and buckling is prevented. In the case of steel, buckling refers to both global buckling of the tower due to compressive loads, as well as local buckling of slender steel elements.

For prestressed concrete, it is common to design the structure for service load conditions, limiting the stress in the members to predetermined values. This approach is preferred because the prestressed member designs are typically governed by serviceability criteria. Compression stresses are typically limited to 45-60% of the 28-day compressive strength (ACI Committee 318, 2008), while a limited amount of tension may be allowed so long as it will not introduce any cracking. An alternative approach would be to allow no tension to develop anywhere in the structure. If the structure satisfies the strength limit state for service levels conditions, factored level loads are applied and its ultimate strength can be checked. LaNier (2005) identifies the following as pertinent strength limit states for prestressed concrete design:

- “Resistance to the design earthquake or wind load…”
- “Zero-tension stress in the concrete under the service wind loads”
- “No failure during construction for temporary wind loads…”

Prestressed concrete members must also be checked for shear cracking at service level loads, and ultimate shear strength for factored level loads. Strength equations for shear are available in ACI 318-08 (ACI Committee 318, 2008). Additionally, if slender concrete elements are used, buckling would also be a design consideration.

2.2.3 Fatigue

Due to the cyclic nature of the tower loading induced by turbine operation, fatigue becomes a necessary concern in tower design. For both concrete and steel towers, this limit state needs to be addressed through a fatigue analysis. For this verification, the total number of cycles and corresponding stress range in the structural elements needs to be known. A detailed analysis or codified approach can then be used to evaluate the fatigue strength of the material. For steel towers, this is likely to be the controlling design limit state. Research completed by Lewin (2010) suggests that this is not the case for concrete towers.

2.2.4 Dynamic Effects

Since wind turbines have multiple excitation frequencies, the natural frequency of the tower is an important design consideration. The most important of these excitation frequencies are the blade rotational frequency (1P) and the blade passing frequency (2P or 3P, for a 2-bladed or 3-bladed turbine, respectively). “Soft towers” are typically designed somewhere in between these frequencies, in what is termed as a “working range” (LaNier, 2005). It is suggested that this working range is bounded by 1P ±10% and 2P/3P ±10% (DNV/Risø, 2002) in order to minimize dynamic amplification effects. It is reported that as the power output of the turbine increases, the working range of the natural frequency decreases (LaNier, 2005) due to the decreasing operating rotor rotational speed. A stiffer tower could be designed with a natural frequency greater than 3P (or 2P for a 2-bladed turbine). However, this would increase the tower cost considerably and thus are not generally preferred by the industry.

3 Code Constraints

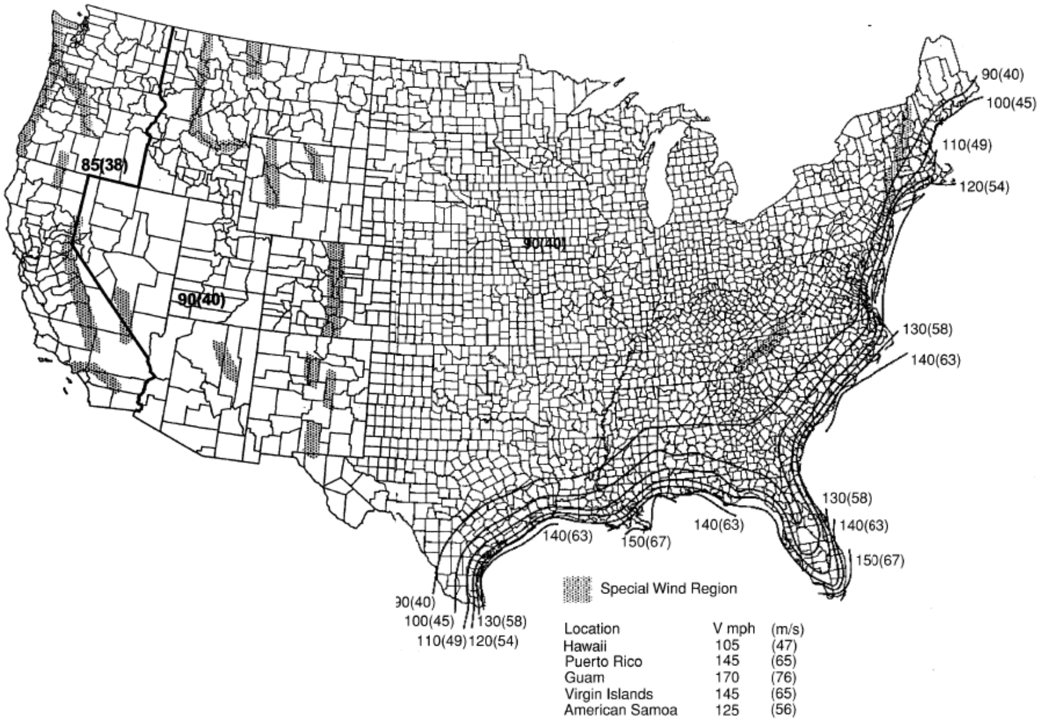
Another significant limitation in the wind turbine tower industry is the lack of a unified design code, created for use in the United States. Existing building standards cannot efficiently be utilized, as wind turbine towers are unique in what they do and the environment in which they operate. Presently, towers are engineered to a variety of specifications. Because of this reason, some towers may actually be over-designed for their task, resulting in higher than necessary costs and profligate use of materials.

One the initiatives suggested by the “20% Wind Energy by 2030” is “Development of appropriate design criteria, specifications and standards” (U.S. Department of Energy, 2008). While Europe has cultivated multiple wind turbine tower design standards, such as IEC 61400-1 (International Electrotechnical Comission, 2007) or DNV/Risø’s “Guidelines for Design of Wind Turbines” (2002), the United States does not have its own wind turbine standard. This practice causes confusion, and fails to ensure uniform reliability in tower design.

A unique concern for wind turbine towers is the high amount of load reversals that they will experience in their design life. Although all buildings and bridges are subjected to dynamic forces, the vibratory characteristics of wind turbines, combined with constantly changing wind conditions and velocity are estimated to result in “5.29×10^8 fatigue load cycles” (LaNier, 2005). Recognized American building standards, such as ACI 215R only account for fatigue in the order of 10^4 cycles. European standards, such as the Model Code 1990 (Comite Euro-International Du Beton, 1990) for concrete, have considered this issue. In the case of steel towers, fatigue is recognized as one of the governing limit states (LaNier, 2005) for design. The absence of this issue illustrates the inadequacy of existing American standards' applicability to wind turbines.

Another area in which American codes fall short is in providing design wind speeds. The ASCE 7 (SEI, 2005) specifies regional wind speeds through the use of its "Basic Wind Speed" map, seen in Figure 3.1. This map gives the 3 second wind speed at 10 m (33 ft) elevation. While the basic wind speeds change drastically at the coasts (largely due to the occurrence of hurricanes), the map gives a reference speed that is essentially constant throughout the interior of the United States. This may be sufficient for building construction, but it is not adequately detailed for wind turbine tower design.

When compared to a map of the United States' wind resources (Figure 3.2), there is a large variation in wind speed that the ASCE 7 does not account for. Other codes, such as IEC 61400-1 (International Electrotechnical Comission, 2007) specify wind speed based on turbine class and turbulence characteristics. This is a more appropriate method, since the wind class inherently takes into account the turbine's design wind velocity; such information will be gathered during wind farm siting.



Location	V mph	(m/s)
Hawaii	105	(47)
Puerto Rico	145	(65)
Guam	170	(76)
Virgin Islands	145	(65)
American Samoa	125	(56)

Notes:
1. Values are nominal design 3-second gust wind speeds in miles per hour (m/s) at 33 ft (10 m) above ground for Exposure C category.
2. Linear interpolation between wind contours is permitted.
3. Islands and coastal areas outside the last contour shall use the last wind speed contour of the coastal area.
4. Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

Figure 3.1: ASCE 7 Basic Wind Speed for Buildings and Other Structures (SEI, 2005)

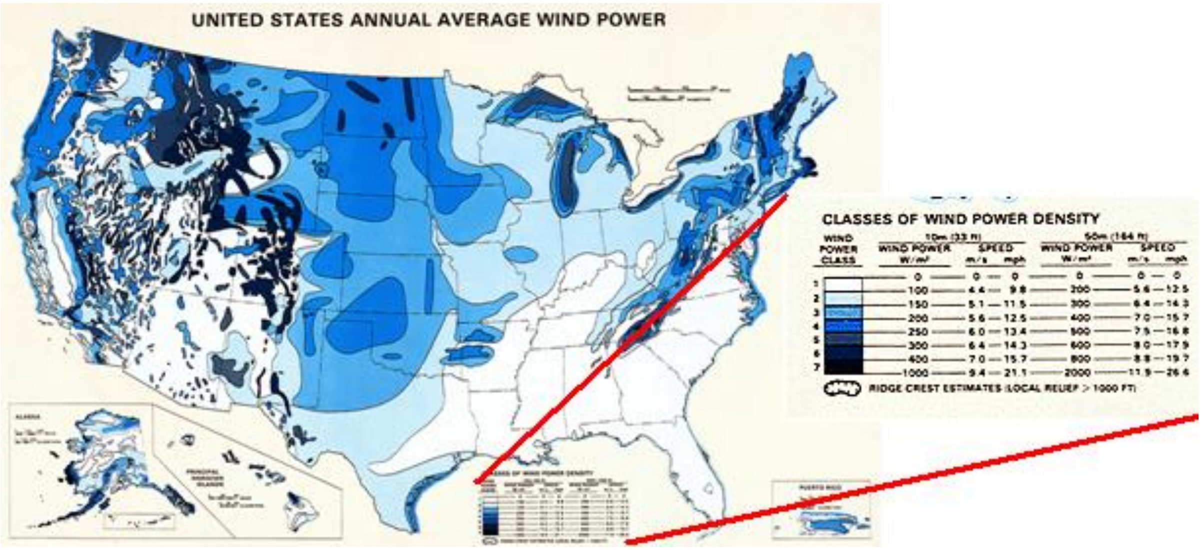


Figure 3.2: The United States' Wind Resource (after National Renewable Energy Laboratory)

Since a unified American standard is not available to handle these issues effectively, a combination of American and European standards is used to complete wind turbine tower designs. This combination also leads to variances in the level of conservatism in wind turbine tower designs. This difference can be illustrated through the comparison of load factors used to verify the ultimate capacity of the design. Load factors are typically determined through statistical analysis, which attempts to predict the lifetime maximum loads a structure will experience. However, American and European standards do not always specify the same load factors (Vazquez & Hagen, 2009; LaNier, 2005). For example, the ASCE 7 (SEI, 2005) uses a maximum factor of 1.6 for load combinations involving wind, while a value of 1.35 is recommended by the IEC 61400-1 (International Electrotechnical Comission, 2007) for wind turbine loads. This implies that turbine towers designed using only American standards (but using the same turbines as their European counterparts) are designed for an 18% higher turbine load. This conservatism may unnecessarily add costs to wind turbine projects.

4 Alternative Materials

While concrete is nearly ubiquitous in the world of civil engineering, as well as the most popular construction material, it is strangely absent from the wind turbine industry. While recently interest in concrete has been rising, its popularity for wind turbine tower design is still secondary to steel. This is likely due to the presence of steel as an established solution for 80 m (262 ft) or shorter towers. However, since current steel designs cannot merely be scaled up to accommodate 100 m (328 ft) or taller hub heights, alternative solutions need to be investigated. Concrete has the potential to meet the demands for designing taller wind turbine towers.

One of concrete’s major strengths is its ready availability. There are many concrete plants throughout the United States. Whereas cast-in-place concrete requires long cure times, precast concrete facilitates rapid construction. Additionally, precast concrete has excellent quality control, minimizing material and construction flaws. Due to the high concentration of precast concrete manufacturers, travel distances can be greatly reduced as it will be possible to find a precast fabricator within a 200 mile radius of any wind farm.

Another beneficial aspect of concrete is its ability to be prestressed, resulting in members that are more slender than those constructed with reinforced concrete. They are lighter, which is an advantage in seismic areas, and maximize the use of both concrete and high strength steel reinforcement. Moreover, prestressed concrete is designed to remain uncracked and typically experience no tensile stresses under service loads. The steel tendons used in these members are also more resistant to fatigue than welded tubular steel (LaNier, 2005). If fatigue were eliminated as the controlling limit state, turbine towers could be re-used after the service life of the original turbine has expired. Research at Iowa State University (Lewin, 2010) has suggested that prestressed concrete wind turbine towers have a very long fatigue life. This characteristic, coupled with prestressed concrete’s excellent corrosion resistance, would drastically extend the design life of the wind turbine tower, as compared to steel alternatives. Because of this fact, a single tower could be used to support multiple turbines over the course of its life cycle. This would add significant value to any wind turbine project.

One disadvantage of concrete compared to steel is the necessity of thicker members, resulting in increased structural weight. Heavier structures may increase the foundation cost. Furthermore, in seismic areas, heavier structures would experience larger forces in an earthquake than a lighter structure (of similar stiffness). These challenges could be mitigated through the use of higher strength concretes. Today concrete is available with compressive strengths of 138 MPa (20 ksi) or beyond. When combined with prestressing, the weight gap between concrete and steel could be lessened.

5 Alternative Construction Methods

In addition to the using alternative materials, the use of alternative construction methods are needed to solve the current challenges associated with building taller towers. As previously mentioned, limited highway/bridge clearances restrict the diameters of current towers. This problem could be solved through the use of prestressed concrete coupled with modular construction methods.

In a modular design, the tower sections are made up of multiple pieces. These modules are then bolted, welded or post-tensioned together to form a complete cross section. The segments are then stacked one on top of the other and connected to form the complete tower.

This method has several important advantages. First, only several unique pieces are needed to construct the entire tower. This allows precasters to construct only a few forms in order to complete the concrete tower modules. Second, since each individual piece is small, they can be stacked on a truck and transported at significantly reduced cost by eliminating the need for using specialized trailers and the associated site development costs. As transportation represents a significant portion of the total tower cost, this is an important factor. Lastly, this design would also eliminate the construction challenge of limited crane lifting capacities. Since the individual concrete components are smaller (and much lighter) than large, heavy steel sections, smaller cranes could be used to lift the concrete to greater heights.

As discussed in Section 4, prestressed concrete towers could be re-used when their turbine's design life is met. If unbonded post-tensioning is combined with modular construction, the towers could even be disassembled, transported to another project site, and reassembled for re-use. This would drastically increase the tower's salvage value and sustainability.

6 Conclusions

To achieve the DOE's "20% by 2030" goal, all potential alternatives to making wind energy more viable must be examined. One possible solution is the use of taller wind turbine towers. With the development of taller towers, establishing a uniform American standard is more important than ever. Its creation would ensure that all necessary limit states are considered, making the requirements for American wind turbine tower clearer. Additionally, it would reduce unnecessary conservatisms inherent in current American building codes that are not wind turbine specific. This would ensure the reliability of future wind turbine projects, and promote the expansion of wind power as a clean energy alternative.

The use of alternative materials and construction methods for tower construction would help to achieve the DOE's "20% by 2030" by presenting a solution to the transportation limitations of current tubular steel towers. In particular, prestressed concrete, combined with modular constructions methods, offers a promising means to increasing tower height and thereby increasing turbine efficiency. Prestressed concrete is readily available, allowing for the continued expansion of the wind turbine market. It also has excellent fatigue resistance, extending its design life, thus making it a sustainable solution. Modular construction is the key to solving transportation limitations on tower diameters, and reduces transportation and site development costs.

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