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Wind Turbine Towers: Precast concrete Hexcrete may help increase renewable energy capacity with taller hub height

Sri Sritharan
Iowa State University, sri@iastate.edu

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Abstract

Wind-energy production has been growing rapidly in the Midwest, but not in other regions of the United States. Increased wind-turbine hub heights of 328 to 459 ft (100 to 140 m) could drastically change this. As wind-turbine towers get taller than 263 ft (80 m), a concrete solution may become more cost-effective than the steel tubular option. The Hexcrete concept was developed with the aim of revolutionizing wind-turbine towers for hub heights of 328 ft (100 m) and more. This tower uses hexagonal columns with posttensioning and rectangular/tapered panels as bracing elements. The prefabricated modules are assembled using posttensioning to form a tapered tower with a hexagonal cross section. Large-scale testing has been used to validate the Hexcrete concept and its connections.

Keywords

Energy, hexagonal, Hexcrete, hub height, tower, turbine, wind

Disciplines

Civil Engineering | Energy Systems | Geotechnical Engineering | Structural Engineering | Structural Materials

Comments

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Sri Sritharan

Wind turbine towers

Precast concrete Hexcrete may help increase renewable energy capacity with taller hub heights

- Taller wind turbines can increase renewable energy capacity.
- Hexcrete is being studied for potential use in the construction of taller wind-turbine towers.
- This potential precast concrete solution could prove to be more cost-effective than currently used steel tubular towers.

Installed wind energy in the United States has grown significantly over the past decade. At the end of 2014, the United States had installed 66 GW of wind energy. In the world, we have the second largest installed capacity, and we are currently ranked first when it comes to annual wind power production. In 2014, U.S. wind-energy production was sufficient to power 17 million average American homes, which is about 4.4% of all electricity generated in the United States. In 2015, the U.S. Department of Energy (DOE) published *Wind Vision: A New Era for Wind Power in the United States*, which forecasts wind-energy production to grow from 10% of the nation's electricity supply in 2020 to 20% in 2030 and 35% in 2050.[1]

These scenarios are certainly achievable given continuous advancements of wind-energy technology and reduction in its levelized cost of energy (LCOE), which expresses the cost of energy production in cents per kilowatt hour. Since 2007, installed wind capacity has quadrupled in the United States, suggesting that reaching 10% wind-energy production by 2020 is not a daunting task. Achieving the 2030 and 2050 suggested scenarios requires an additional 136 GW and 252 GW, respectively, of land-based wind-energy production, which would mean adding more than 100,000 wind-turbine towers by 2050. The current fleet of wind-turbine towers is designed for a 20- to 25-year life span. Repowering these wind farms will introduce more demand for new wind-turbine towers.

Texas, California, and Iowa lead the United States in installed wind capacity today; however, other states (especially in the Midwest) have been rapidly increasing their wind-energy production. With utility-scale wind turbines routinely reaching 263 ft (80 m) hub height, Midwest states are considered to have the most favorable wind resources. In 2014, Iowa led the nation by producing 28.5% of its electricity from wind, and the American Wind Energy Association predicts that Iowa will meet 40% of its electricity demand through wind power in

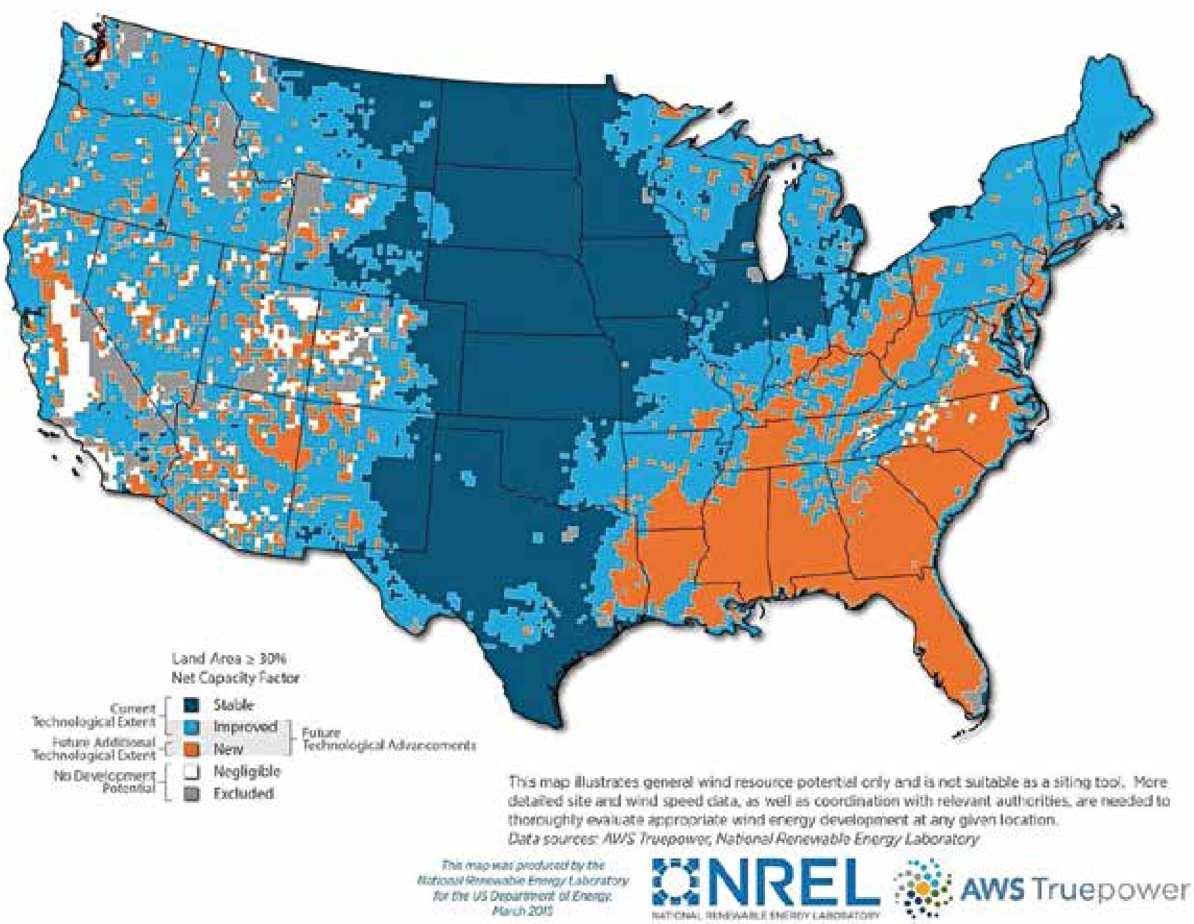

Figure 1. Land area achieving a minimum 30% capacity factor for wind-energy production at a 140 m (459 ft) hub height. This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.

the next five years.[2] In 2014, wind energy contributed to more than 15% of electricity demand in seven states, more than 10% in nine states, and more than 5% in 19 states.

Despite the significant growth in installed wind-energy capacity, one issue has constantly challenged this industry. Although wind-energy production has been growing rapidly in the Midwest, the same cannot be said for the East and West Coasts, where the electricity demand is much higher. Some states (such as those in the Southeast) are considered to have no wind potential, and their renewable-energy capacity today is almost zero. This scenario will drastically change if the wind-turbine hub height can be increased to 328 to 459 ft (100 to 140 m).

In 2015, the DOE released a report calling for wind-energy production at higher elevations. With a 459 ft (140 m) hub height, U.S. Secretary of Energy Ernest Moniz says that all 50 states will have the potential to produce wind energy.[3] **Figure 1**, reproduced from the DOE report, shows the new and improved wind-potential areas, with several Southeast states identified as new regions for wind-energy production. Increasing wind-energy production in regions where the demand is high will continue to increase the role of wind energy in increasing renewable energy sources and significantly reducing greenhouse-gas emissions, air pollutants, and water consumption. For example, U.S. wind generation in 2013 was reported to have reduced CO_2 emissions by more than 125 million tons, sulphur dioxide (SO_2) by 173,000 tons, and water consumption by 36.5 billion gallons.[1]

Taller towers

In any region, taller towers with elevated hub heights will have access to higher wind speeds and steadier wind conditions, both of which will increase the wind-energy-harvesting time and the total wind-energy production. Studies have suggested that increasing the hub height by 66 ft (20 m) can increase wind-energy production by about 10%. Taller hub heights will also be needed to accommodate higher-throughput turbines and longer blades that have been under development. High-throughput wind-turbine systems with an increased rotor diameter can lead to a reduction in the number of towers needed to produce the same amount of energy. All of these features are expected to lower the capital and production costs of wind energy.

Figure 2. A schematic view of a Hexcrete tower section.

Figure 3. Precast concrete Hexcrete components at a tower site.

The benefits of using taller hub heights have long been recognized, and the wind-turbine tower heights have progressively increased from less than 131 ft (40 m) in the 1990s to 263 ft (80 m) for the utility-scale turbines that are used today. Currently, three steel tubular sections—made off-site and transported via specialized trailers—are used to form the 263 ft (80 m) tall towers. The base diameter of this tower is about 13.5 ft (4.1 m), which is just under the vertical clearance permitted on state highway routes. Increasing the hub height of steel tubular sections will significantly increase the cost of taller towers. This is because the tower base needed for taller towers (above 100 m [328 ft]) must be designed using higher-strength steel or segmented base sections that require field assembly.

Concrete towers

It has been reported that as wind-turbine towers get taller than 263 ft (80 m), a concrete solution may become more cost-effective than the steel tubular option. Two concepts have been explored for introducing concrete to wind-turbine-tower design. One is an extension of a steel tubular concept that uses concrete shells for the towers. This concept has been used primarily in Europe with precast concrete modules needing vertical or horizontal connections. With the use of normal-strength concrete, a concrete tubular solution can increase the footprint of the tower by 40% to 50%, and the wall thickness at least fivefold when compared with steel tubular towers with the same hub height. The increased footprint may create a challenge in meeting the blade-tip clearance requirement, whereas increased wall thickness increases the weight of the tower, thus increasing the transportation and erection costs. In addition, making curved sections from concrete (with changing dimensions up the height of a tapered tower) requires high capital costs for specialized formwork, limiting the number of concrete-tower producers and reducing market competitiveness. Depending on how the tower is segmented, transporting curved concrete shells may also pose challenges.

The second concept relies on using concrete to support the steel tubular tower, providing a hybrid solution. In this case, the concrete is used as a pedestal at the base. Although combining steel and concrete can lead to transformative solutions, using a concrete segment to support steel tubular sections limits the innovations that the precast concrete industry can offer to the wind-energy industry, and limits the efficient use of both construction materials.

The Hexcrete tower

The Hexcrete concept was developed with the aim of revolutionizing wind-turbine towers for hub heights of 328 ft (100 m) and more.[4,5] As the first step, basic barriers to precast concrete production of taller wind-turbine towers were identified (for example, easily producible and replicable members and reduced transportation and logistical challenges). The Hexcrete concept was then formulated to introduce the most transformative changes to utility-scale wind-turbine towers to realize multiple benefits.

This tower uses hexagonal columns with posttensioning and rectangular/tapered panels as bracing elements (a segment is schematically depicted in **Fig. 2**). The columns and panels are designed for easy prefabrication. High-performance concrete (HPC), high-strength concrete (HSC), or ultra-high-performance concrete (UHPC) may be used for the columns and panels. The compressive strength of HPC and HSC is in the range of 7 to 14.5 ksi (50 to 100 MPa), whereas UHPC on average has a compressive strength of 26 ksi (180 MPa).[6] The prefabricated modules are assembled using posttensioning to form a tapered tower with a hexagonal cross section (as seen in Fig. 2).

Features

To ensure broad applications with minimal challenges, several attributes were emphasized in the development of the Hexcrete concept. First, the tower uses higher-strength cementitious materials and prestressing to minimize the dimensions of individual structural members and those of the tower. Member section shapes were chosen to eliminate costly specialized formwork (**Fig. 3**) and minimize assembly costs. Next, the modules were designed to be easily transportable without requiring specialized trailers. In addition, the possibility of both off-site and on-site prefabrication of

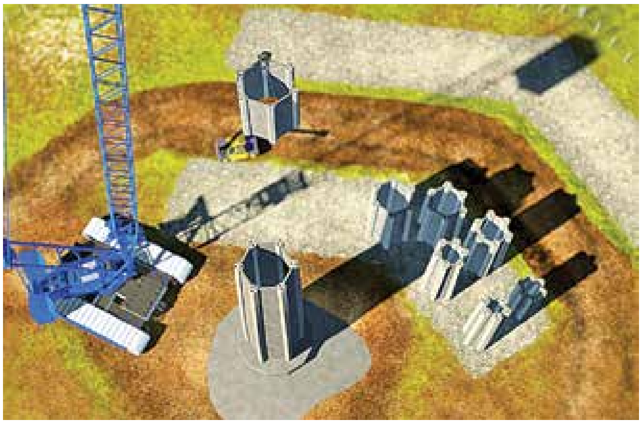

Figure 4. Assembly of a Hexcrete tower using preassembled cells.

Figure 5. Options chosen for levelized cost-of-energy evaluation for 120 m (394 ft) tall Hexcrete towers. On the left are 8 Hexcrete cells with a steel tubular section at the top, and on the right are 11 cells to form the entire tower.

Figure 6. This full-scale Hexcrete cell, which would be located near the top of a 394 ft (120 m) tall tower, has been assembled and subjected to a variety of loads representing operational, extreme, and ultimate limit states.

modules exists, allowing local construction contractors the ability to minimize costs and maximize erection efficiency depending on the job situation. With the use of precast concrete products, dependable connections between precast concrete columns and panels have been developed. Finally, the contractor will have multiple erection options. The tower may be assembled first as vertically stacked Hexcrete cells (**Fig. 4**), or columns may first be erected to a certain height and posttensioned before panels are attached.

Deploying a self-erecting concept may also be possible for Hexcrete towers. The most cost-effective erection methods will evolve as deployment begins. Because the vertical loads of the towers are transferred through the column, both shallow and deep foundations may be used to support the Hexcrete towers. Today, shallow foundations are commonly used for wind-turbine towers, which may not be the most cost-effective solution for all wind farms.

Benefits

Compared with steel and concrete tubular towers, a number of unique benefits can be realized for Hexcrete towers. First, they can facilitate efficient on-site and off-site prefabrication. Second, they do not require specialized formwork. Third, off-site prefabrication modules can be tailored to avoid the need for specialized transportation. Fourth, it is easier to locate a precast concrete plant in close proximity to any potential wind farm, whereas steel tubular towers are sometimes produced overseas and shipped to the jobsite in the United States.

The Hexcrete concept also offers increased versatility to elevate tower height, which can be achieved by increasing the base footprint, column diameter, or wall thickness, combined with changes to posttensioning. Steel-tower designs are governed by fatigue and are designed with an assumed life of 20 to 25 years. With the Hexcrete option, the tower life span can easily be doubled at no significant cost increase due to fatigue not governing the design. Finally, there is potential to reduce the tower decommissioning costs because the tower can easily be disassembled into smaller modules.

Additional supported research

Following the success of the Hexcrete tower concept and the completion of critical connection tests, a multidisciplinary project team secured a grant for tall wind-turbine towers and additional funding to advance the technology and get it ready for commercial use.

As part of this effort, Hexcrete towers are being designed for hub heights of 394 and 459 ft (120 and 140 m) with different turbine sizes, demonstrating the versatility of the Hexcrete towers. The cost-effectiveness of combining the Hexcrete technology with a steel tubular tower segment has also been investigated. The project team is evaluating the competitive advantage of the Hexcrete tower technology at hub heights of 394 and 459 ft (120 and 140 m) by calculating LCOE and comparing it with those established for other tower technologies.

Multiple options for a 394 ft (120 m) tall Hexcrete tower to support a 2.3 MW turbine with a 354 ft (108 m) rotor diameter have been completed. This turbine was designed with a 269 ft (82 m) rotor in 2004, and the increase in tower height and blade-technology advancements have increased the rotor diameter to 394 ft (120 m) in 2015, more than doubling the swept area. The optimal design chosen for the 394 ft (120 m) tall Hexcrete tower uses HSC columns and UHPC panels with the column-to-panel connections relying on horizontal posttensioning. Different assembly options were explored, and two possible solutions were derived (**Fig. 5**).

One is to assemble the Hexcrete tower using eight cells to reach ⅔ of the tower height and use a steel tube for the top third of the tower. The second option is to use 11 Hexcrete cells for the entire tower height. An animation of the assembly options can be found at https://youtu.be/XizC5spy3mg. Considering the cranes available today, minimizing their rental costs dictated the number and size of tower cells and the erection sequence. Engineering and erection drawings for the first option have been produced and will be made public after they are approved for release. The LCOE for the first option has a slight advantage over the second option of using Hexcrete cells for the entire height, which can change as more towers are built and innovative erection techniques are used in the field. A preliminary evaluation shows that LCOEs of both Hexcrete tower options are more competitive than using an 80 m (263 ft) tall steel tubular tower to produce wind energy for a generic site.

Also included in the ongoing projects are two sets of large-scale tests. A full-scale Hexcrete cell, which would be located near the top of a 394 ft (120 m) tall tower, has been assembled and subjected to a variety of loads representing operational, extreme, and ultimate limit states (**Fig. 6**). The main purpose is to evaluate the connection performance and verify the ability of the Hexcrete cell assembled using several precast concrete modules to act as a whole in transferring the turbine loads, which include significant torsion. Application of various load combinations representing the operational and extreme loads saw the tower segment successfully transfer the loads without experiencing any damage. Additional displacement-controlled tests were performed to characterize the failure mechanism of this test unit. During this phase of testing, the Hexcrete cell exhibited ductile response with damage largely limited to spalling of cover concrete in HSC members while continuing to support the axial load simulating the weight of the turbine and rotor. The second test is evaluating the fatigue resistance of the members and connections.

The next phase of the project will focus on the design of 459 ft (140 m) tall Hexcrete towers to support 2.3 and 3.2 MW turbines. This will be completed along with the development of a commercialization plan needed for introducing transformative changes to the wind-energy industry. There will be opportunities for the wind-energy and precast concrete industries to learn about the project outcomes as part of the next phase of the project and contribute to the commercialization plan. PCI members interested in participating in this activity may sign up at the project website at http://sri.cce.iastate.edu/hexcrete/, which also provides additional information and regular updates on project progress.

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About the author

Sri Sritharan is the Grace Miller Wilson and T. A. Wilson Endowed Engineering Professor at the Department of Civil, Construction, and Environmental Engineering at Iowa State University in Ames, Iowa.

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