Hexcrete Tower for Harvesting Wind Energy at Taller Hub Heights – Budget Period 2

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Executive Summary

Interest in designing taller towers for wind energy production in the United States (U.S.) has been steadily growing. In May 2015, it was revealed that taller towers will make wind energy production a reality in all 50 states, including some states that have nearly zero renewables in their energy portfolio. Facilitating wind energy production feasibility in all 50 states will no doubt contribute to increasing the electricity produced by wind from 4.5% in 2013 to a targeted scenario of 35% by 2050 in the Wind Vision report.

This project focuses on the Hexcrete tower concept developed for tall towers using High Strength Concrete (HSC) and/or Ultra-High Performance Concrete (UHPC). Among other benefits, the Hexcrete concept overcomes transportation and logistical challenges, thus facilitating construction of towers with hub heights of 100-m (328-ft) and higher. The goal of this project is to facilitate widespread deployment of Hexcrete towers for harvesting wind energy at 120 to 140-m (394 to 459-ft) hub heights and reduce the Levelized Cost of Energy (LCOE) of wind energy production in the U.S. The technical scope of the project includes detailed design and optimization of at least three wind turbine towers using the Hexcrete concept together with experimental validation and LCOE analyses and development of a commercialization plan.

This report summarizes the progress of research made during Budget Period 2 (BP2), which is from November 2015 to November 30, 2016. A more detailed report was submitted to the Department of Energy along with a separate report at the end of BP1, which focused on 120-m (394-ft) tall towers. Within BP2, the focus was to further advance the Hexcrete tower technology through implementation of new 140-m (459-ft) tall tower designs, optimization of the tall tower erection and construction processes, and the development of an implementation plan to commercialize the new tower technology. The project goal and the key outcomes of various tasks of this effort are summarized below:

- The Hexcrete tower design for this period focused on creating multiple options for a 140-m (459-ft) tall tower with Siemens' 2.3 MW and 3.2 MW turbines. The goal was to help establish a tower design that would minimize the LCOE while reliably and safely harvesting energy at a 140-m (459-ft) tall hub height. (A preliminary 120-m (394-ft) tall tower design for the 3.2 MW turbine and an 80-m (263-ft) tall Hexcrete tower to support a 2.3 MW turbine were also generated, but they were not included in the final tower design process). The different tower

designs were studied by the Siemens Optimization Group to assist in determining the final tower design geometries while high fidelity fluid structure simulations were performed to verify the loads experienced by the tower system with a new cross sectional shape. Both of these tasks contributed to the final design of towers. In addition, further iteration to the tower details were accomplished through a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis workshop involving various industry experts. In this workshop adequate design, construction, assembly, and erection processes were identified prior to arriving at the final solution for the 140-m (459-ft) tall towers designated as HT2 (2.3 MW turbine) and HT3a (3.2 MW turbine). The final HT2 and HT3a tower designs were then completed for both full concrete and concrete/steel hybrid tower systems; the hybrid option was motivated by reducing the assembly time, thus reducing the LCOE. An animation showing the HT3a tower assembly based on the industry input can be found at: https://youtu.be/2bKn9rtjLS0.

- The goal of the tower optimization was to explore variations of the HT2 and HT3a designs in order to realize the impact on LCOE while ensuring structural integrity and performance. The modular nature of the Hexcrete tower concept enables options to refine the design parameters such as the tower base diameter and individual member sizes—a unique feature of the Hexcrete technology. The optimization of the HT2 and HT3a towers was performed by successfully implementing an integrated tool that automatically generated Hexcrete tower CAD models, performed FEA simulation, calculated tower cost, evaluated constraints and performed optimization of the Hexcrete towers to minimize their costs. Tower diameters, column diameters and the number of post-tensioning strands were included as design variables, while upper and lower bound tower geometry, tower frequency, and deflection were used as constraints. Employing parallel computing to increase the speed of the optimization, the established framework was used to optimize both the HT2 and HT3a designs with the use of genetic algorithms and optimal designs were obtained for both towers. Comparing the optimal designs with the initial designs, tower cost reduction (1.3% for HT2 and 6.0% for HT3a) was obtained. The tower diameters did not deviate much from the initial designs. However, for both HT2 and HT3a, column diameters were reduced after the optimization.
- Shallow foundations were designed for the HT2 and HT3a towers with diameters of 26-m (85-ft) and 29-m (95-ft), respectively. The design process has involved five phases of analysis: 1)

foundation stability and ultimate strength; 2) concrete cracking; 3) foundation lift-off; 4) fatigue failure; and 5) foundation stiffness check. A MathCad program was developed for the five phases of analysis and the dimensions and reinforcement of the foundations were finalized by manual iteration of key parameters in the program. To study the soil-foundation interaction, a sophisticated 3-D finite element model was developed with an elastoplastic soil constitutive model and a soil-foundation interface to better capture the soil and foundation responses. The finite element simulations demonstrated that both foundations had sufficient bearing, overturning capacity, and stiffness and can ensure operability of the two towers for a 20-year service life.

- NREL and ISU determined LCOE estimates for six scenarios: 1) an 80-m (262-ft) conventional steel tower for a 3.2 MW turbine, which was used as a baseline for comparison; 2) a 140-m (459-ft) conventional steel tower for a 3.2 MW turbine; 3) a hybrid HT2 140-m (459 ft) tower for a Siemens 2.3 MW turbine, which included a standard steel tower top section; 4) a full concrete HT2 tower; 5) a hybrid HT3a 140-m (459 ft) for a Siemens 3.2 MW turbine, which also included a standard steel tower top section; and 6) a full concrete HT3a tower. The analysis results show that the LCOE for the HT3a hybrid 140-m tower is 20% lower than the LCOE of a conventional 80-m (262-ft) steel tower with a 3.2 MW turbine. In comparison to the LCOE for a 140-m conventional rolled steel tower with a 3.2 MW turbine, the HT3a hybrid tower LCOE is 6% lower. Given that the winning power purchase agreements today are decided based on differences in LCOE of less than 1%, these reductions are significant. Furthermore, the tower costs in LCOE for the Hexcrete towers were estimated in detail using a bottom-up approach with input from industry. However, the 140-m (459-ft) tall steel tower cost was obtained from a top-down approach using available models. Therefore, it is likely that real cost of a 140-m (459-ft) tall steel tower and the corresponding LCOE will go up. Nonetheless, calculated LCOEs show that the Hexcrete technology is competitive against steel tower technologies at tall hub heights placed in wind sites with high wind shear characteristics. The project team expects that the LCOE of wind farms utilizing the Hexcrete technology will continue to reduce following prototyping and broader use of this new technology.
- Developing a solid implementation plan was an important task of this project so that the Hexcrete tower technology can be successfully commercialized. To this end, from the start of

the project key industry partners were identified and engaged in various project activities. They represent foundation, prestressing and precast companies, material suppliers, wind farm developers, turbine manufacturers, crane specialists, wind farm contractors and tower design engineers. Their input during the design and formulation of the tower erection plan has been very crucial and most of their concerns have been already addressed in tower design. Moving forward, the research team and the industry partners have agreed to form a Joint Industry Partnership (JIP), which will be responsible for accomplishing new milestones, thereby helping to commercialize the Hexcrete tower technology. The JIP will be open to any industry partners as long as they can comply with its membership agreement terms and conditions, which are currently being formulated. In comparison to other existing tall tower technologies, potential JIP members appreciate the unique features of the Hexcrete tower technology. Two strategies for prototyping Hexcrete have been planned. The first strategy is to build a 20-m (66-ft) Hexcrete segment as an extension to a tower foundation and support an 80-m (263-ft) steel tower on top. This could be done in the Midwest. The second option would target a 120-m (394-ft) tall tower in a new wind region (e.g., Southeast). For both options, business cases will also be developed to guide the wind industry.

Technical Report for Budget Period 2

Chapter 1 - Summary of Budget Period 1

1.1 Introduction

The Hexcrete Tall Tower Project was completed in two phases corresponding to predefined budget periods with an overall goal of facilitating widespread deployment of Hexcrete technology for taller wind turbine towers. To overcome transportation and other logistics and offer design flexibility, the Hexcrete technology uses prefabricated components made from High Strength Concrete (HSC) and/or Ultra High Performance Concrete (UHPC). Figure 1 summarizes the technical scope, objectives and tasks of this project. The Budget Period 1 (BP1) report was previously submitted to the Department of Energy (DOE) for review and approval, which included technical information regarding the following tasks:

- Design and optimize a Hexcrete tower (i.e. HT1) and foundation with a hub height of 120 m (394 ft) to support a Siemens SWT-2.3 MW turbine (Tasks 1 – 4)
- Provide experimental validation of the Hexcrete tower concept (Task 5-6)
- Perform LCOE analysis for HT1 (Task 7)

The objectives of BP1 were clearly achieved and the outcomes are summarized in the following sections to provide background to the BP2 report.

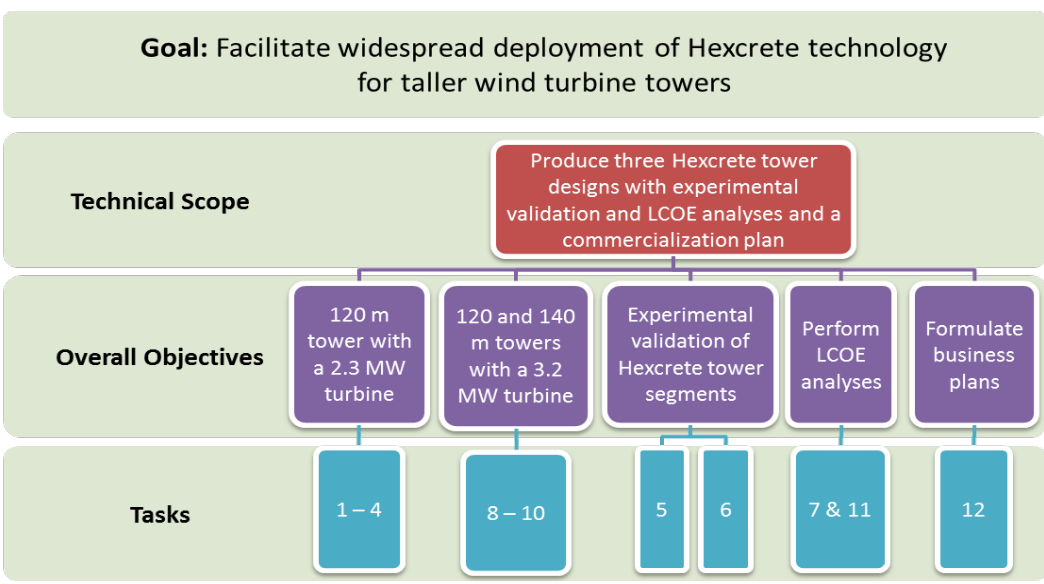


Figure 1.1. The overall plan proposed for Hexcrete tall tower project

1.2 HT1 tower and foundation design

The first phase of design for the Hexcrete tower focused on creating multiple design options for a 120 m (394 ft) tower with a Siemens 2.3 MW turbine. The goal was to provide a tower design that lowers the LCOE while reliably harvesting energy at 120 m hub height. The implemented tower design process, outlined in Figure 1.2, resulted in four different designs based on loads and design parameters provided by Siemens. The different selections were then studied by the Siemens Optimization group to arrive at the final tower design. The optimization process included creation of a parametric CAD model to perform finite element analysis of the tower (Figure 1.3) as well as development of an optimization framework incorporating simulation models and cost refinement calculators. The optimization results indicated a linear proportional relationship between material costs and variations of HT1 base diameter while structural characteristics remained suitable for the entire range of the base diameter. Therefore, reducing the base diameter of the final design did allow for reduction in material costs without a significant impact on the structure. It was realized that adding features, such as the variation in assembly costs, may change the relationship between the cost and base diameter and produce different outcomes. This is further investigated with tower designs planned for BP2.

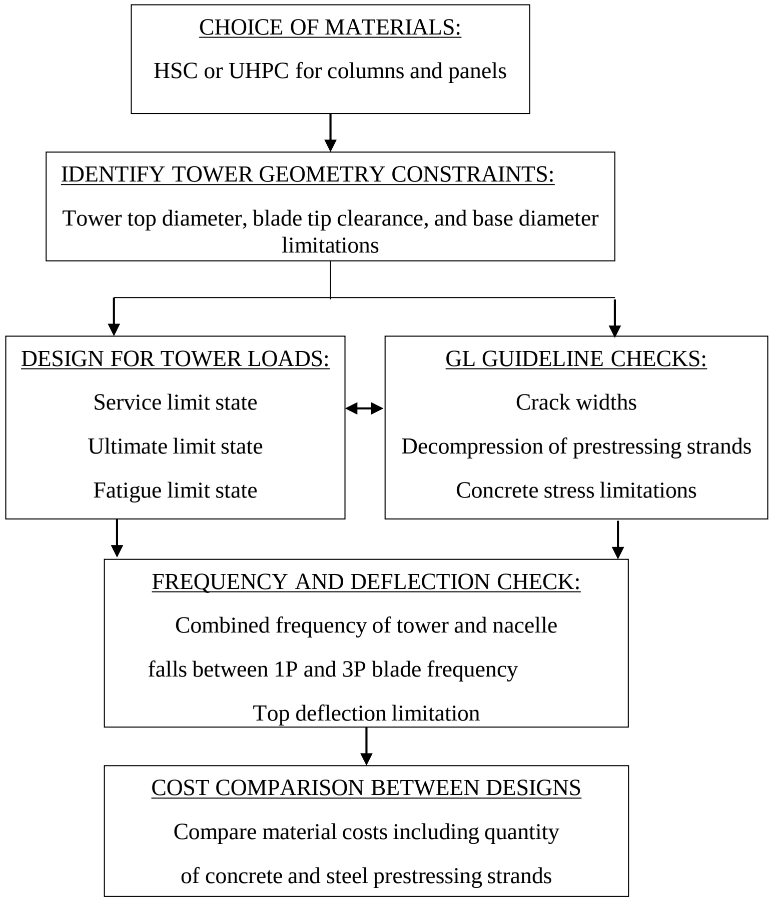
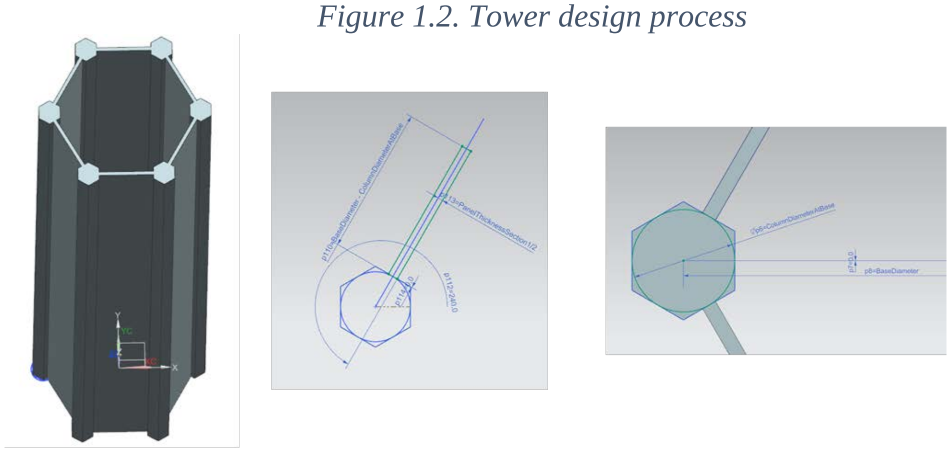


Figure 1.2. Tower design process



(a) (b) (c)

Figure 1.3. Parametric CAD model: (a) Example tower section (b and c) Design parameters encoded in CAD model

Upon completion of optimization, details of the final design were further iterated with input from industry partners. A one-day workshop and follow-up discussion resulted in two options for constructing the HT1 design. The first option (Option 1) considered combining the first 79.3 m (260 ft) of the HT1 design with a 38.1 m (125 ft) steel tube to form a hybrid tower system. The hybrid tower was developed to minimize the number of lifts performed by the largest crane required onsite. The first 79.3 m (260 ft) of concrete would be constructed by a smaller crane and the steel tube section, nacelle, and rotor would be placed by the larger crane. The limited number of lifts for the larger crane would reduce the onsite equipment cost. The second tower option (Option 2) was completely constructed out of HSC and UHPC.

For design of the HT1 foundation, comparisons between shallow and deep foundations were carried out to select the most appropriate foundation type. With input from industry, a shallow foundation was found to be a better solution due to lower risk, higher certainty, and easier construction than a deep foundation. The resulting foundation was a reinforced, cast-in-place concrete slab, which was designed for overturning moment demands, tower weights, and generic soil properties in order to prevent tilting, bearing capacity failure, sliding, buoyancy, and settlement of the soil. No uplift was allowed during any combination of normal operating loads, and the foundation was designed to ensure operability for a 20-year service life. The final shallow foundation was dodecagonal in shape with twelve 7.26-m (23.8 ft) long sides, a diameter of 27.1 m (88.9 ft), a thickness of 1.85 m (6.1 ft) in the middle and 0.71 m (2.3 ft) on the edge, and a 1.2-m (3.9 ft) pedestal. It utilized precast trenches to access the bottom of each column at the base of the tower to complete the vertical post-tensioning. The detailed design of the foundation was completed by BergerABAM.

1.3 Experimental evaluation of Hexcrete tower concept

A proof test of a full-scale Hexcrete tower cell was designed and fabricated to validate the tower design process and the ability of a single Hexcrete unit to act as a composite system. Another goal of the test was to obtain further insight into the response of the tower when subjected to operational, extreme, and ultimate loads and evaluate the ductility capacity of the cell. The test unit was designed as a full-scale section of the HT1 tower and was constructed at the Multi-Axial Subassemblage Testing (MAST) Laboratory in Minneapolis, Minnesota (Figure 1.4). During testing, the test unit was subject to operational and extreme loads corresponding to specific turbine loading conditions. The test unit experienced minimal cracking after the completion of operational loads and minor cracking under extreme loads. The majority of the cracking occurred on the flat wall panels, which received the lowest post-tensioning effect. This situation occurred due the assembly requirement with the indoor space of the laboratory. Nevertheless, the stiffness of the test unit continued to be linear with no decrease in strength as shown in Figure 1.5 and Figure 1.6. For both operational and extreme loads, all the cracks closed completely when the loads were removed from the test unit and no further damage to the test unit was observed.

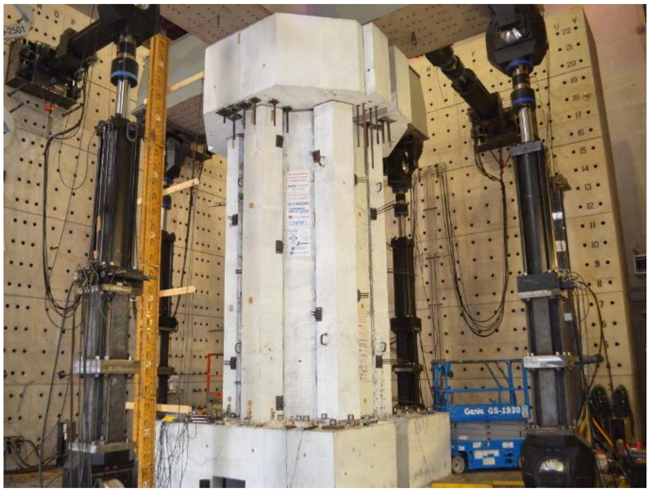


Figure 1.4. Completed full-scale Hexcrete test unit

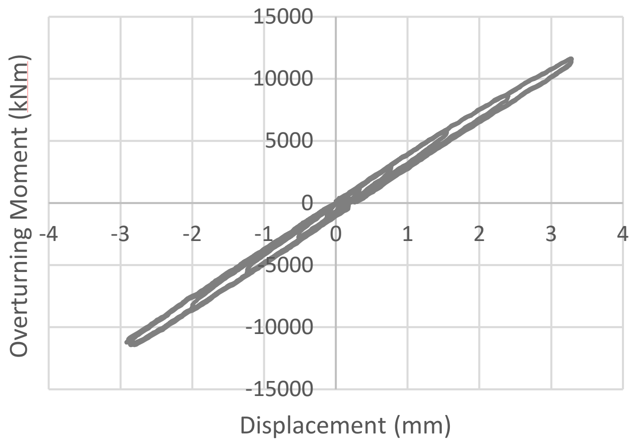


Figure 1.5. Lateral stiffness response of test unit under extreme load

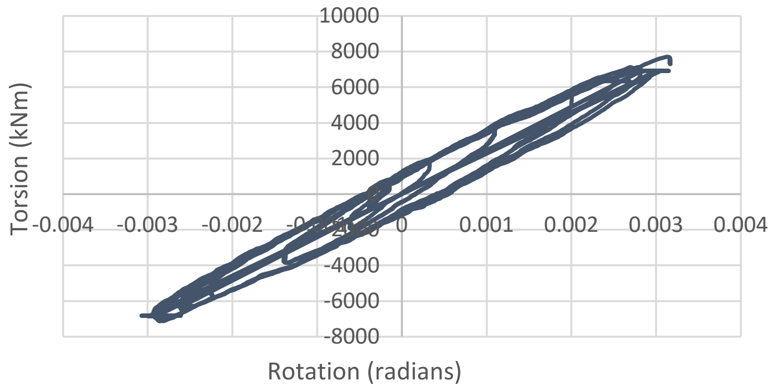


Figure 1.6. Torsional stiffness response of test unit under extreme load

The next step in the testing process was to quantify the capacity of the test unit beyond extreme loads and assess its ductility capacity. The test unit was gradually overloaded by applying large displacements in both the torsional and lateral directions. Cracking of the test unit progressed steadily as torsional displacement increased beyond one degree of rotation (one degree of rotation was five times the rotational displacement for extreme torsional loading). At four degrees of rotation, spalling had occurred on the test unit columns and the test was terminated due to damage to the foundation blocks which made continuation of testing potentially unsafe. The progression of damage to the test unit during overloading is shown in Figure 1.7 while Figure 1.8 shows the tower rotational displacement response. Much of the damage to the test unit was spalling of cover concrete, which protects the steel reinforcement from corrosion. The cover concrete does not significantly affect the structural capacity of the test unit and the unit was still able to support the axial load simulating the weight of the nacelle and rotor after the completion of testing. The overloading response of the test unit demonstrated that the tower had sufficient ductility beyond extreme loads as well as a fair amount of additional load capacity. The testing validated the tower design process and demonstrated that the assembled precast pieces would act as a single unit to resist both operational and extreme loads.

Figure 1.7. Damage progression of test unit under large displacement loading

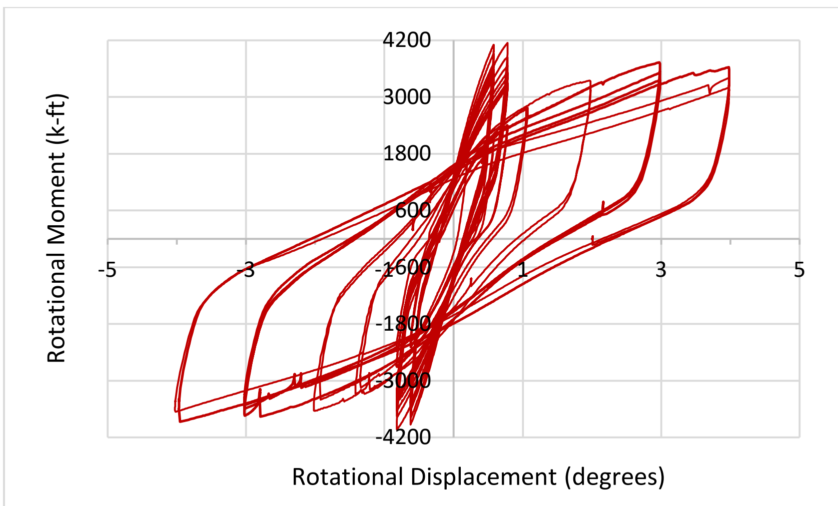


Figure 1.8. Torsional stiffness of test unit under large displacement loading

To test the fatigue resistance of UHPC columns, HSC columns, UHPC panels, and HSC panels, as well as the column-to column and column-to-panel connections used in Hexcrete tower system, a column-panel-column section was designed based on the HT1 tower. In-plane operational loads that created representative fatigue stresses within concrete members and connection interfaces were used to simulate the expected fatigue behavior during the service life of the tower. The test unit was assembled in the ISU laboratory and equipped with strain gages, displacement transducers, and accelerometers to measure its responses (Figure 1.9). The top half of the unit was made from UHPC material and the bottom half used HSC. Typically, wind turbine towers undergo several million fatigue cycles, but the laboratory evaluations are typically done for two million cycles. Therefore, the fatigue test of Hexcrete specimen was subjected to two million fatigue cycles under its operational load condition resulting from a lateral load of 444.8 kN (100 kips) at a frequency of 0.8 Hz. After every 250,000 cycles, the test was paused to inspect the condition of the test unit and connections and to perform a static load evaluation. The performance of the test unit was excellent and showed that the fatigue damage to the connections, interface materials, or structural members was insignificant as indicated by measured strains and deflections. The overall stiffness of the test unit showed a variation of less than 4%. The load was then raised to 556.0 kN (125 kips) and a further 200,000 load cycles were applied at a frequency of 0.6 Hz. Based on the observed performance of the test unit under operational and higher loads, it was determined that the amount of total force in the horizontal strands could be somewhat reduced without increasing the fatigue damage. When the lateral displacements were examined, the maximum and minimum displacements remained constant as the load increased from 22 kN to 556 kN (5 to 125 kips) and a similar linear load-displacement relation was obtained after 2.2 million load cycles. During the 200,000 cycles performed at 0.6 Hz, hairline cracks were formed at the uppermost region of the UHPC panel. However, the cracks only opened up in tension and had little effect on the total system response; the test components and connections did not experience significant damage through the duration of service and extreme loading. At the end of 2.2 million cycles, the test unit was then overloaded to a maximum value of 689.5 kN (155 kips) in the positive and negative direction to investigate the adequacy of the connections at the overload limit state. It was observed that grout pads underneath the columns remained undamaged, and the epoxy interface between columns and panel stayed intact, suggesting that the connections were still effective throughout the entire test.

Figure 1.9. Completed fatigue test unit at ISU

1.4 LCOE Analysis for HT1

To accurately estimate the Levelized Cost of Energy (LCOE) for BP1 of the project, National Renewable Energy Laboratory (NREL) provided ISU with LCOE model and estimates for different tower configurations placed at a generic wind site that has a representative wind condition in the southeastern area of the U.S. The tower configurations included an 80-m (262-ft) steel tower and a 120-m (394-ft) Hexcrete tower. NREL provided support in two key areas: 1) estimating LCOE for the different scenarios; and 2) design and cost estimate of 80-m (262-ft) rolled steel tower. To estimate the LCOE of a wind turbine, a collection of operating systems must be considered. Costs of all the components of the operating system contribute to the calculation of LCOE, together with a number of assembly and erection costs in the construction process. Table 1.1 gives a cost breakdown of wind turbine components that were included in the LCOE computation.

Table 1.1. Cost breakdown of wind turbine components

Major component cost	*Cost required for specific Items*
Rotor	Blade Hub Total pitch mechanism and Bearings Spinner
Drive train, nacelle	Low-speed shaft Main bearing Gearbox Mechanical brake, high speed coupling and associated components Generator Variable-speed electronics Yaw drive and bearing Main frame Electrical connections Hydraulic, cooling system Nacelle cover
Control, safety system	Microprocessor, necessary sensors, housing and interface equipment
Tower components and foundation	Foundation Shop fabrication of concrete modules Connection elements Tower erection and post-tensioning of precast concrete tower Fabrication and installation of access ladders and platforms Interior and exterior surface paint as needed
Site preparation	Access road and civil work; site office and office equipment

Mobilization, assembly and installation	Assemble pedestal cranes Mobilize and demobilize cranes Erection and assembly of precast concrete sections Erection of turbine nacelle Erection of hub and blades Allowance for erection equipment and small cranes
Balance of station (BOS)	Electrical interface & connections Communication system Engineering & permits
Operation and maintenance	Land lease Levelized replacement Operating expense
Overhead and profit	Administration overhead field overhead profit

From Table 1.1, two categories were more thoroughly examined by ISU to calculate the difference in LCOE between traditional rolled steel towers and Hexcrete towers. These two categories were the tower components and foundation as well as mobilization, assembly, and installation costs. With input from industry experts, the two design options for Hexcrete towers were evaluated with considerations to detailed assembly plan and schedule. As stated previously, Option 1 was the hybrid tower and Option 2 was a full Hexcrete tower. Specific variables affecting the cost of the evaluated components included material costs, work sequences, production rates, and workflow scheduling. The overall estimated cost breakdowns for each tower are provided in Table 1.2 and Table 1.3. The cost differential was evaluated for each crew and each activity that differed from the 80 m (262 ft) steel to the 120 (394 ft) m Hexcrete assembly process, and both Option 1 and Option 2 were determined to be technically and financially feasible.

The ISU research team then applied Value Engineering (VE) principles to identify work items that may reduce the capital cost even further. Experienced wind farm construction experts were consulted to identify items for the VE process. These items included potential savings through labor and equipment efficiency, discounts on bulk ordering of materials, and cost savings from reduced steel reinforcement in the final foundation design. After completion of the VE process, NREL cost models were utilized to estimate the cost of the other categories in Table 1.1 that were not examined by ISU. A summary of the overall LCOE for both options (including all Table 1.1 categories) is shown in Table 1.4. When all components were added, the LCOE of Hexcrete tower (Option 1) resulted in 8.3% lower value than that obtained for the 80 m (262 ft) rolled steel tower . This confirmed that the Hexcrete technology is competitive for tall hub heights (e.g., 120 m [394 ft]) placed in wind sites with high wind shear characteristics.

Table 1.2. Cost estimate breakdown for Option 1

Component	**80 m steel tower**	**120 m Hexcrete tower**
Foundation	$102, 746	$319,478
Fabrication and Transportation	$765,000	$700,000
Assembly	$15,750	$387,800
Total cost difference per WTG		$523,782

Table 1.3. Cost estimate breakdown Option 2

Component	**80 m steel tower**	**120 m Hexcrete tower**
Foundation	$102, 746	$319,478
Fabrication and Transportation	$765,000	$610,000
Assembly	$15,750	$568,475
Total cost difference per WTG		$614,457

Table 1.4. Summary of LCOE for BP1 with respect to 80 m (263 ft) steel tower

Cost	120 m Hexcrete Tower Options		
	Option	Percent Change Without Value Eng. (%)	Percent Change With Value. Eng. (%)
Turbine Capital Cost (TUR_{CC})	#1	-11.1	-13.7
	#2	-13.7	-17.0
Balance of System Capital Cost (BOS_{CC})	#1	38.4	21.6
	#2	56.2	35.1
Financial Capital Cost (FIN_{CC})	#1	0.0	-5.41
	#2	2.70	-5.41
Operations and Maintenance (O&M) [pre-tax]	#1	-17.6	-17.6
	#2	-17.6	-17.6
LCOE	#1	**-3.68**	**-8.33**
	#2	**-2.28**	**-7.89**

1.5 Conclusion

In BP1, the overall objective was to explore the design of Hexcrete tower to support a 2.3 MW Siemens turbine with the goal of minimizing the LCOE while ensuring structurally sound design. This objective was accomplished by producing an optimized HT1 design including FSI computations, performing successful full-scale system and fatigue laboratory tests, and collaborating with NREL and industry experts to produce a realistic and accurate LCOE analysis. Furthermore, the LCOE analysis of the Hexcrete tower system was found to be competitive with current rolled steel tower technology used for an 80 m hub height, making the Hexcrete tower an attractive solution for tall towers with hub height of 120 m (394 ft). Also, after completing the LCOE analysis for BP1, NREL expected that the LCOE reductions using Hexcrete technology will become more significant as the Hexcrete tower is further developed and optimized for the 140-m (459-ft) tower analysis in BP2.

Chapter 2 - Summary of Budget Period 2

2.1 Introduction

The Hexcrete tower concept was developed to revolutionize wind turbine towers for hub heights of 100 m (328 ft) and taller in order to realize the benefits of tall wind. These benefits include: 1) accessing high wind speeds and steadier wind conditions; 2) increasing wind energy production time; 3) leveraging opportunities to harvest energy in regions of the U.S. where favorable wind conditions exist only above 100 m (328 ft) and demands for electricity are relatively high (Figure 2.1). The combination of these factors has the potential to reduce the cost of wind energy and allow it to be competitive with other energy sources in all 50 states (U.S. Department of Energy, 2015). The research first determined the basic challenges of taller hub heights that must be overcome, emphasizing the opportunities to engage the local work force, increasing manufacturing in the U.S. and relying on easily accessible construction materials to reduce production and transportation costs while avoiding construction delays (Lewin & Sritharan, 2010). Through this research it became clear that a transformative tower technology was needed to harvest wind energy at higher hub elevations; incremental advancements to existing concepts (e.g. steel lattice and shell towers) would not be competitive for tall towers as outlined by an independent European study (Engstrom, Lyrner, Hassanzadeh, Stalin, & Johansson, 2010).

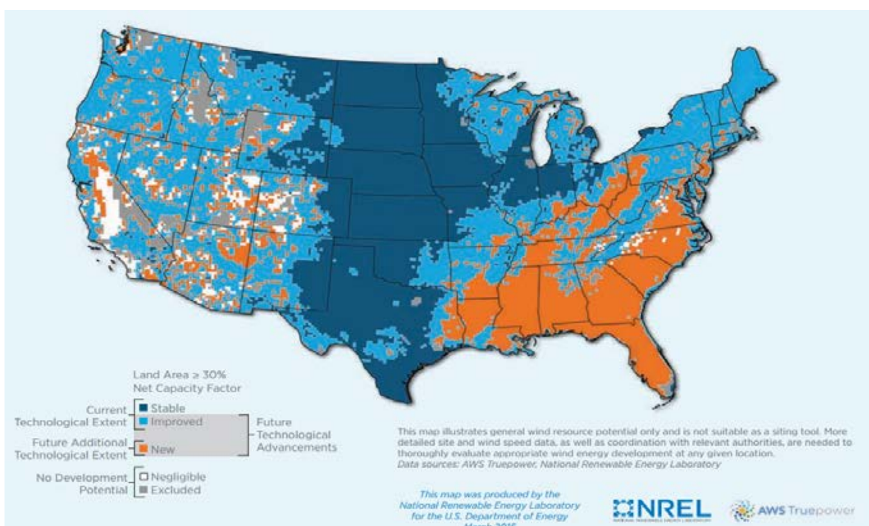


Figure 2.1. Improved and new wind capacity due to 140-m hub heights (U.S. Department of Energy, 2015)

Steel tubular towers, with a hub height of 80 m (263 ft) and base diameter of 4.1 m (13.5 ft), currently dominate the utility scale wind tower market. The transportation of these towers requires consideration for specialized trailers and logistics and has periodically created challenges (Figure 2.2). For a 100 m (328 ft) steel tubular tower, the base diameter expands to 5.5 m (18 ft) to accommodate the higher hub height with the volume of steel increasing by two fold; alternatively, the base diameter can be constrained to 4.1 m (13.5) with an increase in shell thickness but use of thick wall thickness would create manufacturing and fatigue challenges (Lewin & Sritharan, 2010). For the larger base 100 m tower (328 ft), the base must be segmented for transportation resulting in larger installation costs and increased quality control for vertical seam field connections. While these changes can be overcome, the current available solutions are cost inhibitive. Precast concrete shell towers have been introduced in Europe to solve this issue by big companies, but have not yet gained traction in the United States due to the specialty precast forms required to fabricate curved sections. Unlike Europe, the precast industry is well distributed across the U.S., and many are small businesses that would not be able to afford to invest in specialized concrete formwork. Furthermore, the large land area of the U.S. and widespread presence of precast fabricators should enable the engagement of plants and workforce located within 200 miles (322 km) of the wind farms. This attribute would not only benefit the local communities but would also contribute to reducing the cost of energy.

Figure 2.2. Challenge in transport of traditional steel tubular towers (Sun Journal, 2012)

As a result of the wind energy growth in Iowa, together with the stated tall tower limitations, development of the Hexcrete tower began at Iowa State University (ISU) in 2008. The first two phases of development were completed in 2010 (Lewin & Sritharan, 2010) and 2013

(Schmitz, 2013), respectively and resulted in the current Hexcrete tower concept along with the first generation of Hexcrete tower designs for 100 m (328 ft) hub heights. The Hexcrete tower concept is a hexagon shaped concrete tower made up of six hexagonal columns and six wall panels as shown in Figure 2.3. All the precast concrete pieces are flat sided, allowing for simple formwork and are also modular, providing easily repeatable manufacturing processes. The towers utilize a combination of Ultra-High Performance Concrete (UHPC) with a compressive strength of 180 MPa (26 ksi) and High Strength Concrete (HSC) with a compressive strength of 90 MPa (13 ksi). The Hexcrete tower design is also customizable with regard to the length of prefabricated members allowing for optimization of transportation and erection costs. Assembly of the tower will occur onsite at the wind farm; therefore, laboratory connection testing was conducted during the second phase of research to investigate suitable precast connection details. The findings of the connection tests resulted in the selection of post-tensioned connections utilizing seven wire 1860 MPa (270 ksi) low relaxation unbonded tendons. The Hexcrete tower technology was then patented by Iowa State University after completion of the first generation tower designs ((U.S. Patent No. 9,016,012, 2015), (U.S. Patent No. 8,881,485, 2014).

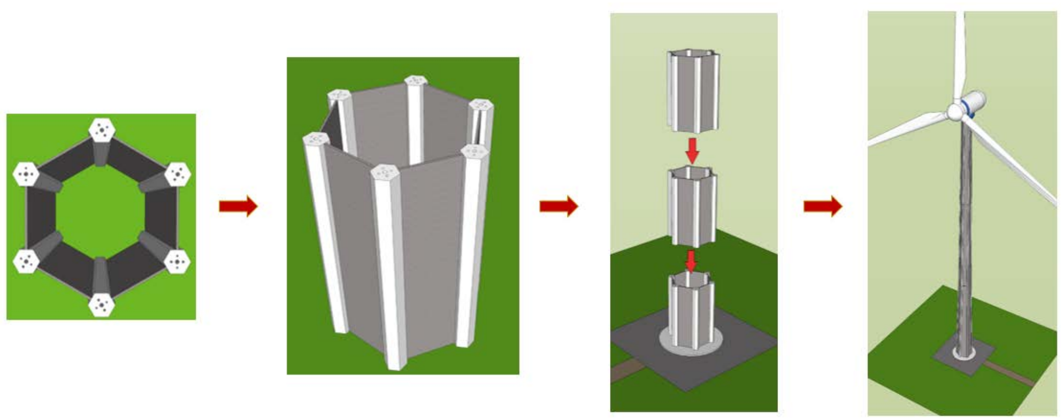


Figure 2.3. Hexcrete tower concept

In 2014, the third phase of Hexcrete tower research began with financial support from the U.S. Department of Energy (DOE), Iowa Energy Center, and LaFarge North America. Budget period one of this phase pushed the tower hub heights to 120 m (394 ft) by working directly with Siemens Wind Power Group and other industry partners to design a tower and foundation for the Siemens 2.3 MW-108 m (354 ft) rotor turbine through processes outlined in the previous chapter. This rigorous investigation resulted in robust a Hexcrete tower design along with an additional hybrid tower designs consisting of Hexcrete and existing tubular steel shells. An erection plan for this tower was developed with industry input, leading to competitive Levelized Cost of Energy (LCOE).

In the second budget period of research the goal was to further advance the Hexcrete tower technology through implementation of new 140 m (459 ft) tall tower designs, optimization of the tall tower erection and construction processes, and the development of an implementation plan so that commercialization of the Hexcrete technology can be realized. These advancements are expected to facilitate the widespread deployment of Hexcrete towers for harvesting wind energy at 120 to 140 meter (m) (394 to 459 ft) hub heights, reduce Levelized Cost of Energy (LCOE) of wind power in the United States (U.S), and increase the market penetration of wind energy to new regions in the country.

2.2 Goals and Objectives

The project goal was to be achieved in BP2 by accomplishing three overall objectives and the corresponding tasks previously detailed in Figure 1.1. These objectives are described below:

1) Design and optimize two Hexcrete towers (i.e., HT2 and HT3a) and foundations with hub heights of 140 m (459 ft) to support Siemens SWT 2.3 MW and Siemens 3.2 MW turbines. During the project, this objective was expanded to include an additional preliminary design (HT3b) for a 120 m (394 ft) tower with a Siemens 3.2 MW turbine (tower and foundation drawings will not be provided). (Tasks 8-10).
2) Perform LCOE analysis for the HT2 and HT3a towers and directly compare with the values obtained for HT1 as well as 80 m (262 ft) and 140 m (459 ft) conventional steel towers. (Task 11)
3) Formulate an implemental plan to commercialize the Hexcrete tower technology. (Task 12)

Each of the towers was designed and optimized with consideration to: a) completely eliminating the transportation and logistical challenges; b) potential benefits in mixing the Hexcrete technology with steel tubular shells to form a hybrid option; c) integrating shallow foundations and developing an erection to plan using currently available technologies; and d) lowering LCOE.

2.3 Report Organization

This report contains nine chapters resulting from collaboration with research partners from a broad range of industries and expertise. Chapter 1 and Chapter 2 contain an overview of budget period one research as well as a summary of the objectives and tasks for budget period two, respectively. Chapter 3 provides design details for the HT2, HT3a, and HT3b towers produced by Dr. Sri Sritharan and the ISU structures group. Chapter 4 describes the tower design optimization process performed by Siemens Research Group. Chapter 5 details the foundation design of the HT2 and HT3a towers designed by the ISU structures group with input from Barr Engineering. Chapter 6 reports the Levelized Cost of Energy (LCOE) for both tower designs as a result of collaboration between staff members from the National Renewable Energy Laboratory (NREL) and the ISU cost estimating group directed by Dr. David Jeong with assistance from industry partners. Chapter 7 was formulated by Dr. Markus Wernli of BergerABAM in collaboration with the ISU research team and proposes a technology implementation plan, which includes a path to form a joint industry partnership (JIP) in order to achieve future milestones for the Hexcrete tower technology. Chapter 8 provides a summary of the project as well as conclusions and recommendations from the designated tasks. An animation showing erection of the 140-m (459) tall Hexcrete tower can be found online at: https://youtu.be/2bKn9rtjLS0.

Chapter 3 - Design of Tall Hexcrete Towers

3.1 Introduction

This chapter describes the structural design of two 140-m (459 ft) tall towers proposed for BP2. The first was for the Siemens 2.3 MW turbine and was labeled the HT2 tower. The second design, the HT3a tower, was for the Siemens 3.2 MW turbine. An additional preliminary design for a 120 m (394 ft) tower with a 3.2 MW turbine, designated as HT3b, was completed; however, as previously agreed upon with the DOE, the HT3b tower was not optimized due to project time constraints.

In the following sections, the tower design process used for HT2 and HT3a is described along with identification of design loads and preliminary tower dimensions. Tower improvements implemented for expedited construction and erection are described and discussion is provided concerning factors affecting tower optimization and load verification. The chapter concludes with the presentation of finalized dimensions for both the HT2 and HT3a towers.

3.2 Design Process

The design of the HT2 and HT3a towers followed the same design process previously outlined for 120-m HT1 in BP1 report, with the addition of an enhanced cost optimization performed by Siemens as well as Computational Fluid Dynamic (CFD) simulations performed for load magnitude verification by Iowa State University (ISU) (Figure 3.1). These two additions enabled improved design of the Hexcrete tower technology and provided further insight into methods available to streamline the design process. Detailed descriptions of both the optimization process and CFD analysis are provided in subsequent chapters with outcomes pertinent to the design process summarized in the following sections.

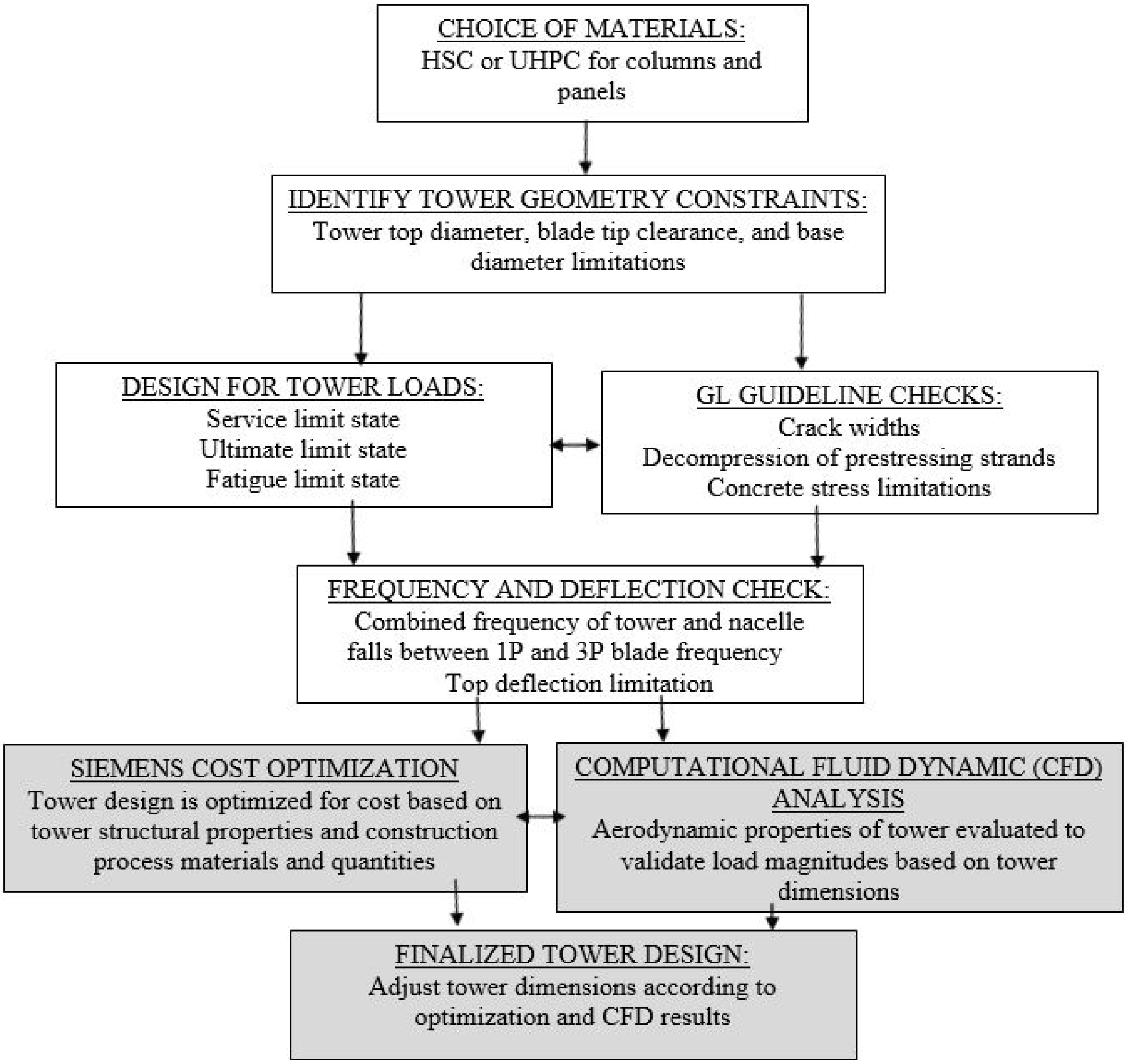


Figure 3.1. HT2 and HT3a design process; grey areas indicate additions to design process

3.3 Design Loads

Both the HT1 and HT2 towers were designed for a 2.3 MW turbine. Following completion of the design of the 120-m HT1 in BP1, loads for the 140-m HT2 tower were established through extrapolation in consultation with Siemens Wind Power. The HT3a tower was also 140 m (459 ft) tall, but designed for a 3.2 MW turbine. Therefore, the loads for HT3a were established by multiplying the loads of HT2 tower by scale factors found in the NREL WindPACT study SR-500-36777 “Evaluation of Design and Construction Approaches for Economical Hybrid/Steel

Concrete Wind Turbine Towers" (Lanier, 2005). The scale factors, which increased the magnitude of the loads from a 2.3 MW turbine with a 108-m (354-ft) diameter rotor to a 3.2 MW turbine with a 113-m (371-ft) diameter, are listed in Table 3.1. Upon completion of the preliminary HT3 design, the tower geometry details were sent to Siemens Wind Power Group for their validation study. The refined loads suggested for the towers were used to finalize the design.

Table 3.1. Scale factors used for translating turbine loads from 2.3 MW turbine to 3.2 MW turbine

Load Type	Scale Factor
Fx	1.3
Fy	1.3
Fz	1.6
Mx	1.45
My	1.45
Mz	1.45

Upon completion of the preliminary tower designs, a closer examination of tower fatigue loads using the *fib* Model Code was also performed for the HT2 and HT3a towers (Comite Euro-International Du Beton, 1990). Concrete normally performs very well under fatigue, but it is possible that the fatigue life of the Hexcrete tower columns could decrease due to the large compressive stresses generated by vertical post-tensioning. After examination of the column stress values, it was found that the magnitude of stress induced by the post-tensioning strands did slightly affect the overall fatigue life of each column. In order to ensure adequate fatigue life, the column size was marginally increased in order to limit the stress experienced by the concrete. The increase in column size did not significantly change the tower design or structural performance and was incorporated into the final dimensions presented in engineering drawings.

3.4 HT2 Tower Design

The preliminary design of the HT2 tower was completed by extrapolating the loads used for the HT1 tower from 120 m (394 ft) to 140 m (459 ft) and the load refinement task completed by Siemens Wind Power as mentioned previously. The dimensions and key structural properties used in the design are shown in Table 3.2 and in Figure 3.2). The overall base diameter of the tower increased from 7.84 m (25.7 ft) for HT1 to 8.5 m (27.9 ft) for HT2, which is a reasonable change in width due to the increase in hub height.

Table 3.2. HT2 Preliminary values of key structural properties used for HT2

Base Diameter	Frequency	Maximum Deflection at Service Load
8.50 m (27.9 ft)	0.266 Hz	0.64 m (2.10 ft)

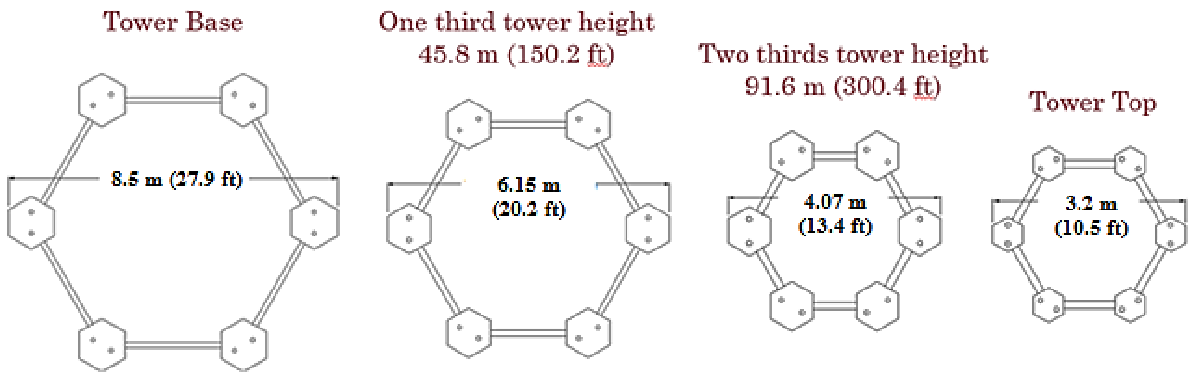


Figure 3.2. Preliminary dimension of HT2 tower at different elevation

The preliminary design of the HT2 tower was further optimized by the Siemens Research Group; the detailed process and results are summarized in a subsequent chapter of this report, but a summary of the results is shown in Table 3.3. The tower optimization process included simplified versions of the structural design equations, and did not include fatigue loads in order to streamline the optimization process (since fatigue loads only slightly change the column size of each design). Therefore, the capacity of the optimized design was rechecked by the Iowa State University (ISU) team to ensure structural reliability. After review of the optimized Siemens design, the number of strands was slightly increased to provide a small amount of additional tower capacity but no further changes were necessary to the optimized design. The difference in number of strands was due to the use of a simplified method (provided to Siemens by ISU) for estimation of the loss of prestress force in the tendons over time. This method provided accurate estimates of prestress losses for the majority of the tower; however, at the tower base, a lower prestress loss was estimated than what was indicated by the more detailed calculations utilized by ISU. This resulted in the need to add six additional strands per column. The improved HT2 design dimensions are presented in Table 3.4.

Table 3.3. Optimized HT2 tower dimensions

	Initial Design in meters (ft)	Optimized Design in meters (ft)
Tower base diameter	8.50 (27.88)	9.20 (30.11)
Tower top diameter	3.20 (10.50)	3.20 (10.50)
Base column diameter	1.02 (3.33)	1.05 (3.45)
Top column diameter	0.94 (3.09)	0.91 (3.00)
Strands per column	76	64
Max deflection	0.64 (2.10)	0.64 (2.10)
Frequency	0.266 Hz	0.268 Hz

Table 3.4. Improved HT2 following design optimization

	Initial Design in meters (ft)	**Improved Design in meters (ft)**	Optimized Design in meters (ft)
Tower base diameter	8.50 (27.88)	**9.20 (30.11)**	9.20 (30.11)
Tower top diameter	3.20 (10.50)	**3.20 (10.50)**	3.20 (10.50)
Base column diameter	1.02 (3.33)	**1.05 (3.45)**	1.05 (3.45)
Top column diameter	0.94 (3.09)	**0.91 (3.00)**	0.91 (3.00)
Strands per column	76	**70**	64
Max deflection	0.64 (2.10)	**0.64 (2.10)**	0.64 (2.10)
Frequency	0.266 Hz	**0.268 Hz**	0.268 Hz

3.5 HT3a Tower Design

The design of the HT3a tower was completed for a Siemens 3.2 MW turbine with a 113-m diameter rotor. The dimensions and key structural properties of the HT3a tower are given in Table 3.5 and Figure 3.3. Although the HT3a tower was the same height as the HT2 tower, the base diameter increased significantly from 8.5 m (27.9 ft) to 10.5 m (34.4 ft) due to the increase in turbine size. The scale factor for overturning moment, which is the driving load in determining tower base diameter, was calculated to be 1.45 (see Table 3.1) when scaling from a 2.3 MW turbine to a 3.2 MW turbine. This accounted for the large increase in diameter as well as a subsequent increase in vertical post-tensioning.

Table 3.5. Preliminary structural properties of HT3a tower

Base Diameter	Frequency	Max Deflection at Service Load
10.47 m (34 ft)	0.318 Hz	0.56 m (1.84 ft)

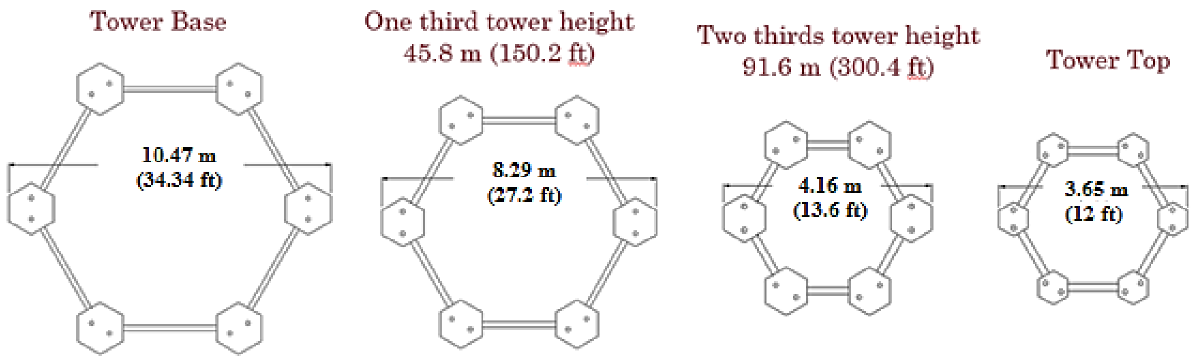


Figure 3.3. Preliminary dimensions of 140-m (459-ft) tall HT3a tower

The load values used for the design of the HT3a tower, which resulted from the applied scale factors, were evaluated by Siemens Wind Power and determined to be conservative by a magnitude of 10-15%. The design was not immediately adjusted to take advantage of this conservatism since the optimization of the preliminary design was still ongoing at that time. However, this factor was considered in the final tower design. The optimization of the HT3a tower was completed by Siemens Research Group and a summary of results is shown in Table 3.6. The optimized HT3a design was also evaluated by ISU to ensure sufficient design capacity and it was determined that no changes were needed to the optimized dimensions. The improved tower dimensions, prior to adjustment for conservative loads, are shown in Table 3.7.

Table 3.6. Optimized HT3a tower dimensions

	Initial Design in meters (ft)	Optimized Design in meters (ft)
Tower base diameter	10.47 (34.34)	11.23 (36.83)
Tower top diameter	3.65 (11.97)	3.65 (11.97)
Base column diameter	1.17 (3.84)	1.09 (3.56)
Top column diameter	1.09 (3.58)	1.07 (3.50)
Strands per column	92	90
Max deflection	0.56 (1.84)	0.69 (2.26)
Frequency	0.318 Hz	0.293 Hz

Table 3.7. Improved HT3a tower dimensions

	Initial Design in meters (ft)	**Improved Design in meters (ft)**	Optimized Design in meters (ft)
Tower base diameter	10.47 (34.34)	**11.23 (36.83)**	11.23 (36.83)
Tower top diameter	3.65 (11.97)	**3.65 (11.97)**	3.65 (11.97)
Base column diameter	1.17 (3.83)	**1.09 (3.56)**	1.09 (3.56)
Top column diameter	1.09 (3.59)	**1.07 (3.50)**	1.07 (3.50)
Strands per column	92	**90**	90
Max deflection	0.56 (1.84)	**0.69 (2.26)**	0.69 (2.26)
Frequency	0.318 Hz	**0.293 Hz**	0.293 Hz

3.6 Design for Tower Construction

Each tower was divided into a number of cells along the height of the tower based on the lifting capacity of the cranes available for tower erection. A Manitowoc 16000 crane was identified for stacking the Hexcrete tower cells (or sections) up to a height of 80 m (260 ft) with a cell weight limit of 109 metric tons (240 kips). For cells above 80 m, a Liebherr 11350 was selected with a cell weight limit of 102 metric tons (225 kips). In accordance with these limitations, each tower was divided into sections as shown in Table 3.8 and Table 3.9 with the first tower section designed to be built in place with the length of each individual member functioning as the limiting factor due to transportation constraints.

Table 3.8. HT2 tower sections according to weight

Section Number	Section Height (m)	Single Column Weight (metric tons)	Single Panel Weight (metric tons)	Total Section Weight (metric tons)
1	16.2	24.7	17.4	252.7
2	7.1	10.6	7.4	107.9
3	7.3	10.9	6.9	107.1
4	7.6	11.3	6.5	106.7
5	8.1	11.8	6.2	107.8
6	8.5	12.3	5.7	108.4
7	9.0	12.8	5.1	107.8
8	9.7	13.6	4.4	108.0
9	9.7	13.4	3.5	101.5
10	10.1	13.8	3.1	101.3
11	10.6	14.3	2.7	102.0
12	11.1	14.8	2.3	102.0
13	11.4	14.9	1.7	99.5
14	11.0	14.1	1.3	92.3

Table 3.9. HT3a tower sections according to weight

Section Number	Section Height (m)	Single Column Weight (metric tons)	Single Panel Weight (metric tons)	Total Section Weight (metric tons)
1	15.9	32.1	12.6	268.5
2	6.4	13.0	4.9	107.8
3	6.6	13.2	4.7	107.8
4	6.7	13.5	4.4	107.2
5	6.9	13.7	4.1	106.5
6	6.7	13.3	4.5	106.5
7	7.0	13.8	4.1	107.4
8	7.3	14.3	3.7	108.0
9	7.6	14.7	3.2	107.9
10	7.9	15.2	2.7	107.3
11	7.8	14.8	1.9	100.2
12	8.1	15.2	1.5	100.5
13	8.4	15.7	1.3	101.6
14	8.6	15.9	1.0	101.6
15	8.6	15.8	1.1	101.3
16	8.5	15.5	1.3	100.7
17	8.4	15.1	1.7	100.8

The tower erection plan was also optimized to provide the most cost-effective tower assembly solution. During discussions with industry partners regarding the erection process, it was found that the number of lifts required for each tower with the Liebherr crane was a major cost driver in the construction sequence. In order to minimize the number of lifts, hybrid towers were designed, which replaced the upper sections of the tower above 80 m (260 ft) with traditional tubular steel shells. The steel shells are lighter which enables the use of fewer, longer sections and results in a smaller number of lifts for the Liebherr crane. Since the design of the Hexcrete towers was implemented to eliminate oversized transportation loads, each steel shell tube was limited to a length of 17.1 m (56 ft) in order to fit on a standard semi-trailer (17.1 m includes one meter of overhang) as shown in Table 3.10 and Table 3.11 below. There is an option to make the steel shells a single piece if the oversized transportation costs do not outweigh the cost of additional crane lifts.

Table 3.10. HT2 hybrid tower sections according to weight (blue shades indicate steel sections)

Section Number	Section Height (m)	Single Column Weight (metric tons)	Single Panel Weight (metric tons)	Total Section Weight (metric tons)
1	16.2	24.7	17.4	252.7
2	7.1	10.6	7.4	107.9
3	7.3	10.9	6.9	107.1
4	7.6	11.3	6.5	106.7
5	8.1	11.8	6.2	107.8
6	8.5	12.3	5.7	108.4
7	9.0	12.8	5.1	107.8
8	9.7	13.6	4.4	108.0
9	9.7	13.4	3.5	101.5
10	10.1	13.8	3.1	101.3
11	14.7	-	-	35.2
12	14.7	-	-	31.8
13	14.7	-	-	28.1

Table 3.11. HT3a hybrid tower sections according to weight (blue indicates steel sections)

Section Number	Section Height (m)	Single Column Weight (metric tons)	Single Panel Weight (metric tons)	Total Section Weight (metric tons)
1	17.1	34.6	15.5	300.6
2	6.1	12.4	5.4	106.4
3	6.3	12.8	5.1	107.3
4	6.6	13.2	4.9	108.3
5	6.7	13.3	4.5	107.3
6	6.6	13.0	4.9	107.4
7	6.9	13.5	4.6	108.4
8	7.2	14.0	4.2	108.7
9	7.5	14.4	3.6	108.1
10	7.9	15.1	3.0	108.2
11	7.9	14.9	2.1	102.0
12	17.0	-	-	37.7
13	17.0	-	-	35.6
14	17.0	-	-	33.4

Another design change resulting from discussion with industry partners was implementation of a quick connect system between the stacked tower sections. Industry professionals recommended that the connections between the tower sections not require grouting immediately following erection. This is because grout set time will significantly delay the tower assembly time. The section connection detail designed for HT1 used rebar splice couplers that required grout to set before the next tower section was stacked. To avoid the delays caused by grout, the quick connect system was developed. The system consists of high strength steel threaded bars run along the interior of each column, which can be flown with the tower cells and quickly coupled together with the bars in lower tower sections. Keyways were also added to the connection design to provide guidance for setting the next tower section and provide additional connection shear capacity during erection (Figure 3.4). The number of threaded bars was determined based on wind loads along the tower as well as placement of the nacelle/rotor combination. The calculated wind loads were based on a maximum 3-sec gust of 22.4 m/s (50 mph) at an elevation of 10 m (33 ft) and utilized a safety factor of 1.5. The wind speed of 22.4 m/s (50 mph) was calculated based on a Mean Recurrence Interval (MRI) of 3-yrs according to ASCE 7-10 wind maps (American Society of Civil Engineers, 2010), and tower section loads were generated utilizing ASCE-7-10 guidelines for chimneys, tanks, and similar structures. The connection between each section will still be sealed with grout before the tower vertical post-tensioning is installed, but this is not required until after erection of the entire tower including the nacelle and rotor. The quick connect system does not change the tower design or dimensions and is simply accomplished by installing steel weld plates at the ends of each column during casting. Steel brackets, which will guide the threaded bars along the columns length, are then welded to the plates before transporting the members to the job site (Figure 3.5).

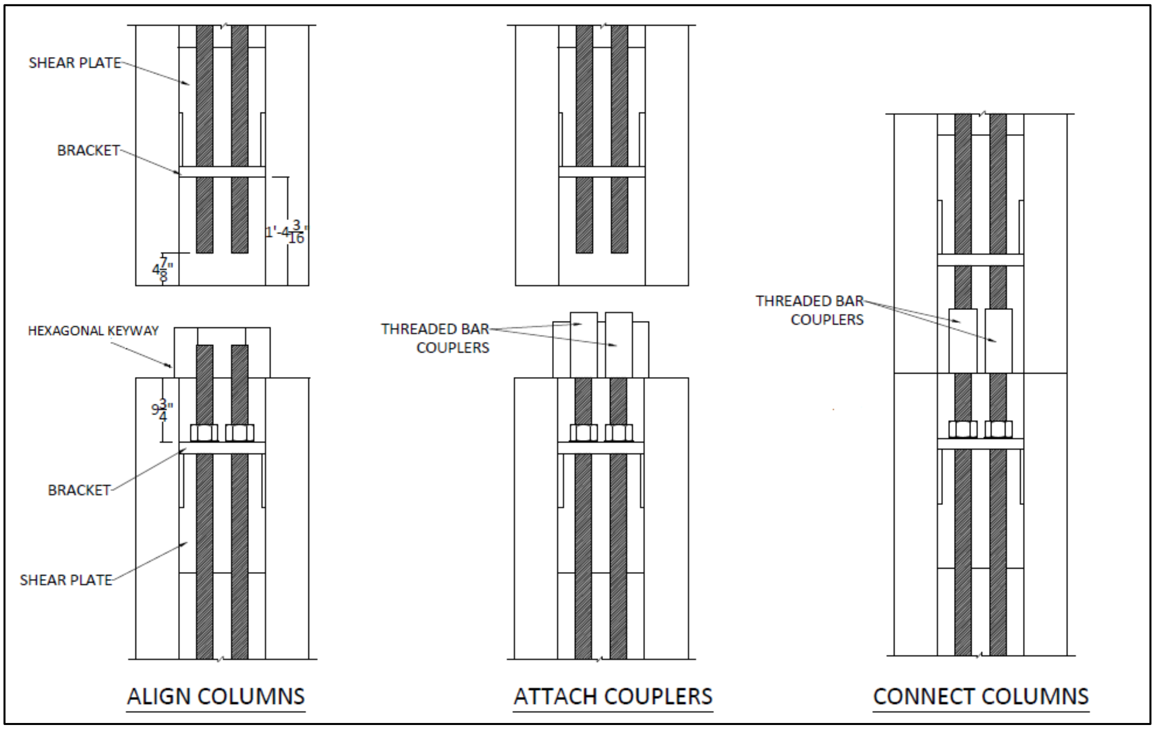


Figure 3.4. Quick connection between Hexcrete sections at columns utilizing threaded bars

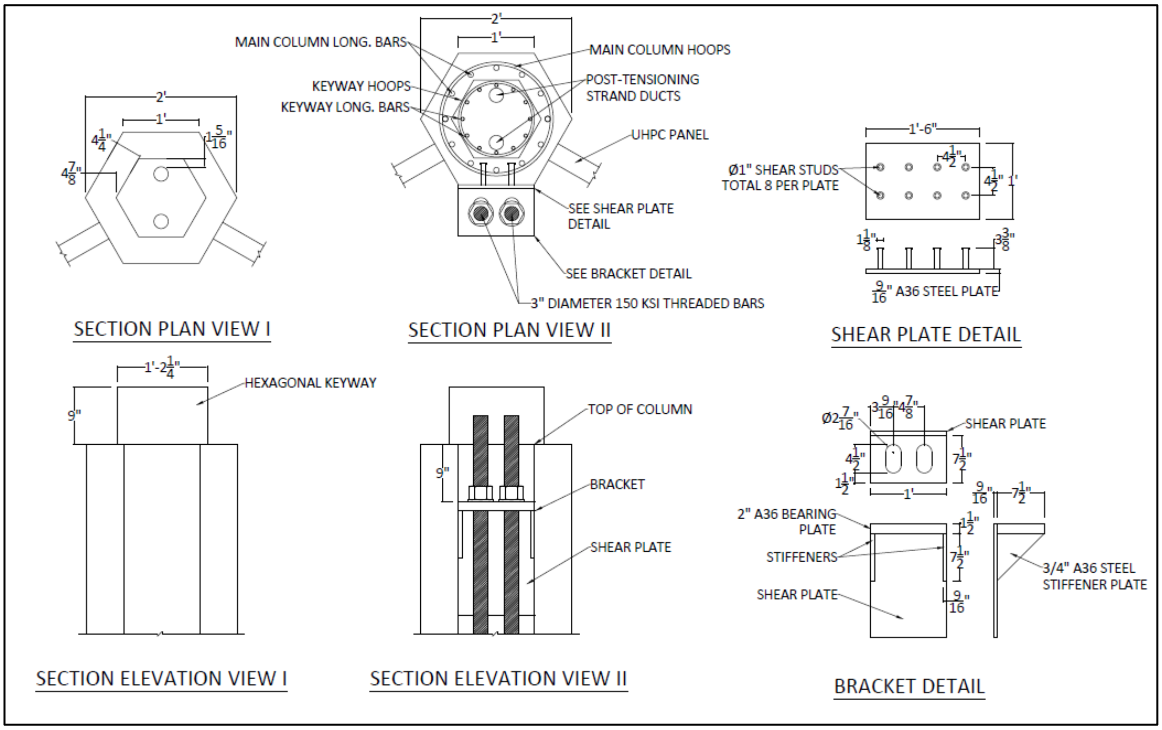


Figure 3.5. Details of quick connection for Hexcrete columns

3.7 Fluid Structure Interaction Effects

In addition to the cost and construction optimizations, the HT2 design was provided to the Fluid and Structure Interaction (FSI) group at ISU, which performed Computational Fluid Dynamic (CFD) analyses on the tower under extreme wind speeds. The CFD analysis of the HT2 tower was compared to a circular tower of equivalent diameter to investigate the difference in wind load produced by the hexagonal shape of HT2. This analysis found that the Hexcrete tower surface may produce a higher wind drag coefficient than a circular tower, which can result in a higher base overturning moment under extreme wind speeds for both operational and ultimate load conditions (including turbine loads). The hybrid tower option reduced the moment at the base of the tower due to a lower drag coefficient for the circular steel cross-section at the tower top.

Although CFD simulations were not run for the hybrid HT3 tower, the percentage change in load is assumed to remain consistent with the HT2 results. This is a conservative assumption based on the breakdown of loads on a wind tower. Wind tower loads come from two sources: 1) wind pressure against the tower surface, which is quantified using drag coefficients dependent on the tower shape and surface roughness; and 2) loads transferred to the tower from operation of the turbine. The turbine loads generally account for over 50% of the total tower loads. For the HT2 and HT3a towers, the drag coefficient difference only increases wind loads on the tower structure and does not influence the loads generated by the wind turbine. For the 3.2 MW turbine on the HT3 tower, larger turbine loads than the HT2 2.3 MW turbine will be generated, resulting in an increase in the percentage of the total load produced by the turbine. The percentage change in drag force will remain consistent for the HT2 and HT3a due to the similar Hexcrete shape. As a result, the HT3a drag coefficients will account for a smaller percentage of the total tower load and result in a smaller total load increase for the HT3 tower than for the HT2 tower at extreme loads.

3.8 Final Tower Design Refinements

After completion of the CFD simulations by ISU, a final design reevaluation was performed for both the full Hexcrete and hybrid HT2 and HT3a towers. The extreme wind speed load case was examined for both operational and ultimate load conditions. It was found that all four towers had sufficient capacity at ultimate load conditions, but that some adjustment was necessary to all designs for operational load conditions. The HT3 tower design adjustment also included the 10-15% conservatism of the initial design loads discussed earlier. The finalized design dimensions for all four towers are shown in Table 3.12 and Table 3.13.

Table 3.12. Finalized full concrete HT2 and HT3a designs

Tower	**HT2 Full Concrete**		**HT3a Full Concrete**	
	Improved Design in meters (ft)	**Final Design in meters (ft)**	Improved Design in meters (ft)	**Final Design in meters (ft)**
Tower base diameter	9.20 (30.18)	**9.81 (32.18)**	11.23 (36.83)	**10.49 (34.41)**
Tower top diameter	3.20 (10.50)	**3.29 (10.79)**	3.65 (11.97)	**3.78 (12.40)**
Base column diameter	1.05 (3.44)	**1.04 (3.41)**	1.09 (3.58)	**1.19 (3.90)**
Top column diameter	0.91 (2.98)	**1.04 (3.41)**	1.07 (3.51)	**1.08 (3.54)**
Strands per column	70	**96**	90	**114**
Frequency	0.268 Hz	**0.31 Hz**	0.293 Hz	**0.32 Hz**

Table 3.13. Finalized hybrid HT2 and HT3a designs

Tower	**HT2 Hybrid**		**HT3a Hybrid**	
	Improved Design in meters (ft)	**Final Design in meters (ft)**	Improved Design in meters (ft)	**Final Design in meters (ft)**
Tower base diameter	9.2 (30.18)	**9.6 (31.49)**	11.23 (36.83)	**11.23 (36.83)**
Tower top diameter	3.2 (10.50)	**3.2 (10.50)**	3.65 (11.97)	**3.77 (12.37)**
Base column diameter	1.05 (3.44)	**1.02 (3.35)**	1.09 (3.58)	**1.12 (3.67)**
Top column diameter	0.91 (2.98)	**0.97 (3.18)**	1.07 (3.51)	**1.07 (3.51)**
Strands per column	70	**80**	90	**92**
Frequency	0.33 Hz	**0.39 Hz**	0.42 Hz	**0.45 Hz**

3.9 Summary

The design process for the HT2 and HT3a tower produced four optimized designs including both full Hexcrete and hybrid tower options. The hybrid options were formulated from interaction with industry partners to take advantage of erection cost savings while CFD simulations showed that hybrid towers also provided an advantage by lowering the tower base overturning moment. While the Hexcrete hybrids towers provide some advantages, the full concrete Hexcrete towers are also cost competitive as shown in the LCOE calculations. Both tower options provide flexibility in design and position the Hexcrete technology as an economical tall tower solution for the current wind market.

Chapter 4 – Tower Optimization

4.1 Introduction

Unlike other wind turbine towers, the Hexcrete towers offer multiple ways to make them cost effective by refining the design parameters, while maintaining their structural characteristics, and satisfying transportation and construction constraints. The modular nature of this tower allows the design space to be easily parameterized to investigate possible design variations. The goal of this optimization chapter is to explore variations of the Hexcrete tower design in order to minimize the tower cost while ensuring that the optimized tower would be meet the structural criteria and that it would be easy to construct.

During BP1, a preliminary framework for tower optimization coupled with tower structural analysis was implemented. Design of experiment studies were performed for HT1 and the impact of design parameters on tower cost were evaluated. In BP2, the optimization framework has been further advanced. A fully automated optimization workflow was implemented, which took the initial tower design and tower loads as input and performed tower optimization using an automated Hexcrete Tower structural simulator coupled with an optimization module. This automated workflow was used to optimize both HT2 and HT3a, and the results are presented in the following sections.

4.2 Optimization Framework Overview

The optimization of the Hexcrete Tower is performed by utilizing DAKOTA (an open source optimization toolkit (Sandia National Laboratories, 2016)) in conjunction with Siemens NX Open (a collection of APIs that allows users to create custom applications (Siemens PLM Software, 2010)). The genetic algorithm toolbox in DAKOTA was used to perform a population-based search of the best design candidate. An NX Open executable was developed to perform automatic finite element analysis (FEA) using Siemens NX CAE and Nastran. The overall workflow is summarized in Figure 4.1.

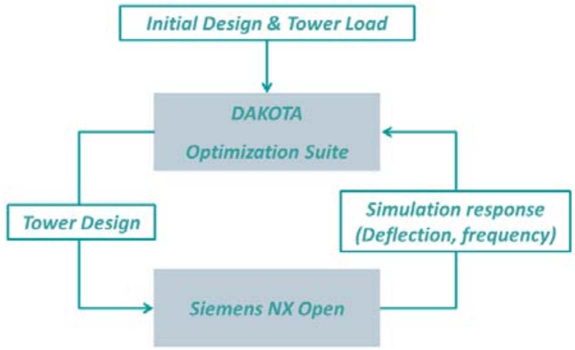


Figure 4.1. The overview of the workflow used for Hexcrete tower optimization

The objective of the optimization was to minimize the total tower cost. This optimization was subjected to structural characteristic constraints (i.e., deflection, maximum stress, moment along the tower height, and natural frequency), and geometric constraints (including geometric design, transportation limits and construction constraints). The design parameters included: 1) height of tower sections, 2) tower diameter at the ends of each section, 3) column diameter, 4) panel thickness, 5) number of post-tensioning strands, and 6) panel and column material. Due to the huge design space that governs the Hexcrete tower design, the optimization included a subset of the design parameters that have the most impact on tower cost and design including tower diameters at the ends of each section, column diameters at the ends of each section and the number of post-tensioning strands. A detailed workflow of the optimization framework is illustrated in Figure 4.2.

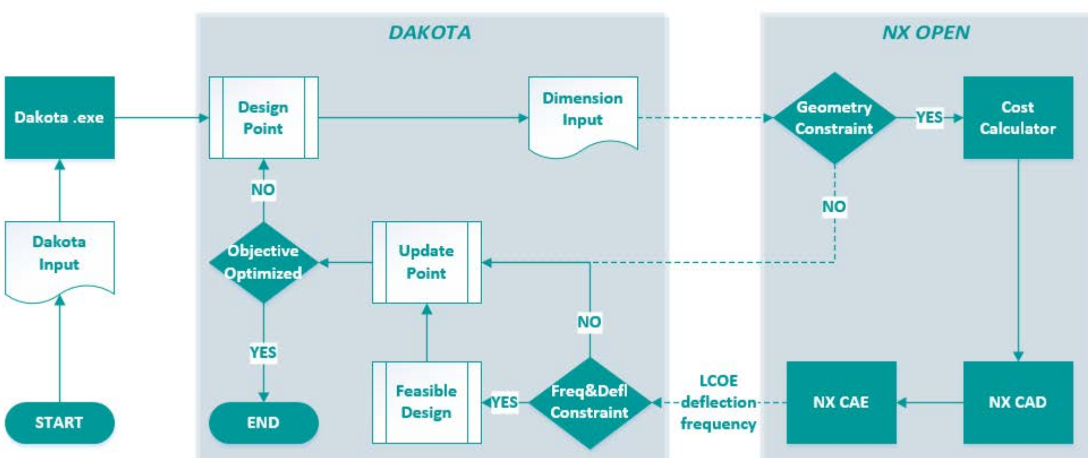


Figure 4.2. Detailed flowchart of the tower optimization workflow

Accordingly, DAKOTA took two files as input, including: (i) the dimension file of the initial design, in the form of panel thickness, tower and column diameters at multiple horizontal planes along the height of the Hexcrete tower; and (ii) the load input file, which included the magnitudes of forces and moments at different locations along the tower. DAKOTA then generated multiple tower design variations and produced a dimension input file for each design. Consequently, based on the input dimensions, NX Open evaluated whether the design violated the given tower geometric constraints. If the constraints were satisfied, the tower cost was subsequently calculated. After that, NX Open automatically created the computer-aided design (CAD) model and performed computer-aided engineering (CAE) evaluation using FEA based on the specific tower design. From the NX Open simulator, tower deflection and frequency were obtained for each tower design and this information was transferred back to DAKOTA to perform optimization. On the other hand, if the geometric constraints had been violated, tower cost was not calculated and all the subsequent steps (CAD and CAE) were skipped to minimize computation time. After gathering all this information and confirming that geometric, deflection, and frequency constraints were not violated, DAKOTA performed the tower optimization. The optimization was declared complete after enough generations have been evaluated and the optimizer converged to a single design.

4.3 Parametric CAD Models

A parametric CAD model was created in the Siemens NX CAD software to encode the design parameters (Figure 4.3). Given the cross section dimensions at a particular height along the tower, a sketch was created in NX. On each sketch, the necessary components (e.g., panels) were drawn based on the given dimensions. CAD model geometric constraints (e.g., location of the center of the tower) were set on each sketch. Then curved surfaces were created to connect the sketch components between two horizontal planes. All the geometric parameters (e.g., the height of the sketch plane, tower diameter) were encoded as expressions in NX software. The NX Open executable generated the initial CAD model from scratch if it had not been created previously; or else it updated the expressions of an existing CAD model as the new design.

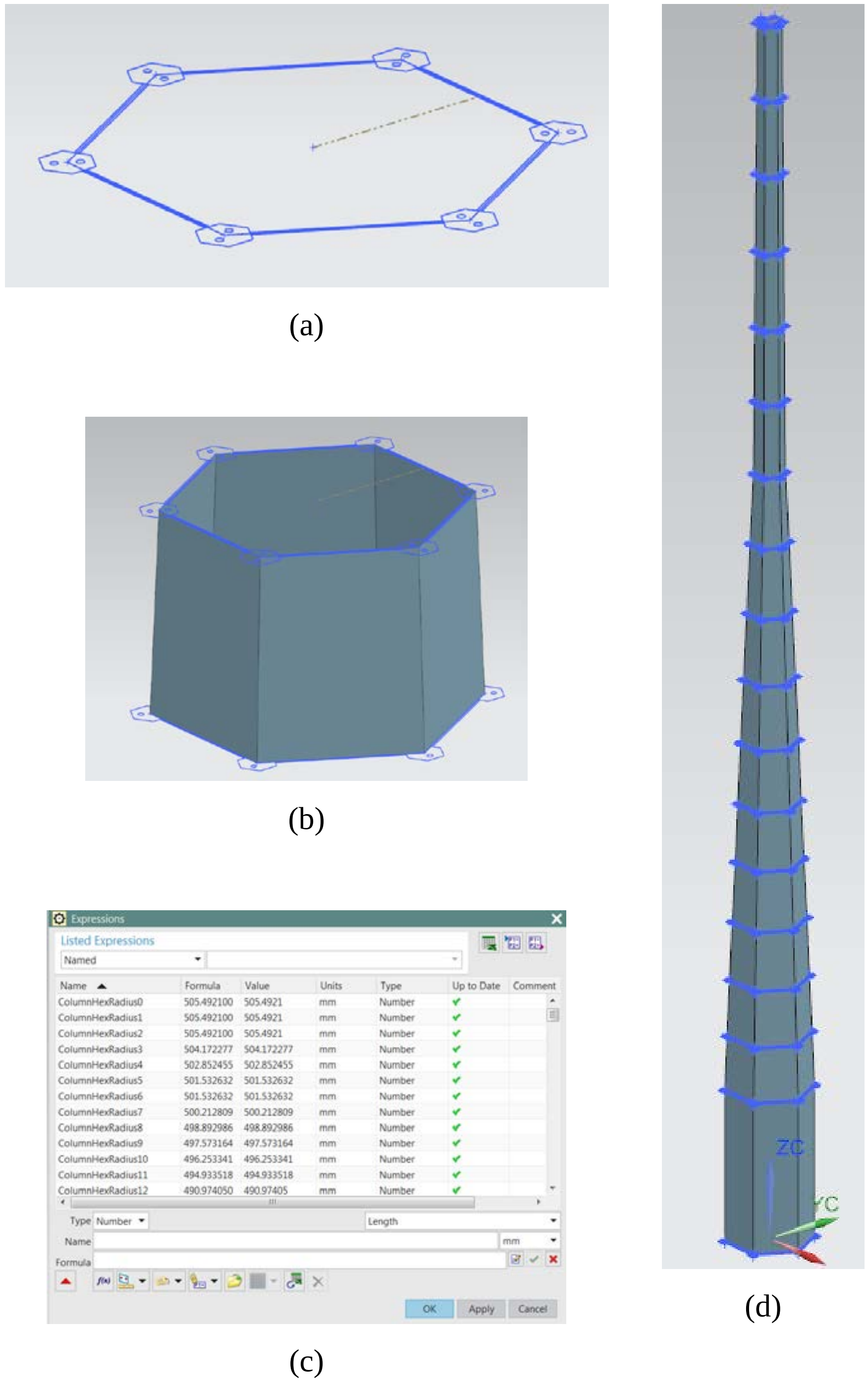


Figure 4.3. Parametric CAD model: (a) Example of a sketch of a tower cross section, (b) Creation of panels using ruled surfaces by joining lines from two adjacent sketches, (c) design parameters encoded as Expressions in NX to allow easy update, and (d) CAD model

4.4 Finite Element Analysis Model

The goal of performing an FEA simulation was to obtain the frequency and the deflection of a tower design under the wind load conditions obtained from Siemens Wind Power and Iowa State University (ISU). NX Nastran "SOL 101 Linear Statics" solver was applied to calculate the deflection. NX Nastran "SOL 103 Real Eigenvalues" solver was applied to evaluate the frequency of the tower. The following sections describe the finite element model setup and boundary conditions used for the simulations.

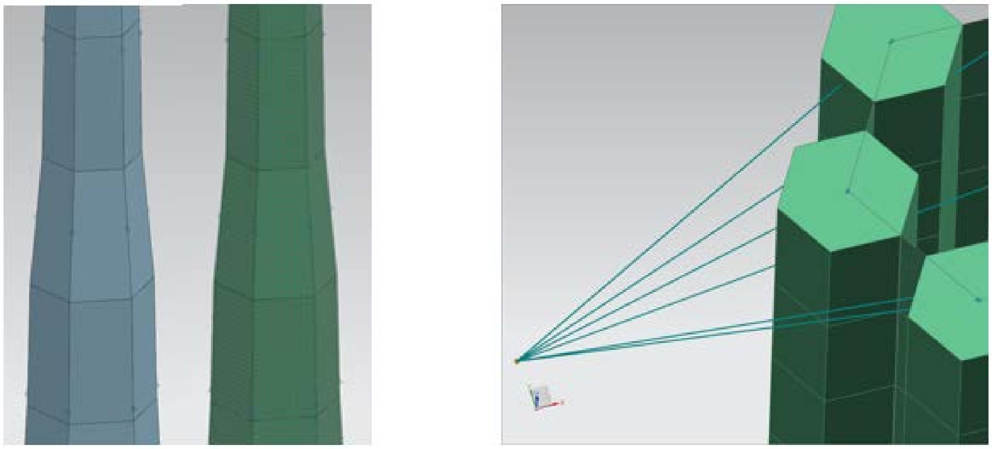
4.4.1. Finite Element Model

The finite element model of the Hexcrete tower consisted of two parts, columns and panels. The columns have hexagonal cross sections and the panels have rectangular cross sections. To speed up the analysis, it was justified to use beams (1D element) and shells (2D element) to perform FEA simulation, instead of 3D solid elements. By reducing the number of degrees of freedom (DOF), this simplification significantly accelerated the meshing and solving processes without loss of accuracy. This reduced order model was validated with a full 3D FEM model as well as with ISU's analysis results. Details of both the column and panel finite element properties are given in Table 4.1.

Table 4.1. Summary of the Finite Element Model

	Column	Panel
Element Type	CBEAM (Hexagon Section)	CQUAD4
Mesh Size	1000 mm	1000 mm
Material	HSC	UHPC
Young's modulus	44816 MPa	51359 MPa
Density	2402.8 kg/m3	2402.8 kg/m3
Poisson's ratio	0.2	0.2

In statics analysis (NX Nastran SOL 101), wind loads were applied at specific locations on the columns according to the conditions provided in the wind load input file. To ensure that a node is present at the locations specified in the load input file, mesh points were first created in the CAD model. These mesh points served as mesh seeds when generating 1D mesh of the beam elements and mapped 2D mesh of the shell elements (Figure 4.4a).



(a) (b)

Figure 4.4. Mesh details: (a) Nodes were created at the load locations, (b) CONM2 linked to nodes on top plane

In modal analysis (NX Nastran SOL103), the inertia of the nacelle and rotor was included by adding a 0D concentrated mass (Nastran element type CONM2) at the location of Rotor Neutral Axis. 1D linking element (REB2) was used to fix the element to the top plane of tower (Figure 4.4b). In the actual Hexcrete towers, the post-tensioning force compresses the concrete columns and connects the tower sections. However, since the post-tensioning force has a negligible effect on the tower frequency it was not included in the modal analysis. As a result, the nodes of the columns between adjacent sections were merged so that the entire tower was joined as a single unit, which correctly represented the behavior of the tower as if the post-tensioning were present. An example of the finite element model is illustrated in Figure 4.5. A mesh sensitivity analysis was also performed to evaluate an appropriate element size without comprising solution accuracy (Table 4.2). Element sizes of 500 mm, 1000 mm and 2000 were analyzed. There were little differences in deflection as the element size was increased. There was no change in the frequency with respect to the element sizes studied. Therefore, 1000 mm was chosen as the Element size to minimize the computation time.

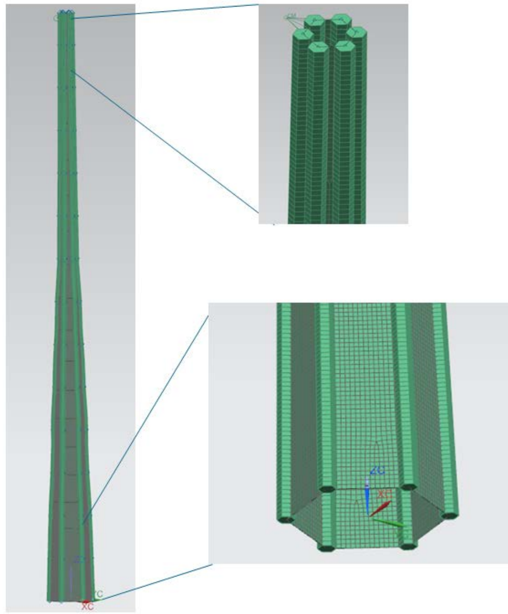


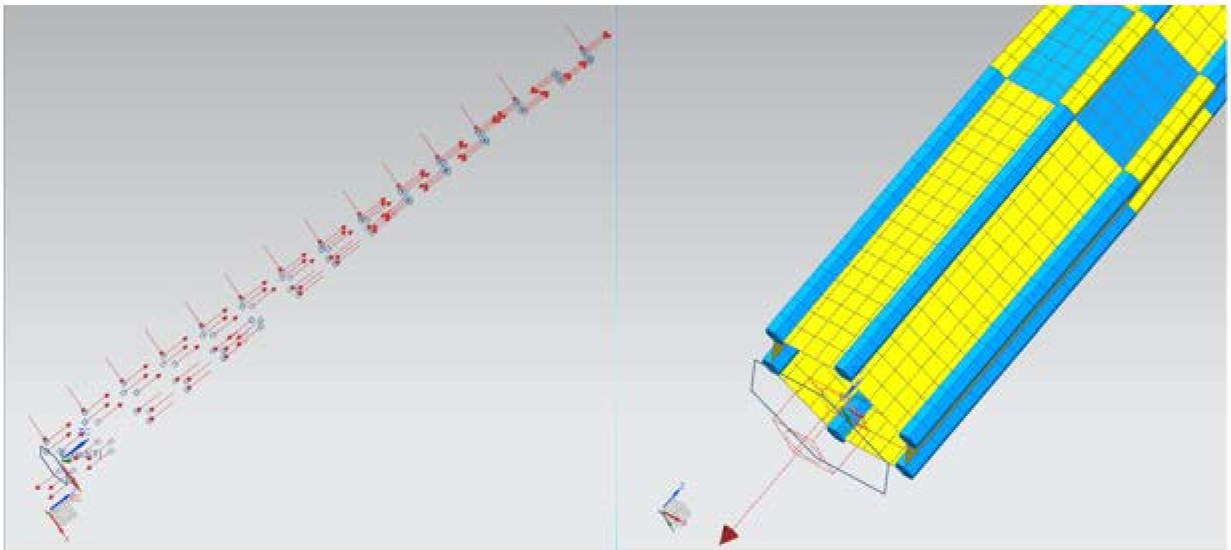
Figure 4.5. Illustration of the finite element model: quadrilateral thin shell elements for the panels and hexagonal beam elements for the columns

Table 4.2. Mesh Sensitivity Analysis

Element size [mm]	Number of Nodes	Deflection [mm]	Frequency [Hz]
500	15013	564.32	0.3180
1000	4261	564.31	0.3180
2000	913	564.04	0.3180

4.4.2. Boundary Conditions

The locations of the load application for the statics and modal analyses are illustrated in Figure 4.6. Displacement boundary conditions (BCs) were applied in the FEA to constraint the tower base. The horizontal plane of the tower base (i.e., Z=0) was fixed in all directions and rest of the tower sections were left unconstrained. These BCs were applied to both statics analysis and modal analysis. In the statics analysis, the wind loads included bending moment and shearing force. Bending moment was distributed to the nodes of the six columns at the corresponding heights defined in the wind load input file. A linear distribution of normal stresses on the horizontal plane was used to calculate the forces that generated the moment. These force values were then applied to each column. In the modal analysis, only gravity was applied as prestress in the longitudinal direction. Post-tensioning force was neglected because it would have little effects on the frequency.



(a) (b)

Figure 4.6. BC used for different analyses: (a) statics analysis; and (b) modal analysis

4.4.1 Sample Simulation Results

An NX Open executable was created to automate the CAD creation and FEA simulation, which required the tower dimensions and wind loads as input. The initial design's geometric dimensions and wind loads were used as a test case for the simulator. Figure 4.7 shows the deflection (displacement in X direction) and the first flexural mode shape of the initial design of HT3a. These quantities were verified with ISU's analytical results.

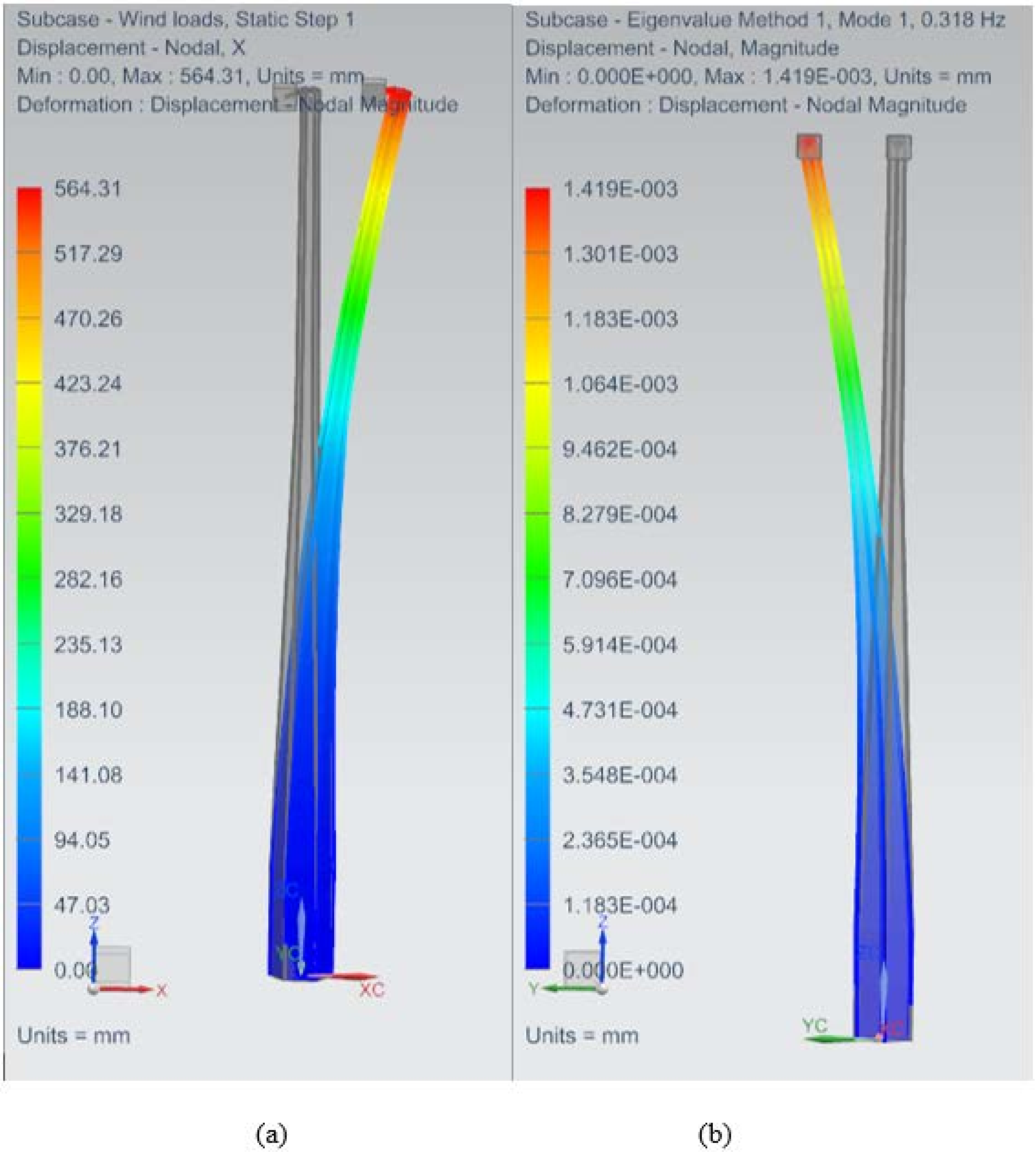


Figure 4.7. HT3a (a) deflection of 564.31 mm; (b) frequency of 0.318 Hz

4.5 Hexcrete Tower Optimization Framework

The preliminary Hexcrete tower was designed to meet certain demands and performance requirements. This optimization framework was expanded significantly since completing BP1 of this project. The advanced optimization framework developed in BP2 was to achieve a design solution meeting the chosen performance goals. The Siemens NX software-driven optimization framework was introduced here to help designers explore optimal design solutions for the Hexcrete Tower.

4.5.1 Optimization Problem Statement

The general Hexcrete tower design optimization problem can be stated as:

$$\begin{aligned} &minimize: f(\boldsymbol{x}) \\ &\qquad \boldsymbol{x} = [D_1 \cdots D_i, d_1 \cdots d_j, n_s]^T \\ &subject\ to:\ c_1(\boldsymbol{x}) \le Def_{max} \\ &\qquad Freq_1 \le c_2(\boldsymbol{x}) \le Freq_2 \\ &\qquad c_3(\boldsymbol{x}) = 0 \\ &\qquad \boldsymbol{x}_L \le \boldsymbol{x} \le \boldsymbol{x}_U \end{aligned} \tag{4.1}$$

In this formulation, f *(x)* is the objective function and $\boldsymbol{x}$ is a vector of real-valued design variables describing the geometry of a Hexcrete tall tower. $[D_1 \cdots D_i]$ is a vector of tower diameters from base to top; $[d_1 \cdots d_j]$ represents the column diameters at each tower horizontal cross section; n_s is an even integer number of post-tension strands in each column. The vectors $\boldsymbol{x}_L$ and $\boldsymbol{x}_U$ are the lower and upper bounds on the design variables, respectively. Constraint function c_1 examines if the maximum deflection of the tower is below requirement Def_{max} (maximum deflection limit). The frequency constraint c_2 has both lower and upper bounds $Freq_1$ and $Freq_2$, respectively. The equality constraint c_3 contains some geometry requirements that will be introduced later.

The objective of this optimization is to minimize the total cost function of Hexcrete tower, f, while satisfying all other constraint functions. The total cost of the Hexcrete tower is computed using standard cost estimating procedure accounting for both material and assembly costs of the tower:

$$C_{Total} = C_{Material} + C_{Assembly} \tag{4.2}$$

The unit prices of the costs in this formula are listed in Table 4.3 as well as the total cost breakdown of the HT2 and HT3a initial designs. Assembly cost is assumed to be linearly deductible from initial design if weight is reduced by 350 kips. These costs were established as appropriate values for the optimization purposes and they were refined later as part of LCOE calculations. The ratio difference between the different options, however, provides valuable information.

Table 4.3. Total cost breakdown

	Unit Price	HT2 Initial	HT3a Initial
Material ($C_{Material}$)	HSC \$1176/m^3; UHPC \$3660/m^3; Strand \$0.59/ft	\$1,356,358	\$1,511,443
Assembly ($C_{Assembly}$)	Cost reduced by 2.5% /350kips	\$552,200	\$804,270
Total (C_{Total})		\$1,908,558	\$2,315,713

The nonlinear constraint functions c_1 and c_2 were evaluated from FEA by NX Nastran simulations, where c_1 is the deflection of the tower, and c_2 is the frequency of the tower. The bounds of c_1 and c_2 were guided with expert opinion from Siemens Wind Power. Besides the requirements of deflection and frequency on the tower design, there was a geometric constraint function, $c_{3,}$ that covered several design rules regarding the tower design. These design rules are summarized in Table 4.4**,** in which $M_{wind}$is the wind-load induced bending moment ing_1. The moment capacity of each section, M, needs to exceed the wind-load moment as the first check. The non-negative c_3 constraint function, as defined below, comprises all of these geometry constraints and gives an overall metric reflecting the geometric feasibility of Hexcrete tower design. A penalty term ρ with a value of 10^4 was also added to capture the small geometry constraint violations. Geometry feasibility is strictly maintained if c_3 is zero; otherwise one or several geometric constraint functions listed in Table 4.4 would be violated, making that design structurally deficient.

$$c_3(x) = \rho(\sum_{i=1}^{7}(\max[0, -g_i(x)])^2)^{0.5} \tag{4.3}$$

Table 4.4. Geometry Constraints Summary

Geometry Constraint	**Description**	**Formula used in optimization**
$\boldsymbol{g_1}$: Section Moment (M)	$\geq M_{wind}$	$g_1 = 1 - \frac{M_{wind}}{M}$
$\boldsymbol{g_2}$: Section Stress (σ)	≤ 5.85 ksi	$g_2 = 1 - \frac{\sigma}{5.85}$
$\boldsymbol{g_3}$: Max Length (L_{max})	≤ 54 ft	$g_3 = 1 - \frac{L_{max}}{54}$
$\boldsymbol{g_4}$: Max Width (w_{max})	≤ 14 ft	$g_4 = 1 - \frac{w_{max}}{5.85}$
$\boldsymbol{g_5}$: Max Weight (Wt)	≤ 80,000 lb	$g_5 = 1 - \frac{Wt}{80000}$
$\boldsymbol{g_6}$: Max Section Weight (Wt_{sec})	≤ 240 kips ≤ 225 kips(above 260ft)	$g_6 = 1 - \frac{Wt_{sec}}{240(225)}$
$\boldsymbol{g_7}$: Diameter at 274 ft (D_{274ft})	≤ 14.75 ft	$g_7 = 1 - \frac{D_{274ft}}{14.75}$

4.5.2 Optimization Algorithm

In this work, a Single Objective Genetic Algorithm (SOGA) was adopted as the global optimizer. SOGA is one of the evolutionary algorithms inspired by natural evolution. Evolutionary algorithms are distinguished by the use of natural selection and a population of candidate designs to evolve to an optimal design solution. SOGA was chosen as the optimization algorithm due to the following reasons:

- Genetic Algorithm (GA) is a gradient-free optimizer, meaning that it does not require gradient information in the search process. In this simulation-driven optimization process, there is a practical difficulty in computing accurate gradient information from NX Nastran simulations. In addition, this design optimization problem involves discrete design variables, which makes the process more challenging to obtain correct gradients. The GA allows the designer to explore a design space without any gradient computation.
- GA is a population-based optimizer. While traditional optimizers iterate with a single design point, the genetic algorithm examines a population of candidate design points

simultaneously. This strategy makes the genetic algorithm more powerful in searching for the optimal design point. A population-based optimization is also intuitive for parallel implementation and thus, significant speed up can be obtained by utilizing parallel computing resources.

- A population-based optimizer has more advantageous in searching for multiple optimal design points. When multiple design solutions are equally important for decision makers to make trade-off analysis between multiple objectives, a GA is more suitable for multi-objective optimization. In this sense, adopting genetic algorithm provides a good foundation for future multi-objective optimization studies on Hexcrete tower trade-off design analysis.

The pseudo code for SOGA is outlined below in Algorithm 1 (Figure 4.8), which is initiated with a random population of designs. Then the algorithm starts the iterative process that evaluates and updates the current population to create new population of individual designs. In GA, the iteration counter is represented with generation number. The creation of new individual designs relies on three main GA operators: crossover, mutation, and selection. When the stopping criteria of SOGA are met, the best design in the current population is considered as the optimal design point.

```
Begin

Initialize a population of candidate designs
Evaluate each candidate design
While Termination criteria is not met do

Generate new individual designs by Crossover and Mutation
Evaluate new individuals
Select best individuals to form new population

end While
Output the best individual in current population
End
```

Figure 4.8 Algorithm 1 pseudo code for SOGA

4.5.3 Implementation of the Proposed Optimization Problem

In the implementation of the proposed tower design optimization problem, several computing management strategies were utilized to improve the efficiency of the optimization. The computational cost of the proposed optimization is directly associated with the number of NX Nastran simulations. Therefore, it is necessary to avoid invoking the simulation procedure when the candidate design is clearly in the infeasible domain. Before each candidate design is being evaluated in NX Nastran in the optimization run, the geometric constraint c_3 will be evaluated first to pre-screen this candidate solution. If the equality constraint c_3 is not satisfied, the constraint function c_1 and c_2 will be assigned with constant values p_1 and p_2, rather than evaluated via NX Nastran FEA simulations.

$$\left.\begin{matrix} c_1(x)=p_1 \\ c_2(x)=p_2 \end{matrix}\right\} \quad if\ c_3(x) > 0 \tag{4.4}$$

In equation above, constant values p_1 and p_2 are specified with infeasible values outside the bounds of deflection and frequency. This prevents a large number of infeasible design from being evaluated in time-consuming FEA simulation, and helps improve the efficiency of SOGA implementation. To achieve the maximum efficiency of SOGA implementation, the computational process was parallelized for individual evaluations. Parallel computing implementation of genetic algorithm is the most direct way to make the proposed real-world engineering design optimization computationally tractable. In this project, an 8-processor parallelization was implemented and tested. This parallelization strategy can be easily extended to larger number of processors when higher performance computational resources are available.

The parameters used by SOGA to solve the optimization problem are listed in Table 4.5. As the proposed design optimization problem involves discrete design variable, the SOGA implementation is specified as binary encoded. The crossover is performed at four crossover points in the binary gene of two candidate design individuals while mutation is introduced with random variation on a random design variable using uniformly distributed value. The selection criterion for offspring reproduction favors feasible designs. This makes sure that SOGA always prefers a more feasible design to a less feasible design. These SOGA parameter specifications are encoded in DAKOTA input files for optimization of the HT2 and HT3a Hexcrete tower designs.

Table 4.5. SOGA Parameters

SOGA parameter	Value
Population number	100
Generation number	100
Crossover rate	0.70
Binary crossover operator	Multi-point of 4
Mutation rate	0.30
Mutation type	uniform

4.6 Application to Tall Tower Designs

The described optimization framework was demonstrated for the design of two wind turbine towers:

- HT2 – Hub height 140m (459ft) to support a 2.3 MW turbine
- HT3a – Hub height 140m (459ft) to support a 3.2 MW turbine

In each case, the optimization objective is to explore more cost-effective design solutions while satisfying certain tower design constraints. In consideration of the smoothness of the tower geometry, the number of tower diameter design variables at different sections is restricted to two. Tower diameters at other sections are linearly interpolated with a constant taper relationship. Both design optimizations were repeated with several independent runs to examine the influence of probabilistic selection, mutation, and crossover on the optimization convergence. The SOGA operator parameters listed in Table 4.5 were proved robust and consistent in achieving the optimal design solutions.

4.6.1 HT2 Design Optimization

The general design optimization problem is specified in the equation below for HT2 design optimization:

$$minimize\colon\ f(\boldsymbol{x})$$

$$\boldsymbol{x} = [D_1, D_2, d_1 \cdots d_{15}, n_s]^T$$

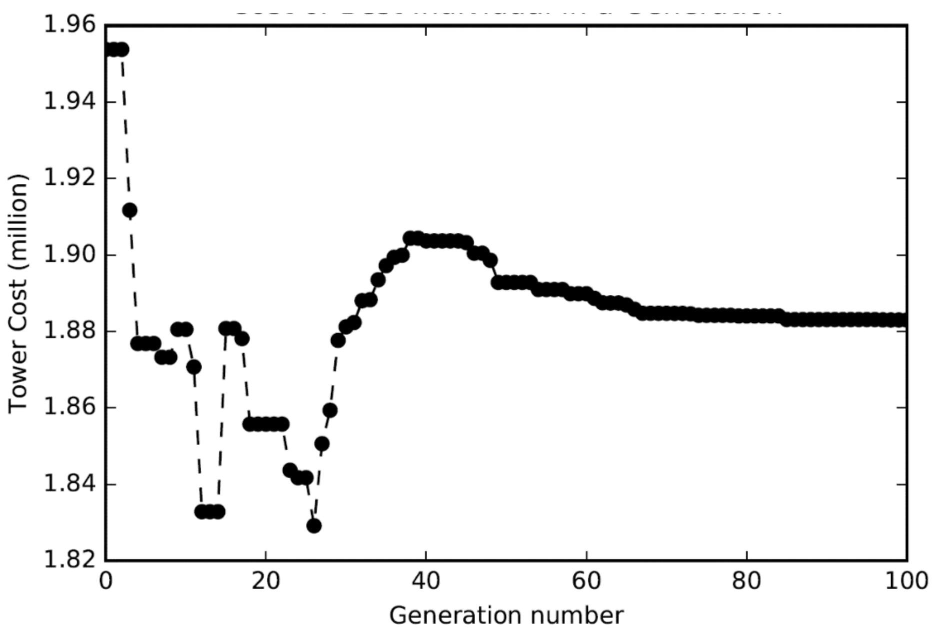
$$subject\ to\colon\ c_1(\boldsymbol{x}) \le 700mm \qquad (4.5)$$
$$1P \le c_2(\boldsymbol{x}) \le 3P$$
$$c_3(\boldsymbol{x}) = 0$$
$$\boldsymbol{x}_L \le \boldsymbol{x} \le \boldsymbol{x}_U$$

There are 15 column diameter design variables, along with tower diameters and strand number for this design problem. The design domain for these variables is shown in Table 4.6. It should be noted that the variables D_1 and D_2 are measured from the center points of the outermost columns, while in the previous chapter on tower design the reported diameters reference the outside edges of the outermost columns. This difference was implemented to streamline the formulation of the FEA simulations and the diameter values can be easily compared to the values given in the tower design tables by adding d_1 and d_9 to D_1 and D_2 respectively. The deflection at the top of the tower is constrained to be less than 700 mm while the tower and nacelle combined frequency range is restricted within an interval of the turbine 1P and 3P frequencies.

Table 4.6. Design variables for HT2

Design variable	**Description**	**Type**	**Lower bound**	**Upper bound**
D_1	Base tower diameter	Continuous	24 ft	32 ft
D_2	Tower diameter of Section No. 9	Continuous	9.0 ft	12.5 ft
$d_1,\ldots,d_{15}$	Column diameter of 15 planes	Continuous	3.0 ft	5.0 ft
n_s	Number of post-tension strands	Discrete	50	120

The HT2 design optimization problem was solved in the optimization scheme previously described. To illustrate the convergence process of SOGA optimization, the best individuals in each generation are plotted in Figure 4.9 for the cost objective function value. It shows that the SOGA captured and preserved the better feasible solution as the optimization evolved. In the later generations, the optimal solution was kept unchanged until SOGA was terminated.



P

Figure 4.9. Convergence of the cost objective function in HT2 design optimization

The SOGA optimizer evaluated 9,354 individuals in total, while only 5,639 simulations were performed and used to locate the optimal solution. This ensured that FEA simulations were not performed for the infeasible designs to save computational cost. The optimal design of HT2 found by SOGA optimizer is presented in Table 4.7 to compare with the initial HT2 design. The difference between the optimal design and the initial design parameters is also plotted in Figure 4.10. It can be observed from the results that the optimal column diameters are much lower compared to the initial design and that the number of post-tensioning strands within each concrete column was also reduced from 76 to 64.

Table 4.7. HT2 initial design vs. optimal design

Descriptor	Initial design (ft)	Optimal design (ft)
D_1	25.00	26.66
D_2	11.50	11.90
d_1	3.33	3.45
d_2	3.33	3.29
d_3	3.31	3.28
d_4	3.29	3.19
d_5	3.27	3.16
d_6	3.25	3.10
d_7	3.23	3.10
d_8	3.20	3.07
d_9	3.18	3.03
d_{10}	3.16	3.02
d_{11}	3.14	3.02
d_{12}	3.12	3.01
d_{13}	3.11	3.01
d_{14}	3.09	3.01
d_{15}	3.09	3.00
n_s	76	64
Weight	**3493 kips**	**3387 kips**
Deflection	**643.2 mm**	**636.9 mm**
Frequency	**0.266 Hz**	**0.268 Hz**
Total Cost	**1.908 million**	**1.883 million**

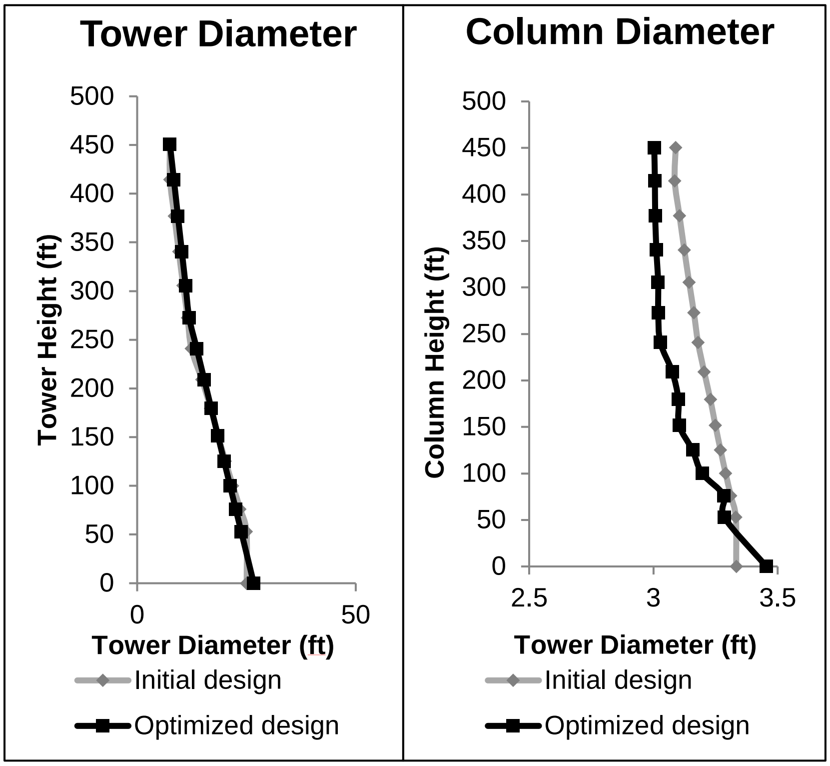
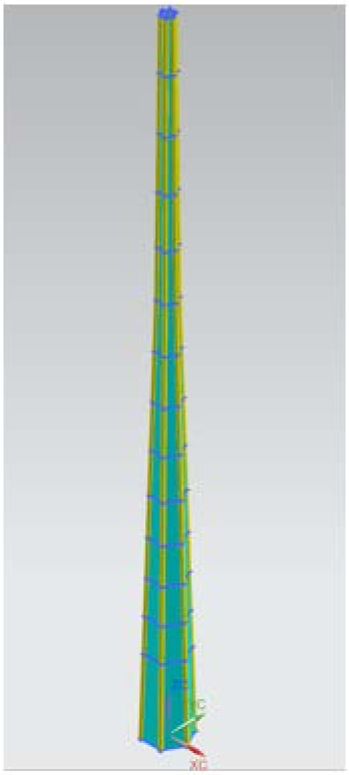
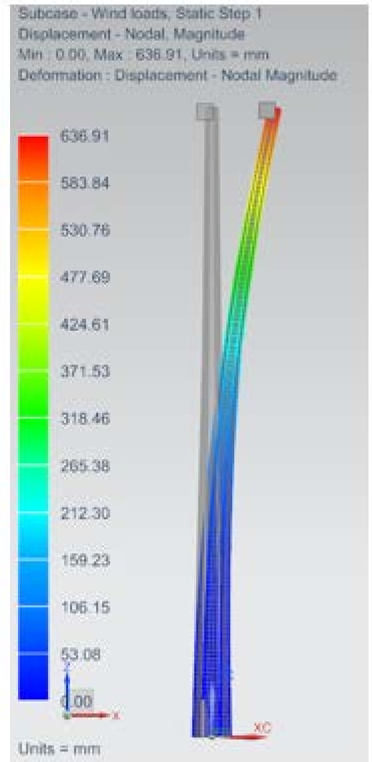


Figure 4.10. Comparison of the tower and column diameters of HT2 initial design and the optimal design

In the exploration of the best solution through SOGA optimization, the FEA evaluation with Siemens NX Nastran ensures the engineering performance of the optimal design. The CAD model and deflection obtained from FEA simulation under the tower service load are plotted in Figure 4.11. The presented simulation-driven optimization proved to effectively reduce the material needed for the Hexcrete tower while satisfying the geometric and performance requirements of the tower. The optimal design shows a 1.31% reduction of total cost from the initial design.



(a)



(b)

Figure 4.11. (a) CAD model of the optimal design; (b) deflection obtained from FEA simulation

4.6.2 HT3a Design Optimization

The HT3a tower has to support a larger weight as it is designed to support a larger wind turbine. Therefore, the HT3a total tower weight is higher than HT2. This resulted in a larger number of tower sections and column design variables in the optimization process. The design optimization problem is defined in Equation 4.6 below. The increased number of column design variables pose a more complex design problem for optimization. The design variables for HT3a optimization problem are defined in Table 4.8. The tower top deflection constraint is 700 mm as used for HT2. The frequency range constraint also changed due to the new turbine on the tower structure.

$$
\begin{aligned}
minimize:\ & f(\boldsymbol{x}) \\
& \boldsymbol{x} = [D_1, D_2, d_1 \cdots d_{18}, n_s]^T \\
subject\ to:\ & c_1(\boldsymbol{x}) \leq 700mm \\
& 1P \ \leq c_2(\boldsymbol{x}) \leq 3P \\
& c_3(\boldsymbol{x}) = 0 \\
& \boldsymbol{x}_L \leq \boldsymbol{x} \leq \boldsymbol{x}_U
\end{aligned} \tag{4.6}
$$

Table 4.8. Design variables for HT3a tower

Design variable	Description	Type	Lower bound	Upper bound
D_1	Base tower diameter	Continuous	28 ft	36 ft
D_2	Tower diameter of Section No. 11	Continuous	9.0 ft	14.5 ft
$d_1,\ldots,d_{18}$	Column diameter of 18 planes	Continuous	3.50 ft	3.83 ft
n_s	Number of post-tension strands	Discrete	60	130

The HT3a design optimization problem was successfully solved with the presented optimization framework. The convergence process of SOGA optimization is shown in Figure 4.12 where the best individuals are plotted with their performance in total tower cost, deflection, and frequency. The SOGA optimizer evaluated 9,277 candidate designs in total, and 8,293 of them were examined though NX Nastran simulation due to their geometry feasibility.

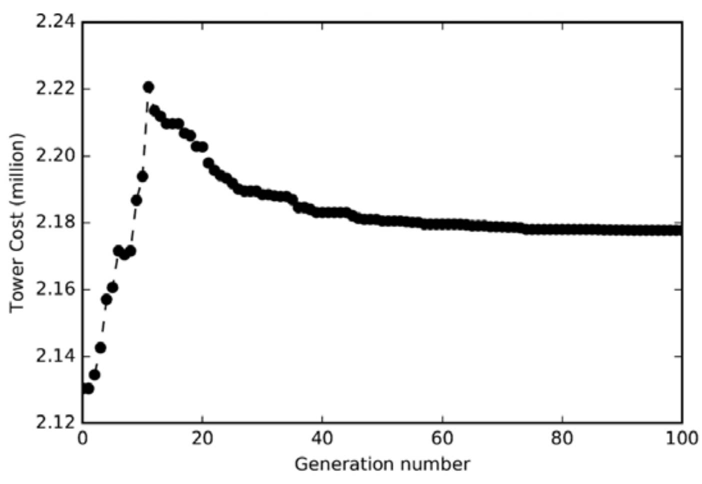


Figure 4.12. Convergence of the cost objective function in HT3a design optimization

Optimal design of HT3a is presented in Table 4.9 to compare with the initial design solution. The comparison of the two designs with respect to tower and columns diameters are shown in Figure 4.13. The optimal solution of HT3a has reduced column diameters compared to its initial design. Both HT2 and HT3a optimizations indicated that there is a great potential in material savings by improving the column design.

Table 4.9. HT3a initial design vs. optimal design

Descriptor	Initial design (ft)	Optimal design (ft)
D_1	31.03	33.27
D_2	11.00	10.70
d_1	3.83	3.56
d_2	3.83	3.55
d_3	3.83	3.54
d_4	3.82	3.54
d_5	3.81	3.53
d_6	3.80	3.53
d_7	3.80	3.52
d_8	3.79	3.51
d_9	3.78	3.51
d_{10}	3.77	3.51
d_{11}	3.76	3.51
d_{12}	3.75	3.50
d_{13}	3.72	3.50
d_{14}	3.69	3.50
d_{15}	3.65	3.50
d_{16}	3.62	3.50
d_{17}	3.59	3.50
d_{18}	3.59	3.50
n_s	92	90
Weight	**4357 kips**	**3904 kips**
Deflection	**564.11 mm**	**686.08 mm**
Frequency	**0.318 Hz**	**0.293 Hz**
Total Cost	**2.315 million**	**2.177 million**

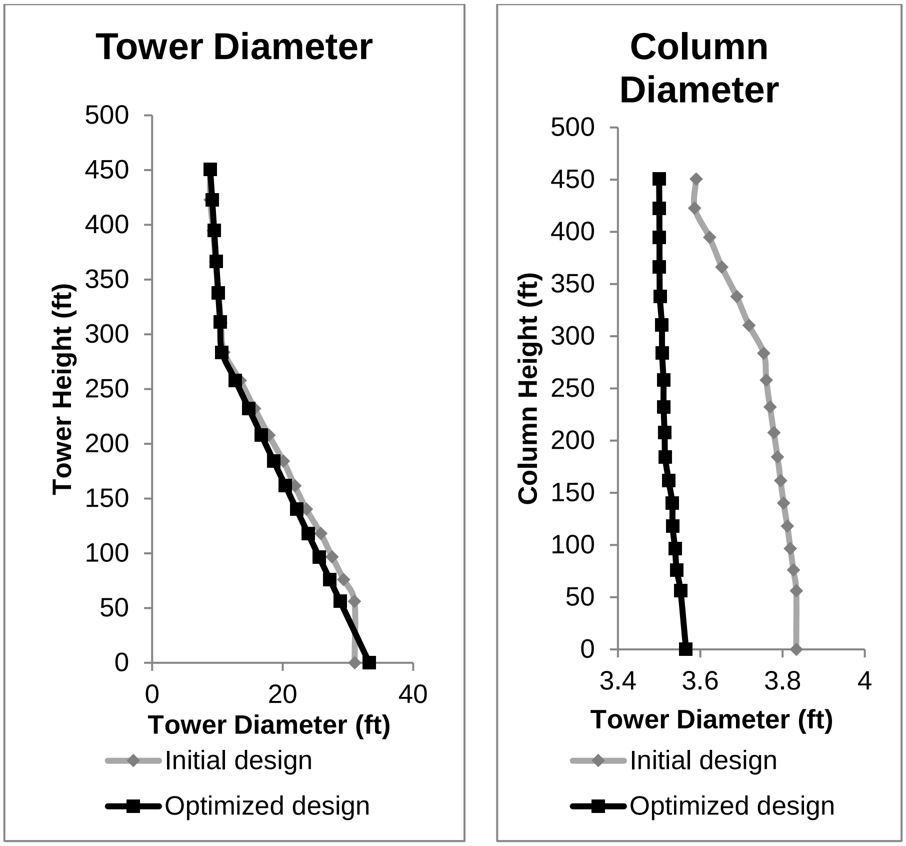
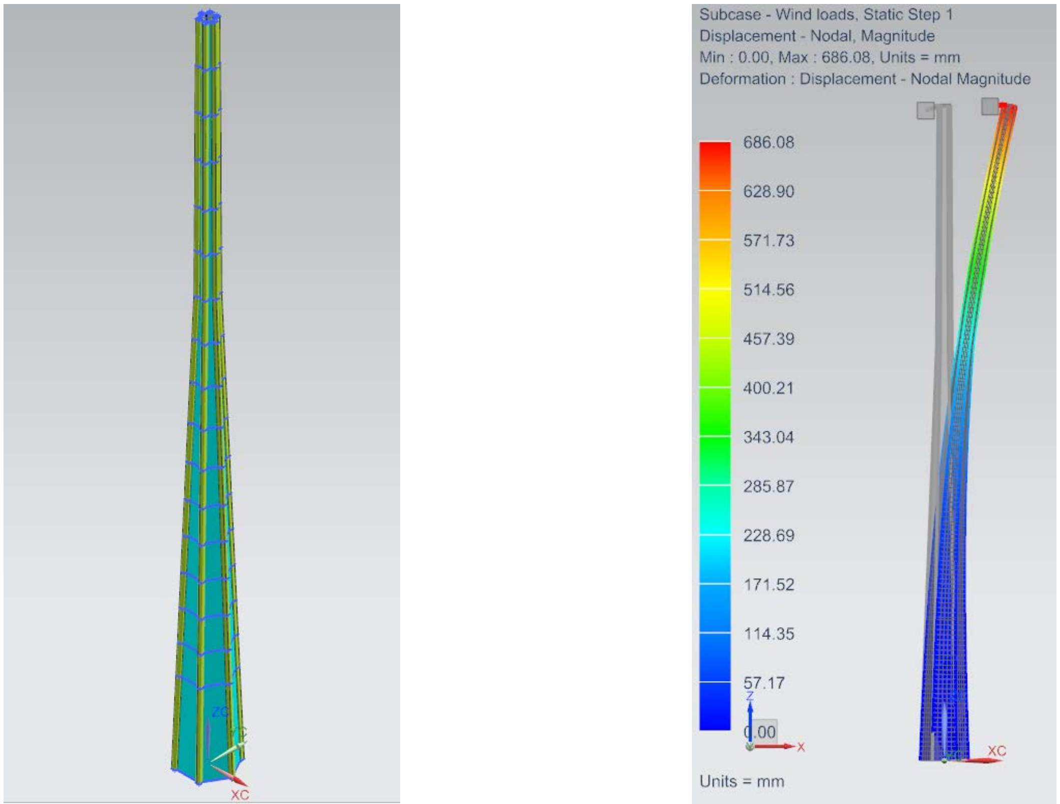


Figure 4.13. Comparison of HT3 initial design with optimal design

The cost reduction from the initial design achieved by the optimization of HT3a is significant. Optimal design solution reduces the total cost of the tower by 5.96%. NX Nastran analysis of the optimal design solution for the tower deflection is shown in Figure 4.15. The optimal design has larger deflection compared to the initial design. This finding is validated by the intuition that lighter structure tends to be more easily deflected under the same loading condition. If minimizing the deflection also becomes a design concern, a multi-objective design optimization can be performed to investigate the trade-off between tower cost and deflection.



(a) (b)

Figure 4.14. (a) CAD modeling of optimal design; (b) FEA analysis of the deflection under service load

4.7 LCOE Analyses of Optimal Designs

To evaluate the cost performance of optimized HT2 and HT3a design solutions with respect to their net energy production value, the Levelized Cost of Energy (LCOE, \$/MWh) was calculated following the standard NREL formula:

$$\mathrm{LCOE} = \frac{\mathrm{ICC} \times \mathrm{FCR} + \mathrm{AOE}}{\mathrm{AEP_{net}}} \quad (4.7)$$

ICC	Installed Capital Cost (\$/kW)	Tower cost included
FCR	Fixed Charge Rate (%)	9.5%
AOE	Annual Operating Expenses (\$/kW/yr)	35
AEP_{net}	Net Annual Energy Production (MWh/MW/yr)	HT2=6235; HT3a=7697

The results are listed in Table 4.10. Optimization has helped to reduce the LCOE further. Considering the current optimization only focused on the installation cost of the Hexcrete tower, a refined cost objective function involving maintenance cost and life-cycle cost could potentially achieve larger LCOE reductions through optimization in the future.

Table 4.10. LCOE of HT2 and HT3 designs*

LCOE ($/MWh)	Initial design	Optimal design
HT2	46.93	46.76
HT3	36.22	35.69

*This LCOE is a simplified calculation, which does not account for some variables and therefore is not fully realistic; a thorough, more accurate LCOE evaluation is presented in Chapter 6 of this report

4.8 Summary

The optimization of the Hexcrete tower was performed by successfully implementing an integrated tool that automatically generates Hexcrete tower CAD models, performs FEA simulation, calculates tower cost, evaluates constraints and performs optimization of the Hexcrete tower cost. Tower diameters, column diameters and the number of post-tensioning strands were included as design variables. Tower geometric constraints, tower frequency and deflection constraints were evaluated. Parallel computing was also applied to increase the speed of the optimization.

This framework was applied on the optimization of HT2 and HT3a designs. With the use of genetic algorithm, optimal designs were obtained for both towers. Comparing the optimal designs with the initial designs, tower cost reduction (1.31% for HT2 and 5.96% for HT3a) was obtained. The tower diameters did not deviate much from the initial designs. For both HT2 and HT3a, column diameters were reduced after the optimization.

Several key findings related to wind tower optimization were obtained from this study. The optimization framework introduced in this study improved the initial designs without violating the geometric and structural constraints. Since the optimization was automated and parallelized, the optimization took less than one day to complete. It was found that setting up the initial tower design, determining the appropriate wind load conditions and LCOE model actually took more time than the optimization process. On the other hand, in the future, more detailed and realistic cost models can be introduced in the objective function when such data would be available. In addition, genetic algorithm is complex and time consuming. When the number of design variables is large, high performance computing can be utilized to increase the speed of the optimization.

Chapter 5 – Foundation Design

5.1 Introduction

Three shallow foundations were designed to support three Hexcrete towers with different tower heights and turbine capacities: a 140 m (459 ft) tower with a Siemens 2.3 MW turbine (HT2), a 140 m (459 ft) tower with a Siemens 3.2 MW turbine (HT3a), and a 120 m (394 ft) HT tower with a Siemens 3.2 MW turbine (HT3b). Design and analysis of the three foundations are discussed in the following sections.

5.2 Foundation design

5.2.1 Design Objectives

The foundations were designed to supplement the towers designed by Iowa State University. This effort was geared towards a Component Certification (A-Design Assessment) proposed by DNV-GL for a generic turbine that meets the loading criteria of this basis of design and for a generic soil condition. The design of the foundation for the Hexcrete wind turbine tower was aimed at accomplishing the following objectives:

- The foundation shall be designed as slab foundation.
- The tower base shall be designed to avoid the need for soil improvement.
- The tower base and all connections shall be designed for high durability, minimum maintenance need, and the ability to replace or repair damaged parts; all connections shall be easily accessible for inspections.
- The design shall focus on detailing with mostly proven technology.
- The foundation shall be designed to minimize overall construction cost including site preparation, transportation and logistics, and site construction.

The foundation is a reinforced, cast-in-place concrete slab and was designed for load demands, tower weights, and generic soil properties. The soil properties will have to be confirmed by a geotechnical engineer for prototype structures. The foundation was designed to prevent tilting, bearing capacity failure, sliding, and settlement of the soil. No uplift shall be allowed during any combination of normal operating loads. The concrete cover shall be as specified in ACI 318 (ACI Committee 318, 2011).

5.2.2 Design Standards and Load Cases

The basis of design is primarily following the rules and guidelines per the ASCE/AWEA RP2011 Recommended Practice for Compliance of Large Land-based Wind Turbine Support Structures (ASCE/AWEA, 2011). In this document these rules and guidelines are referred to as "ASCE/AWEA RP2011". The foundation is designed to ensure operability for a 20-year service life. An ultimate limit state analysis of the foundation shall be completed and verified by calculations and/or tests to demonstrate the foundation's structural integrity, with appropriate factors of safety, for various design load cases. The design load cases are a combination of:

- Normal design situations with appropriate normal or extreme external load conditions;
- Fault design situations with appropriate external load conditions; and
- Fabrication, transportation, erection, and maintenance design situations with appropriate external load conditions.

Normal load conditions include the effects of inertial and gravitation loads, aerodynamic loads, operation loads, and other environmental loading conditions. When relevant, other parameters should be taken into account, including wind field perturbations due to the wind turbine itself, the influence of three-dimensional flow on the blade aerodynamic characteristics, unsteady aerodynamic effects, structural dynamics and the coupling of vibration modes, aeroelastic effects, and the behavior of the control and protection systems of the wind turbine.

Extreme wind conditions, usually with a 50-year return period, include the extreme wind speed at the site (EWM), extreme operating gust at hub height (EOG), extreme turbulence model (ETM) extreme direction change (EDC), extreme coherent gust with direction change (ECD) and extreme wind shear (EWS). Hurricane winds may also be taken into account. Assessing the seismic resistance of the tower is only necessary when required by the regional codes. No seismic design was required for this phase of design. No accidental loads were considered. The analysis of the foundation shall be done in five phases: analysis of foundation stability and ultimate strength, analysis of concrete cracking, analysis of foundation lift-off, analysis of fatigue failure, and foundation stiffness check. For the design of the foundation, not all of the dynamic load cases will be critical. The required design checks are found in Table 5.1.

Table 5.1. Required foundation design checks for dynamic load cases

Design Check		Load Cases
1	Ultimate strength check (LRFD)	Factored extreme events (all Design Load Cases (DLCs))
2	Stability check, foundation overturning check, and maximum deflection check	Unfactored extreme events (all DLC)
3	Maximum concrete compression check (GL 5.4.3.3)	Unfactored extreme operational one-year gust load plus loss of grid (DLC 1.5), 50 year extreme wind gust during power production (DLC 1.6), and non-turbulent power production plus temperature effects (DLC 9.4).
4	Serviceability check for cracking of reinforced concrete with bonded tendons if chloride induced corrosion can be excluded (GL 5.4.3.4.(2))	Unfactored extreme operational one-year gust load plus loss of grid (DLC 1.5) and non-turbulent power production plus temperature effects (DLC 9.4) plus heat influence per GL 6.6.6.1.2.(2).
5	Serviceability check for cracking of reinforced concrete or reinforced concrete with unbonded tendons (GL 5.4.3.4.(2))	Unfactored Quasi-permanent combination of actions such as operational turbulent power production loads (DLC 1.1) and normal turbulent wind in parked condition (DLC 6.4) with a probability of exceedance of 1750 h in 20 years ($p_f = 10^{-2}$).
6	Serviceability check on concrete decompression for prestressed concrete with bond if chloride induced corrosion can be excluded (GL 5.4.3.4.(1)) or for reinforced or unbonded prestressed concrete if omitting the load-dependent stiffness reduction (GL 5.4.3.5.(2))	
7	Checking of foundation lift-off at tower bottom (GL 6.7.6.3.(3))	
8	Fatigue check	Fatigue loads in form of spectra and associated (estimated) mean values
9	Dynamic characteristic check	Turbine/tower resonance criteria per GL 6.6.5

Design check 1, 2, and 7 will be used to define the overall geometry of the tower base. Design check 3 to 6 will be used to define the concrete outline and post-tensioning. Design check 8 will be used for the fatigue check of all structural components of the tower base. The five phases for the analysis of the foundation are detailed as follows:

1) Analysis of foundation stability and ultimate strength

To ensure the safety of the tower, partial safety factors are applied to the known loading conditions. For the "ultimate" (U) design load cases, these safety factors are classified as either normal (N), abnormal (A) or transport and erection (T). Normal load cases are expected to occur frequently within lifetime of turbine. Abnormal load cases are less likely than normal events and usually correspond to design situations with severe faults that result in the activation of system protection functions. The stability requirements of the foundation is to provide a 1.5 safety factor over overturning.

2) Analysis of concrete cracking

The service limit state condition to limit concrete cracking under extreme operational conditions shall be analyzed per Section 5.7.3.4 of the AASHTO LRFD Specifications (AASHTO, 2007). The check is performed on unfactored loads.

3) Analysis of foundation lift-off

The service limit state condition to avoid lift-off of the foundation under non-turbulent power production and normal startup and shutdown conditions shall avoid a change of the dynamic characteristic of the tower due to a change of foundation stiffness. The criteria is described in ASCE/AWEA Section 8.6.1.5 (ASCE/AWEA, 2011). The check is performed on unfactored loads.

4) Analysis of fatigue failure

Fatigue analysis (F), performed using Miner's rule, assesses the fatigue strength of the tower using appropriate factors of safety. Fatigue effects shall include the effects of both cyclic range and mean stress levels. Partial safety factors shall be included for the effects of load, material and consequences of failure when determining the incremental damage associated with each fatigue cycle. The fatigue analysis of steel components shall be based on equivalent damage loads, fatigue load spectra, or Markov Matrixes as appropriate. The damage accumulation due to fatigue shall be represented as stress ranges; each stress range shall be paired with its associated stress cycle number and mean stress where needed. The Palmgren/Miner rule shall be used to verify that the accumulated damage is less than 1.

$$D = \sum_i \frac{n_i}{N_i} \leq 1 \qquad (6.1)$$

where n_i is the number of stress cycles for one stress range and N_i is the number of allowable stress cycles for one stress range or stress pair (mean and range). The number of allowable stress cycles, N_i, is the number of stress cycles related to the stress range, $\Delta\sigma_i * \gamma_m$, on the S/N curve.

Simplified fatigue analysis for the reinforced concrete foundation shall follow one of the three fatigue methods in the *fib* Model Code 2010. The following parameters are required for the analysis:

- Maximum load range
- Load range with largest concrete compressive stress, σc,max
- Load range with smallest concrete compressive stress, σc,min
- Load range with largest mean value for concrete compressive stress

The fatigue analysis procedure is based on characteristic S/N curves for mild steel, and concrete. The concrete S/N curves are developed for compression, compression-tension, and pure tension or tension-compression. To calculate the damage accumulation for foundation, the procedure set forth in the Model Code 2010 shall be followed. This procedure determines maximum design life, in number of cycles, for a given mean stress/stress range pair for a maximum and minimum load level.

5) Foundation stiffness check

The foundation shall be checked that under zero foundation uplift (i.e. under nonturbulent power production and normal startup/shutdown loads), the foundation meets the requirement to provide a minimum rotational stiffness of 900 MN-m/rad and a minimum horizontal stiffness of 300 MN/m.

5.3 Foundation materials

Cast-in-Place Concrete for Foundation

- Normal weight concrete of a unit weight of 2,400 kg/m^3 (150 pcf) without reinforcement
- Characteristic concrete strength (f'_c) of 28 MPa (4,000 psi) at 28 days

Reinforcement

The mild reinforcement in the various elements of the concrete base shall be designed to combat local temperature and shrinkage effects. Select mild reinforcing properties per ACI 318 are as follows:

- ASTM A615 Grade 60
- Steel Grade Class B/C
- Characteristic yield strength (fy) of 414 MPa (60 ksi)

- Ratio of characteristic tensile strength to yield strength (f_{tk}/f_{yk}), k, greater than or equal to 1.08 and less than 1.35
- Characteristic strain at maximum force, εuk, greater than 5.0%

5.4 Soil assumptions

The final design of the wind turbine tower foundation shall be based on soil data determined as a result of a site specific geotechnical investigation. The Hexcrete tower foundation shall be designed for a soil profile with the following generic properties:

- Allowable bearing pressure under operation conditions: 115 kPa (2,402 psf)
- Allowable bearing pressure under extreme conditions: 237 kPa (4,950 psf)
- Poisson's ratio: v = 0.5 (saturated)
- Dry weight: γ_d = 17 kN/m^3 (108 pcf)
- Location of ground water table below surface: D_f = 2 m (6.6 ft)

This is considered a typical condition for wind turbine tower foundation soil in the Midwest.

5.5 Soil-foundation interaction

Soil stiffness has a significant influence on the dynamic behavior of the tower. To advance the understanding of the soil-foundation interaction, a comprehensive 3-D finite element model (Figure 5.1) was developed in Abaqus with an elastoplastic soil constitutive model (Anastasopoulos et al. 2011, see Figure 5.2). The model can accurately capture the soil dynamic behavior, and includes a soil-foundation interface that allows the foundation to move relative to the soil (e.g., detach and slide). The 3-D soil model is a three-layer soil column with a diameter of 66 m (217 ft) and a total depth of 16.5 m (54 ft). The soil properties of this soil model are shown in Table 5.2. This 3-D FE method is different from the most common simplified method that uses equivalent springs to represent soil stiffness in the following aspects:

1) This 3-D FE method simulates the soil stiffness using solid elements and dimensions of interest, whereas the simplified method simplifies the 3-D soil model with equivalent springs;

2) The 3-D FE method simulates the foundation structure using soild elements and actual dimensions, whereas the simplified method simplifies the foundation slab with a shell model and the pedestal part with rigid links.

3) The 3-D FEM method simulates the soil-foundation interface with special “gap” elements (Abaqus), allowing the foundation to rock on the soil, whereas the simplified method simplifies the interface with a tied connection between springs and the foundation slab.

4) The 3-D FEM method simulates the soil behavior with an elastoplastic soil model to capature soil elastic settlement and consolidation, whereas the simplified method can only rely on empirical equations.

5) The 3-D FE method simulates the soil profile with multiple layers to better represent the real site condition for foundation dynamic characteristic check, whereas the simplified model can only employ empirical equations for a soil profile with two layers (i.e., one stratum over bedrock or half-space).

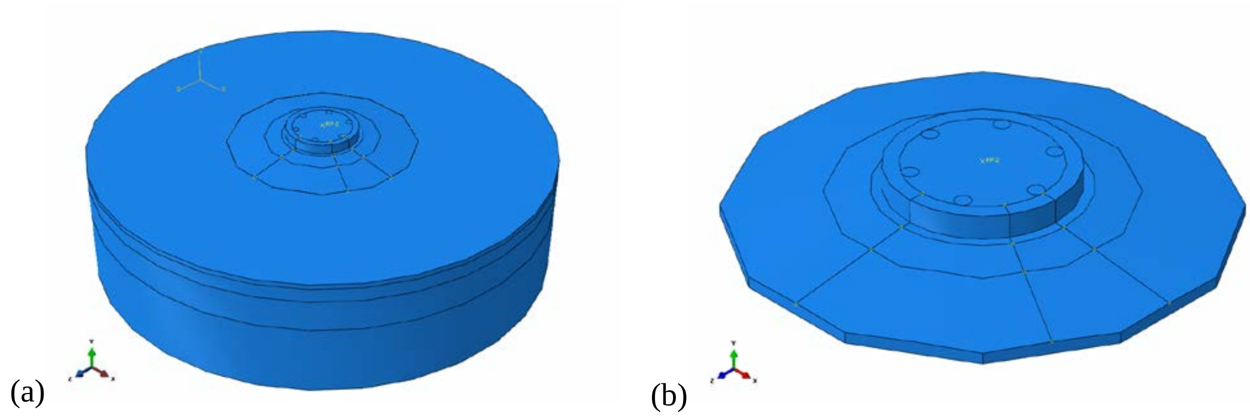


Figure 5.1. 3-D FE model: (a) foundation-soil and (b) foundation

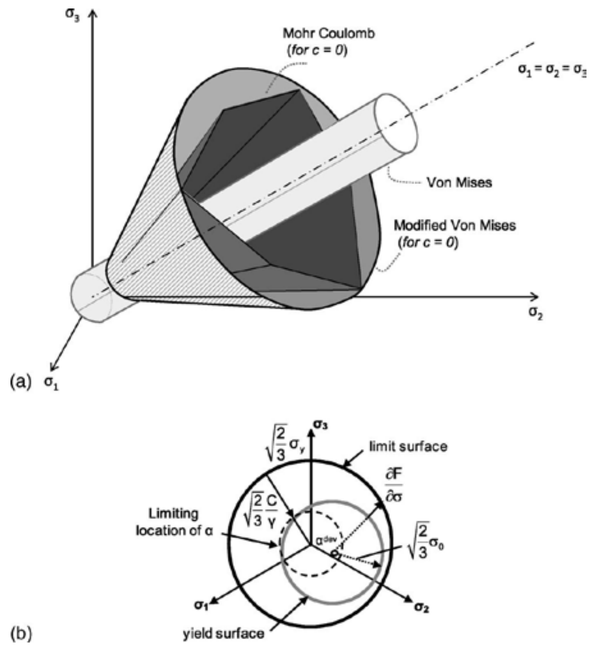


Figure 5.2. Simplified constitutive model: (a) representation of the extended pressure-dependent Von Mises failure criterion in the principal stress space (hashed shape) together with the Von-Mises (light grey shape) and the Mohr Coulomb failure criterion (dark grey shape); (b) projection of the failure surface at pressure $p = (\sigma_1+\sigma_2+\sigma_3)/3$ on the π-plane. (Anastasopoulos et al. 2011)

Table 5.2. Soil properties of a three-layer clay profile underneath the foundation bottom

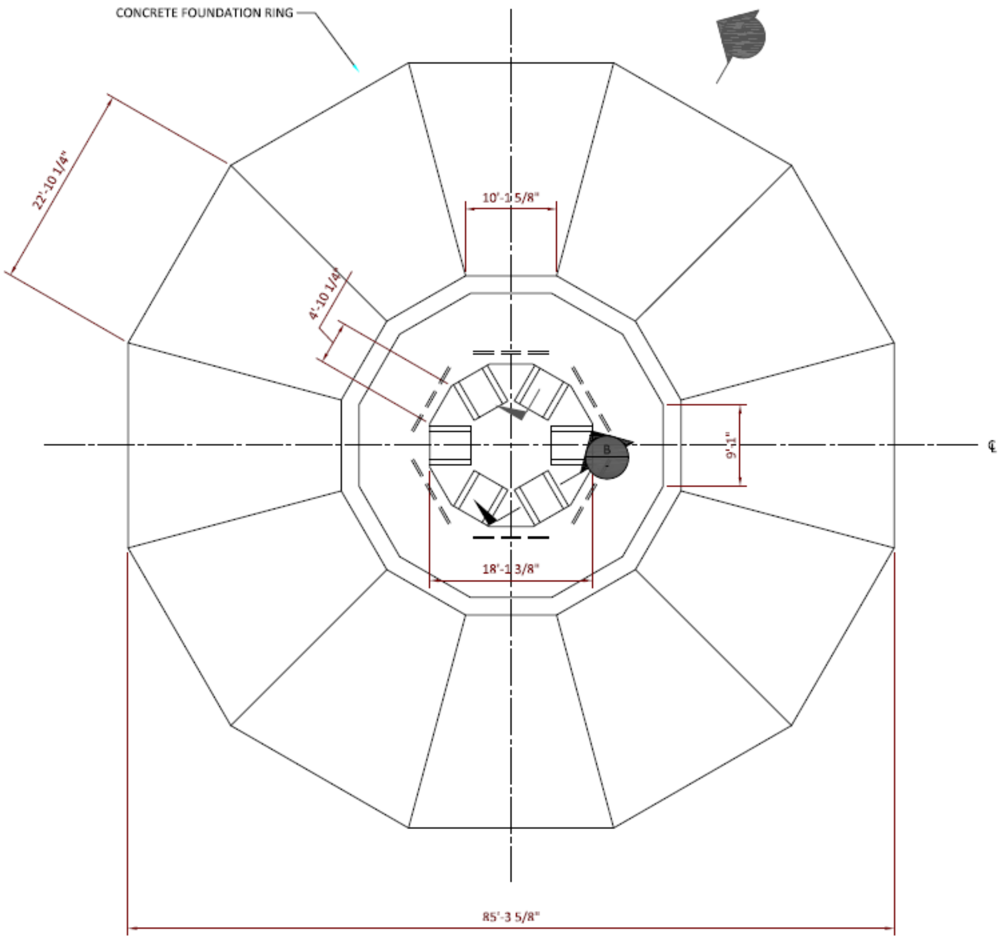
Layer #	Thickness	Undrained shear strength	Young's modulus
1	2 m (7 ft)	50 kPa (1,044 psf)	50 kPa (1,044 psf)
2	4.5 m (15 ft)	100 kPa (2,089 psf)	100 kPa (2,089 psf)
3	10 m (33 ft)	200 kPa (4,177 psf)	200 kPa (4,177 psf)

5.6 Foundation details

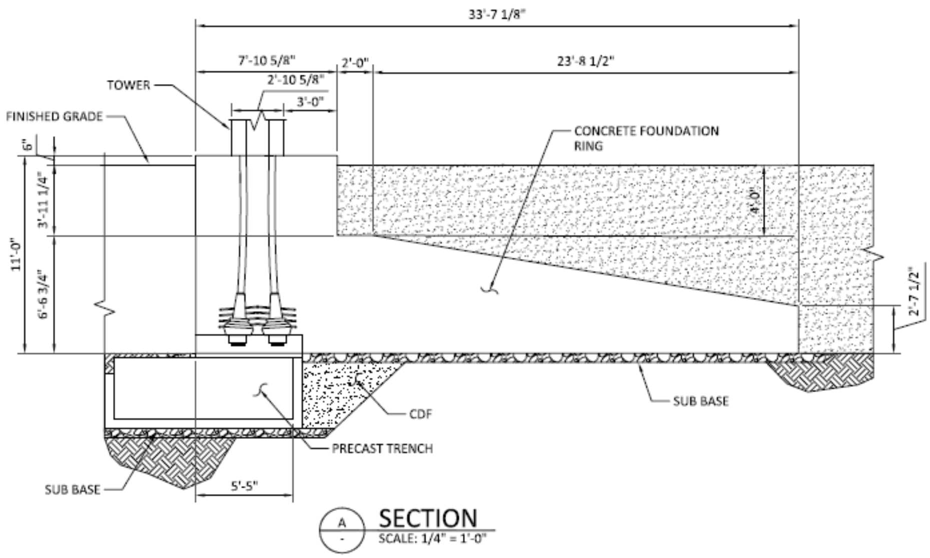
The final designs are three dodecagonal shallow foundations; dimensions of the three foundations are listed in Table 5.3. These foundations use precast trenches to access the bottom of columns to complete the post-tensioning. Plan and section views of HT2 and HT3a foundations are shown in Figure 5.3.

Table 5.3. Dimensions of three foundations.

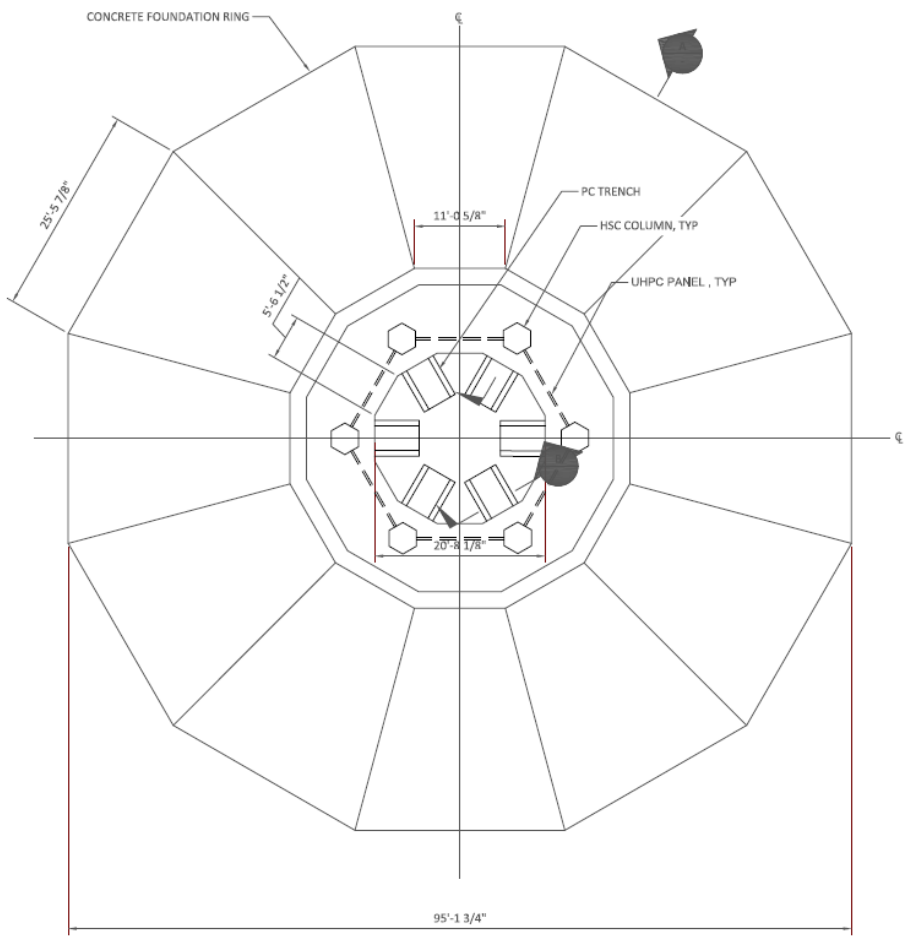
Foundation	Diameter	Slab Thickness		Pedestal Thickness
		Middle	Edge	
HT2 (140-m, 2.3 MW)	26 m (85 ft)	2 m (78.7 in)	0.85 m (33.5 in)	1.35 m (53.2 in)
HT3a (140-m, 3.2 MW)	29 m (95 ft)	2.15 m (84.6 in)	0.95 m (37.4 in)	1.35 m (53.2 in)
HT3b (120-m, 3.2 MW)	27 m (89 ft)	2.05 m (80.7 in)	0.85 m (33.5 in)	1.35 m (53.2 in)



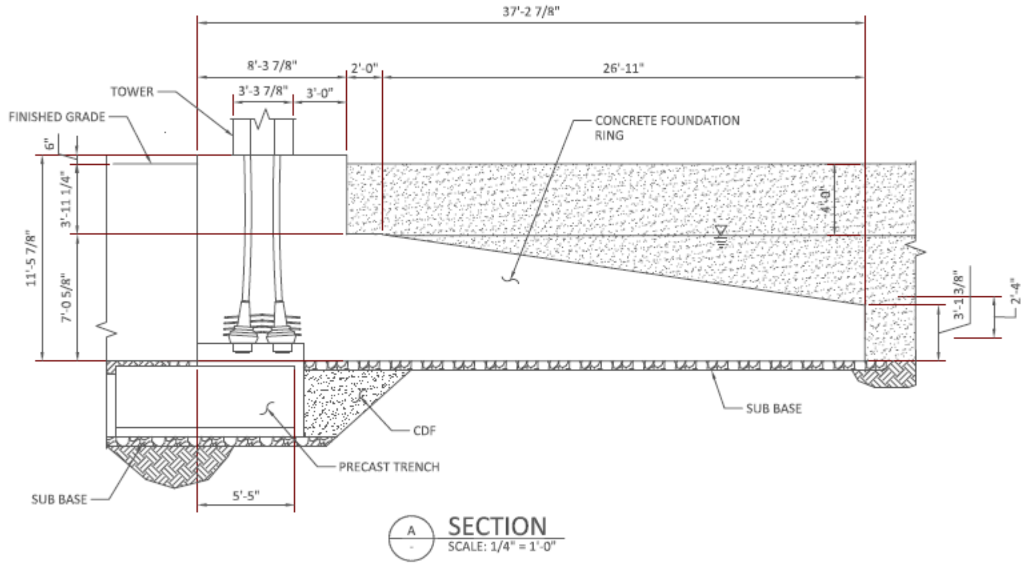
(a)


33'-7 1/8"
7'-10 5/8"
2'-0"
23'-8 1/2"
2'-10 5/8"
3'-0"
TOWER
FINISHED GRADE
CONCRETE FOUNDATION RING
6"
3'-11 1/4"
11'-0"
6'-6 3/4"
4'-0"
2'-7 1/2"
CDF
PRECAST TRENCH
SUB BASE
SUB BASE
5'-5"
A
SECTION
SCALE: 1/4" = 1'-0"

(b)


CONCRETE FOUNDATION RING
25'-5 7/8"
11'-0 5/8"
PC TRENCH
HSC COLUMN, TYP
UHPC PANEL , TYP
5'-6 1/2"
20'-8 1/8"
95'-1 3/4"

(c)



(d)

Figure 5.3. Plan and section views of the dodecagonal shallow foundations: (a) and (b) for HT2, and (c) and (d) for HT3a.

5.7 Analysis of foundation performance

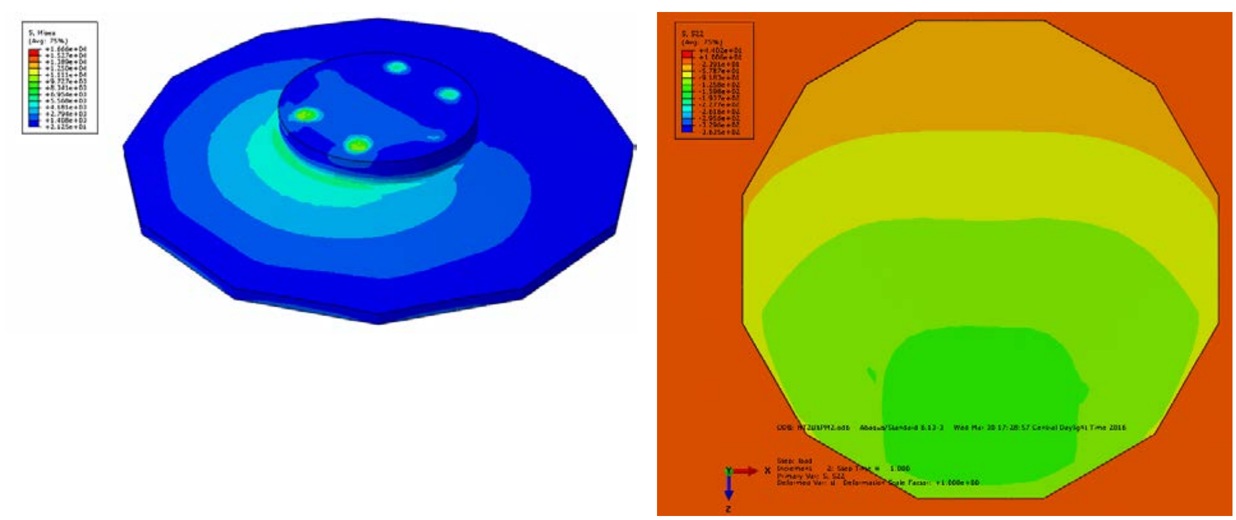
After first checking foundation size for bearing and overturning capacity, the results from the design calculation program and FE simulation demonstrate that all three foundations have sufficient bearing and overturning capacity with a diameter of 26, 29, and 27 m. Basic information of the three foundations is listed in Table 5.4. Generally, the foundation weight and amount of reinforcement increase as the tower height and turbine capacity increase. Although three foundations are different, they all have an eccentricity ratio of about 0.15, much smaller than the tolerance value of 0.3.

Table 5.4. Basic information of three foundations

Foundation	Concrete weight (US ton)	Reinforcement weight (US ton)	Eccentricity ratio	Tower plus turbine weight / Foundation weight
HT2 (140-m, 2.3 MW)	2,132	159	0.16	0.74
HT3a (140-m, 3.2 MW)	2,867	234	0.15	0.88
HT3b (120-m, 3.2 MW)	2,338	182	0.15	0.89

Results from finite element simulations of the three foundations under ultimate loads are shown in Figure 5.4. The stress information from the simulations can be used to get design force diagrams from center to edge: 1) a moment diagram about the radial (circumferential) axis for a unit width can be calculated with the maximum normal stresses in the circumferential (radial) direction at the column edge, pedestal edge, midsection, and edge of the foundation, and 2) a vertical shear force diagram can be calculated by integrating the vertical shear stresses over an area that has a unit width and the depth of those locations. The Von Mises stress contours in Figures 5.4a, c, and e demonstrate that the stress decreases as the distance from the foundation center increases, and thus so do the slab thickness and reinforcement amount. The soil vertical stress contours in Figures 5.4b, d, and f demonstrate that: 1) the soil vertical stress has the maximum value close to one edge and the minimum close to the opposite edge, and 2) all soil underneath the foundation is under compression—any edge of the foundation will not be lifted and detached from soil.

a) b)



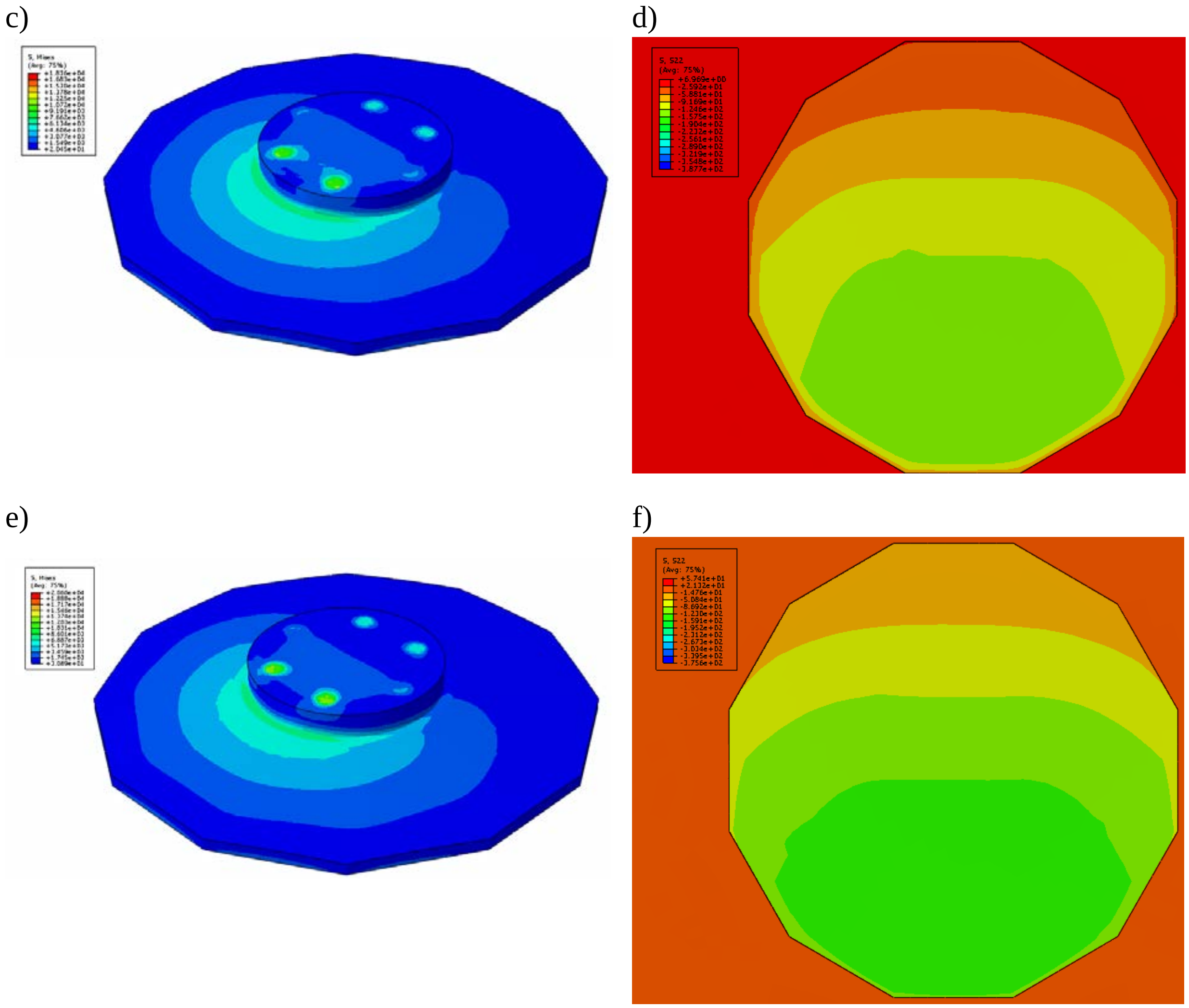


Figure 5.4. Von Mises stress in foundation and vertical stress in soil from FE simulation under ultimate load: a) and b) for HT2, c) and d) for HT3a, and e) and f) for HT3b

The fatigue analysis is based on Markov Matrix, as shown in Figure 5.5. The Markov Matrix of a 115-m, 2.3-MW tower provided by Siemens was scaled for the three foundations according to tower height and turbine capacity. The fatigue design ensures that the accumulated damage of concrete and the demand capacity ratio of steel are both less one.

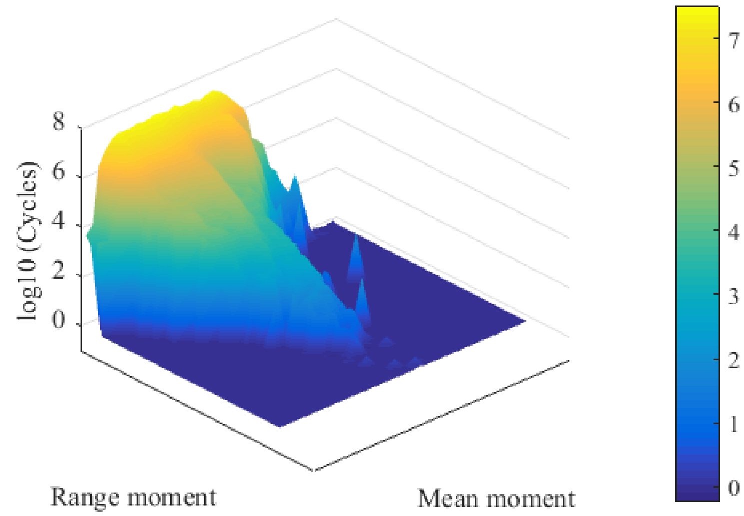


Figure 5.5. Markov matrix for fatigue analysis

The foundation dynamic characteristic check uses the vertical, rotational, horizontal, and torsional displacement responses from the FE simulations under axial, moment, shear and torque loads, respectively. The global model stiffness under each load scenario, as summarized in Table 5.5, indicates that all three foundation-soil systems have sufficient stiffness under four load scenarios.

Table 5.5. Global model stiffness

Foundation	Vertical (MN/m)	Rocking (MN-m/deg)	Horizontal (MN/m)	Torsional (MN-m/deg)
HT2	17,590	12,940	1,805	6,136
HT3a	24,810	19,440	5,310	10,000
HT3b	17,980	1,2940	1,804	3,046
Minimum value		> 900 MNm/deg	> 300 MN/m	

5.8 Summary

The designed three shallow foundations have diameters of 26, 29, and 27 m for HT2, HT3a, and HT3b, respectively. The design process has involved five phases of analysis: 1) foundation stability and ultimate strength, 2) concrete cracking, 3) foundation lift-off, 4) fatigue failure, and

5) foundation stiffness check. A MathCad program was developed for the five phases of analysis and dimension and reinforcement of the foundations were finalized by manual iteration of key parameters in the program. To study the soil-foundation interaction, a sophisticated 3-D finite element model was developed with an elastoplastic soil constitutive model and a soil-foundation interface to better capture the soil and foundation responses. The finite element simulations demonstarted that all three foundations had sufficient bearing, overturning capacity, and stiffness and can ensure operability of the three towers for a 20-year service life.

Chapter 6 – Levelized Cost of Energy

6.1 Introduction

This chapter discusses construction cost analysis and results obtained from 140 m Hexcrete wind tower options (HT2- 2.3MW and HT3a- 3.2MW) and the LCOE analysis results. To ensure the most reliable LCOE, a bottom-up approach was used to estimate the construction costs by breaking down construction sequences into work package level activities and estimating each activity's schedule and cost. The model utilized by NREL was used to determine the LCOE of each option by incorporating the tower construction cost estimates into their existing LCOE framework.

6.2 Data collection

Hexcrete towers have not been built before; therefore, the research team engaged industry experts to obtain reliable information regarding constructability, construction, and assembly sequences, required resources and realistic production rates of construction activities. The research team identified subject matter experts from the industry for each estimation activity. In addition, the research team organized a workshop with a group of industry experts to draw the most practical approaches for constructing and erecting the 140 m Hexcrete towers. Note that a similar approach was followed in BP1 with the LCOE analysis of HT1.

6.3 Industry Workshop

An industry workshop was held on the 23rd and 24th of March 2016 at a Mortensen facility in Minneapolis, MN. In this workshop, industrial and academic members brainstormed and discussed various Hexcrete tower construction processes for 140-m (459 ft) tall Hexcrete towers and also conducted a Strengths, Weaknesses Opportunities, Threats (SWOT) analysis of the new tower technology. At the end of the workshop, realistic and effective solutions for the tower erection were identified. The companies and other entities engaged in this workshop besides the project partners included:

- Barr Engineering – Foundation design
- Coreslab Structures of Omaha – Precast concrete manufacturer
- Mammoet USA– Erection crane rental (Participant was formerly with Bigge Crane and Rigging Co.)

- Mortensen – Wind farm contractor
- NREL – LCOE model developer
- Pattern Energy – Wind power owner and developer
- Wells Concrete – Precast concrete manufacturer

The topics discussed in this workshop specific to towers ranged from transportation of the precast concrete sections to identifying efficient assembling sequences for the tower components on site. Additionally, equipment choices were assessed for each distinctive phase of the assembly process to ensure an efficient process. Since a 140-m (459 ft) Hexcrete tower is much taller and much heavier than the 120-m (394 ft) Hexcrete tower, it is essential to identify the correct equipment and logical sequence of assembly, as the wind farm will contain 100 turbines. To produce this quantity of tall towers is a challenge that researchers heavily discussed during the meeting. Since the focus was to build a tower at a hub height of 140-m, a crane supplier at the workshop found a suitable high-capacity crane to stack the tower cells. With the right equipment identified for the assembly process, the researchers began to assess the procedure of how the tower would be assembled on site. Each expert provided their knowledge and experience in their area of specialization, which helped the team select the appropriate crew size, production rates, schedule, and costs. Among the many assembly options discussed, the workshop team ultimately chose the following two assembly options for further consideration:

- Option I (HT2 and HT3a): Build the entire tower using Hexcrete cells
- Option II (HT2 Hybrid and HT3a Hybrid): Use Hexcrete cells for the bottom 70% of the tower and steel sections for the remainder.

Table 6.1 lists the two options for the two towers in terms of the required Hexcrete cells and the number of steel sections. The number of sections were determined based on the weight limits imposed by the crane supplier.

Table 6.1. Two Tower Options for HT2 and HT3

Options	Type of tower	Number of Hexcrete cells	Number of steel sections
Option I	HT3a	16	N/A
	HT2	14	N/A
Option II	HT3a hybrid	11	3
	HT2 hybrid	10	3

HT3a Option I and HT2 Option I are to be assembled for a total of 16 and 14 Hexcrete cells, respectively (see Figure 6.1 and Figure 6.2). The precast concrete columns and panels will be transported to the site individually and will be assembled on the ground into cells on site. The cells up to approximately 80 m (263 ft) will be erected vertically by a 400-ton crawler crane such as the Manitowoc 16000. The cells above 80-m (263 ft), the nacelle, and the rotor will be erected with a much higher capacity crawler crane (1,000 ton) such as the Liebherr 11350 with a maximum hoist height of 196 m (643 ft).

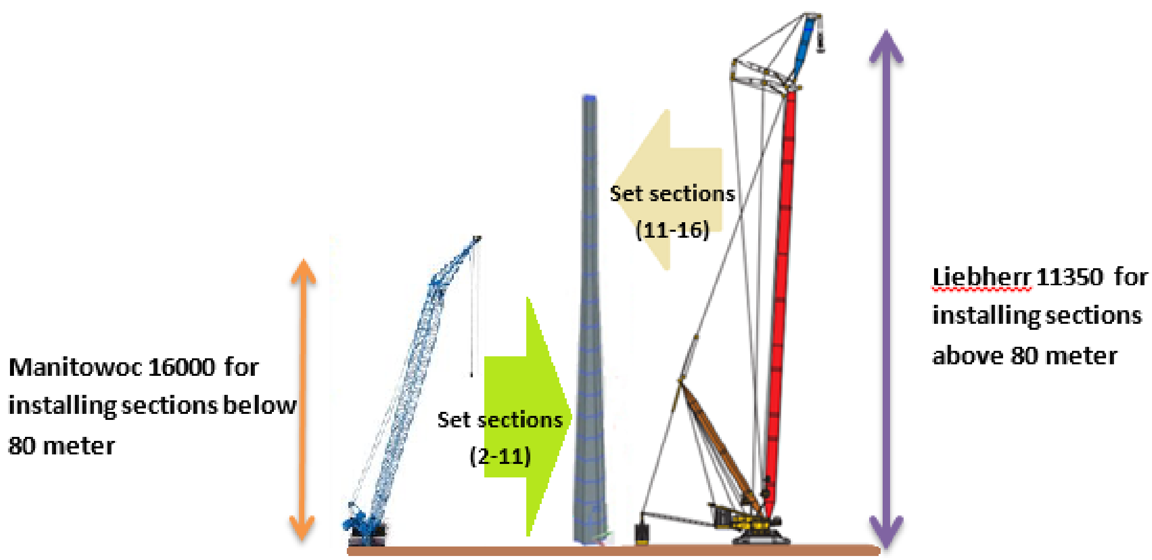


Figure 6.1. Option I chosen for HT3a tower

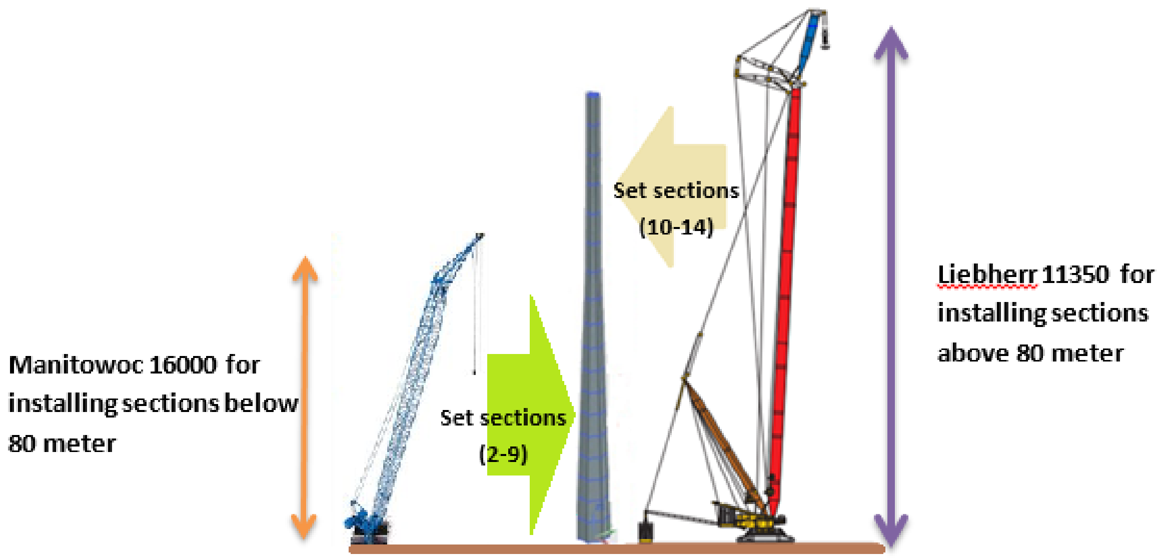


Figure 6.2. Option I chosen for HT2

As shown in Figure 6.3 and Figure 6.4, HT3a Option II (i.e., the hybrid option) consists of a total of eleven Hexcrete cells up to the assembled height of 85 m (279 ft) with three steel top sections for the remaining height; smaller steel sections were preferred so that no special trailer would be required to transport them. HT2 Option II consists of ten Hexcrete cells up to 93 m (305 ft) and three steel sections for the remainder of the tower. Option 2 will also have the precast panels and columns shipped to the site and assembled into cells on the ground prior to assembling the tower. The first cell for all tower options will be assembled directly on the top of the foundation, followed by the stacking of the other Hexcrete cells up to the height of 80 m (263 ft) using a 400-ton crawler crane. The last Hexcrete cell, steel sections, nacelle, and rotor will be assembled using the higher capacity crawler crane.

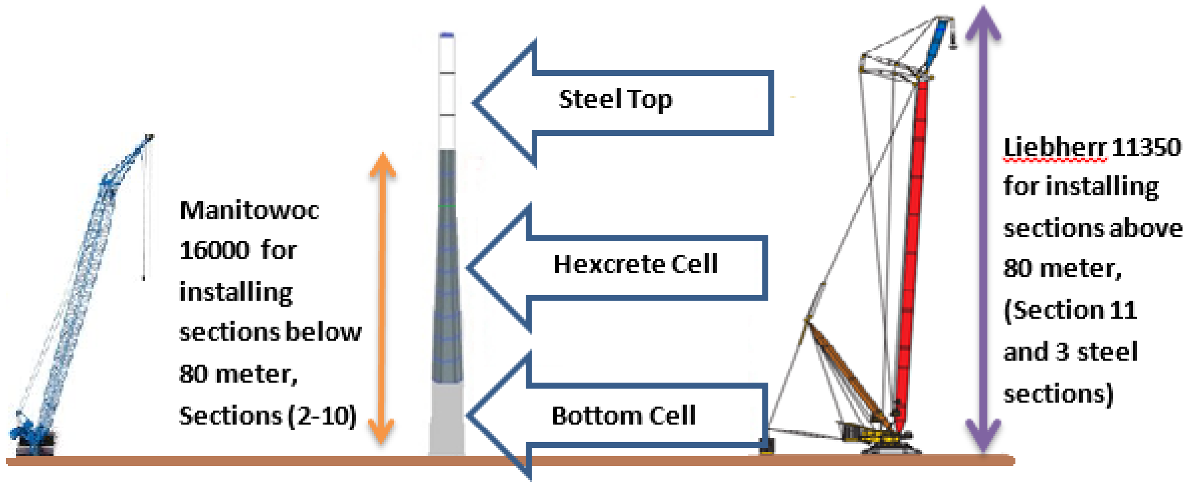


Figure 6.3. Option II chosen for HT3a hybrid tower

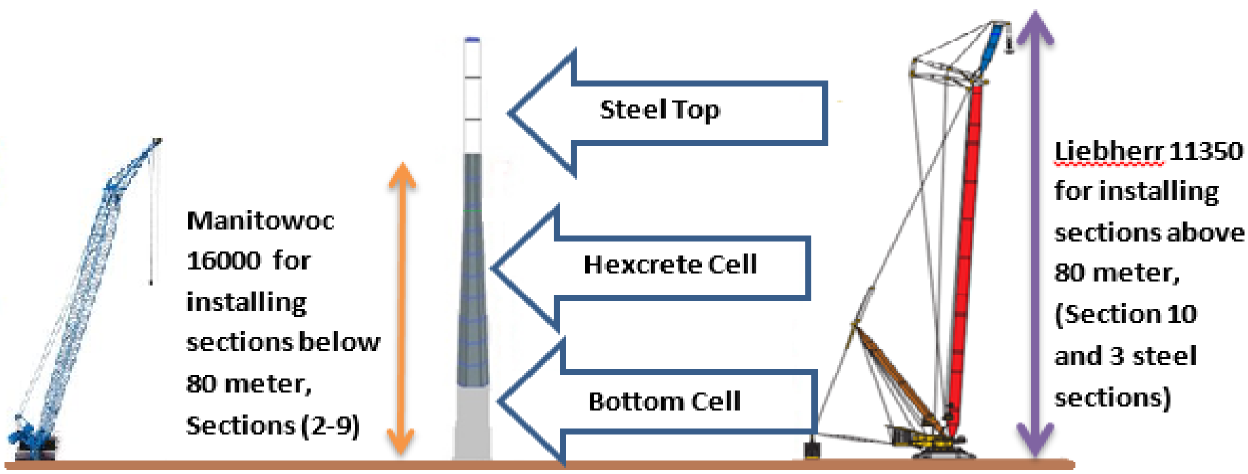


Figure 6.4. Option II chosen for HT2 hybrid tower

6.4 Work Breakdown Structure (WBS)

To obtain realistic cost estimates, the work sequence for a 140-m Hexcrete tower construction project was divided into five major work activities:

1) Mobilization and access road construction
2) Foundation construction
3) Fabrication and transportation of Hexcrete columns and panels
4) Delivery of wind turbine components
5) Assembly of wind tower components

Figure 6.5 shows the WBS for HT2 Option I and Option II. For these two options, the work sequences are the same, except that Option 1 (all Hexcrete cells) will continue to stack Hexcrete cells while Option 2 (hybrid model) will stack Hexcrete cells and then steel sections, as shown in Figure 6.5.

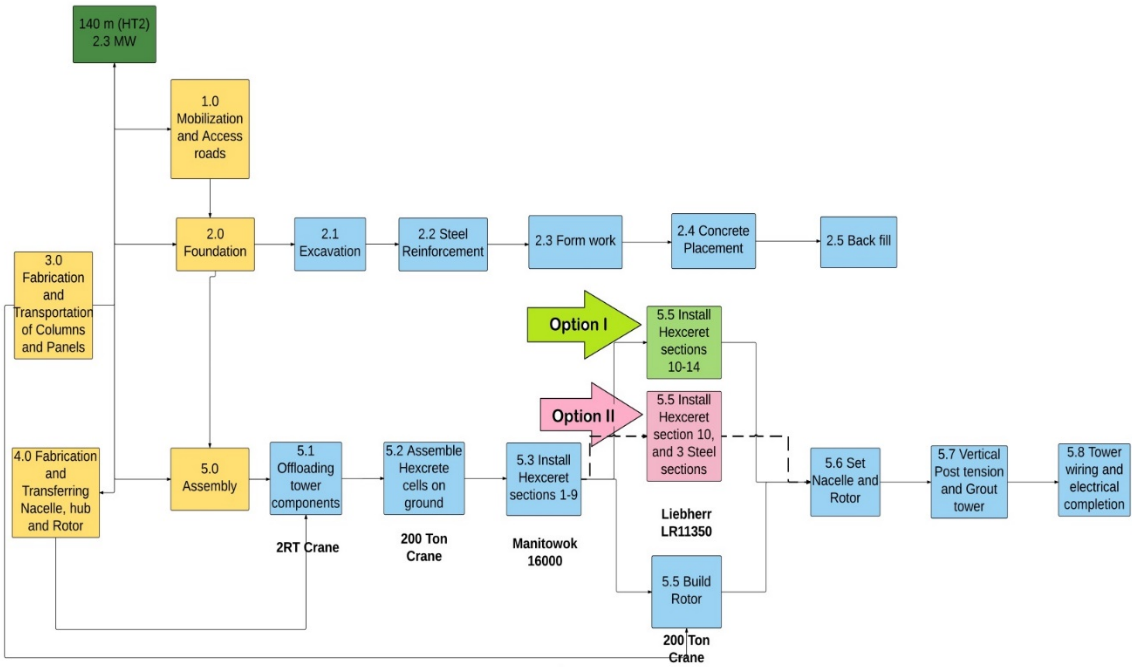


Figure 6.5. Work Breakdown Structure for HT2 towers

6.5 Mobilization and access roads

In this phase, the primary resources are mobilized, and access roads are constructed to facilitate the transportation and delivery of materials, Hexcrete tower components, and construction equipment. These roads can be easily built with the current industry practices and no new technology is required. Additionally, they can be built between existing public roadways and the wind farm site, which will eventually be converted to permanent transportation routes.

6.6 Foundation

Foundations are constructed by excavating the tower foundation area, placing reinforcing steel, and pouring concrete into the excavation. Only the very center of the foundation remains above the soil surface when grading is complete. Work sequence of foundation is visualized in Figure 6.6. The current construction technologies can be used to build the foundation.

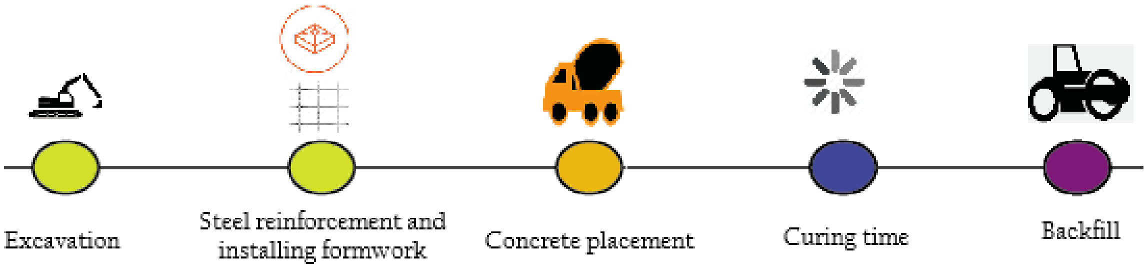


Figure 6.6. Stages assumed for foundation construction

6.7 Fabrication and transportation of Hexcrete columns and panels

Precast concrete panels and columns are fabricated from a manufacturing plant and transported to the job site. The transportation distance is assumed to be 200 miles (322 km), to match the distance estimation used in the NREL's LCOE model. A precast concrete manufacturer's cost estimate based on the Hexcrete tower design and quantity of work was used to approximate the costs of material, fabrication, and transportation. Wind turbine components including nacelle, blades, and transition pieces are transported to the job site using standard methods and no innovation is applied to this task.

6.8 Assembly of wind tower components

Precast concrete columns and panels will be offloaded using two rough terrain (RT) crawler cranes and three forklifts. Then, each of the Hexcrete sections will be assembled on ground. For assembling each cell, all six of the columns and panels would need to be placed in the correct upright position, leveled, and braced. When all the columns and panels are leveled and in the right position, epoxy is placed between the column and panels. The post-tensioning strands are then installed around the circumference of the unit and tensioned. In the end, internal ladders will be fitted within the cell (Figure 6.7).

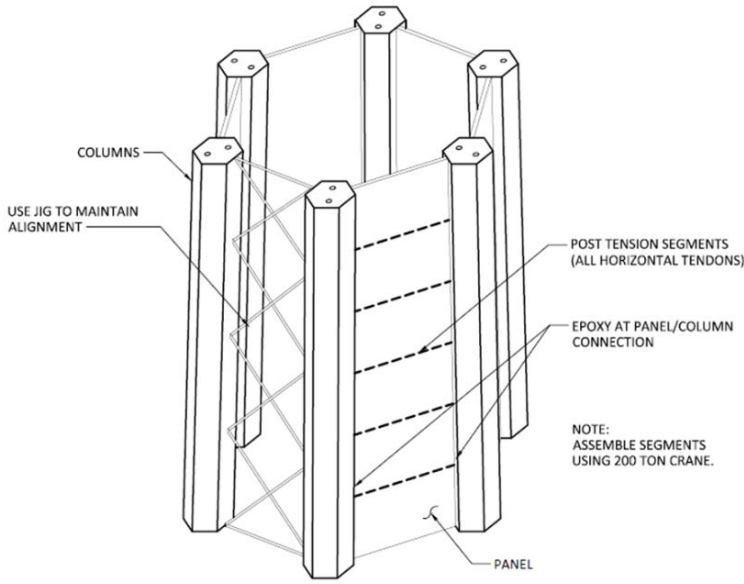


Figure 6.7. Assembly of a Hexcrete cell

Individual cells are assembled first using a 400-ton crane until all cells are joined, as shown in Figure 6.8. These joints located between the cells will be sealed with grout and vertical post-tension cable will run the entire length of the tower and be post-tensioned. A Liebherr crawler crane will be brought to the site to erect the Hexcrete cells above 80-m and the steel top sections (for the hybrid option). Meanwhile, the turbine components will be offloaded, and a 200-ton crawler crane will be used to build a rotor. The Liebherr crawler crane will be used to lift the assembled rotor and install the turbine as well. The tower will be marked as fully finished when all wiring and mechanical processes are completed. The overall work sequence of assembly is visualized in Figure 6.9.

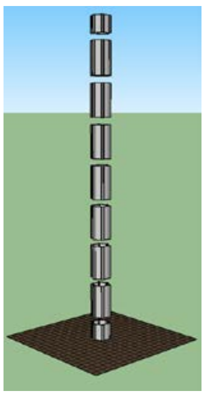


Figure 6.8. Stacking cells on each other

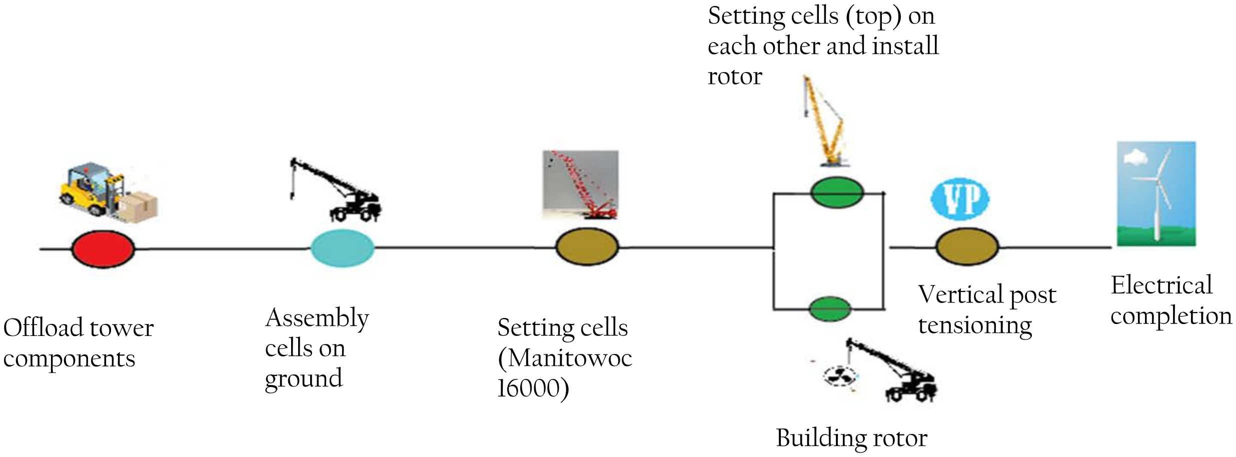


Figure 6.9. Assembly work sequence

6.9 Production rate estimation

A good estimation of production rates for work activities is critical for construction cost estimating, as the production rates determine the crew size, activity duration, and activity cost. The production rates of most work items such as excavation, concrete pouring, installation of steel reinforcements and formwork, vertical post-tensioning, offloading tower components, and mechanical and electrical completion can be satisfactorily obtained based on the current industry practices as shown in Table 6.2.

Table 6.2. Production rates for common construction activities in industry.

Activity	**Task**	**Production rate**
Foundation	Excavation	2080 (B.C.Y*/Day)
	steel reinforcement	50 (T/ Day)
	Formwork	1300 (L.F/Day)
	Concrete placement	700 (C.Y/Day)
	Backfill	1500 (B.C.Y/Day)
Assembly		
	Offload Hexcrete columns and panels	3 (Days/WTG)
	Offload other wind tower components	3 (Days/WTG)
	Build rotor	1 (Day/WTG)
	Vertical post tensioning	2 (Days/WTG)
	Tower wiring	2 (Days/WTG)
	Electrical completion	2 (Days/WTG)

*B.C.Y. - Bank Cubic Yard

Currently there is no historical production rate data available for assembling Hexcrete cells on ground and setting the cells on top of each other. The research team and experts from the industry discussed constructible options and their work sequences together with required resources based on the equipment available today and developed three different plausible production rates. As shown in Table 6.3, they were termed low, most likely and high production rates. Based on these production rates, three possible scenarios were developed for assembling each 140-m Hexcrete tower option as detailed in Table 6.4.

Table 6.3. Three production rates selected for critical assembly work items

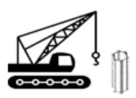
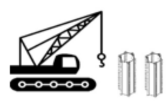
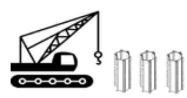
Activity / Production Rates	Worst Case Scenario	Most Likely Case	Best Case Scenario
Assemble Cells on Ground	1 cell per day 	2 cells per day 	3 cells per day 
Setting Hexcrete Cells on Each Other	3 cells per day 	4 cells per day 	5 cells per day 

Table 6.4. Three possible scenarios for 140 m tall tower assembly

Worst case scenario	Most likely scenario	Best case scenario
• Assemble one Hexcrete cell on the ground per day. • Stack three Hexcrete cells per day	• Assemble two Hexcrete cells on the ground per day. • Stack four Hexcrete cells per day	• Assemble three Hexcrete cells on the ground per day. • Stack five Hexcrete cells per day

6.10 Scheduling

A construction schedule for each scenario was then developed with the assumption that a wind farm of 100 towers is built at a typical wind farm site in Iowa. With wind farm construction activities being repetitive, it would be beneficial to align production rates with the optimal number of crews to minimize idle time and optimize the field schedule. To find the most realistic schedule for assembly of activities, the linear scheduling method (LSM) was used. This method is best at scheduling the outcome for a project with repetitive activities, as it visually aligns the production rates of each activity. For determining the total project duration from mobilization to mechanical completions, the bar chart schedule was used to give a visual and simple representation of the project plan. It includes all project activities, activity durations, and the start and end dates of the activities. Table 6.5 presents the crew numbers for each tower option that resulted from the exercise described above. The number of crews is identified through the LSM-based schedule development by adjusting the crew size to find the most aligned production rates of the activities. Experienced industry partners provided input for the number of crews. Depicted in Figure 6.10 and Table 6.6 is the linear schedule developed for the HT2 most likely scenario.

Table 6.5. Number of crews identified for each activity

Activity	HT3a	HT3a Hybrid	HT2	HT2 Hybrid
Excavation	1	1	1	1
Steel reinforcement	4	3	3	3
Concrete placement and Formwork	2	2	2	2
Backfill	1	1	1	1
Offload Hexcrete panels and columns	3	3	3	3
Offload tower components	3	3	3	3
Assembling cells on ground	7	5	6	5
Setting cells below 80 meter	2	2	2	2
Building rotor	1	1	1	1
Setting cells above 80 meter and assembling rotor, turbine, nacelle	2	2	2	2
Building rotor	1	1	1	1
Vertical post-tensioning	2	2	2	2

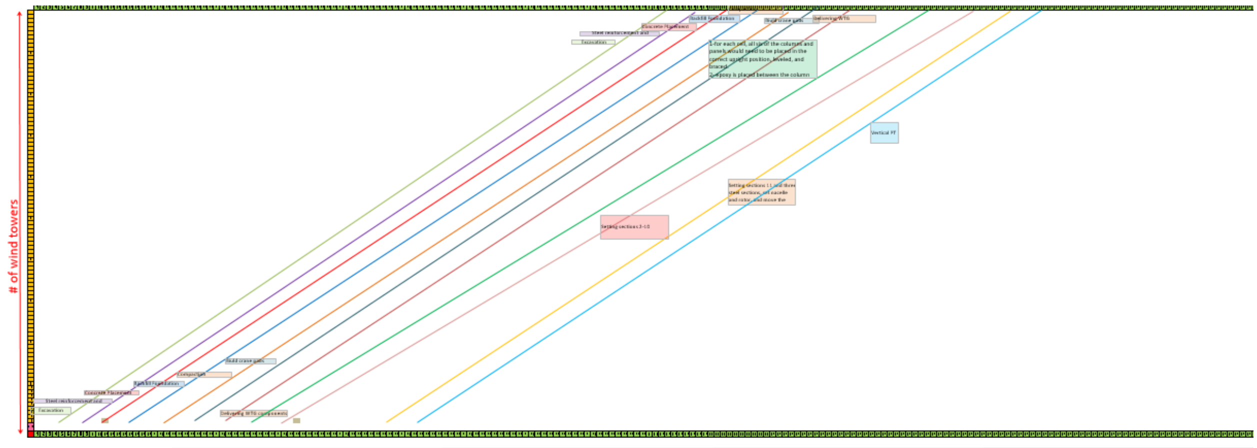


Figure 6.10. Linear scheduling developed for the HT2 most likely scenario

Table 6.6. Activity descriptions for linear scheduling

Number	Activity	Line Color
1	Excavation	light green
2	Steel Reinforcement and Formwork	purple
3	Concrete Placement	red
4	Backfill Foundation	blue
5	Compaction	orange
6	Building Crane Pads	dark teal
7	Delivering WTG Components	dark red
8	1-For each cell, all six of the columns and panels would need to be placed in the correct upright position, leveled, and braced. 2- Epoxy is placed between the column and panels 3- Horizontal PT 4- Internal ladders for each cell would be installed.	green
9	Set sections (below 80 meter)	pink
10	Set sections (above 80 meter)	yellow
11	Vertical Post-tensioning	light blue

In the next step, the total duration for assembling 100 wind towers (in working days) was estimated as shown in Table 6.7. Days Monday thru Friday were considered as working days, with Saturday and Sunday as non-work days. The weekends could be used for catching up with the schedule, if necessary.

Table 6.7. Estimated duration for 100 Hexcrete wind turbine towers

Wind tower type	Worst scenario (working day)	Most likely scenario (working day)	Best case scenario (working day)
HT3a	305	197	185
HT3a hybrid	270	174	162
HT2	290	177	164
HT2 hybrid	255	161	157

6.11 Total project duration

In addition to tower assembly activities, early non-assembly activities, such as mobilization and site access road construction, must be included to determine the complete project schedule. Also, a calendar day schedule was developed to determine the overall site project management cost. Figure 6.11 shows the detailed bar chart schedule developed for building the entire wind farm using the HT2- most likely scenario. Table 6.8 shows the overall wind farm construction schedules for different types of wind towers under the three scenarios.

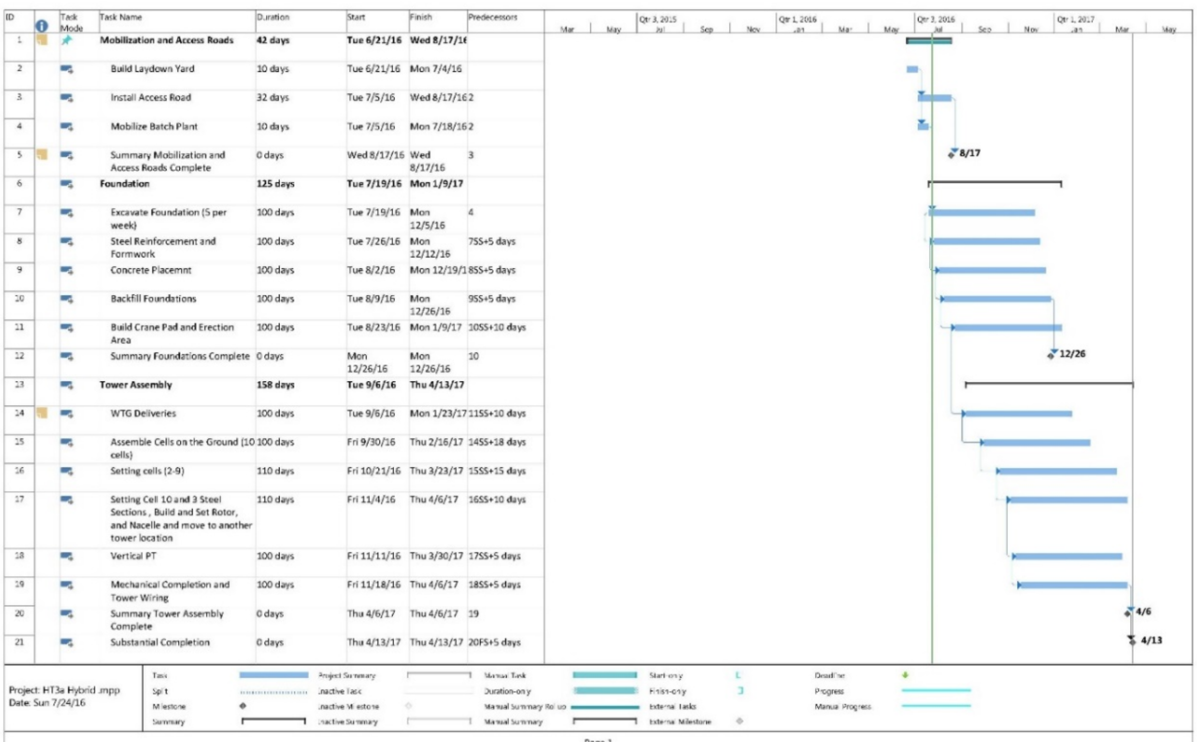


Figure 6.11. Bar chart schedule for an entire wind farm based on HT2 most likely scenario

Table 6.8. Total project duration established for various scenarios

Wind tower type	Worst scenario (calendar day)	Most likely scenario (calendar day)	Best scenario (calendar day)
HT3a	485	329	293
HT3a hybrid	426	299	281
HT2	440	301	286
HT2 hybrid	391	296	279

6.12 Cost Estimation

The WBS described in Section 7.4, crew information, and scheduling details in Section 7.10 were used in cost estimation. Some major assumptions made for cost estimation are: a) the project involves construction of 100 wind towers in Iowa; b) the distance between the wind turbines is 0.75 miles (1.2 km); c) the cost of labor is assumed to be $75/man-hour; and d) the transportation distance from precast manufacturing plant to the project site is 200 miles (322 km). The overall construction process will require the use of four different types of crawler cranes, with assist equipment, that include rough terrain cranes, telehandlers, and man lifts. The crane mobilization costs and monthly rental costs used are based on the industry input and are provided in Table 6.9.

Table 6.9. Crane Rental and Mobilization Costs

Crane	Monthly Bare Rate, 200 Hours	Mobilization cost
LR 11350	$275,000	$500,000
M16000	$115,000	$150,000
200 ton mobile crane	$36,000	$48,000
RT 130	$28,000	$33,000

6.12.1 Fabrications and Transportation of Hexcrete columns and panels

For this project, the precast concrete columns were assumed to be made from High-Strength Concrete (HSC) and the panels were made from Ultra High-Performance Concrete (UHPC). The unit costs of HSC and UHPC, including labor and shipping, were estimated by a precast concrete manufacturing company based in the Midwest. Table 6.10 shows the summary of precast concrete costs for different tower options. For hybrid options, the cost of the steel top is also included.

Table 6.10. Estimated cost for Hexcrete columns and panels

Type of tower	Hexcrete columns	Hexcrete panels	Steel Top	Total cost
HT3a	$597,600	$649,600	N/A	$1,247,200
HT3a Hybrid	$504,900	$462,000	182,812	$1,149,712
HT2	$576,900	$691,600	N/A	$1,268,500
HT2 Hybrid	$396,900	$613,200	160,875	$1,170,975

6.12.2 Foundations

Wind tower foundation construction cost can easily be estimated with current practices, as it does not require any new technology or process. Total cost of foundation construction for each type of wind towers as designed are shown in Table 6.11.

Table 6.11. Estimated cost of foundation construction

Type of wind tower	Estimated foundation cost
HT3a	$351,847
HT3a Hybrid	$290,380
HT2	$252,784
HT2 Hybrid	$252,784

6.12.3 Assembling tower components

The Hexcrete tower assembly was divided into three major work activities as follows: a) cell assembly; b) cell erection and post-tensioning; c) erection of the steel top (for hybrid towers), turbine, nacelle, and rotor. Assembling cells on the ground was assumed to be accomplished by using a 200-ton crawler crane. For setting Hexcrete cells below 80-m (263-ft) height, a Manitowoc 16000 was selected. For installing segments above 80 meters (263 ft), as well as the rotor and nacelle, a LR11350 was assumed. In addition, the estimated time to partially disassemble the

LR11350, move it to another tower location, and assemble it again was assumed to be one day based on the input from a crane expert.

The primary materials required for completing assembly of the tower components include temporary/permanent bracing and platforms, epoxy grout, post-tensioning hardware, and post-tension tendons. The cost of these materials contributes significantly to the overall cost when converting from a 120-m Hexcrete tower (i.e., HT1) to a 140-m tower. There is also a substantial increase in material costs for the HT3a Hexcrete towers designed to support a 3.2 MW turbine in comparison to the 2.3 MW turbines utilized for the HT2 and HT1 towers. The larger turbine significantly increased the loads on the tower, as explained in the previous chapters, resulting in a larger material cost for HT3a when compared to HT1. Detailed cost estimation of the assembly for the HT2 most likely scenario is presented in Table 6.12. The total estimated assembly cost of the worst, most likely, and best case scenarios for each type of wind tower can be found in Table 6.13.

Table 6.12. Detail cost estimation for the assembly of HT2 most likely scenario

Work Breakdown Structure Activity	**Equipment cost**	**Quantity (Man-hour)**	**Labor**	**Material Costs**	**Production Rates (days/WTG*)**
Offloading Hexcrete cells, Tower Components, Nacelle, Hub, and Blades	$23,279	144	$10,800		3
Assembling Hexcrete Cells on Ground	$19,733	560	$42,000		7
Steel Bracing	included in cell assembly cost on ground			$110,000	included in assembly
Misc. Ladders and Platforms	included in cell assembly cost on ground			$39,000	included in assembly
Horizontal post tensioning	included in cell assembly cost on ground			$75,864	included in assembly
Grout Tower Sections	included in cell assembly cost on ground			$155,200	included in assembly
Set Tower Sections	$43,142				
Set Sections 2-9		208	$15,600		2
Set Sections 10-14		130	$9,750		1
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertical post-tensioning		96	$7,200	$148,651	2
Project management cost	$47,200				N/A
Total	$87,373		$88,950	$527,715	
Total Assembly Cost					$753,238

*WTG: Wind Tower Generator

Table 6.13. Estimated total assembly cost for each assembly scenario

Type of wind tower	Worst case	Most likely	Best case
HT3a	$923,133	$802,826	$760,244
HT3a Hybrid	$717,440	$627,752	$597,968
HT2	$869,703	$753,238	$729,062
HT2 Hybrid	$669,196	$595,523	$569,490

6.13 LCOE comparison

The Levelized Cost of Energy (LCOE), as previously noted, is an economic measurement method to effectively compare different sources of electricity. LCOE represents the average value per unit of energy production (measured in dollars per kilowatt-hour ($/kWh)) that would be required by a project owner to recover all cost and operating expenses over a predetermined project financial life and duty cycle (Wind Energy News, 2015). NREL's LCOE model was used as a baseline to determine the LCOEs of different 140-m Hexcrete tower options. Among various LCOE components, this study only evaluated the following four components: a) tower module; b) assembly and installation; c) foundation; and d) operation and maintenance. The other components were assumed to be the same across different tower options. This exercise was completed in collaboration with NREL staff, who also provided estimates of the Annual Energy Production (AEP) for different hub heights. Table 6.14 shows the calculated LCOEs for different types of 140-m Hexcrete towers. Although the differences in these LCOE estimates are less than 7%, NREL has advised, based on recent stakeholder discussions, that even small improvements in LCOE are sufficiently compelling to motivate development and investments in new wind technologies. For example, although there are many factors that influence the selection of awardees for power purchase agreements (PPAs), LCOE typically plays the most important part. PPA winners are often selected on differences in LCOE of less than 1%. In turn, wind turbine manufacturers invest and develop new technologies that have potential to improve LCOE by only a few percent.

Table 6.14. Comparisons of LCOE for different options

Wind Tower Type	Worst case (percentage increase)	Most likely (Reference)	Best case (percentage reduction)
HT3a	1.56%	1.0	0.52%
HT3a Hybrid	1.17%	1.0	0.45%
HT2	1.63%	1.0	0.52%
HT2 Hybrid	1.16%	1.0	0.45%

6.14 Sensitivity analysis

Sensitivity analysis is the study of how the uncertainty in the system can be apportioned to different sources of uncertainty in its inputs (Chau, 1994). To find the impacts of the range of production rates (worst case, most likely, best case) of two key assembly activities and the possible AEP changes, a sensitivity analysis was performed using the Monte-Carlo Simulation. In this analysis, it is important to note that the AEP was assumed to vary ±5% from the given AEP value to approximately match with the range of the Balance of Station cost due to different production rates. Table 6.15 shows the ranges of AEP values for different turbine types at the hub height of 140 m (459 ft).

Table 6.15. AEP inputs used for the sensitivity analysis

Turbine type	AEP (MWh/year) at the hub height of 140 m (459 ft)		
	Worst case (5% less than NREL's prediction)	Most likely (NREL's prediction)	Best case (5% more) than NREL's prediction
Siemens 2.3 MW	592,325	623,500	654,675
Siemens 3.2 MW	731,215	769,700	808,185

Figure 6.12 shows the results of the sensitivity analysis for HT2, which clearly demonstrates that LCOE is highly sensitive to AEP values approximately 3.5 times more than the cost variation of assembly and installation by different production rates. This outcome implies that the risk of implementing the Hexcrete tower technology in practice is actually less significant than the positive potential benefit of harvesting wind energy at taller hub heights.

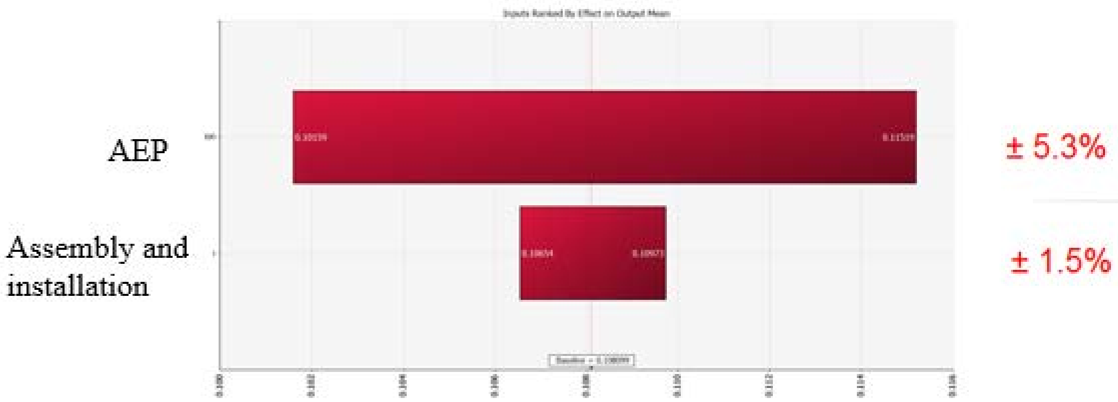


Figure 6.12. Results of sensitivity analysis conducted for HT2 tower designs

It is also important to note that the variations in the hybrid tower designs discussed in Chapter 3 due to the CFD simulation fall within the average 1.5% range of LCOE variation identified in the sensitivity analysis. Therefore, even with slightly increased dimensions due to higher drag coefficients, both the HT2 and HT3a hybrid tower LCOEs do not increase beyond 1.5%. For the HT2 and HT3a full concrete towers the increase in LCOE due to the CFD simulations is slightly more substantial at 3% due to the increased wind flow interaction.

6.15 Comparison of Hexcrete vs. steel tower LCOEs

In parallel with the LCOE cost estimation presented in this chapter, NREL estimated the LCOE for two steel tapered tubular towers in BP2. They used 80 m (263 ft) and 140 m (459 ft) hub heights to support a 3.2 MW turbine and estimated the LCOEs with those produced for HT3a hybrid tower (most likely scenario). This comparison is presented in Table 6.16. As seen in this table, HT3a hybrid option reduces the LCOE by 20% and 6% when compared 80 m (263 ft) tall and 140 m (459 ft) tall steel tubular towers, respectively. Although these reductions appear small, they are considered by the stakeholders to be significant improvements in reducing the cost of wind power.

As previously noted, the LCOE estimation for the Hexcrete towers used a bottom-up approach whereas the NREL estimation approach can be labeled as a top-down estimation based on available cost models. Two drawbacks of the top-down approach are that a) extrapolation of costs may not appropriately account for significant increase in costs associated with work package level activities, and b) some constraints used in LCOE evaluation may introduce practical constraints. For example, to assemble the 140-m (459-ft) tall steel towers, a 1,000 ton capacity crane would be required on site and the subsequent mobilization and rental costs may not be accurately represented in a top-down approach whereas this issue was carefully addressed in the LCOE analyses of Hexcrete towers. Furthermore, the design of the 140-m (459-ft) tall steel tower used the same base dimension as the current 80-m (263 ft) tall steel tower. This assumption was necessary due to the lack of knowledge in estimating the cost of segmented steel towers, especially for the bottom 60-m (197 ft) of the 140-m (459-ft) tall tower. This assumption increases the wall thickness of the steel tube to 89 to 102-mm (3.5 to 4 in). Such a large wall large thickness for the steel tube could cause manufacturing challenges and potential performance issues for the steel towers.

To understand the impact of using a large crawler crane on site, the research team attempted to evaluate the LCOE of a 140-m (459-ft) tall steel tubular tower using an erection approach similar to that used for the Hexcrete towers. It was found that the crane requirement would increase the Balance of System Capital cost by 8% (i.e. from 0.0185 to 0.0200 $/kWh), thereby slightly increasing the LCOE of the steel tubular tower. Similarly, manufacturing and transportation of steel tubes with larger wall thickness can increase the capital cost. Therefore, it is noted that because of the use of a top-down model, the cost of LCOE estimated for the 140-m steel tower is likely to be a lower bound and that the true benefit of the Hexcrete tower is most likely greater than that is reflected in Table 6.16. While the approach adopted by NREL uses the current state of knowledge satisfactorily, a more realistic cost estimate for tall steel towers would require significant effort. To alleviate the concerns associated with performance issues of 140-m (459-ft) tall steel towers, the constraint for the base dimension should be eliminated. This will lead to a base dimension of 23 ft (7 m) with a wall thickness of about 1.85 in. (48 mm) for a 140-m (459 ft) tower. This option will then require segmenting some of the steel tubes for transportation purposes and assembling them on site. This requirement, which is costly and can introduce maintenance issues, is believed to be a primary reason that most steel tubular towers in the U.S. are less than 100-m (328 ft) tall. Table 6.16 shows potential reductions in LCOE for tall steel towers.

Table 6.16. Comparison of LCOE results obtained for a Hexcrete and steel tubular towers

	*140m Rolled Steel – 3.2 MW ($/kWh)	140m Hexcrete - HT3a - Hybrid (Most Likely)[1] – 3.2 MW ($/kWh)	Change in LCOE between 140m Rolled Steel and 140m Hexcrete – 3.2 MW Scenarios (%)
Turbine Capital Cost[2] (TUR_{CC})	-6.3	-16.5	-10.2%
Balance of System Capital Cost[3] (BOS_{CC})	-11.5	13.4	24.9%
Financial Capital Cost (FIN_{CC})	-7.0	-9.3	2.3%
Operations and Maintenance (O&M) [pre-tax]	-34.0	-40.4	-6.3%
LCOE	**-11.6**	**-16.4**	**-6.0%**

*Estimated by NREL

Chapter 7 – Implementation Plan for Hexcrete Tower Technology

7.1 General Information

7.1.1 Introduction

One task of the Hexcrete tall tower project was to develop an implementation plan so that prototyping as well as broader application of this technology can be realized in practice. This plan, which addresses any future development and commercialization of the technology, was developed with significant input from members of the wind energy and concrete industries, including those who participated in the commercialization workshop conducted as part of the tall tower project.

7.1.2 Purpose of Implementation Plan

The implementation plan presented in this chapter is to serve as a guideline on what has been accomplished to date and what steps must be taken to get the Hexcrete wind turbine tower technology fully commercialized. The chapter will be updated as further steps are taken toward commercialization, new knowledge is gained, and market conditions change. The implementation plan demonstrates to stakeholders, such as current and potentially new technology partners, licensees, and investors, a pathway to commercialization. The implementation plan was formulated using the following major components:

1) **Technology Evaluation –** discusses what has been done so far for the implementation of the Hexcrete tower technology in terms of technical development as well as commercial efforts.
2) **Technology Qualification Plan –** gives guidelines on what technical challenges have been identified and still need to be addressed.
3) **Commercialization Plan –** gives guidelines on commercial challenges and opportunities that have been identified and still need to be addressed and gives a model for financing the implementation.
4) **Manufacturing Plan –** describes how a supply chain for the fabrication and installation of Hexcrete towers will be established.
5) **Intellectual Property Management Plan –** will stake out how intellectual property will be shared between participating partners and licensees to encourage the implementation of the Hexcrete tower technology.

Each of these topics is addressed below based on the completed work to date and the current state of knowledge regarding wind energy production at tall hub heights.

7.1.3 General Implementation Strategy

To move the technology forward and familiarize industry partners with the construction of Hexcrete towers, a two-step process is envisioned. These steps, which could be executed in parallel by different teams, will also increase the chance of using the technology in the near future. The tall tower project created opportunities to interact with and educate several industry partners and other potential participants from different wind energy and concrete sectors. There is significant interest among the industry partners to form a Joint Industry Partnership (JIP) between all interested universities, industry members, and non-profit organizations. Iowa State will lead this effort and formulate the JIP in 2017.

Under the JIP, different implementation strategies will be explored for the Hexcrete technology and interested members from the JIP are expected to participate in realizing the different strategies. Two strategies that will be undertaken by the JIP are: 1) utilization of a 20 to 40 m tall Hexcrete tower segment to realize a hybrid tower in the Midwest; and 2) build one (or a small group of) 120-m (394 ft) or taller Hexcrete wind turbine tower(s) in the Midwest or southeastern part of the U.S. While both are attractive paths to commercialize the new tower technology, they have different financial implications. The first strategy requires less external financing and enables industries in the Midwest with wind farm development experience and expertise to work together and realize the strategy within a short time frame. Those companies will also be in a position to provide in-kind contributions towards this effort. The required financing for the second strategy would be significant and would need significant support from agencies such as DOE. Such an effort, however, can include multiple objectives to further reduce the LCOE, besides prototyping Hexcrete towers.

7.2 Technology Evaluation

The Hexcrete technology has been developed over the past 7 years by Iowa State University and has been subjected to small- and large-scale testing mostly funded through the Department of Energy, the Iowa Energy Center, Grow Value Iowa Funds and Iowa State

University as well as in-kind support from industry partnerships. The technology is at a high development level and has been well publicized within the relevant industries.

7.2.1 Industry Outreach

The Hexcrete technology has been publicized through direct stakeholder involvement during project phases, publications, presentations, and its website (http://sri.cce.iastate.edu/hexcrete/). Specifically, two industry stakeholder meetings were held within the last 1½ years, in which companies provided input on potential tower erection modalities and a SWOT analysis on the technology. A formal presentation of the technology was given to the public and the Department of Energy in June 2016. Technical articles have been published in the U.S. and Europe and several technical presentations have been made to different audiences.

7.2.1.1 Stakeholder Involvement

During the most recent project phases, Iowa State University involved companies from the wind, concrete, prestressing, consulting engineering firms, crane specialists, and construction industry as either project partners or workshop participants. The stakeholder involvement has helped to promote the technology within the relevant industries, provide input from relevant subject experts, and allow some of the barriers typically encountered during implementation of new technologies to be eliminated. The feedback from the partnering and participating stakeholders was generally very positive and many expressed their interest in continued involvement. The stakeholders that were involved in the current project phase are listed in Table 7.1.

Table 7.1. Industry Involvement in Current Project Phase

Industry	**Company**	**Partner**	**Participant**
Tower Technology Providers	Iowa State University	x	
	Postensa Wind Structures		x **)
	Keystone Tower Systems		x **)
	Trinity Structural Towers		x **)
Turbine Manufacturer	Siemens	x	
	GE		x
Engineering	BergerABAM	x	
	BARR Engineering		x
	EnCon Design		x **)
Concrete Industry	Lafarge North America		x *)
	Coreslab Structures (OMAHA)	x	
	Oldcastle Precast		x
	Midstate Precast		x
	Wells Concrete		x
	A.L. Patterson		x
	Larsinos		x **)
	Norwalk Concrete Industries		x **)
	Plump Creek Structures		x **)
	Roman Stone Precast		x **)
	Vector Construction		x **)
	VStructural (VSL)		x
	Sumiden Wire		x
	Dywidag International		x **)
	CCL		x **)
Prestress technology	Bigge Crane and Rigging		x
	Mortenson Construction		x
	Lawrence Construction		x **)
	Pattern Energy		x
Crane Suppliers	Blattner Energy		x **)
Contractors	Goodwind Energy		x **)
	DoE (EERE)		x *)
Wind Developer / Operator / Owner	National Renewable Energy Laboratory	x *)	
	Iowa Energy Center		x *)
	Vaisala		x **)

*) Sponsor
**) Commercialization workshop attendee only

7.2.1.2 Media Outlet

As noted above, Iowa State University has hosted a web site to publicize the Hexcrete technology that incorporates a DOE funded project description, activities and updates (http://sri.cce.iastate.edu/hexcrete). To date the website has received more than 2500 hits from all 50 states in the U.S. and 55 countries (see Figure 7.1). The Hexcrete tower was featured in local newscasts, blogs, and newspapers and articles were published in magazines and blogs catering to the concrete, construction, and wind energy industry nationally and internationally. The technology was presented at important conferences such as the WindPower Conference of the American Wind Energy Association and the Convention of the American Concrete Institute. Through these activities, the tower technology has become well known in the industry.

Figure 7.1. Location of visitors to project website

7.2.1.3 Hexcrete Workshops

During the course of the project, two technical workshops and one commercialization workshop were held for participation of industry members. The first two were invitation only workshops that were designed to engage strategic industry partners in ongoing research activities. All project participants also attended these workshops. The first workshop, held in San Diego, CA, under the leadership of Iowa State University, focused on the erection of a 120-m tall Hexcrete tower to support a 2.3 MW Siemens turbine. This effort led to an assembly plan for this particular tower (i.e., HT1) with due considerations of crane limitations, scheduling, concrete fabrication and transportation. An animation showing the final assembly can be found at: https://www.youtube.com/watch?v=XizC5spy3mg.

The second workshop, held under the leadership of BergerABAM in Minneapolis, MN, had two objectives. One was to figure out an assembly procedure for a 140-m Hexcrete tower and the other, as previously noted, was to conduct Strength/Weakness and Opportunity/Threat (SWOT) analysis on the Hexcrete technology with input from strategic industry partners. The outcome of the first objective can be seen in animation at: https://www.youtube.com/watch?v=2bKn9rtjLS0, while the second objective is discussed further in the next section.

7.2.2 Strength/Weakness and Opportunity/Threat Analysis

As the first step of the implementation plan, a Strength/Weakness and Opportunity/Threat (SWOT) analysis was performed during the second workshop as this was considered an important step for the implementation plan. By discussing the strength and weaknesses of the Hexcrete tower technology, the intention was to identify opportunities to improve the technology, and to recognize threats so that mitigation strategies could be developed for the technology implementation.

The SWOT analysis exercise concluded that the Hexcrete tower technology is generally at a high technical readiness level and that there are no inherent fatal flaws. The analysis identified room for improvements in terms of detail design and fabrication and erection procedures that should be addressed in future development phases, including the construction of prototype towers and/or tower segments. The technical and commercial risks identified in the workshop are included in the preliminary technology qualification plan and commercialization plan, respectively.

7.2.3 Evaluation of Levelized Cost of Energy

In Chapter 7, it was shown that LCOE of tall Hexcrete towers is expected to be competitive when compared to both 140-m (459 ft) and 80-m (263 ft) tall steel towers and that LCOE of 140-m (459 ft) tall steel towers is more competitive than 80-m (263 ft) tall steel towers. It is believed that more reliable LCOE numbers for 140-m tall steel tubular towers can only be obtained with significantly more effort. Therefore, what has been established can be best viewed as lower bound values only. The wind energy industry expected tall towers with a hub height of 140-m (459 ft) to be prevalent about five years ago. If the wind industry had realized that the LCOE of 140-m (459-ft) tall steel towers is truly more competitive than 80-m (263 ft) tall steel towers, taller steel towers would have been frequently used by the industry today.

7.3 Technology Qualification Plan

Based on the tower technology evaluation above, a Technology Qualification Plan has been derived, describing the steps that have to be taken to reduce the technical risks of the Hexcrete technology to an acceptable level for a commercial wind farm project. Once in collaboration with a third-party review institution, this plan can be further refined. The following three steps have been identified.

7.3.1 Wind Tunnel Test

Perform a wind tunnel test of a scaled tower with turbine to confirm the results of the computational fluid dynamic analyses of the dynamic behavior of the tower. Vortex shedding has been identified as a behavior to examine during different erection phases and under operational loads. Gathering information on the interaction between tower and turbine blades will also be useful.

7.3.2 Design Towards Certification

Complete the design for strength, service, and fatigue limit states and submit to a third-party review by an accredited certification institution. This design can be for the prototype tower, but should include details such as

- Tower/turbine transition element;
- Access door;
- Connection details (panel/column, column/column, and column/foundation)
- Post-tensioning anchor details (circumferential, internal and external vertical post-tensioning); and
- Tower internals and their attachments (lift, ladder, trays, platforms etc.)

The design should consider the construction and erection method and should study implications of fabrication and erection tolerances on the tower performance.

7.3.3 Prototype Testing

Build a prototype turbine to validate constructability, operation, maintenance performance, and cost. Document fabrication and erection processes and monitor the structural behavior of key components, such as panels, columns, post-tensioning steel, panel/column connection, column/column connection, column/foundation connection, post-tensioning couplers, and tower/turbine transition element. This information could be used to further refine the tower design and details. The prototype shall demonstrate the following:

- Fabrication of UHPC panels and HSC columns can be done within the required tolerances, quality, cost, and schedule;
- The tower segments can be assembled and installed within required tolerances, quality, cost, and schedule;
- The assembly and installation procedure and equipment is safe and can meet the expected schedule and cost;
- All connection details work as intended;
- The turbine behaves satisfactorily under all operational and testing conditions
- The tower can be maintained as intended; and
- The tower is satisfactorily esthetic and acceptable to the surrounding communities

7.4 Commercialization Plan

7.4.1 Current Market Environment for Tall Towers in the U.S.

The Energy Efficiency & Renewable Energy Office of the U.S. Department of Energy releases an annual Wind Technologies Market Report that describes the current market conditions and trends in the wind industry. The U.S. wind industry grew to a cumulative investment total of $128 billion within the past 10 years with annual investments rates varying from almost nothing in 2013 to more than $20 billion in 2012, dependent on the highly politicized Production Tax Credits (PTC) and state Renewable Portfolio Standards. The current PTC has been extended to the end of 2016 with a gradual phase out through 2019, giving the industry a more stable tax basis. With a currently installed total capacity of about 75 GW in the U.S., the wind industry can provide power for over 5% of the nation's electricity demand. Wind power has become a major part of our country's energy supply and investments in the wind industry will continue to fund new wind power plants and to repower aging ones as the early plants reach their typical 20-year service life.

Most regions that provide well suited conditions for wind plants (consistent wind, access to market, and suitable terrain) have been developed and, to get the momentum of the wind industry going into the future, the Department of Energy is incentivizing technologies that enable cost effective wind energy developments in other regions, such as low wind speed regions and offshore.

The use of taller towers enables harvesting higher elevation winds that are typically more consistent (stable) and at higher velocity. While the average installed turbine in the U.S. has remained at a hub height of about 80-m (263 ft) within the past 10 years, the turbine nameplate capacity and rotor diameter increased steadily (Figure 7.2). There is, thus, an opportunity for the tower technology to catch up and raise existing turbine technology to higher hub height to make it suitable for low-wind speed regions and more efficient for regions with high wind shear. Figure 7.3 shows that at an average height of 80-m (263 ft), the most suitable sites for wind plants lie within the "wind corridor" spanning from the Dakotas in the North to West Texas in the South with less suitable sites spread around the country, suggesting that the Southeastern states of the U.S. are unsuitable for wind development. This wind map is reflective of the currently installed wind capacity across the country. A newer map showing the wind speeds at 140 m height presents a different picture (Figure 7.4), suggesting that most regions in the U.S. can actually be suitable for wind developments, if the turbine hub height is raised. Thus, the opportunities for tall towers can be found in these new markets across the country and, particularly, in the Southeast.

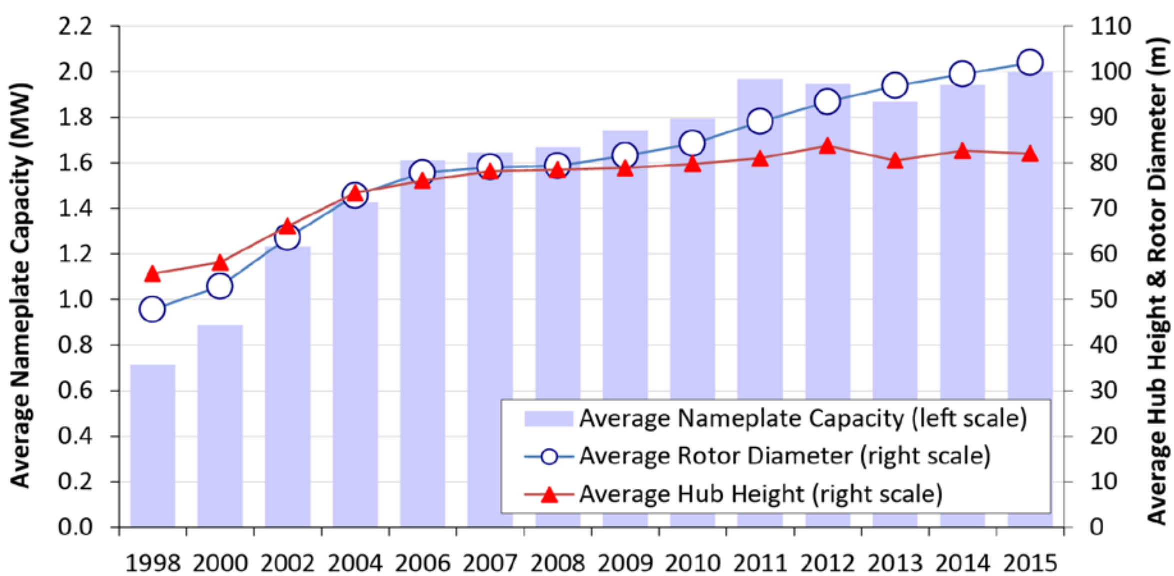


Figure 7.2. Average Commercial Turbine Size Installed (U.S. Department of Energy, 2015)

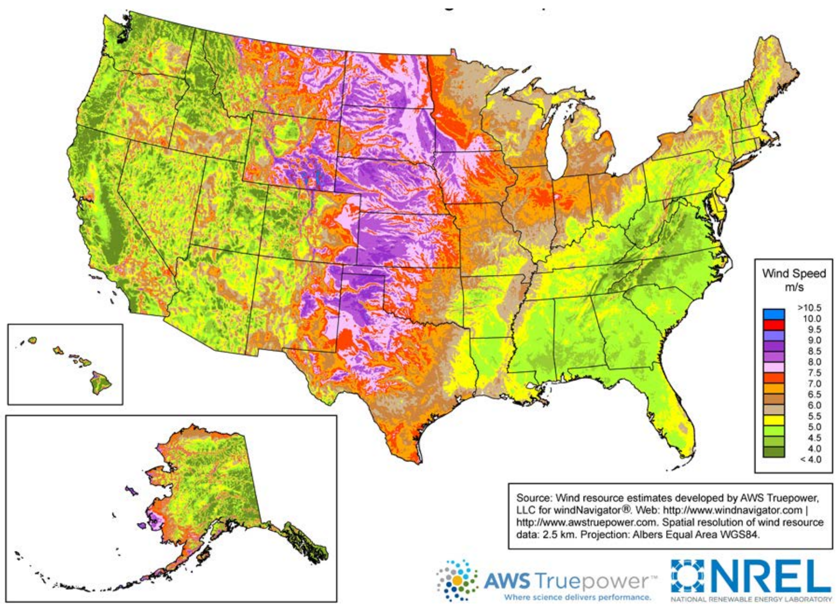


Figure 7.3. Annual Average Wind Speed at 80 m elevation (National Renewable Energy Laboratory, 2015)

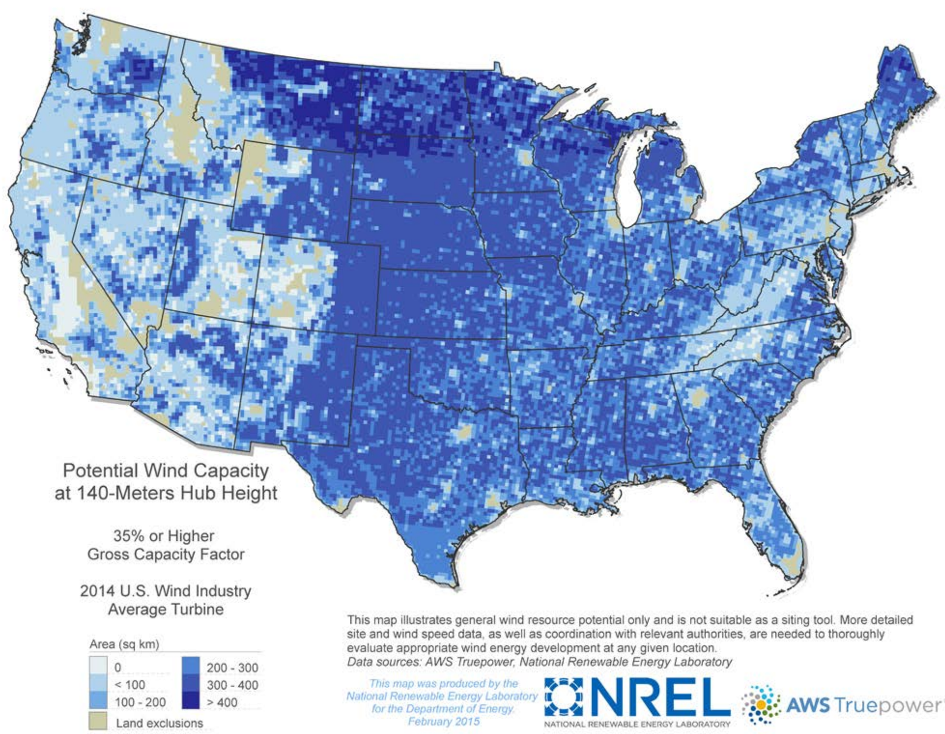


Figure 7.4. Potential Wind Capacity at 140 m Hub Height (National Renewable Energy Laboratory, 2015)

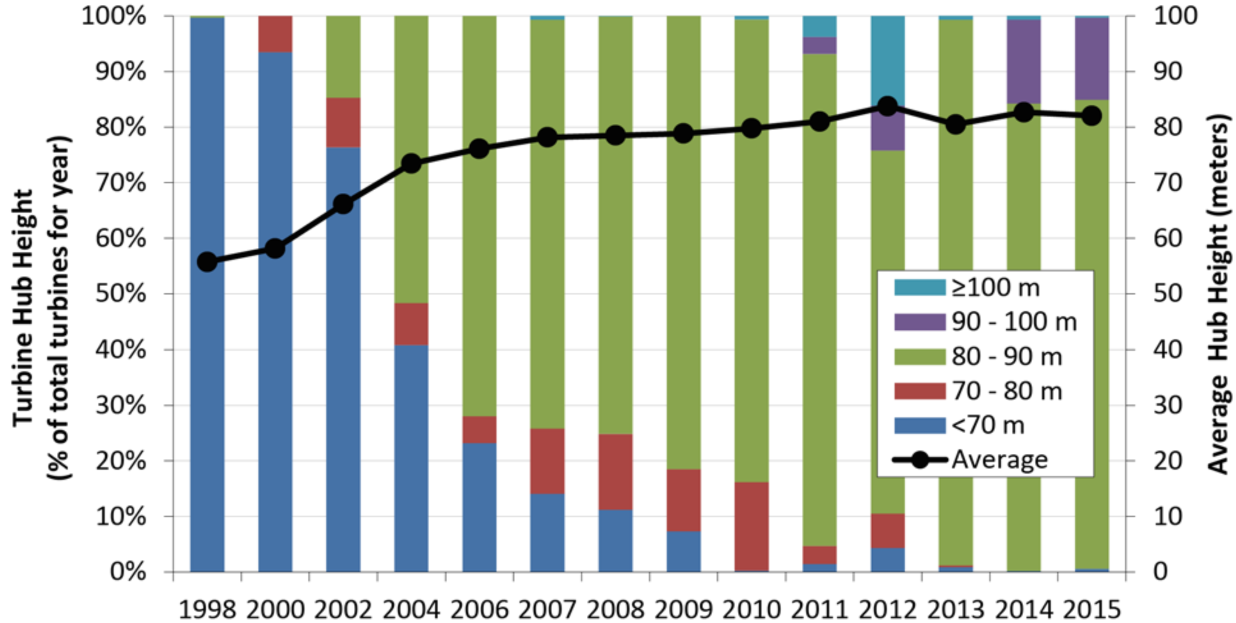


Figure 7.5. Trend in Turbine Hub Heights in U.S. (U.S. Department of Energy, 2015)

The 2015 Wind Technologies Market Report further notes that turbines originally designed for low-wind speed regions are now in widespread use in all wind speed regions across the U.S. and taller towers (≥ 90 m [296 ft]) are already deployed in regions of high wind shear, such as in the Great Lakes and Northeast. By 2015, these taller towers achieved a market share of 67% in the Great Lakes and 43% in the Northeast. An interactive web site hosted by the DOE (http://energy.gov/articles/new-interactive-map-shows-big-potential-america-s-wind-energy-future) presenting the growth of the wind industry over the next 35 years estimates that by 2030, the land based wind industry will grow about 11 GW in the Southeast states (i.e., MS, AL, GA, TN, NC, LA, AR, KY, VA, WV) and 34 GW in the Great Lakes (mostly in IL and IN, but also in OH, WI, and MI). If these regions are developed with 2.3 MW turbines and tall towers have a market share of 50 percent, then these regions alone can grow to a market of about 10,000 tall towers over the next 15 years or about 600 tall towers per year.

7.4.2 Preliminary Business Case

An attempt has been made to establish a business case for tall towers. The major roadblock of this effort was to find reliable wind characteristics at elevated hub heights. One method of wind measurement utilized recorded data from tall meteorological towers in Iowa. Figure 7.6 shows the location in Iowa where wind information was collected up to a height of 200-m (656 ft). Data obtained from the Homestead tower was used to obtain a reliable AEP, which concluded that the capacity factor at this site could be increased by 17% and 22% at 120-m (394 ft) and 140-m (459 ft) hub heights respectively for a 3.2 MW turbine when compared to an 80-m (263 ft) hub height. The increases of 17% and 22% are relatively small because the corresponding capacity factors were very high (i.e. a capacity factor of 0.8 for the 140-m (459-ft) tall tower). This information, together with the LCOE values estimated for Hexcrete towers in Chapter 6, suggests that tall towers can also be suitable for wind rich regions such as Iowa and Texas. While the industry partners agree that building a 20 to 40-m tall Hexcrete segment would allow them to exercise the new tower technology in the Midwest, their interest in utilizing taller towers seems to be coupled with wind market penetration in new regions (e.g., Southeast). Therefore, it imperative that appropriate steps should be taken to establish reliable AEPs for new wind regions that will benefit from 120 to 140-m (394 to 459 ft) tall Hexcrete towers.

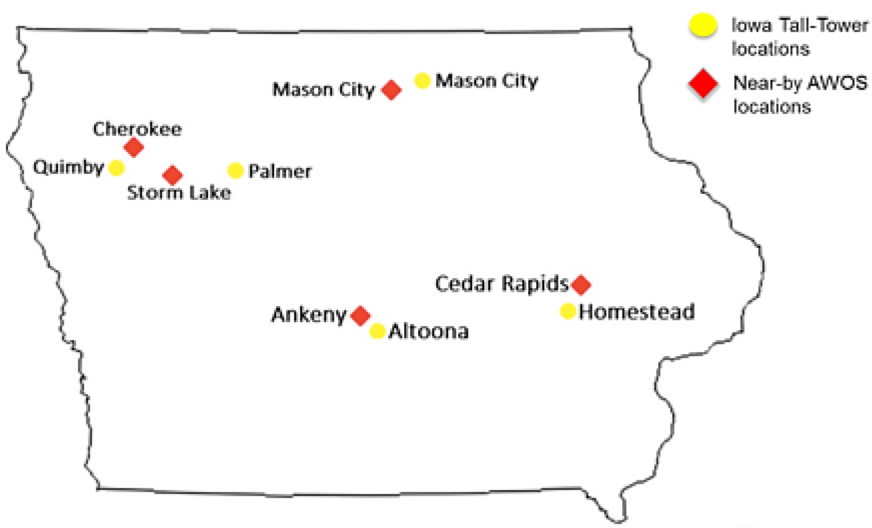


Figure 7.6. Location of tall meteorology towers (Walton, Takle, & Gallus Jr., 2014)

The Iowa State team is in the process of obtaining measured SODAR data from the Southeast region. As soon as this information is available, similar capacity factor calculations will be completed and reliable LCOEs for taller towers can be established. With more members joining the JIP, it is likely that the research team will have access to more measured data. It is in the interest of the research team to continue to work with industry partners and establish a reliable business case for the Southeastern eastern part of the country where tall towers can introduce new wind energy markets.

Once a business case is established for tall towers, the Hexcrete technology will facilitate market penetration since the precast industry is already well established in the Southeast. Similarly, regions of high wind shear such as the Great Lakes and the Northeast, where 100-m (328 ft) steel towers already have a large market share, offer another opportunity for market penetration. Per Section 7.4.1 above, this market should support about 600 tall towers per year. The Hexcrete has the following distinct advantages over the competing tower systems to influence the market share:

- Hexcrete has very simple and relatively light prismatic concrete elements that require minimum formwork and can be transported with conventional highway trucks. As a result, the precast elements can be built at any prequalified precast plant and transported over longer distances, without special transportation permits.
- The simplicity of the elements keeps the investment cost for fabrication tooling low so that it does not become a significant burden on project cost, in particular for small projects. For larger projects where site fabrication may be considered, a temporary precast plant can be established based on simple long casting-lines for multiple panel and column elements. This feature makes the Hexcrete equally attractive for smaller projects with difficult access to the site as well as larger projects requiring high production output.
- In spite of the modular construction, Hexcrete is a slender, aesthetic tower that is robust and durable.

A more refined business case will have to be developed in a later phase based on construction cost estimated for an actual wind farm. Though construction cost estimates have been developed in detail during this development phase, the true cost are only understood once a prototype tower is built. However, the generally high interest in Hexcrete from major companies in the wind and concrete industries such as Siemens, GE, Pattern Energy, Blattner Energy, and Mortenson Construction is a testament that this technology is seriously considered as a future player in the tall tower market.

7.4.3 Market Timing

The availability of tall-tower technologies in the market suggests that there is currently not a technical challenge to reach higher hub heights, but rather that the market in the U.S. is not ready for tall towers yet. Certainly, if the cost benefit of building a wind farm with one of the currently available tower technologies were significant, the U.S. market would move quicker. However, tall towers are expensive and difficult to install, so that with the current technologies, most benefits from harvesting winds at higher hub heights are offset by the higher tower cost. Tall towers have yet to undergo a learning curve to optimize their technologies and become more competitive, at which point some of the technologies will thrive and others will disappear from the market. Before that happens, tall towers are most likely to appear in markets where wind development cannot become cost effective without tall towers, such as in low-wind regions, or in regions of high wind shear, where the increased wind production at higher hub heights can significantly offset the higher tower cost.

Looking at the history of tall tower development in the U.S., tall tower technology providers have been waiting for this market to develop at least since 2010 after which the number of towers 100-m (328 ft) or taller started to grow over a period of 3 years (see Figure 7.2) only to stall again in 2013. It is, thus, hard to predict when such a market will grow and if more tall tower prototypes will be built in the U.S. to establish a clearer business case for such towers and reduce some of the cost risks. In parallel to the development of the tower technology, more research will be needed at these low-wind sites to gain more certainty that higher and more consistent winds actually exist at higher hub heights to justify the development of wind farms. Thus, even with incentives for tower technology development and wind map research, it might still take some time for such a market to develop, and it is likely that the Hexcrete technology will be demonstrated by a prototype before market development.

7.4.4 Distribution Channels and Strategy

There are three distinct strategies to get the tower technology to the market, once it is developed.

1) Sell or license the technology exclusively to a turbine manufacturer and collaborate to build up a supply chain. The tower becomes part of the turbine manufacturer’s product offering and its success is dependent on the market growth of the specific turbine/tower offering.

2) Sell or license the technology to a wind developer or contractor who then incentivizes turbine manufacturers to use this technology where suitable to become more competitive.

3) Sell or license the technology to one or multiple tower suppliers that offer the tower to any turbine manufacturers.

The first strategy to work exclusively with a turbine manufacturer is the most typical one, in particular since the tower remains within the responsibility and warranty of the turbine manufacturer. It fits well within the proprietary nature of the wind industry. However, it restricts the technology to the turbine manufacturer's market share and it might not provide enough volume to grow a cost effective supply chain. The third strategy might offer a pathway to a larger market share if multiple turbine manufacturers are willing to collaborate with the tower supplier(s). In that case, the offered tower technology must have a significant cost advantage before a turbine manufacturer would prefer it over an exclusive technology. The second strategy is somewhere in between as it still needs full collaboration with a turbine manufacturer, but a developer has leverage to choose their tower system for their project.

The current strategy for the Hexcrete tower is a combination of the three above strategies by establishing a Joint Industry Partnership (JIP) between a turbine manufacturer and a small number of developers, contractors, and tower manufacturers. The goal is not to develop an exclusive agreement among the JIP partners, but an agreement that gives the partners preference or compensation if a company outside of the JIP is selected instead. The close terms of the JIP will be formed in negotiation with the interested partners and have not been completely determined at this point. In a first round, it is important to establish a JIP for the next step of development through prototype testing. The JIP partnership will have conditions for companies that want to sell their JIP rights or new companies that want to join.

7.4.5 Potential Commercialization Milestones

There seems to be enough time for the Hexcrete technology to get ready for an emerging tall tower market. However, it is important for the technology to be deployable once the market emerges. The following five major milestones have been identified for commercialization the Hexcrete technology and its broader use.

Table 7.2. Potential Major Milestones

Milestone		Target Year
1.	Establishment of JIP	2017
2.	Wind Tunnel Test	2017
3.	Design Certification: High Foundation w/ Hexcrete	2017
4.	Construction and Manufacturing Certification of a Prototype Hexcrete Tower Base Raising One Regular Turbine of a New Wind Farm by 20 to 40 m	2018
5.	Certification and Construction of a Full-Size 120 to 140 m Tall Hexcrete Tower as Part of a New Wind Farm	2019
6.	First Small Wind Farm in One of the Target Markets	2020

7.5 Preliminary U.S. Manufacturing Plan

Concrete structures are typically manufactured locally and imported only if a local supply chain does not exist. Hexcrete follows this model. The tower elements are manufactured either in a precast plant near the project site or in a field plant at the project site. Hexcrete will take advantage of more than 250 certified precast plants in the U.S. that will generally be able to fabricate the tower elements. It will, thus, be fairly easy to build up a tower segment supply chain across the U.S. Hence, the majority of the manufacturing and labor associated to the tower fabrication will occur locally.

7.5.1 Prequalification of Precasters

Ultra High Performance Concrete has not yet broadly entered mainstream construction. Although a number of precast companies have some experience with UHPC, it will be required to prequalify prospective concrete tower element suppliers. In order to qualify, a precaster will have to demonstrate that it can fabricate elements within the required tolerances and performance criteria and can yield the production rate needed to meet the project schedule. The fabrication of a mock-up panel will most likely be a part of this demonstration. The prequalification procedure will be developed project specific and become part of the project specification if UHPC is used in the Hexcrete tower design. The goal is to prequalify multiple suppliers to allow for multiple competitive bids.

The first Hexcrete tower will be most likely fabricated by precasters that are members of the Joint Industry Partnership (JIP) for the development of the prototype tower. Depending on the JIP and license agreement, these precasters will likely become the preferred suppliers for future projects as they have gained production experience with the prototype tower and as they might have a cost advantages due to a reduced license fee. A minimum supply chain for precast tower element is, thus, basically established with the prototype project.

7.5.2 Formwork

The formwork for the Hexcrete tower has to be designed for mass production with fast turnover. Though simple in concept, the formwork can be designed to provide sophistication in terms of handling, adaptability, and robustness and will, therefore, most likely be made of steel. Typically, formwork is the responsibility of the precaster and could potentially be fabricated in the US or abroad, unless there is a "buy American" requirement in the construction contract documentation. However, formwork is a small component of the overall cost of the concrete towers of a larger wind farm. It is also possible that the formwork will be developed and owned by the JIP for the prototype tower and then leased out to precasters of future tower projects. In this case, it is very likely that the formwork will be designed and fabricated in the U.S., in particular if the JIP receives a grant from the U.S. government. This approach was used in other successful demonstration type projects. A U.S. formwork company has expressed interest in joining JIP and have also expressed interest in providing some in-kind support towards this effort.

7.5.3 Construction Material

Construction materials such as concrete, reinforcement steel, and post-tensioning steel will be supplied by the international market and may or may not be fabricated in the U.S., unless the construction documentations specifically call for U.S. products. Obtaining these materials from the manufacturers in the U.S. in not a challenge. The supply of UHPC might bear a challenge for large projects as the amount of UHPC needed for one larger wind farm might be greater than the current typical yearly demand for this material in the U.S., which could potentially result in longer lead times. However, UHPC is also manufactured in the U.S. and can meet the "buy American" act, if required. A supplier that worked as an industry partner for the Hexcrete project has confirmed that supplying UHPC in large quantities would not be a challenge and is within the capability of the company.

7.5.4 Assembly and Handling Equipment

There is no particular need for the development and manufacturing of expensive specialized handling, assembly, and erection equipment such as sophisticated transporters or cranes. Existing equipment, both, manufactured in the U.S. or abroad, can be used. For future larger wind farms, it is anticipated that equipment will be modified and new tooling such as handling racks will be developed and fabricated to increase productivity. Such tooling can be fabricated in the U.S.; however, it will represent a small portion of the project cost.

7.5.5 Site Work

A considerable portion of the work will still occur at the site such as the assembly of the tower segments, the erection of the tower, and the post-tensioning. This work will be performed locally and most likely with local workers.

7.6 Preliminary Intellectual Property Management Plan

Iowa State researchers have had multiple discussions with an internal university team specializing in industry contracting and license management about the structure of the JIP. Meetings are planned with licensing managers and intellectual property offices to finalize the handling of background intellectual property. One of the project industry partners, BergerABAM, will then review the plan, before circulating it to initial JIP members for review and signature.

7.7 Summary and Next Steps

Since receiving the DOE grant, the Hexcrete technology has been advanced in multiple fronts to help commercialize the tower technology. An important success of the project is engagement of several partners from different sectors within the wind energy and concrete industry. It is believed that the partnerships that have already been established will soon be formalized through the formation of the JIP which will be a key factor in the successful demonstration of tall towers using the Hexcrete technology. There is clearly a market in the U.S. for tall towers, but solid business cases need to be established for market penetration. Even though wind rich regions such as Iowa and Texas can benefit from tall towers, the industry seems more interested in using the new technology to establish new wind markets, where rich wind resource information is not currently available. While a high foundation concept utilizing the Hexcrete technology may be more attractive in the wind rich corridor, tall towers needs to be marketed as a means to unlock unused wind potential in the Southeast, Northeast and Great Lakes.

It is important to continue the momentum that has been developed toward taller towers so that market penetration in new regions can be eventually realized. As a step toward achieving this goal, this chapter has articulated several milestones for the Hexcrete technology. It is believed that achieving these milestones will help fuel the wind industry towards new regions and continue to grow the installed wind capacity in the U.S. As more activities are undertaken, this implementation chapter will be updated and used as a living document to help guide the industry with the use of new technology. As next steps, the following activities will be undertaken:

- Stakeholder management
- Purposeful education of potential users of the technology through conference and media outlets
- Meeting with potential stakeholders and exploring avenues to strengthen the business case
- Active engagement in industry organizations such as American Wind Energy Association, American Concrete Institute, and the Precast/Prestressed Concrete Institute
- Solicitation of funding
- Further development of the detailed business case to inform potential development partners
- Solicitation of potential business partners
- Identification of suitable grants to assist in accomplishing milestones
- Identification of opportunities for construction of prototype Hexcrete towers systems

Chapter 8 – Conclusions and Recommendations

This report has presented project activities completed in BP2, which have focused on further advancing the Hexcrete tower technology by designing 140-m (459 ft) tall wind turbine towers. These designs were further refined through optimization, fluid-structure interaction studies, and establishment of realistic tower erection and construction processes. For the latter task, experienced industry partners were engaged to ensure the planned erection schedule was efficient and appropriate under field conditions so that realistic LCOEs can be realized. The model developed by NREL was used for calculating the LCOE with the research team providing the tower cost for different scenarios. Finally, an implementation plan has been developed to commercialize the Hexcrete technology which includes specific milestones to be completed in the coming years, with the ultimate goal of promoting widespread deployment of Hexcrete towers for harvesting wind energy at 120 to 140 meter (m) hub heights, reducing the Levelized Cost of Energy (LCOE) of wind power, and promoting wind energy production in new regions of the United States. Conclusions and recommendations drawn from this study are summarized below:

- The Hexcrete tower design process has been expanded to 140-m (459 ft) tall concrete and hybrid towers and their designs were improved through a systematic optimization process and fluid-structure interaction tools. It was found that both the HT2 and HT3a hybrid tower systems, with approximately the top third of the tower using steel tubes, provided the best structural design solution to take advantage of the Hexcrete tower fabrication, transportation, and construction advantages while utilizing a strength of existing steel towers, namely lower drag coefficients which result in lower tower loads.
- As a result of industry collaboration a quick connection system between tower cells was designed to allow erection of the entire tower structure prior to placing grout between the columns of different cells and applying vertical post-tensioning. A small amount of post-tensioning has been moved inside the tower to help stabilize the tower as needed on strong wind days. This system reduces construction time, ultimately reducing the LCOE.
- The tower optimization process was expanded by implementing an integrated toolkit that automatically generated Hexcrete tower CAD models, performed FEA simulation, calculated tower cost, evaluated constraints and performed optimization of the Hexcrete tower cost.

Comparing the optimal designs with the initial designs, tower cost reduction (1.31% for HT2 and 5.96% for HT3a) was obtained.

- Shallow foundations were designed for both HT2 and HT3a towers with diameters of 26 m (85 ft) and 29 m (95 ft), respectively. To study the soil-foundation interaction, a sophisticated 3-D finite element model was developed with an elastoplastic soil constitutive model and a soil-foundation interface to better capture the soil and foundation responses. The finite element simulations demonstarted that both foundations had sufficient bearing, overturning capacity, and stiffness and can ensure operability of the two towers for a 20-year service life.
- In the BP1 analysis, assembly and installation costs as well as foundation costs contained relatively high uncertainties. However, in BP2, input from industry experts resulted in greatly reduced levels of uncertainty and increased confidence in the bottom-up approach used to estimate foundation and tower costs.
- LCOE estimates were compared for three specific scenarios: an 80-m (262-ft) conventional steel tower for a 3.2 MW turbine; a 140-m (459-ft) conventional steel tower for a 3.2 MW turbine; and the hybrid HT3a 140-m (459 ft) tower for a 3.2 MW turbine. The analysis results showed that the LCOE for the HT3a hybrid 140-m tower would be 20% lower than the LCOE of a conventional 80-m (262-ft) steel tower and 6% lower than the LCOE of a 140-m conventional rolled steel tower. Such reductions are considered huge because a reduction of less than 1% in LCOE decides the winning power purchase agreements in today's market. These results show that the Hexcrete technology is competitive against steel tower technologies at tall hub heights (e.g., 140 m (459 ft)) in wind sites with high wind shear characteristics. The project team expects further reduction to LCOE of Hexcrete towers as the technology becomes more broadly used and the precast concrete industry gains experience in fabricating the tower components.
- To successfully commercialize the Hexcrete technology, an implementation plan has been formulated. With input from industry partners, this plan focuses first on formulating a Joint Industry Partnership (JIP). The JIP will target multiple milestones and complete prototyping of the Hexcrete technology. Two of these milestones are: 1) use of a 20 m (66 ft) tall Hexcrete segment as an extension to the foundation in a wind rich area with an 80 m (263 ft) tall steel tubular tower on top; and 2) building a 120 m (394 ft) tall full or hybrid Hexcrete tower in a

potentially new wind market region such as the Southeast. Both efforts would require public funds in addition to the support from the industry partners and Iowa State University. By completing these key milestones and obtaining appropriate certifications, it is believed that the Hexcrete technology will not only introduce tall towers in the U.S., but it will also help bring wind power to states that have nearly zero renewable energy in their portfolio.

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