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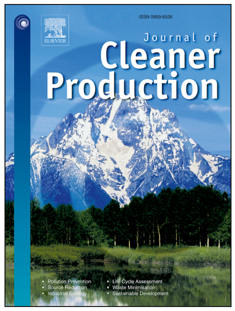

Evaluating commercial feasibility of a new tall wind tower design concept using a stochastic levelized cost of energy model

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Title Page:

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Evaluating Commercial Feasibility of a New Tall Wind Tower Design Concept Using a Stochastic Levelized Cost of Energy Model

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1 ABSTRACT

Wind power generation has seen a dramatic increase in the 21st century and the Department of Energy (DOE) envisions that wind energy will become a much larger part of overall power generation in the U.S. by 2050. Wind turbines have continued to grow in size during the last few decades with towers commonly built at a height of 80 m for typical utility-scale turbines in the Unites States, and this is accompanied by certain transportation and logistics challenges. The newly proposed tall tower technology has been designed to be cost-effective in assembling towers as high as 140 m from precast concrete module components that are capable of transport on the U.S. road system. This paper presents an alternative wind tower design with potential for reducing the overall levelized cost of energy (LCOE); it evaluates a hexagonal precast concrete wind tower solution that facilitates use of a taller wind turbine generator for harvesting stronger, steadier, and more frequent wind resources to increase wind energy production and lower the overall LCOE. An integrated team of industry experts was consulted to support development of a stochastic life cycle cost model using a parametric estimate of the cost and fabrication and assembly schedules of this new wind tower design concept as well as forecasting the projected revenue to be created by the new technology. The study concludes that this new design concept is a commercially viable solution, with an estimated LCOE savings ranging from 2% to 4% compared with the typical 80 m turbine deployed in the United States, and it also provides wind power potential to previously untapped regions in the country. This paper helps to inform energy

developers, manufacturers, and policy makers, both regionally and nationally, of a possible economically feasible wind tower design solution.

2 INTRODUCTION

Wind energy has undergone meaningful growth over the last decade and is expected to play an elevated role in overall United States power generation sustainability strategy in the future (Aghbashlo et al., 2018; Kaldellis and Zafirakis, 2011). “Wind power generation in the United States has tripled, increasing from 1.5% of annual electricity end-use demand in 2008 to 4.5% through 2013. As of 2013, there were more than 61 gigawatts (GW) of wind generating capacity installed” (DOE, 2015). Wind-power generation has exhibited a dramatic increase during the 21st century (Burton et al., 2011), and the Department of Energy (DOE) has a vision of wind energy becoming a much larger part of overall power generation in the U.S. by 2050 (Figure 1). The DOE has created Wind Vision, a future strategic plan for use of wind energy in the U.S. that envisions wind energy serving 10% of the nation’s end-use demand by 2020, 20% by 2030, and 35% by 2050.

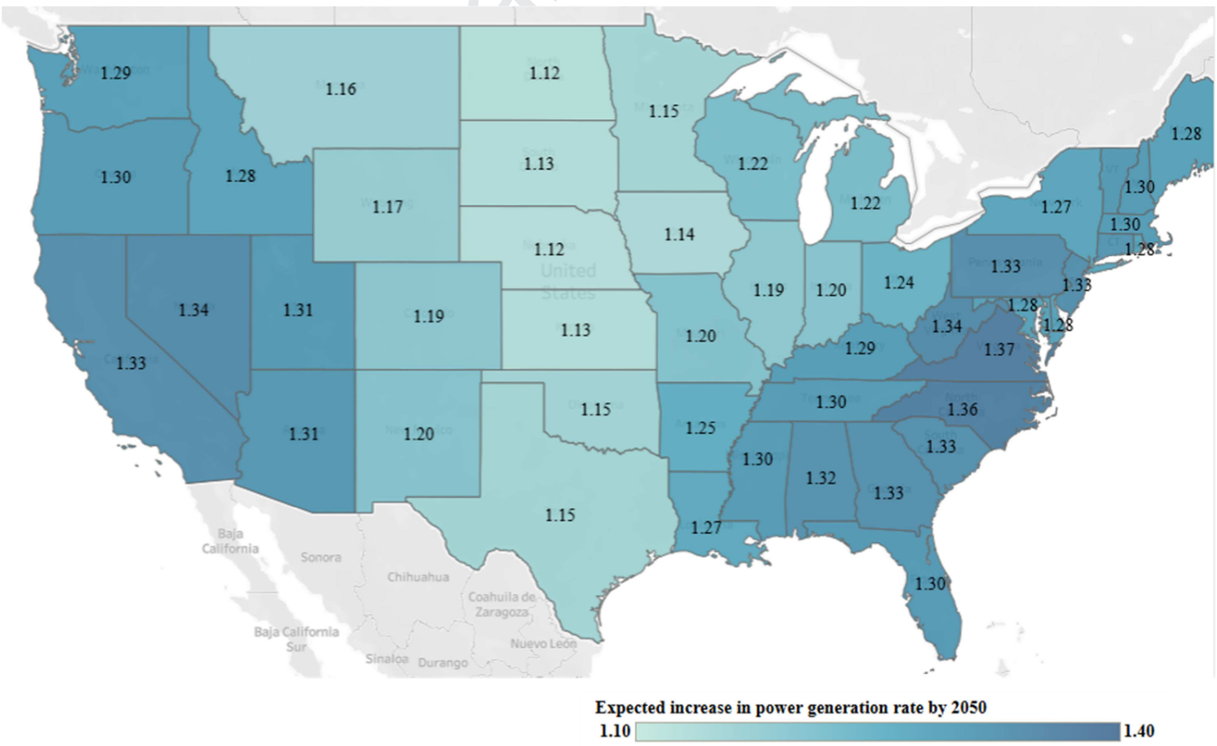
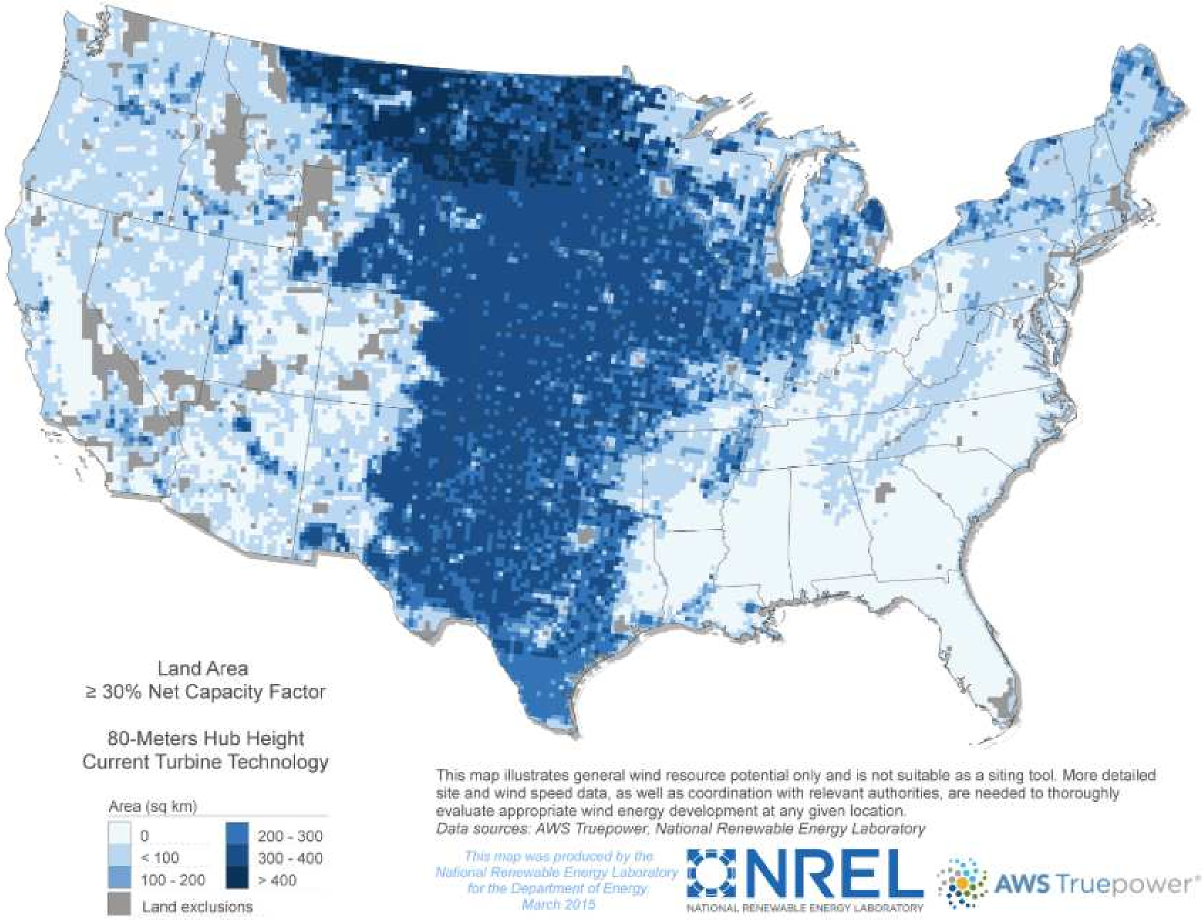


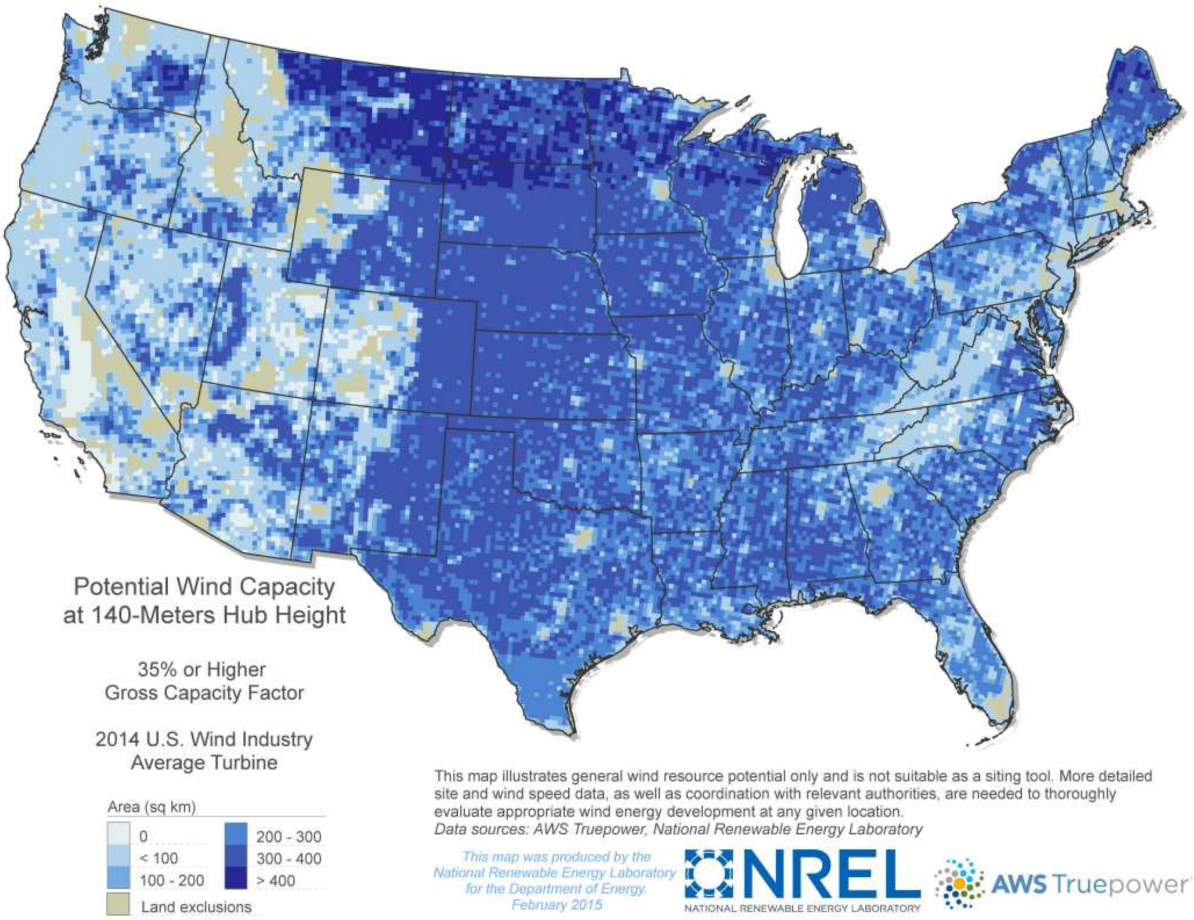
Figure 1 Expected increase of wind energy production rate by 2050, created based on the data obtained from DOE Maps & Data (WINDExchange, 2019).

Because the demand for wind energy is expected to continue to increase in the future, the industry has also looked to it becoming a more economically feasible solution for electrical power generation. Investment in wind power generation and the economic impact associated with wind energy have increased over recent years, and wind power has proven to be cost-effective and reliable. Wind power capacity, generation, and investment have grown dramatically. Global investment in wind power grew from $14 billion in 2004 to $110.3 billion in 2016 (DOE, 2015). As evidenced by its increased role in overall power generated and its financial and economic growth in recent years, wind energy is a growing market affecting the world both environmentally and economically (Jiang et al., 2018; Johansson et al., 1992; Kumar and Sinha, 2016; McCrone et al., 2017).

Technology advancements in the wind energy industry have led to a dramatic decrease in the cost of energy for wind power (Bielecki, 2002; Short et al., 1995). In recent years, there have been many improvements in wind energy technology, allowing wind power generation to become much more efficient and cost effective (Laslett et al., 2017). “Technology development and improvements in reliability have helped drive a 33% cost reduction in land-based utility scale LCOE from 2008-2014” (DOE, 2015). Increasing the height and rotor diameter of a wind turbine can greatly increase the efficiency and the amount of energy generated by each turbine. “The wind power that at any given wind speed can be captured by the rotor is proportional to its swept area, and larger rotors therefore capture more energy”(DOE, 2015). It is important to note that wind speed generally increases with increased height above the ground, and taller towers therefore provide access to stronger winds, as depicted in Figure 2.


Land Area
≥ 30% Net Capacity Factor
80-Meters Hub Height
Current Turbine Technology
Area (sq km)
0
< 100
100 - 200
200 - 300
300 - 400
> 400
Land exclusions
This map illustrates general wind resource potential only and is not suitable as a siting tool. More detailed site and wind speed data, as well as coordination with relevant authorities, are needed to thoroughly evaluate appropriate wind energy development at any given location.
Data sources: AWS Truepower, National Renewable Energy Laboratory
This map was produced by the National Renewable Energy Laboratory for the Department of Energy. March 2015
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
AWS Truepower

(a)



(b)

Figure 2 Impact of wind towers' height on energy production: a) 80 meters hub height; b) 140 meters hub height (DOE, 2015).

Figure 2 illustrates how wind resource vary tremendously with geographic location in the US, and the height of the wind energy resource varies over different regions of the US. Darker blue indicated presence of stronger and steadier wind, which results in higher wind power generation capacity. As shown in the Figure 2, the central plains region have an adequate wind resource at a minimum of 80 m hub height, while the southeast region has a much more optimal wind resource at higher hub heights.

3 BACKGROUND

Wind energy is not a new technology; people have been harvesting the power of wind as far back as 5000 B.C. "The wind has played a long and important role in the history of human civilization. The first known use of wind dates back 5,000 years to Egypt, where boats used sails to travel from shore to shore. The first true windmill may have been built as early as 2000 B.C. in ancient Babylon. By the 10th century A.D., windmills were grinding grain in the area now known as eastern Iran and Afghanistan" (Iowa Energy Center, 2000). When a combination of a rotor and a generator is used to turn mechanical wind energy into electric power, the resulting machine is called a wind turbine. In the 1930's and 1940's, hundreds of thousands of electricity-producing wind turbines were built in the U.S. They typically had two or three thin blades that rotated at high speed to drive electrical generators (Johnson, 1985). These wind turbines provided electricity to farms lying beyond the reach of power lines and were typically used to charge storage batteries, operate radio receivers, and power a light bulb or two (Burton et al., 2011).Today wind power generation has grown to a level where it supplied more than 61 gigawatts of electricity over 39 states in the US by the end of 2013. "Two states, Iowa and South Dakota, both produced more than 25% of their in-state [power] generation from wind" (DOE, 2015).

The current typical land-based utility scale wind turbine in the U.S. has a rotor hub height of 80 m above the ground, and most wind turbine generators in today's market have a power-generating capacity between 1.5 megawatts and 3.0 megawatts (Laslett et al., 2017). There are four principal components of a wind turbine: the foundation (base), the tower, the nacelle, and the rotor (including both center and cutting edges) (Figure 3).

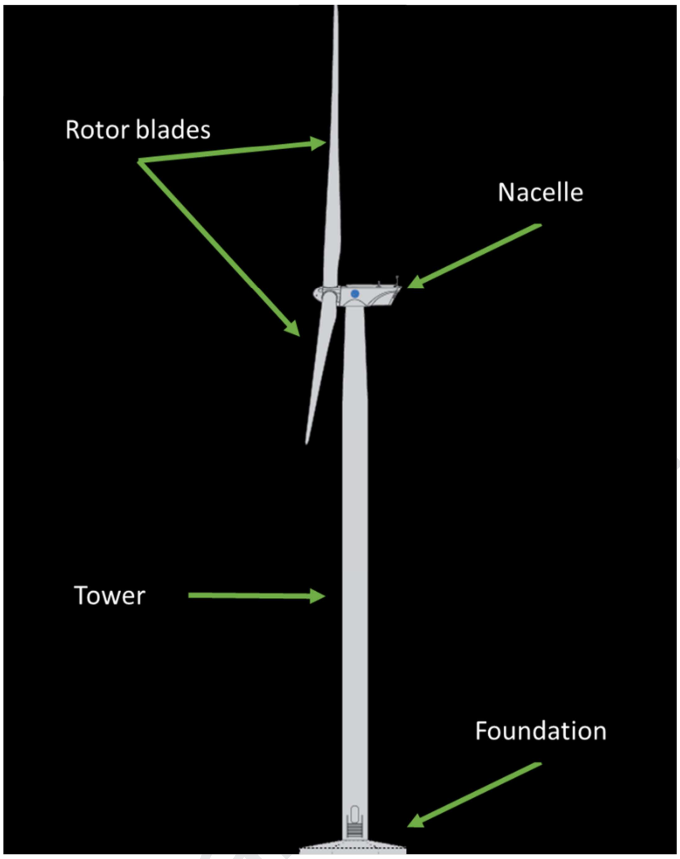


Figure 3 Major wind tower components.

The rotor transforms wind energy into rotational movement. The nacelle contains the electrical generator and associated elements that convert the mechanical rotor movement into electrical power. The tower underpins the nacelle and rotor, and the foundation serves as an anchor to support the entire structure. Most 80 m steel wind turbines in the U.S. are comprised of three steel tower sections: the base, mid, and top (Kumar and Sinha, 2016). “Rolled steel is the primary material used in wind turbine tower structures for utility-scale wind projects. Plate steel is rolled and machine-welded at the factory, then transported to and assembled at the project site” (Mone et al., 2015). The concept of on-site assembling of precast components is common in other types of structures due to its construction speed and efficiency (Arabi et al., 2019, Arabi et al., 2018). Conventional rolled-steel towers can be transported with tower sections up to 4.6 m in diameter over roads and 4.0 m in diameter via railroad; towers with diameters exceeding 4.6 m are difficult to transport, and transport restrictions can result in sub-optimal tower design and increased cost for tower heights exceeding 80 m (Nahvi, 2017; Sri, 2017a). In addition, the county road pavements are not designed to carry such heavy loads. Therefore, in some states, secondary road authorities would charge wind warm developers with impact fees for damaging the local infrastructure (Ahmed, Karim et al., 2011).

A structurally-optimized tower would have a larger base diameter, thinner walls, and would require less total steel, so overcoming transport limitations would reduce project costs and LCOE.

The wind energy industry has explored various solutions for overcoming these transportation limitations for all towers, including use of a hybrid material wind tower with base sections of precast concrete and upper sections of conventional rolled steel, and new tower configurations that would overcome transport limitations are being evaluated) (Sri, 2017b). These new configurations - known as hybrid towers - use concrete tubes for the lower, larger-diameter sections and steel for the upper sections. Concrete towers can have separate, pre-fabricated concrete elements with diameters up to 14.5 m, and large-diameter bottom segments can be produced in the form of two or three partial shells that can be shipped on conventional transportation systems (DOE, 2015). The most frequent alternatives examined by the industry have attempted to include such a hybrid concept along with curved concrete shell towers, and neither technology by itself completely overcomes the transportation and logistical challenges.

To eliminate transportation and logistical constraints, the Hexcrete Tower design using segmented concrete tower sections was developed; it can be easily shipped using the current transportation system. This concrete solution uses prefabricated tower sections to support a wind turbine to heights up to 120 m; each section consists of six hexagonal columns and six tapered or rectangular panels connected with prestressing (Sri, 2017a) (Figure 4).

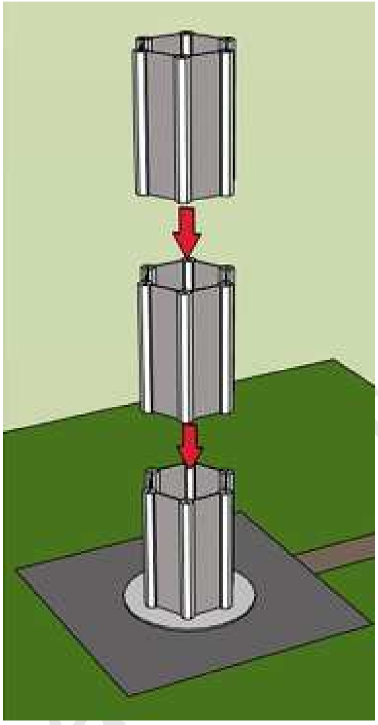


Figure 4 A schematic view of a Hexcrete tower section (Sri, 2017b).

Since traditional round or curved precast sections can cause constructability problems if an on-site assembly process is used, configuring the tower into a hexagonal shape with six separate columns and panels can overcome transportation limitations while maintaining ease of assembly at each turbine site (Sri, 2017b) (Figure 4). The Hexcrete tower is designed to use high performance concrete (HPC) and ultra-high performance concrete (UHPC) components, reducing component sizes and thus eliminating transportation and logistics constraints associated with construction of taller wind turbine towers (Nahvi, 2017; Sri, 2017a).

Various studies evaluated and discussed structural designs of Hexcrete towers and its ability to withstand high winds compared to the steel towers in details (Peggar, 2017; Sauber, 2009; Sri, 2017a; Sritharan, 2015). However, commercial feasibility and constructability of this novel technology have not been evaluated yet. Developing commercial feasibility plans for new wind tower technologies would help decision makers (e.g. wind farm developers, contractors, states and federal agencies) to make informed decisions regarding the costs and benefits of deployment of such technologies. The cost of producing energy is measured by using the levelized cost of energy (LCOE). "Levelized cost of energy (LCOE) is a metric used to evaluate the cost of electricity generation and the total plant-level impact from technology design changes." LCOE can be used to compare costs of all types of electricity, as long as consistent formulas and calculations are used for each type (Tegen et al., 2012).

4 OBJECTIVES

The objective of this paper is to use a stochastic levelized cost of energy (LCOE) model to evaluate the commercial feasibility of a new wind tower design that facilitates a taller wind turbine generator to take advantage of stronger, steadier, and more frequent wind resources for increased wind energy production. This study seeks to answer the question "Can this new tower design provide a constructible and commercially viable solution that will increase wind energy production while lowering the overall levelized cost of energy?"

5 LCOE COMPONENTS

The Levelized Cost of Energy (LCOE) represents the average value per unit of energy production that would be required by a project owner to recover all cost and operating expenses over a predetermined project financial life and duty cycle measured in dollars per kilowatt hour ($/kwh) (Short et al., 1995). LCOE is calculated using the following formula (Mone et al., 2015):

$$LCOE = \frac{(ICC \times FCR) + AOE}{(\frac{AEP}{1,000})} \quad (1)$$

Where ICC is the initial capital cost (ICCA), to include turbine capital costs (TUR_{cc}) and balance of station costs (BOS_{cc}), FCR is financing costs, AOE is annual operation expenses, and AEP is annual energy production.

The evaluation process used the LCOE model developed by the National Renewable Energy Laboratories (NREL) (Reategui and Tegen, 2008; Tegen et al., 2012). There are four basic inputs into the LCOE equation, the first three being ICC, annual operating expense (AOE), and annual energy production (AEP), enabling this equation to determine system-level impact resulting from design changes (e.g., taller wind turbine towers), while the total costs of financing are represented by the fourth basic input - a fixed rate charge (FCR) – that determines the amount of revenue required to pay the carrying charges on an investment while determining expected plant life (Lantz and Tegen, 2008; Tegen et al., 2012). The financing assumptions included in the FCR refer to the cost of interest and other carrying charges, to include the cost of debt or equity and are captured in the discount rate, which is in turn used to estimate the cost of energy of the overall life of the facility (Stehly et al. 2017). For this analysis, the life of a wind project was assumed to be 20 years. Figure 5 illustrates the breakdown of ICC for the NREL land-based reference project.

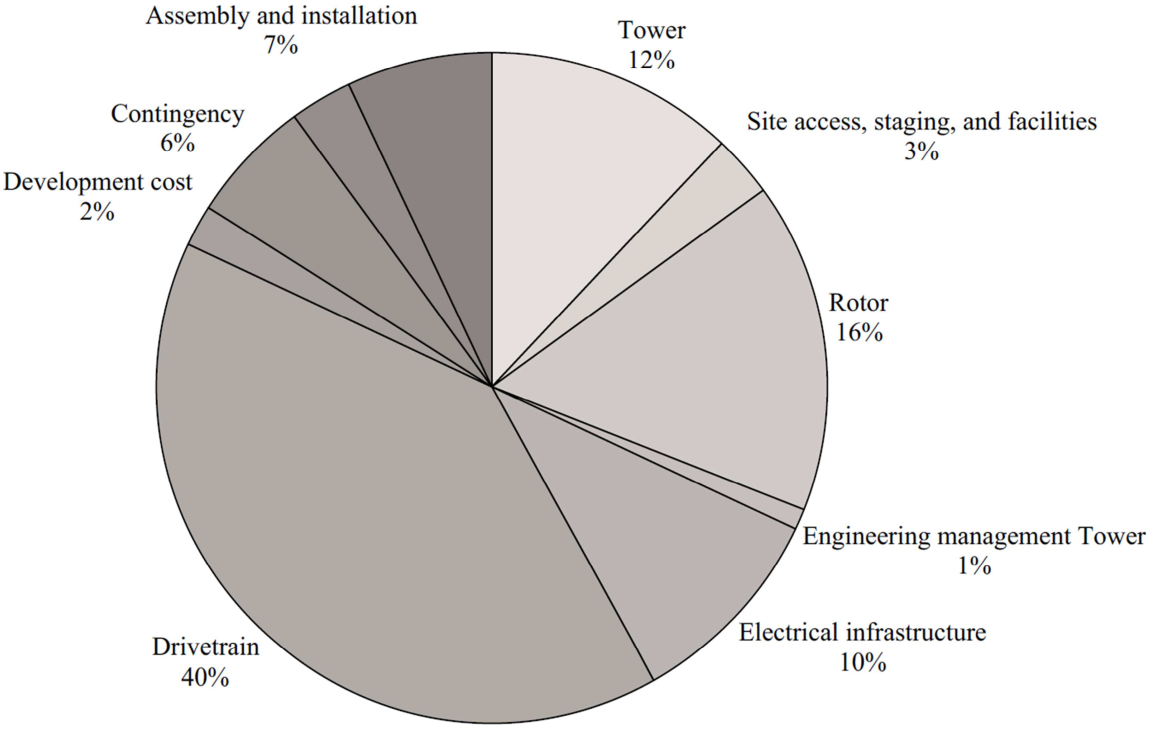


Figure 5 Capital costs for land based wind power projects, data from (Tegen et al., 2012)**.**

AOE typically include land-lease costs, operation and maintenance (O&M) wages and material, and levelized replacement costs. O&M costs are generally grouped into two categories:

1) Fixed O&M, including known operational costs (e.g., scheduled maintenance, rent, leasing, taxes, utilities, or insurance payments).

2) Variable O&M, including unplanned maintenance and other costs that may vary throughout the project life depending on how much electricity is generated (Lantz and Tegen, 2008; Tegen et al., 2012).

AEP for this analysis was computed using the NREL wind turbine design cost and a scaling model that computes annual energy capture and other related factors, e.g., capacity factor, for a wind project specified by generic input parameters (Stehly et al., 2017). Turbine parameters are characteristics specific to a particular turbine and independent of wind characteristics, and they consist not only of turbine size parameters (such as rated power, rotor diameter, and hub height), but also of turbine operating characteristics such as maximum rotor capacity, maximum tip speed, maximum tip-speed ratio, and drivetrain design (Zhang et al., 2017). Although some losses can be affected by turbine design or wind characteristics, losses have been treated as independent of any other input in this simplified analysis; they include array losses, collection and transmission losses, soil losses, and availability. Net annual energy production (AEP net) has been calculated by applying all losses to the gross AEP (Lantz and Tegen, 2008; Reategui and Tegen, 2008).

Throughout 2011, the financing environment remained relatively steady for land-based wind development, and the cost of capital for both term debt and tax equity investment in 2011 did not depart significantly from 2010 levels. Because there were no large fluctuations in the cost and availability of debt and equity capital from 2010 to 2011, the financing assumptions were taken to be the same as those used in previous land-based wind LCOE analysis (Tegen et al., 2012).

6 APPROACH

Historical data for determining costs of manufacture, transport, and assembly of the Hexcrete tower is not available because neither a hexagonal concrete tower nor a wind tower built to a height of 120 m has ever been constructed in the US. Using a real-scale prototype to quantify data was also infeasible because of the cost, size, and complexity of building a prototype wind farm of Hexcrete turbines anywhere in the US. Because there was no historical data, and suitable data could not be obtained, panels of subject matter experts were assembled and queried. “Expert Judgement techniques are useful for quantifying models in situations in which, because of either cost, technical difficulties, or the uniqueness of the situation, it has been impossible to make enough observations to quantify the model with real data” (Bedford et al., 2016).

In this paper, a new approach to evaluating the commercial feasibility of a new wind tower design, comparing with the conventional wind tower structures is presented. This approach uses expert judgements derived from subject matter experts along with Monte Carlo simulation (MCS) to develop a stochastic LCOE analysis of the input cost variables. Figure 6 graphically represents the details of the research methodology.

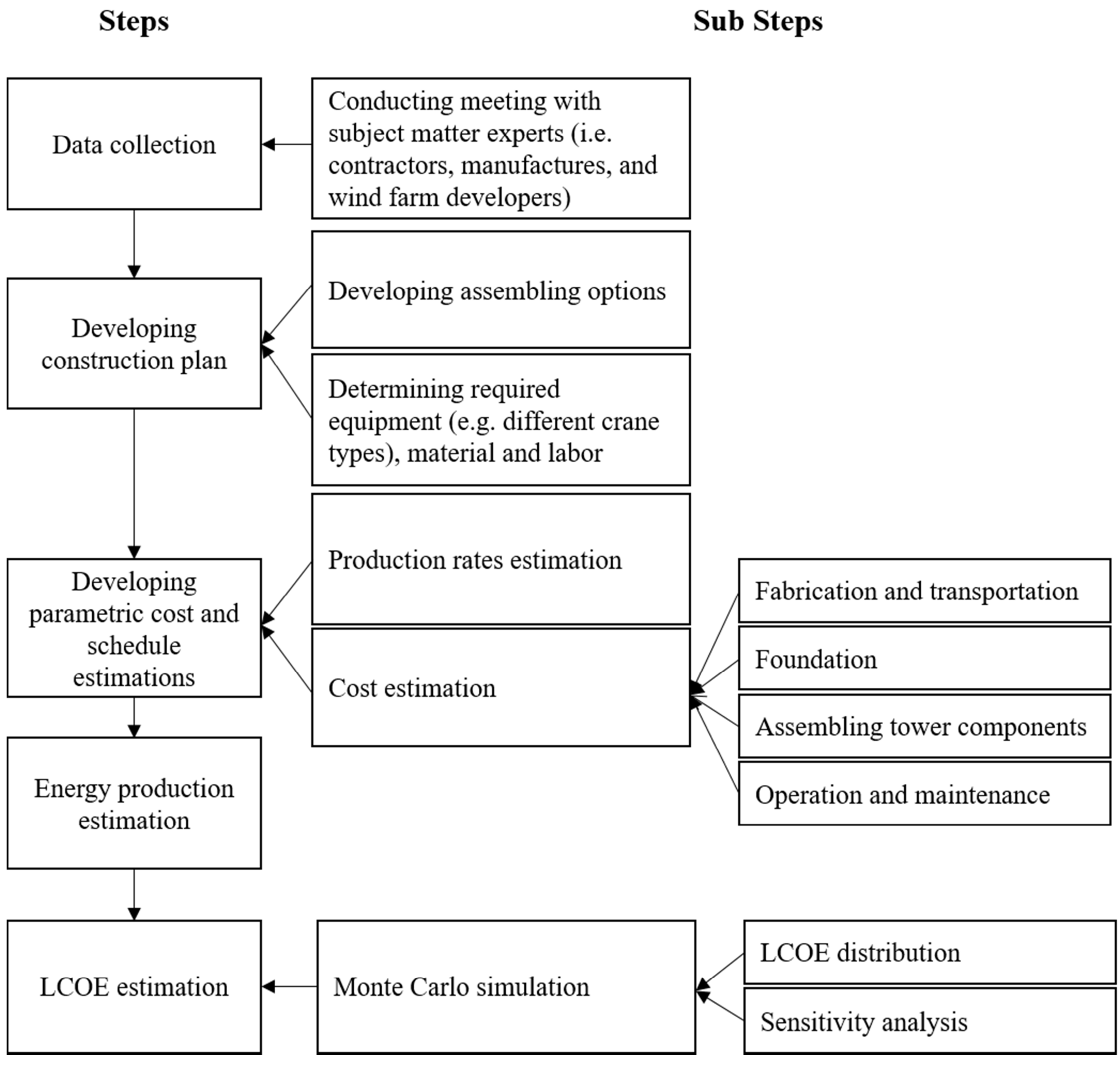


Figure 6 Research methodology.

To improve project outcomes, parties from all appropriate areas of specialization and expertise required to successfully manufacture, transport, and assemble a Hexcrete wind tower project, were involved early in the study. Following the development of the work sequence, the production rate of each activity, and associated schedules, the construction cost of 120 m Hexcrete tower was estimated. A realistic project configuration was used to compare the LCOE of a 120 m Hexcrete tower with that of an 80 m steel tower which consisted of 100 2.3 MW wind turbines located at a site in the "Heartland" of America such as Iowa. The LCOE model assumes wind resource characteristics for generation of AEP associated with such a wind-rich region in the US.

The research compared the difference of the LCOE values between an 80 m steel tower and a 120 m Hexcrete tower and evaluated the commercial feasibility of the new technology.

In order to effectively address the inherent uncertainty issues associated with those estimated values, the Monte Carlo Simulation (MCS) technique was employed (Gransberg and Scheepbouwer, 2010; Kendall et al., 2008; Touran and Wiser, 1992). MCS can perform a risk analysis to quantitatively evaluate the LCOE differences between the two competing technologies. In this method, every cost component with a high potential for variability can be modeled as a random variable (Brandes, 2003; Geweke, 1996; Gransberg and Kelly, 2008).This study considered any variables differing between the two tower options as random variables for MCS. In addition, a sensitivity analysis was conducted to determine the level of impact of each individual input variable on the overall LCOE.

7 DATA COLLECTION

The research team conducted multiple workshops and meetings attended by 19 representatives from all appropriate areas of specialization and expertise needed to successfully manufacture, transport, and assemble an all-concrete wind tower project. The different fields represented are shown in Figure 7.

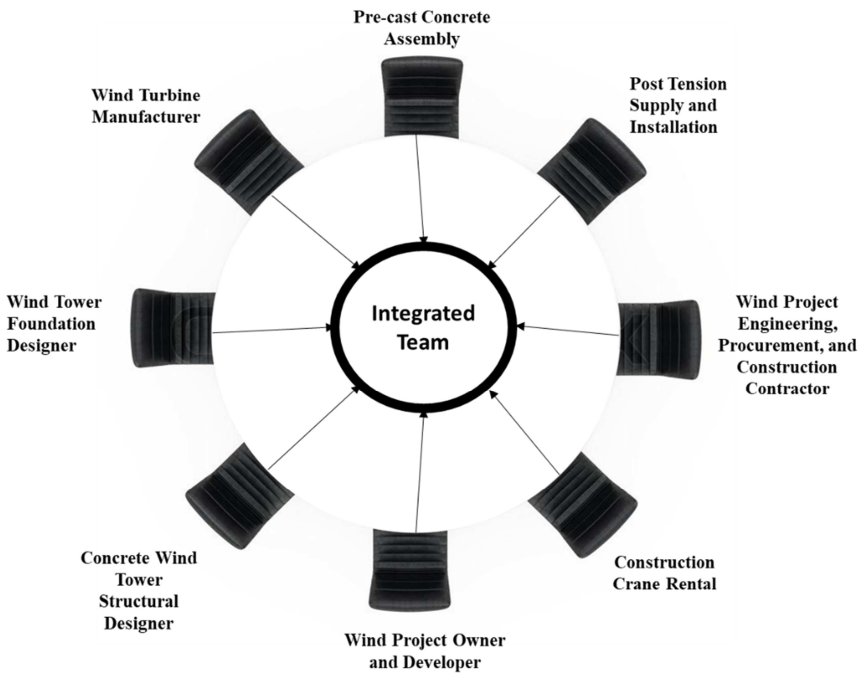


Figure 7 Subject matter experts engaged in the workshops.

All these subject matter experts were engaged in a discussion of advantages and disadvantages of the Hexcrete concrete tower, with each such expert suggesting a choice of input variables, including cost, production rates, and schedule, for each of their areas of specialization.

8 DEVELOPING A FEASIBLE CONSTRUCTION PLAN

During the meeting with subject matter experts, the integrated team developed many assembly options and ultimately concluded on the following two optimized constructability options.

- Option I – Hexcrete/Steel Hybrid Tower (Figure 8a)
- Option II – All Hexcrete Cells (Figure 8b)

Option I (hybrid option) consists of eight Hexcrete tower sections reaching a total assembled height of 80 m and one transition steel top section added to achieve a total height of 120 m. Option I would have panels and columns shipped to the site and assembled on the ground in cells that would then be vertically erected in sections using a crawler crane. The steel top-transition member, the nacelle, and the rotor would be assembled using a different crawler crane configuration. Option II (all Hexcrete) consists of 11 Hexcrete tower sections reaching a total assembled height of 120 m. Similarly, to Option 1, the columns and panels for all 11 sections would be individually transported to the site and assembled on the ground into cells that would then be vertically erected by a crawler crane, except for the final 3 cells, the nacelle, and the rotor, that would be erected using a different crawler-crane configuration.

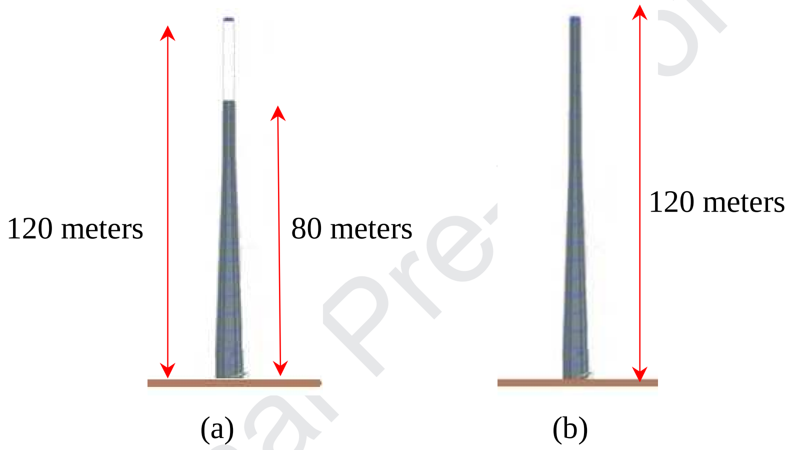


Figure 8 Assembley options; a) Option I – Hexcrete/steel hybrid tower, b) Option II – All Hexcrete cells.

8.1 Work sequence

The work sequence for the 120 m Hexcrete tower can be divided into five major work activities. Option II's construction methodology is very similar to that of Option I, the major difference being that the entire tower height of 120 m will be made of Hexcrete concrete, with only a small steel transition piece lying between the Hexcrete tower and the nacelle.

1. Mobilization and access road construction
2. Foundation construction
3. Fabrication and Transportation of Columns and Panels
4. Fabrication and Transferring Nacelle, hub and Rotor
5. Assembly

First, the primary project management resources must be mobilized and access roads constructed to facilitate the transportation and delivery of materials, the Hexcrete tower pieces, construction equipment, etc. The tower foundation would then be constructed through excavation, reinforcing steel installation, concrete placement, and backfill. Foundation construction costs can be easily estimated by comparison with current practices because that activity requires no new technology or process. While the foundation work is in process, the Hexcrete pieces are transported to the site, with separate columns and panels placed at each individual turbine location. Each of the eight or eleven Hexcrete sections (Figure 9) for option 1 and option 2, respectively, will be assembled and horizontally post-tensioned on the ground in cells after all six columns and panels have been placed in the correct position. The individual cells would then be erected one by one until all cells and tower components have been erected and grouted into place.

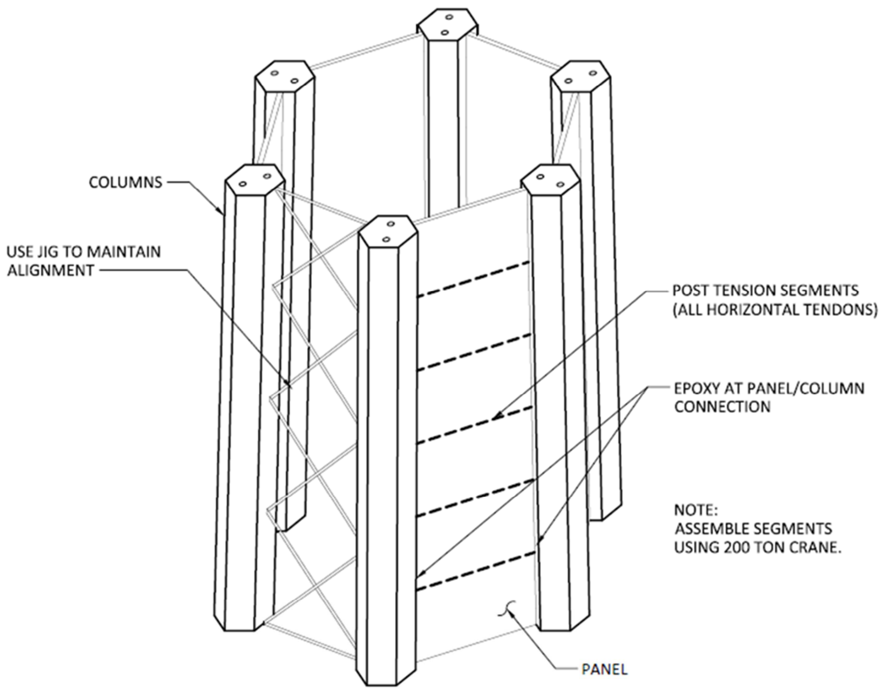


Figure 9 One Hexcrete section.

A vertical post-tension cable would then run through all tower sections and the entire 393-foot length would be post-tensioned. Tower wiring, mechanical completion, and commissioning would also be performed using current wind industry construction practices. The work breakdown structure is presented in Figure 10.

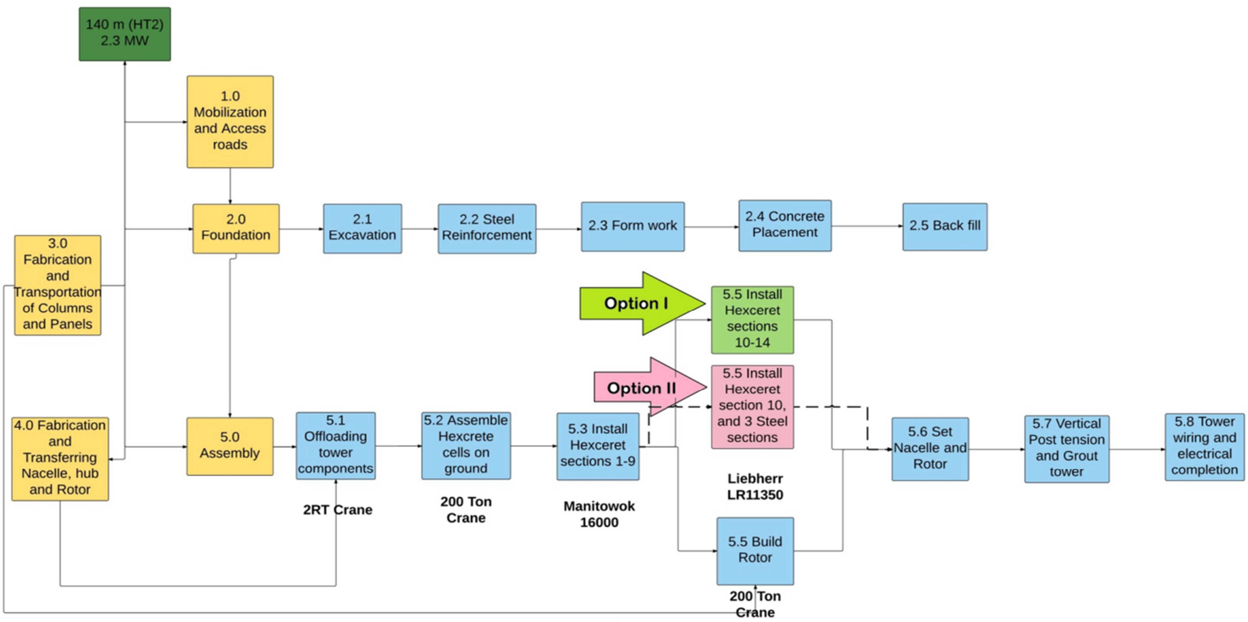


Figure 10 Work breakdown structure (WBS).

9 COST AND SCHEDULE ESTIMATION

9.1 Production Rates

A good estimation of production rates for all work activities is critical for construction cost estimating because such 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, off-loading tower components, and mechanical and electrical completion can be reliably obtained based on current industry practices.

Currently there is no available historical production rate data for assembling Hexcrete cells in this configuration to create a wind turbine support structure. The research team and industry experts discussed constructible options, associated work sequences, and the resources required based on presently-available equipment and developed three different plausible production rates. As shown in Table 1, they were termed low, most likely and high production rates. Based on these production rates, three possible scenarios were developed for assembling each 120 m Hexcrete tower option, and they are detailed in Table 1. Also detail of the production rate of each activity was presented in Table A.1 and Table A.2.

Table 1 Three production rates selected for critical assembly work items.

Activity	Worst case scenario	Most likely scenario	Best case scenario
Assemble cells on ground	1 cell per day	2 cells per day	3 cells per day
Setting Hexceret cell on each other	3 cells per day	4 cells per day	5 cells per day

9.2 Parametric Cost Estimation

Following development of the work sequence, the production rate of each activity, and associated schedules, the construction cost of Option I and Option II were estimated. The basic philosophy used in estimating the cost of the conceptual 120 m Hexcrete tower was to use costs from NREL's LCOE model as a baseline while quantifying cost differences based on activity differences between the 80 m steel and the Option I 120 m Hexcrete tower. The cost differential was evaluated for each crew and for each activity that differed between the 80 m steel and the 120 m Hexcrete assembly processes. The overall cost differential was categorized into fabrication and transportation of the tower module, tower erection, and foundation construction costs. Specific equipment, crew size, crew production, and material used for each crew were determined for the differing activities for both the 80 m steel and the 120 m Hexcrete towers.

Note that The LCOE model published by NREL does not take into account the demand variation of electricity such as at peak times. However, the objective of this study was to compare the commercial feasibility of the existing technology, an 80 M steel wind tower, to a new concrete tower design built to 140 M. The NREL LCOE model provides a good baseline comparator to evaluate the relative commercial feasibility of the current technology to a new conceptual design thus was used as our comparison model.

9.2.1 Fabrications and Transportation of Hexcrete tower components

The precast concrete columns for this project will be made from High-Strength Concrete (HSC) with the panels made from Ultra High-Performance Concrete (UHPC). Based on discussion with precast concrete manufacturing companies based in the Midwest, three possible cost estimate scenarios were developed using the following key assumption:

- Dedicated facility for full time production of the components. The quantity of components will demand a dedicated facility and this is consistent with current wind energy production practices in the industry.
- Very little project management or engineering and drafting time, or jobsite patching, etc. This is assumed to be a standard manufacturing process following pre-engineered designs.
- Some labor provisions for steaming UHPC components as this is the current practice for UHPC curing.
- The costs of post-tensioning material and labor are included in the assembly process.
- $2500/CY provision for UHPC material in the panels, which is the current market cost for UHPC material.

- Specialized trailers to haul columns with more than typical weight and some minimalist pup trailers with saddles. This was assumed due to current wind energy industry practices of utilizing specialized hauling equipment.
- Panel to be hauled on edge in a rack system because they are too slender to be hauled flat.

Table 2 shows the volume of UHPC and HSC needed for the 120 m Hexcrete tower. The ratio of the fabrication and transportation costs for tower components of Hexcrete tower to those of 80 m steel-based tower were also compared and are presented in Table 2 for the different scenarios. For hybrid options, the cost of the steel top is also included.

Table 2 Cost ratio comparison of Hexcrete columns and panels with 80 m steel-based tower.

Type of tower	Volume of UHPC (m^3)	Volume of HSC (m^3)	Tower component cost ratio 120 m Hexcrete Vs. 80 m steel-based		
			Low	Most likely	High
120 m- hybrid option- 2.3 MW	79	256	1.84	1.92	2.07
120 m- all concrete- 2.3 MW	94	336	1.81	1.91	2.10

9.2.2 Foundations

Since it requires no new technology or process, wind tower foundation construction cost can easily be estimated from those of current practices. The tower foundation cost for a Hexcrete tower is approximately two times more than for an 80 m steel-based tower. Detailed costs estimation for foundation of Hexcrete towers and 80-meter steel tower were presented in Table A.3

9.2.3 Assembling tower components

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 using a 200-ton crawler crane. For setting Hexcrete cells below the 80-m (263-ft) height, a 400-ton crawler crane was selected, while for installing segments above 80 meters (263 ft), as well as the rotor and nacelle, a 650-ton crawler crane was assumed. Estimates of the ratio of assembly costs of tower components of a Hexcrete tower to those of an 80 m steel-based tower were based on different production rate scenarios, and the comparison is shown in Table 3. Note that detail rental and mobilization costs associated with cranes used for design of construction of Hexcrete towers were presented in Table A.4. In addition, detailed assembly costs estimation for one type of Hexcrete towers (HT2) was presented in Table A.5.

Table 3 Assembly cost ratio comparison of Hexcrete tower with 80 m steel-based tower.

Type of tower	Assembly cost ratio 120 m Hexcrete Vs. 80 m steel-based		
	Low	**Most likely**	**High**
120 m- hybrid option- 2.3 MW	2.56	2.66	2.85
120 m- all concrete- 2.3 MW	2.83	2.96	3.31

9.2.4 Operation and maintenance

Calculating operations and maintenance (O & M) life cycle costs for renewable energy plants, specifically wind energy plants, differs greatly from that used for other electrical power generation facilities centered around burning of fossil fuels. The fuel resource used for wind power generation is wind, not a traded commodity and therefore not requiring additional costs to plant users for obtaining it. Fossil-fuel-based power generation facilities, on the other hand, must pay for fuel such as natural gas or coal, to create electrical energy. The life cycle costs for O & M of a wind power generation plant therefore would be much lower and have higher cost certainty than for fossil fuel power generation plants, so the O & M costs included in the overall LCOE model have relatively low impact compared to those of fossil fuel generation facilities of the same capacity.

The O & M costs included in the LCOE model represent costs for local leasing agreements for land on which the turbines reside, general O & M management and staff of the operating facility, and maintenance items ranging from routine maintenance such as tower bolt re-torqueing up to full gearbox and blade replacement procedures. Typically, the land leasing agreements are fixed payments agreed to at the inception of the project during its development phase, so these costs tend to be quite static throughout the project life cycle. The O & M management personnel requirement is typically 1 staff member per 10 turbines (Conover et al., 2000), so the hypothetical wind power facility depicted in this study would over the project life have about 10 staff members to perform routine O&M activities. Larger planned maintenance activities including gearbox and blade replacement procedures would require additional equipment, personnel, and material, and costs for these activities would include costs of replacing operating equipment such as the gearbox or rotor blade, costs for mobilizing specialized personnel, and costs of mobilizing large equipment such as cranes to perform the maintenance work. These costs are treated as an average annual cost distributed over the project life cycle.

10 AEP

One critical item in estimating LCOE of wind energy is the AEP for a single turbine or a wind farm. AEP is accumulative energy output for a wind project over a given year, and the net AEP is the AEP adjusted for production losses during the lifetime of the wind project.

To facilitate the LCOE analysis for the Hexcrete tower design, estimation of AEP and its related parameters was performed by NREL, who worked as a cost-estimate consultant for this project, based on prior experiences on cost analysis of wind farm and current-status of technology for utility-scale wind turbines. In this section, the net AEP will be estimated using the NREL wind turbine design cost and scaling model with the consideration of assumed losses from turbine availability and production (Fingersh et al., 2006). Parameters for estimating the energy production are categorized into turbine operation characteristics, wind resource, and operation losses, which are summarized in the following three subsections.

10.1 Wind turbine parameters in the AEP assessment

Chosen as the practical size for most today's onshore wind turbines, 2.3 MW turbine with a 108 m long blade was used in the studied to assess the energy production of a 100-turbine wind farm per year. The power curve for the 2.3 MW turbine is derived from public available dataset (StudyLib, 2011). Because steel tubular wind tower dominate the U.S. market and the averaged hub height of land-based turbines is approximately 80 m, this type of tower and hub height was selected for the baseline wind tower technology in this study. A summary of the turbine parameters is shown in Table 4.

10.2 Wind resource parameters in the AEP assessment

To perform the LCOE analysis, wind resource parameters were carefully determined for a generic wind site in the United States (Sri, 2017a) whose parameters are assumed to be consistent with the NREL 2013 cost of wind energy review as summarized in Table 5 (Mone et al., 2015). To estimate the wind energy potential at higher hub heights not commonly found at present sites, the AEP model applies the annual average wind speed at a height of 50 m above ground obtained from the NREL database, and a presumed wind-shear exponent, to vertically extrapolate wind speeds for higher elevations. The annual average wind speed at the 50 m height has been taken as 5.22 m/s, and this is combined with a wind shear exponent of 0.240 to compute wind speeds at different elevations. A sea level elevation of 450 m has also been assumed, resulting in an average air density of 1.163 kg/m^3 at a hub height of 80 m.

10.3 Losses and availability in the AEP assessment

Since production losses in estimating the net AEP were not available from the actual project site, assumptions for production efficiency of a wind farm in the AEP model were also made in accordance with the NREL 2013 cost of wind energy review, and they are listed in Table 4

(Mone et al., 2015). This model implements a 15% reduction in the AEP estimate to account for losses such as array wake losses, electrical collection and transmission losses, and blade soiling losses. 98% availability was assumed to indicate that wind turbines would be ready to produce power 98% of the time when the observed wind speed is within the range of cut-in and cut-off speeds. The gross AEP for a wind farm can be determined by the sum of the AEPs for all turbines in the chosen location, and the corresponding net AEP for this wind farm can thus be simply calculated by applying all losses and availability considered for turbines to the gross AEP.

Table 4 Summary of AEP assumptions in the LCOE estimate (Sri, 2017a)

Input parameters	**80 m rolled steel (baseline)**	**120 m Hexcrete**
Turbine capacity, MW	2.3	2.3
Rotor diameter, m	108	108
Hub height, m	80	120
Number of turbines	100	100
Tower concept	Conventional rolled steel	Hexcrete
Wind speed at 50 m, m/s	5.22	5.22
Weibull K factor	2.0	2.0
Shear exponent	0.240	0.240
Altitude above mean sea level, m	450	450
Air density at 80 m, kg/m^3	1.163	1.163
Cut-in wind speed, m/s	3	3
Cut-out wind speed, m/s	25	25
Energy losses	15%	15%
Availability	98%	98%
Net AEP, MWh/year	480,400	583,400

10.4 AEP estimate for baseline wind tower technology

To assist in investigating the economic benefits of Hexcrete tower design, NREL provides an AEP estimate for the conventional tower design height of 80 m. AEP Assumptions for the 80 m tower have remained equivalent to the estimate for Hexcrete tower design except for different hub height, leading to a more than 20% increase in the AEP result for a 40 m increment in hub height.

10.5 Different annual average wind speed scenarios

AEP assessment primarily depends on the sites chosen for wind projects, and areas with better wind resource quality are expected to provide up to a 13% increase in AEP over that of low-quality wind resource areas, resulting in a nearly 12% decrease in LCOE (Mone et al., 2015). Therefore, to capture the LCOE changes directly resulting from different wind resource scenarios, this study used ± 10% of the referenced AEP result as boundary estimates, and the influence of changing annual average wind speed on the projected LCOE is presented in the next section.

11 STCOHASTIC LCOE ESTIMATION

As mentioned in the methodology section, the outcome of a deterministic analysis depends on numerous estimates, forecasts, assumptions, and approximations, with each factor having potential for introducing error. Therefore, Monte Carlo simulation (MCS) was used to address probabilistic uncertainty in cost and benefit estimations. MCS has been used widely for addressing uncertainty in cost estimating for various construction projects (Ceylan et al., 2018; Nahvi et al., 2019a, 2019b, 2018; Sadeghi et al., 2010). MCS supports quantification of the range of possible LCOE values by performance of sensitivity analysis to identify how each input variable affects the overall LCOE model. Selection of an appropriate probability distribution for each input variable is an important step in the stochastic LCCA approach (Gransberg and Scheepbouwer, 2010).

Figure 11 shows the general structure of MCS, which consists of (1) generating random variables; (2) performance function evaluation; and (3) extracting probabilistic information (Touran and Wiser, 1992).

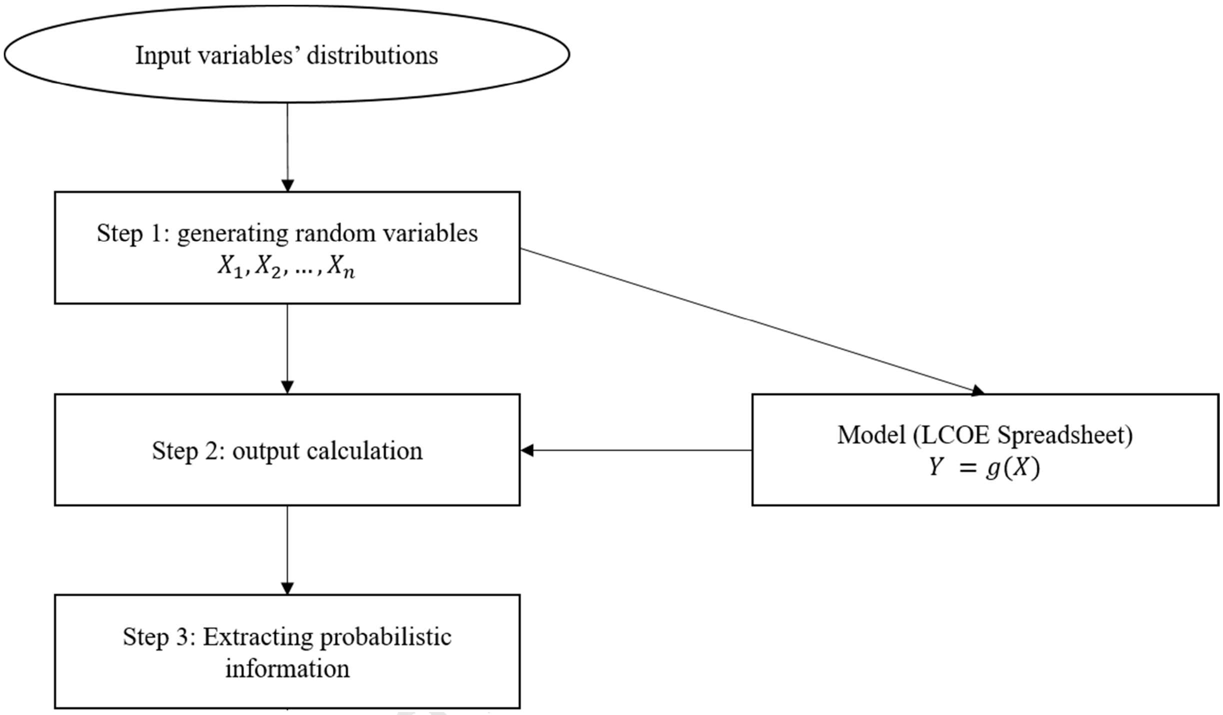


Figure 11 Monte Carlo simulation steps.

MCS conducts random sampling and performs a large number of computational experiments. In each simulation, the possible input values are generated according to their distribution curves (X_1,X_2,…,X_n) (Flanagan et al., 1987; Gransberg and Scheepbouwer, 2010; Swendsen and Wang, 1986). Then by using the input values generated, the output values are calculated using the performance function (Y =g(X)) to provide the probabilistic results. In this study, the LCOE equation is the performance function and the LCOE estimates are presented as a probabilistic distribution curve via the MCS as shown in Figure 12.

In conducting the stochastic life cycle costs analysis (LCCA), each simulation lasted from 20 s to 55 s, and simulations were conducted with a commercial software (@Risk) using one hundred thousand iterations. The result of running a Monte Carlo simulation is a probability density function (PDF) that produces a relative likelihood of LCOE (Figure 12).

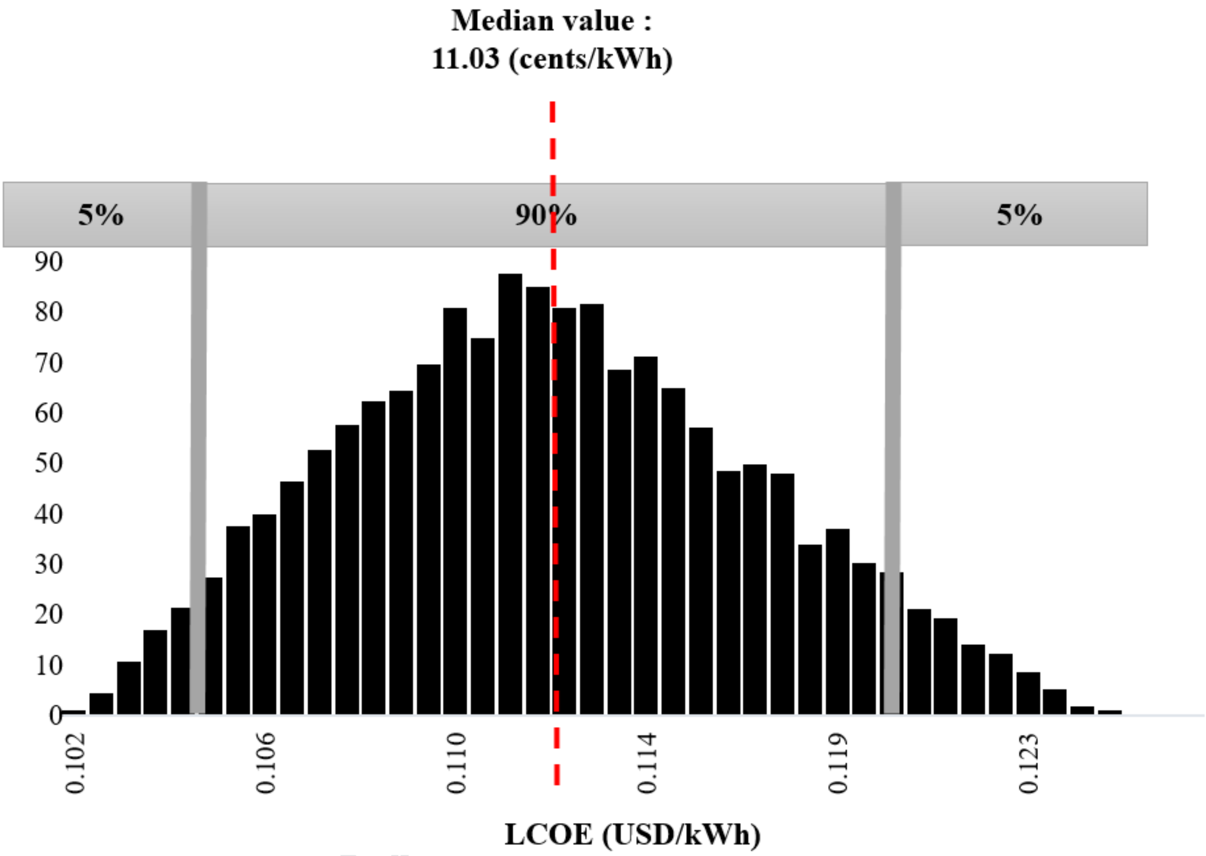


Figure 12 LCOE probability distribution for Option I.

For option I (hybrid option), the estimate range with a two-tailed 90% confidence interval is 10.5 cents to 12.0 cents, with a median value of 11.03 cents. The median is a good measure because, regardless the distribution shape, half the values are above the median and half are below the median (Boddy and Smith, 2009). In addition, the median value for option II (all Hexcrete) was 11.15 cents. The baseline LCOE for the 80 m steel tower is 11.4, and it is important to note that the baseline model used for comparison was the NREL model using historical data obtained prior to 2013. Table 5 gives a cost comparison of the different LCOE components of an 80 m rolled-steel tower versus a 120 m Hexcrete tower including both Options I and II. The LCOE costs illustrated in Table 5 were calculated using the method described by Tegen et al. (2012) for LCOE analysis using inputs from the stochastic estimating process.

Table 5 LCOE results after value engineering**.**

Cost	80 m Rolled Steel (Baseline) ($/kWh)	120 m Hexcrete		
		Option	Cost ($/kWh)	Percent change (%)
Turbine capital cost (TUR_{CC})	0.0641	#1	0.0575	-11.1
		#2	0.0553	-13.7
Balance of system capital cost (BOS_{CC})	0.0185	#1	0.0256	38.4
		#2	0.0289	56.2
Financial capital cost (FIN_{CC})	0.0074	#1	0.0074	0.0
		#2	0.0076	2.70
Operations and maintenance (O&M) (pre-tax)	0.0239	#1	0.0197	-17.6
		#2	0.0197	-17.6
LCOE	0.1140	#1	0.1103	-3.68
		#2	0.1115	-2.28

Although the cost savings associated with deploying 120 m Hexcrete tower are not significant (savings ranging between 2% and 4%), utilizing this innovative tall tower design offers opportunities to support broaden deployment of wind energy in the nation, especially for the low wind-speed regions which have less wind resource at the typical height of 80 m.

12 SENSITIVITY ANALYSIS RESULTS

As mentioned in parametric estimation and AEP sections, there are uncertainties associated with some of the variables (i.e. expected values for assembly and installation, tower module, maintenance and operation costs, and AEP). Another objective of running MCS is to determine individual impact of input variables on the LCOE, so sensitivity analysis was performed on all the random variables to understand how the variability of each would affect the total LCOE. The sensitivity analysis was conducted using one-at-a-time (OAT) method. The technique considers one input variable at a time to change within a prearranged series, while other variables remain at the assigned values (Faheem et al., 2018; Fathi et al., 2018; Saltelli et al., 2008, 1999).

The analysis showed that the random variable with the greatest potential impact on the overall LCOE was the AEP (Figure 13). The tornado graph below presents the results of the sensitivity analysis for option I (hybrid option).

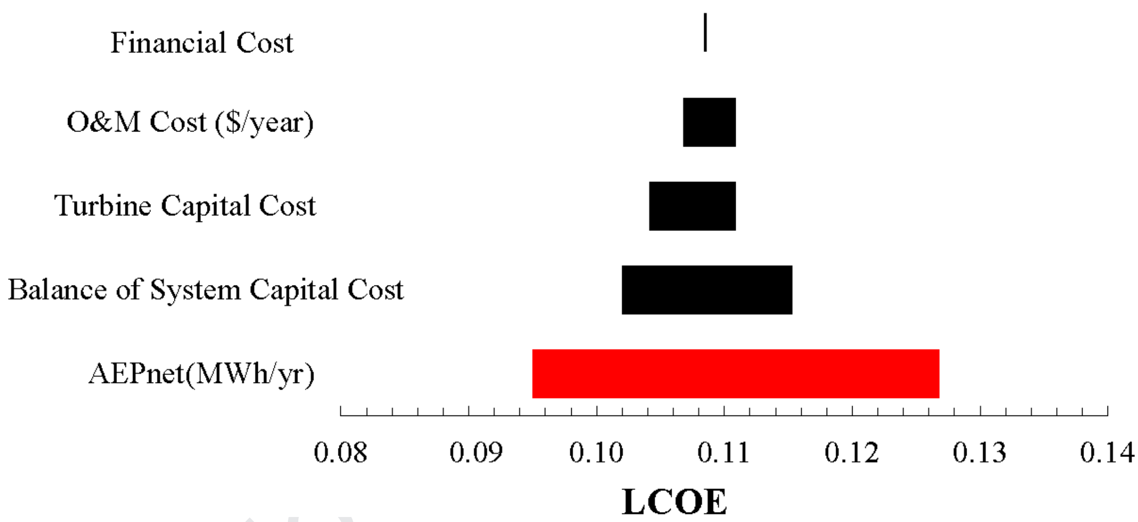


Figure 13 Result of Monte Carlo simulation, tornado graph for Option I (Hybrid option).

Figure 13 demonstrates that the LCOE is more sensitive to the AEP than to the cost variation of fabrication and transportation, O&M cost, and assembly using different production rates. This outcome carries a significant implications because it means that the risk of implementing the Hexcrete tower technology in practice might be less significant than the positive potential benefit of harvesting wind energy at taller hub heights.

13 CONCLUSION

The goal of the research project was to find a constructible, financially feasible wind tower design alternative to 80 m steel tower platform with potential to reduce the overall levelized cost of energy. The LCOE has been used as a metric to compare life-cycle costs and economic benefits of using an 80 m steel tower design to those using a 120 m Hexcrete tower design. An integrated team of subject matter experts were able to formulate a constructible design and a commercially feasible construction plan for assembly of Hexcrete wind towers. Input cost and schedule parameters provided by the integrated team of experts were used to develop a stochastic LCOE model and the LCOE results were used for a life cycle cost comparison with other competing technologies. The key findings of this study can be summarized as follows:

- The novel technology described in this study offers a commercially feasible wind energy solution to previously untapped regions of the US, and the findings of this paper offer reliable data to policy makers when developing future energy strategies over their governance areas.
- By using taller towers, a wind turbine generator can harvest stronger, steadier, and more wind resources for increased wind-power production. While taller wind turbines are desired to increase AEP at a wind energy site, the current tower design does not allow a tower to reach the heights of 120 m or higher because of transportation and logistics constraints. Hexcrete tower design allows wind towers to be built to a height of more than 120 m to harvest better wind resources.
- There are potential LCOE savings ranging between 2% and 4% associated with the utilization of a 120 m Hexcrete rather than an 80 m steel tower on generic wind sites in the United States.

According to the DOE wind vision report (DOE, 2015), "The wind power that at any given wind speed can be captured by the rotor is proportional to its swept area, and larger rotors therefore capture more energy. Wind speed increases with increased height above the ground, and taller towers therefore provide access to stronger winds." This study compared two identical wind turbines with equal generator and rotor sizes, changing only the tower height and the material used to support the tower, 80 m steel versus 120 m Hexcrete. In addition to harvesting stronger winds at 120 m, the Hexcrete concrete tower also facilitates a platform that can support a larger generator and larger rotor size to allow the WTG to exhibit increased electrical capacity and production. The study recommends further study on how such a Hexcrete platform can be used in conjunction with other wind energy technological advances such as bigger generators and larger rotors to further lower the cost of wind power production. At the end, building a wind tower at 140 M will tap into a resource with not only higher wind speeds but also much steadier wind resource thus reducing the variability in energy production allowing a more certain output to incorporate into the overall system balance of supply and demand. In theory, this 140 m design may provide additional benefits if evaluated from a system LCOE analysis as compared with the current 80 m design. However, since there are no towers currently built to 140 m in the United States, there is no data that can provide sufficient evidence to support this claim and further investigations are needed on this matter.

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15 APPENDICES

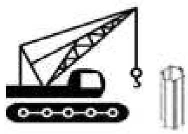
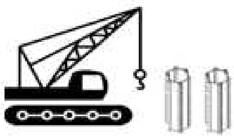
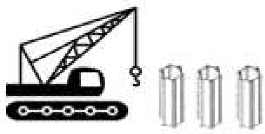
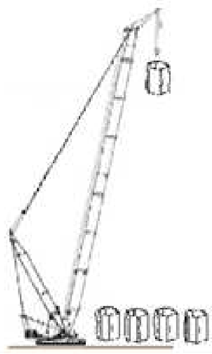
15.1 Appendix A (production rates)

Table A.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

Table A.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 

15.2 Appendix B (Cost estimations)

Table A.3 Estimated cost of foundation construction.

Total	**Compaction**	**Backfill**	**Concrete placement**	**Formwork**	**Steel reinforcement**	**Excavation**	**Item**	
	870	943	884	650	182	1827	All concrete	Volume
	870	817	806	650	159	1623	Hybrid option	
	C.Y.	C.Y.	C.Y.	L.F.	Ton	C.Y.	Unit	
	N/A	N/A	100	1.47	750	N/A	Cost of material per unit($)	
	N/A	N/A	88,400	955	136,500	N/A	All concrete	Material($)
	N/A	N/A	133,400	955	211,200	N/A	Hybrid option	
	0.15/C.Y	0.53/C.Y	16/C.Y	3.65/L.F	750/ton	0.32/C.Y		Labor per unit($)
	130	500	21,344	2,372	28,800	585	All concrete	Total labor cost($)
	130	450	7,200	2,372	21,600	520	Hybrid option	
	135/WTG	350/WTG	5/C.Y	N/A	N/A	2.7/C.Y		Rental cost of equipment ($)
	135	350	4,420	N/A	N/A	4,935	All concrete	Total cost of equipment($)
	135	350	6,670	N/A	N/A	7,800	Hybrid option	
	1 Day/WTG	1500 B.C.Y/Day	700 C.Y/Day	Half day/WTG	50 T/Day	2080 B.C.Y/Day	Production rate	
$290,380	1,222	850	114,164	3,327	165,300	5,518	All concrete	Total($)
$252,784	265	785	94,470	3,327	145,620	8,319	Hybrid option	

Table A.4 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

Table A.5 Detail cost estimation for the assembly for HT2 most likely scenario.

Work Breakdown Structure	Equipment cost($)	Quantity (man-hour)	Labor($)	Material costs($)	Production rates (days/WTG*)
Offloading Hexcrete cells, tower components, nacelle, hub, and blades	$22,154.29	144	$10,800		3
Assembling Hexcrete cells on ground	$13,264.97	320	$24,000		4
Steel bracing	include in assembling cells on ground			50,000	include in assembly
Misc. ladders and platforms	include in assembling cells on ground			24,000	include in assembly
Horizontal post tension	include in assembling cells on ground			21,990	include in assembly
Grout tower sections 1-8	include in assembling cells on ground			87,300	include in assembly
Set tower sections	$25,892.86				
Set sections 1-8		182	$13,650		1.75
Set top section		26	$1,950		0.25
Build rotor, set nacelle, and rotor	$1,200	48	$3,600		1
Vertica post tension	$800	96	$7,200	64,710	2
Project management cost			$85,600		N/A
Total	$63,312		$146,800	$248,000	
Total assembly cost					$458,112

*WTG: Wind Tower Generator