LEVELIZED COST OF ENERGY (LCOE) ANALYSIS OF HEXCRETE WIND TOWERS

by

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ABSTRACT

Wind power generation has witnessed a dramatic growth in the 21st century. The Department of Energy (DOE) had a vision for wind energy that it would change into an extensively greater part of overall power generation in the U.S. by 2050. As specified by the DOE, wind power generation has grown by trifold from 2008 to 2013. This study presents a constructible, financially feasible alternative wind tower design to the 80 m steel tower platform which has the potential to decrease the overall Levelized cost of energy (LCOE). A hexagonal concrete wind tower solution is evaluated to facilitate the fabrication of a taller wind turbine generator to harvest more powerful, stable, and frequent wind resources for elevating wind energy production to cut down the overall LCOE. Subject matter experts from the industry were benefitted from to develop a process and estimate the cost and schedule of development and assembly of this process. To mitigate uncertainties and quantify risks, a sensitivity analysis was carried out on cost and schedule estimates.

Also, estimating LCOE of wind towers is a primary requirement for efficient assimilation of wind power generation in the electricity market. In the state of Iowa, wind power is rapidly becoming a significant electricity generator. Unpredictable outputs and different options for deploying wind towers are one of the major problems of power system operators. Good estimation tools are important and will be needed to integrate wind energy into the economic power plant. The other objective of this research is to propose a GIS-based map to visualize LCOE of different wind tower construction options in various locations. Therefore, wind speed GIS mapping by using weather information will be crucial. Calculation of energy output by applying wind gradient formula to wind speeds energy are performed.

The research concludes of Hexcrete towers can be achieved by use of the 120m and 140 m Hexcrete tower platform on certain wind sites in the United States.

1 INTRODUCTION

1.1 Overview and motivation

Installation of wind towers has developed significantly throughout the past decade in the United States which has generated 66 GW of wind energy at the end of 2014. At a global scale, US has the second largest installed capacity, and it is currently standing first considering annual wind power generation. In 2014, U.S. wind energy generation was sufficient to power 17 million medium American houses, accounting for about 4.4% of all power generated in the United States. A report was published called Wind Vision by American Department of Energy (DOE) in 2015: “A New Era for Wind Power in the United States”. The report forecasts wind-energy generation to increase from 10% of the nation’s electricity supply in 2020 to 20% in 2030 and 35% in 2050.

Evidently, these scenarios are achievable thanks to the progressive advancements of wind-energy technology and the decrease in its Levelized Cost of Energy (LCOE), which gives the cost of energy production in cents/kW. Since 2007, the installed wind capacity has quadrupled in the United States, implying that reaching 10% wind-energy generation by 2020 is not far-fetched. To achieve the 2030 and 2050 suggested scenarios, an additional 136 GW and 252 GW, respectively, of land-based wind energy generation is required to be generated. This action implies over 100,000 wind-turbine towers by 2050. The available set of wind-turbine towers today is designed for a 20- to 25-year life span. Provided that these wind farms are repowered, greater demand will be introduced for the new wind-turbine towers.

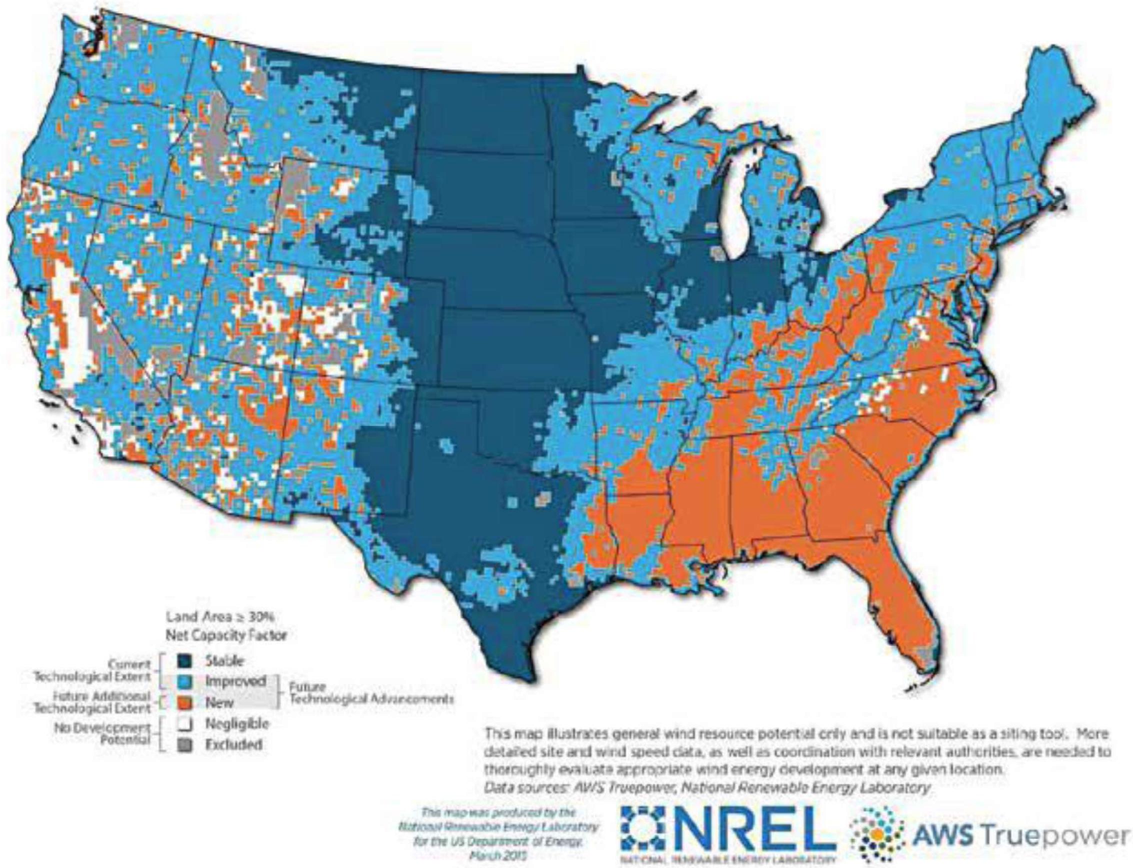


Figure 1. Land area achieving a minimum 30% capacity factor for wind-energy production at a 140 m (459 ft.) hub height

In spite of the considerable growth in the capacity of wind energy, one problem has continuously challenged this industry. Although wind-energy generation has been developing fast in the Midwest, the same cannot be claimed for the East and West coasts, where the demand for electricity is far greater. A number of states (e.g. those in the Southeast) are considered to lack any wind potential, and today their capacity for renewable energy is close to zero. This scenario will change dramatically if the wind-turbine hub height could be elevated to 328 to 459 ft. (100 to 140 m) (Sri 2015).

The advantages of utilization of taller hub heights have long been understood, where the wind-turbine tower heights have constantly increased from below 131 ft (40 m) in the 1990s to 263 ft (80 m) for the utility-scale turbines employed today. Currently, three steel tubular sections—built off-site and shipped via specialized trailers—are applied to develop the 263 ft (80 m) tall towers. The base diameter of this tower is about 13.5 ft (4.1 m), which is just under the vertical clearance permitted on state highway routes. Developing the hub height of steel tubular sections will considerably raise the cost of taller towers. The reason is that the tower base required for taller towers (above 100 m [328 ft]) should be designed by higher-strength steel or segmented base sections, necessitating field assembly.

As wind-turbine towers become taller than 263 ft (80 m) a concrete solution can prove to be better than the steel tubular alternative, in terms of cost-effectiveness. In this regard, two concepts have been studied for the introduction of concrete into the design of wind-turbine tower. One notion is a development of a steel tubular concept that employs concrete shells for the towers. This notion has mainly been used in Europe with precast concrete modules requiring vertical or horizontal connections. With the help of normal strength concrete, a concrete tubular solution can raise the footprint of the tower by 40% to 50% as well as the wall thickness by at least five times when compared with steel tubular towers with the same hub height.

The Hexcrete tower has been constructed at Iowa State University (ISU) to completely eliminate transportation constraints, modularize construction, and facilitate construction of taller towers. This new concept employs easily producible (onsite or offsite) and transportable columns and panels. It also relies on high strength concrete and pre-stressing steel, and develops the tower with a hexagonal-shaped cross-section (Sri & Schmitz 2013).

1.2 Problem statement

This research project is evaluating the use of a precast concrete solution divided into six column and panel configurations that are assembled on-site to create a hexagonal shaped tower (Fig 2) to support the wind turbine generator at an overall hub height of 120m (Sri 2015). The purpose of configuring the tower into a hexagonal shape with six separate columns and panels (Fig 3) is to overcome the transportation limitation while maintaining ease of assembly at each turbine site location (Sri 2015). Traditional round or curved precast sections can cause constructability problems with the assembly process on-site. The hexagonal concrete tower (Hexcrete tower) is designed to use high strength and ultra-high strength concrete components, to eliminate the transportation and logistics constraints associated with construction of taller wind turbine towers.

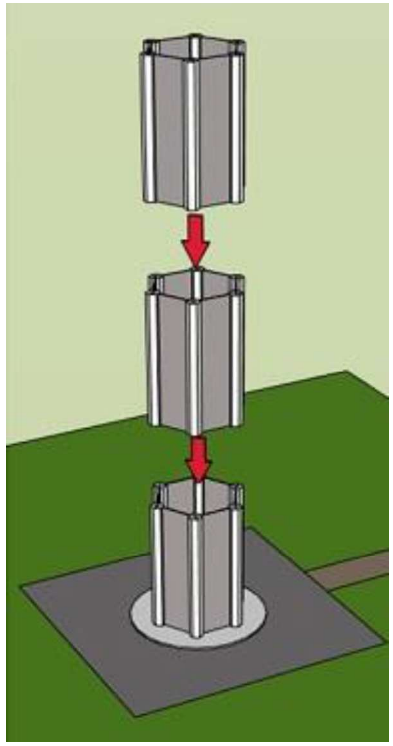


Figure 2. Schematic view of a Hexcrete tower section

Figure 3. Precast concrete Hexcrete components at a tower site

This paper looks to answer, “Is the hexagonal concrete wind tower solution a constructible option while lowering the overall levelized cost of energy?”

1.3 Research objectives

The literature has shown that Hexcrete wind towers can be a decent alternative for steel and concrete tubular towers. However, Hexcrete towers are the conceptual concept, and they have never been built before.

This research seeks to answer two questions. First "can a hexagonal concrete wind tower solution facilitate a taller wind turbine generator to harvest stronger, steadier, more frequent wind resources for increased production of wind energy while decreasing the total levelized cost of energy?" and second "how do LCOEs of wind towers vary over different construction options and various locations?" These objectives are explored by focusing on the following five tasks:

- *Obtaining reliable information regarding constructability issues, construction and assembly sequences, required resources and practical production rate information.*
- *Find a constructible, fiscally feasible option to construct Hexcrete towers.*
- *Estimating the construction costs by breaking down into construction activities and estimating each activity's schedule and cost to improve the accuracy of cost estimating.*
- *Estimating LCOE cost using NREL's spreadsheet and performing sensitivity analysis to find out sensitivity of each input variable.*
- *Develop a GIS-based map to evaluate LCOE of different wind tower construction options.*

2 LITRETURE REVIEW

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) When a combination of a rotor and generator is used to turn mechanical wind energy into electric power, the 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 had two or three thin blades which rotated at high speeds to drive electrical generators. These wind turbines provided electricity to farms beyond the reach of power lines and were typically used to charge storage batteries, operate radio receivers and power a light bulb or two." (Iowa Energy Center) Today wind power generation has grown to supplying over 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 2014)

Wind power generation has seen a dramatic increase in the 21st century 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. "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 2014) The DOE has created a future strategic plan for wind energy in the U.S., named Wind Vision. "The Wind Vision centers on a future scenario in which wind energy serves 10% of the nation's end-use demand by 2020, 20% by 2030, and 35% by 2050." (DOE 2014)

Investment in wind power generation and the economic impact associated with wind energy have increased over recent years. "Wind power is cost effective and reliable. Wind power capacity, generation, and investment have grown dramatically." (DOE 2014) "According to the United Nations Environment Programme, global investment in wind power grew from $14 billion in 2004 to $80 billion in 2013, a compound annual growth rate of 21%...An estimated 834,000 global direct and indirect jobs were tied to wind power in 2013." As evidenced by the increase in overall power generated and the financial and economic growth in recent years, wind energy is a growing market affecting the world environmentally and economically.

The cost to produce energy is measured 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 the same formula and calculations are used for each type." (Tegen 2013) The cost to produce wind power has seen a dramatic decrease in the last 30+ years. "Through technology advancement and turbine scale-up, the average LCOE for U.S. land-based wind projects in good to excellent sites dropped more than 90% from 1980 to 2013 – that is, from more than $0.50/kilowatt-hour (kwh) in 1980 to just $0.045/kWh in 2013, excluding the federal production tax credit." (DOE 2014)

Technology advancements in the wind energy industry have allowed for this dramatic decrease in the cost of energy for wind power. In recent years, there have been many improvements in wind energy technology allowing wind power generation to become much more efficient and cost effective. "Technology development and improvements in reliability have helped drive a 33% cost reduction in land-based utility scale LCOE from 2008-2013." (DOE 2014) By 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 2014) "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."

The current typical land-based utility scale wind turbine in the U.S. has a rotor hub height of 80 m above the ground. Most wind turbine generators in today's market have a power capacity of 1.5 megawatts to 3.0 megawatts. The tower supporting the wind turbine generator, nacelle, is made of rolled steel and is manufactured in sections. There are four principle parts of a wind turbine: the foundation (base), the tower, the nacelle, and the rotor (center and cutting edges get together). The rotor changes over the vitality of the wind into rotational movement. The nacelle contains the electric generator and different segments that evolve over the mechanical turn of the rotor into power. The tower underpins the nacelle and rotor, and the foundation goes about as an anchor that supports the whole get together. Most 80m steel wind turbines in the U.S. consist of three steel tower sections; the base, mid, and top. "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." (DOE 2014) "Conventional rolled steel towers can be transported with tower sections up to 4.6 m in diameter over roads and 4.0 m via railroad. Tower diameters exceeding 4.6 m are difficult to transport. These transport restrictions result in sub-optimal tower design and increased cost for tower heights exceeding 80 m. A structurally optimized tower would have a larger base diameter, with thinner walls and less total steel. Overcoming this limitation would reduce project costs and LCOE."

The wind energy industry has looked at different solutions for overcoming this transportation limitation. Some solutions include a hybrid material wind tower, the base sections of the tower consist of precast concrete while the taller sections are made of the conventional rolled steel. "New tower configurations are being evaluated to overcome transport limitations. These new configurations-known as hybrid towers- include concrete tubes for the lower, large-diameter sections and steel for the upper sections. Concrete towers have separate, pre-fabricated concrete elements with diameters up to 14.5 m. Large-diameter bottom segments can be produced as two or three partial shells that can be shipped on conventional transportation systems." (DOE 2014) The frequent alternatives that the industry has attempted include the hybrid concept as described and curved concrete shell towers. Neither technology completely overcomes the transportation and logistical constraints.

3 RESEARCH METHODOLOGY

The overall methodology and validation techniques used in this research are illustrated in Figure 4.

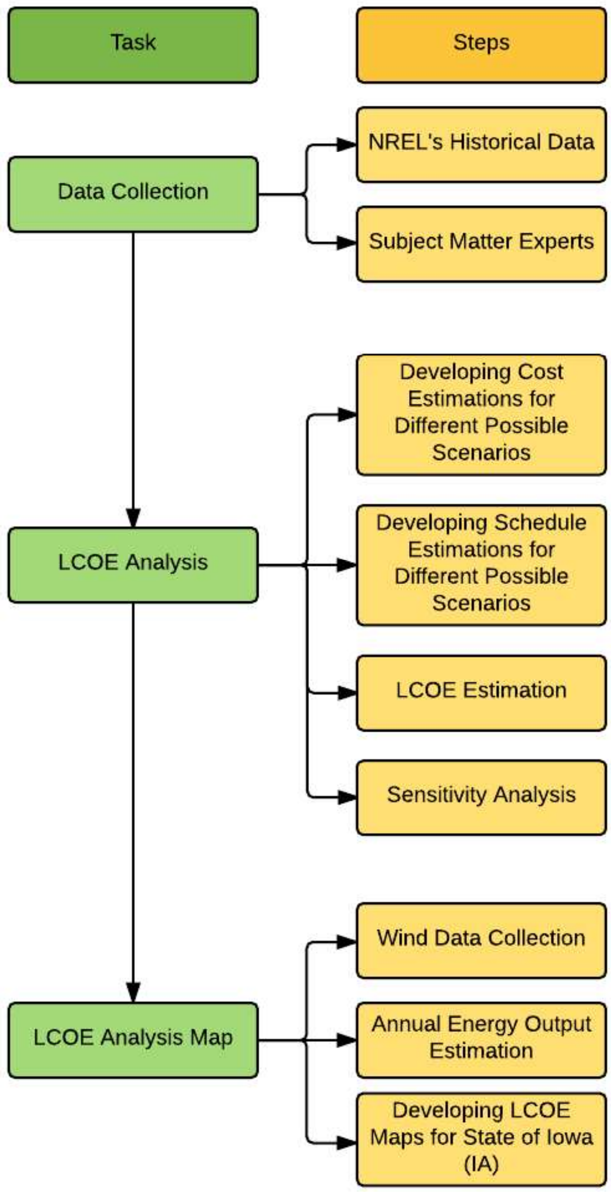


Figure 4. Research methodology

3.1 Data Collection

Historical data to determine the cost to manufacture, transport, and assemble the Hexcrete tower was not feasible due to the fact neither a hexagonal concrete tower or a wind tower built to a height of 120 m and 140 m have ever been assembled in the US before. Using a prototype or a model to quantify data was infeasible due to the cost, size, and complexity of building a wind farm of prototype hexcrete turbines somewhere in the US. Due to the fact there was no historical data, and data could not be obtained through modelling, panels of subject matter experts were utilized for this study. "Expert Judgement techniques are useful for quantifying models in situations in which, because of either cost, technical difficulties or the uniqueness of the situation under, it has been impossible to make enough observations to quantify the model with 'real data.'" (Bedford 2001).

3.2 LCOE analysis

Bottom up approach is used to develop cost estimation for different types of Hexceret towers. Utilizing a bottom-up approach is important to determine the construction costs by separating the project into construction activities and figuring every work package's timetable and cost to enhance the precision of cost estimating. In bottom-up estimating, considering a three-stage process is vital. To begin with, estimators work from the most minimal level of detail in the work breakdown structure (WBS). In a bottom-up approach, estimating starts by building up a detailed work package to run with the WBS. Detailing the scope and essential deliverable that every colleague will create is fundamental.

In addition, a construction schedule for each wind tower option was developed with an assumption that a wind farm of 100 towers is built in a typical wind farm site in Iowa. Wind farm construction activities are very repetitive. Thus, aligning the production rates of those activities is critical by finding the optimal number of crews and to minimize the idle time of field resources and optimize the field schedule. The linear scheduling method (LSM) is used to find the most realistic schedule of the assembly activities since LSM works well for a project with repetitive activities and aligning production rates of activities (Matilla & Park 2003).

For determining the total project duration from mobilization to mechanical completions, a bar chart scheduling is used. The bar chart schedule gives a visual and simple representation of the project plan. It includes all project activities, their durations, and the start and end dates of activities.

The research will compare the difference in the LCOE for an 80 m steel tower and 120 m and 140 m Hexcrete tower. The research will also determine and estimate what cost difference variables between the 80m steel and different types of Hexcrete towers

Use of a Monte Carlo simulation will be used to perform the sensitivity analysis of the cost estimate difference between towers. “One of the more common methods of evaluating the probability of cost in construction projects is the Monte Carlo simulation technique” (Touran 1992) “In this method, every cost component with a high potential for variability is modeled as a random variable.” This research will consider any variables different between the 80 m steel tower and 120 m and 140 m Hexcrete tower as random variables.

3.3 LCOE analysis maps

The overall goal of this study is create maps to evaluate LCOE of different wind tower construction options. The specific objectives to accomplish this are collecting weather information from the local weather station, estimating AEP at different hub height, and finally creating LCOE maps using Arc GIS.

4 LCOE ANALYSIS

4.1 Data collection

A workshop was conducted in San Diego, California in February, 2015, with representatives from all appropriate areas of specialization of expertise needed to successfully manufacture, transport, and assemble an all concrete wind tower project. Representatives from the different fields included:

- Wind Turbine Manufacturer
- Wind Tower Foundation Designer
- Concrete Wind Tower Structural Designer
- Wind Project Owner and Developer
- Wind Project Engineering, Procurement, and Construction Contractor
- Construction Crane Rental
- Pre-cast Concrete Assembly
- Post Tension Supply and Installation
- Pre-cast Concrete Fabrication

A discussion of advantages and disadvantages of the Hexcrete concrete tower was performed with all subject matter experts. Each subject matter expert provided input variables for each of their areas of specialization to include, cost, production rates, and schedule. A range was determined for each input variable to include in a Monte Carlo Simulation. A sensitivity analysis was performed using the Monte Carlo simulation to determine how sensitive each input variable was to the overall model.

Considerations varied between hauling the precast concrete sections to the site to assembling sequences of all components at the site. Equipment choices were evaluated for the distinctive phases of the assembly process with the expert analysis of the crane supplier. A 140m Hexcrete tower is far taller and heavier than a 120 m Hexcrete tower. Finding the right pieces of equipment and identifying the logical sequences of work to assemble this taller and heavier tower on a 100 turbine wind turbine site became a major topic in the workshop. Considering the end target to achieve the taller height, from 120m to 140m, the crane supplier was examined to find a high capacity crane option to stack cells on top of each other at the new 140m hub height. With the suitable equipment selected for the assembly process, the group started to evaluate the procedure as to how the tower would be assembled on site. Each subject matter expert presented inputs for each of their areas of specialization for the research team to pinpoint the crew size, production rates, schedule, and costs.

Among many assembly options mentioned, the workshop team finally concluded the following two assembly options for further consideration. The two main assembly options for HT2 and HT3 consist of:

- Option I (HT2a and HT3a) – All Hexcrete cells
- Option II (HT2a Hybrid and HT3a Hybrid) – Hexcrete cells and steel top sections

Table 1 provides the two options with the number of Hexcrete cells and the number of steel sections.

Table 1. Numbers of cells and steel sections for each wind tower options

Type of tower	Number of Hexcrete cells	Number of steel sections
HT3a	17	N/A

HT 3a hybrid	11	3
HT2a	14	N/A
HT 2a hybrid	10	3

HT3a Option I and HT2a Option I consist of 16 and 14 hexcrete cells respectively (see Figure 5 and Figure 6). The precast concrete columns and panels will be shipped to the site individually and will be assembled on ground into cells. The cells will be erected vertically by a crawler crane with the cells above 80-m, nacelle, and rotor erected with a higher capacity crawler crane.

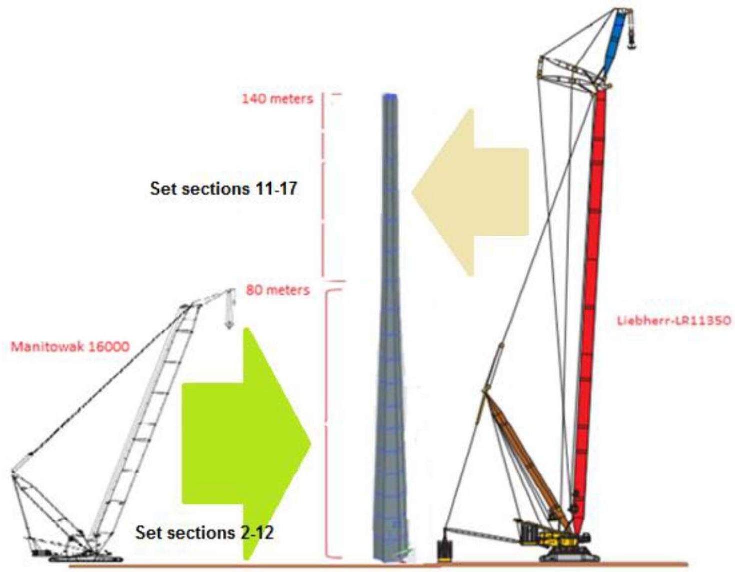


Figure 5. Option one HT3a

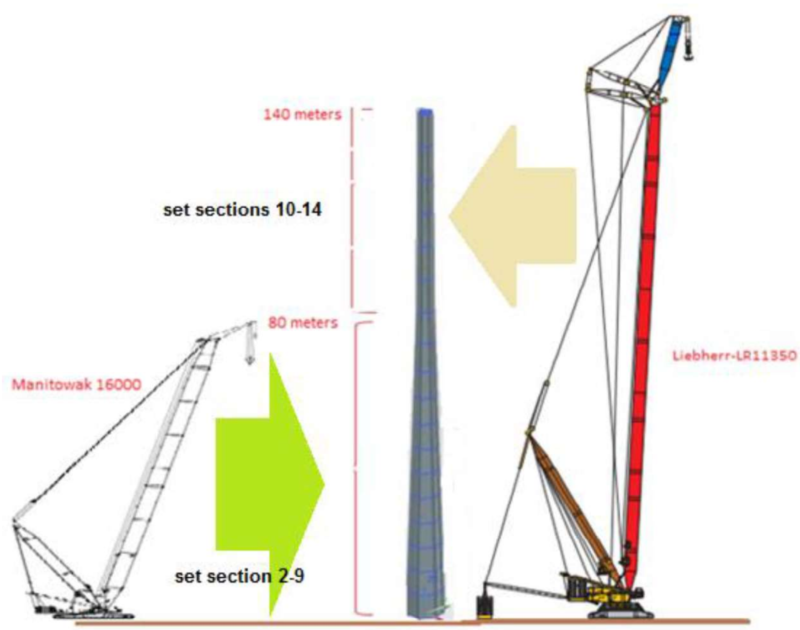


Figure 6. Option one HT2a

HT3a Option II (hybrid option) consists of eleven hexcrete cells up to the assembled height of 284.5 (feet) and three steel top sections for the remaining height. HT2a Option II consists of ten hexcrete cells up to 305.75 (feet) and three steel sections. Option 2 will also have the precast panels and columns transported to the site and assembled on ground in cells. The cells will then be set each other by sections by a crawler crane. The steel top sections, nacelle, and rotors will be assembled using a higher capacity crane.

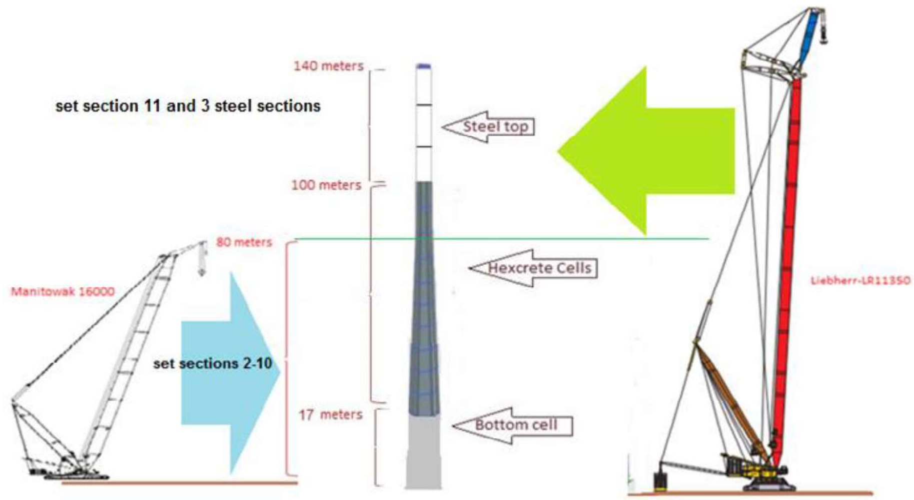


Figure 7. Option two HT3a Hybrid

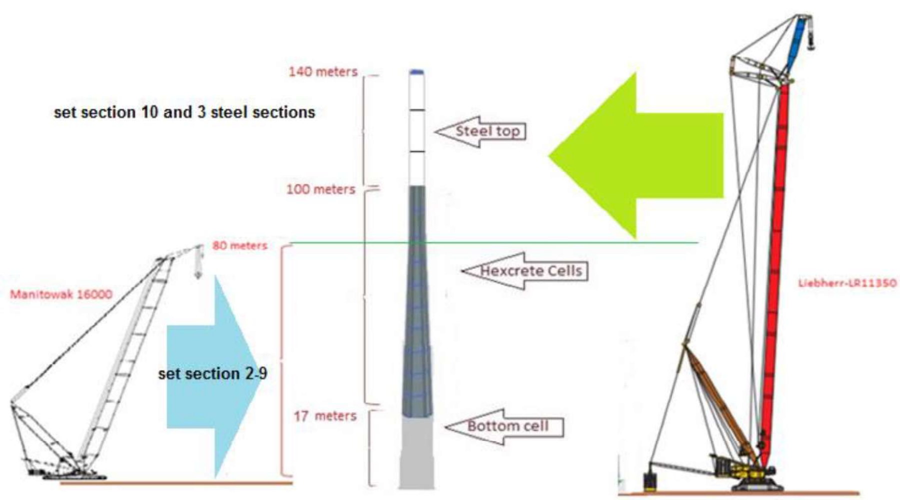


Figure 8. Option two HT2a Hybrid

4.2 Work breakdown structure (WBS)

The work sequence for a 140-m Hexcrete tower construction project can be categorized into five major work activities;

1) Mobilization and access road construction

2) Foundation construction

3) Fabrication and delivery of Hexcrete columns and panels to the job site

4) Delivery of wind turbine components to the job site

5) Assembly of wind tower components

Figure 9 reveals the WBS for HT2a Option I and Option II. For these two options, the majority of 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 indicated in Figure 9. Appendix A provides the WBS for HT3a.

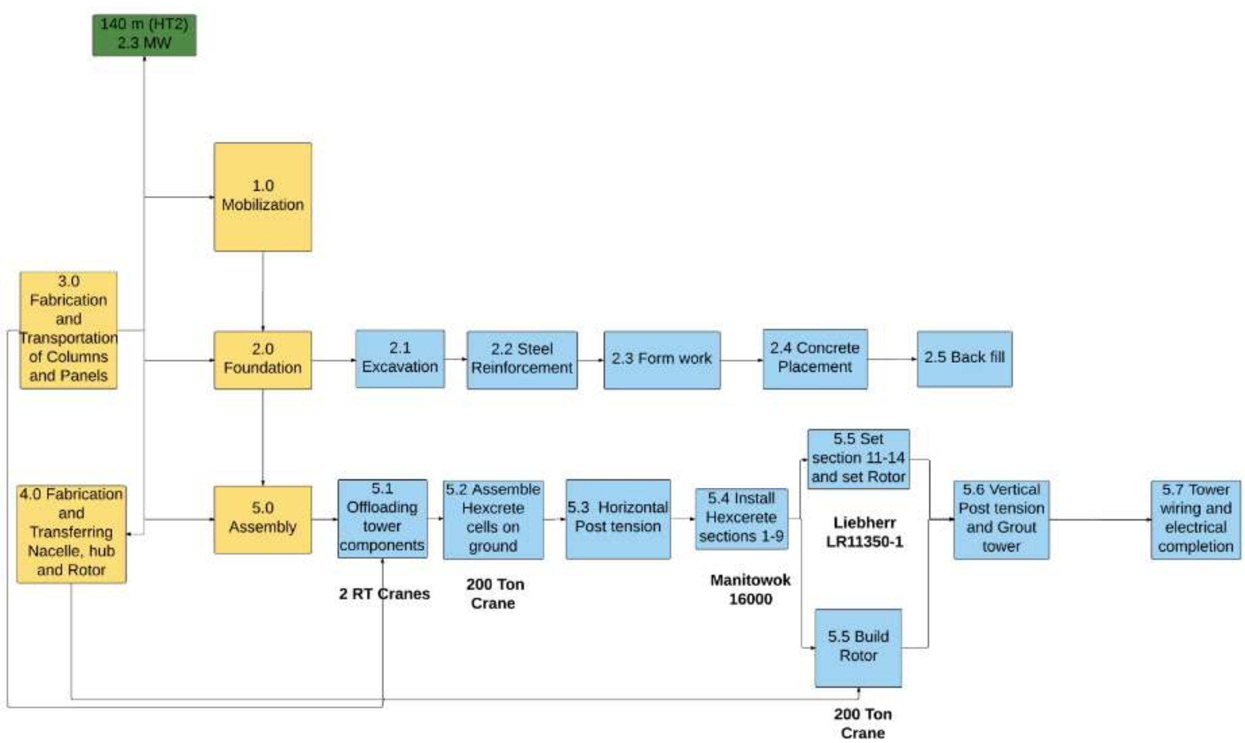


Figure 9. Work break down structure for HT2a

4.2.1 Mobilization and access roads

The main project resources are mobilized, with access roads being developed to ease the transportation and delivery of materials, Hexcrete tower pieces, and construction equipment. Access roads are constructed out of the current public roadways to a wind farm. Once the construction is completed, temporary access roads will be converted to permanent roads. These roads can be easily constructed with the current industry practices since it does not need any new technology.

4.2.2 Foundation

Foundations are built through excavation of the area of tower foundation, setting up reinforcing steel and finally discharging concrete into the excavation. The only part that remains above the soil surface when grading is complete is the very center of the foundation. The work sequence of foundation is represented in Figure 10.

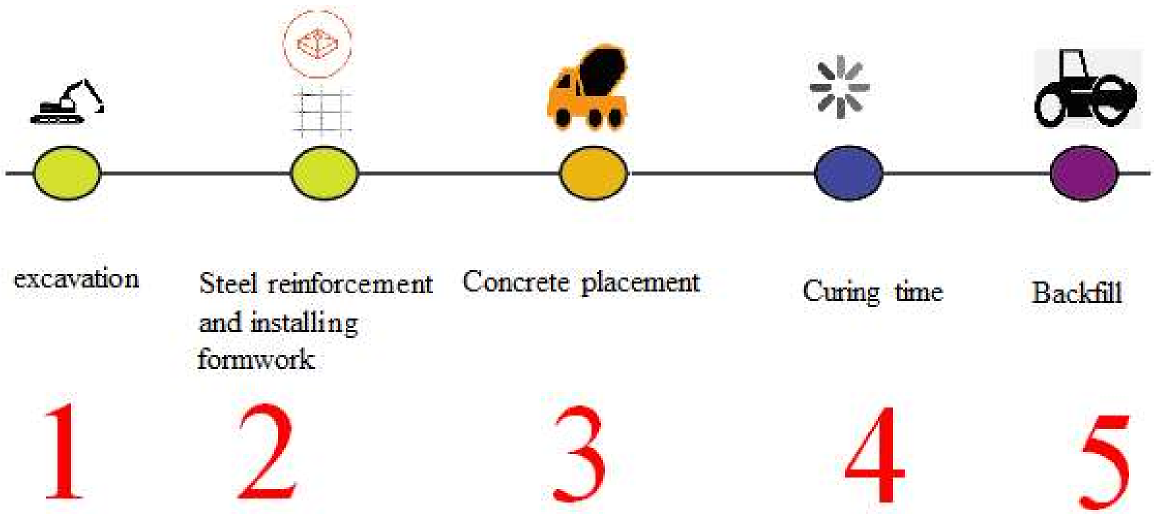


Figure 10. Stages of foundation construction

4.2.3 Fabrication and delivery of Hexcrete columns and panels to the job site

Precast concrete panels and columns are developed by a manufacturing factory and delivered to the job site. The transportation distance is assumed to be 200 miles, to match with the distance assumption utilized in the NREL's LCOE Model.

4.2.4 Delivery of wind turbine components to the job site

Wind turbine elements including nacelle, blades, and transition pieces are carried to the job site.

4.2.5 Assembly of wind tower components

Precast concrete columns and panels will be offloaded by 2 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 (Figure 11).

Next, each cell will be erected individually until all cells are erected and grouted in place (Figure 8). A Liebherr crawler crane will move to the site to erect the Hexcrete cells above 80 m and three steel top sections (for the hybrid option). In the meantime, the turbine components will be offloaded, and a 200-ton crawler crane will be employed to develop a rotor. The Liebherr crawler crane will be utilized to also fly the rotor and install the turbine. Thereafter, the vertical post-tension cable will be driven through all tower sections, and the whole length of the tower will be post-tensioned. Eventually, tower wiring and mechanical completion will be performed by the current practices of wind industry construction. Figure 11 outlines the general work sequence of assembly.

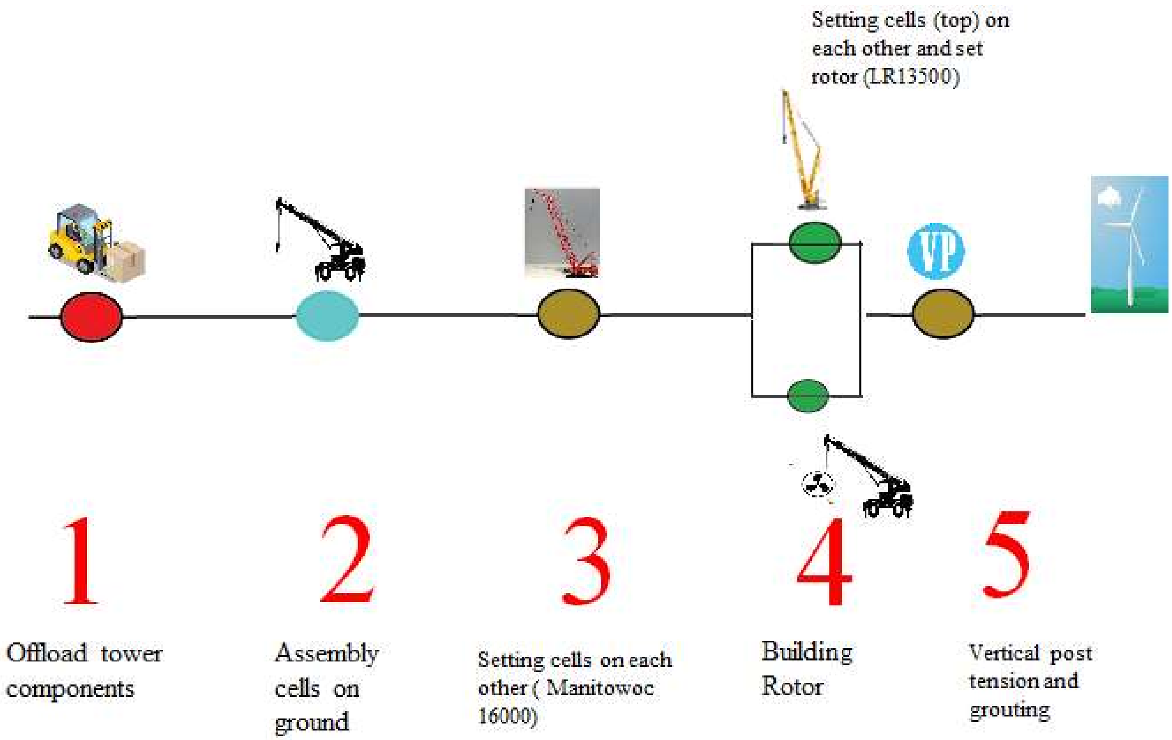


Figure 11. Assembly work sequence visualization

4.3 Production rates

A plausible calculation of production rates for work activities is crucial for estimation of construction cost, since the production rates set the crew size, activity duration, and activity cost.

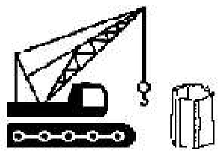
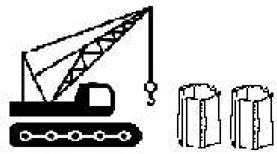
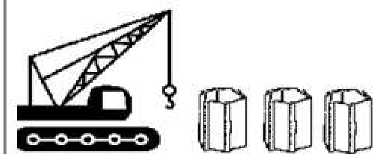
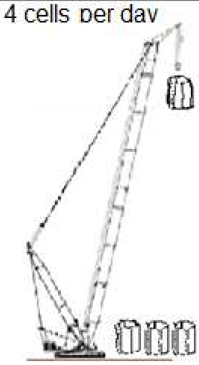
The production rates of the majority of work activities such as excavation, concrete pouring, installing steel reinforcements and formwork, vertical post-tensioning, offloading tower components, and mechanical and electrical completion are contingent upon the current industry practices, according to Table 2.

Table 2. Production rates for activities which are same with current industry practices

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 wind tower component	3 (Days/WTG)
	Build rotor	1 (Day/WTG)
	Vertical post tension	2 (Days/WTG)
	Tower wiring	2 (Days/WTG)
	Electrical completion	2 (Days/WTG)

However, there is no data available of historical production rate to assemble hexcrete cells on ground and setting Hexcrete cells on top of each other. The research team and experts from the industry discussed constructible options and their work sequences in conjunction with the esssential resources and developed three various feasible production rates (low, most likely and high), as provided in Table 3.

Table 3. Three possible production rates for critical items in assembly

Activity / Production rates	Low	Most likely	High
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 

4.3.1 Nine possible scenarios

According to the production rates in Table 3, three possible scenarios are developed for each 140-m hexcrete option (Table 4).

Table 4. Three possible scenarios

Worst case scenario	Most likely scenario	Best case scenario
• Assembling 1 cell on ground per day. • Stacking 3 cells per day	• Assembling 2 cells on ground per day. • Stacking 4 cells per day	• Assembling 3 cells on ground per day. • Stacking 5 cells per day

4.4 Scheduling

A construction schedule for every scenario was developed with the assumption that a wind farm with 100 towers is constructed in a typical wind farm site in Iowa. The events of wind farm construction are very repetitive. Hence, adjusting the production rates of those activities is crucial through obtaining the optimal number of crews. It is also necessary to minimize the idle time of field resources and optimize the field schedule. The linear scheduling method (LSM) is employed to find the most realistic schedule of the assembly activities, as LSM operates well for a project with repetitive activities and adjusting production rates of activities. A bar chart scheduling is utilized to pinpoint the total project duration from mobilization to mechanical completions. The bar chart schedule offers a visual and simple representation of the project plan, which involves all project activities, their durations, and the start and end dates of activities.

Table 5 provides the crew numbers for each tower option. The number of crews is determined through development of the LSM-based schedule by adjusting the crew size to find the most arranged production rates of the activities.

Table 5. Number of assumed crew for each activity

Category	HT3a	HT3a Hybrid	HT2a	HT2a 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
Setting cells above 80 meters	2	2	2	2
Building rotor	1	1	1	1
Vertical post tension	2	2	2	2

Figure 12 shows the Linear schedule developed for HT2a (most likely scenario). The linear schedules for other wind tower options are provided in Appendix C.

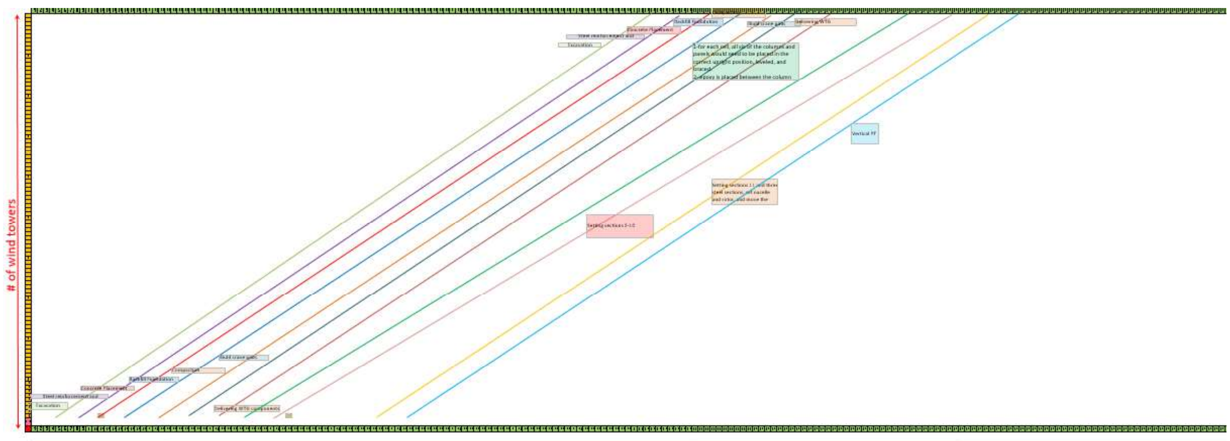


Figure 12. Linear scheduling for HT2a (Most likely scenario)

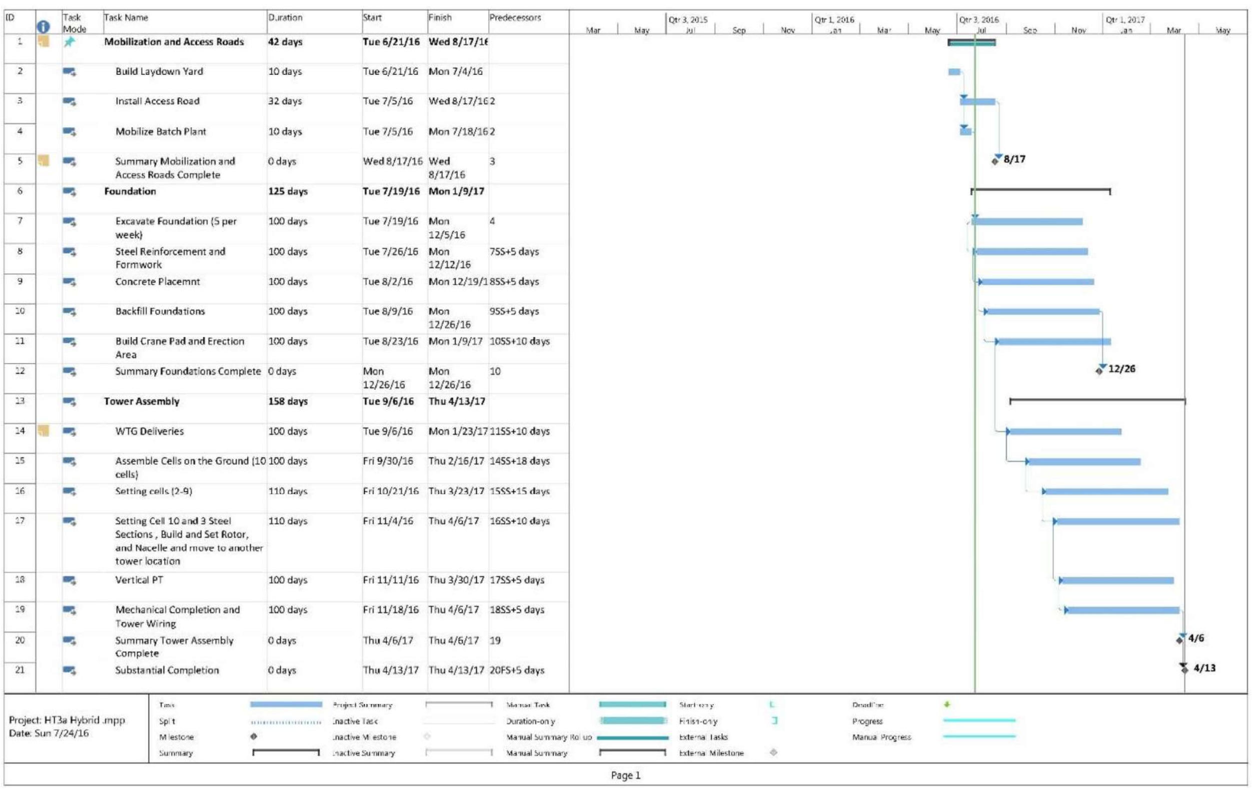
Table 6 presents the total durations in working days of assembling wind. Five days a week is considered as working days with Saturday and Sunday as off days and extra days for catching up the schedule, if necessary.

Table 6. Assembly duration

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
HT2a	290	177	164
HT2a hybrid	255	161	157

4.4.1 Total project duration

In order to develop an entire schedule for wind farm construction, a bar chart was employed. Early non-assembly activities such as mobilization, site access road construction are also included in addition to assembly activities. Moreover, a calendar day schedule was developed to specify the cost of site project management as well. Figure 13 indicates the detailed schedule for HT2a- most likely scenario. In addition, Appendix B outlines the bar schedules for other types of wind towers.



ID	Task Name	Duration	Start	Finish	Predecessors
1	**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/1€**	
2	Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3	Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4	Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5	Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6	**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7	Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8	Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9	Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1	8SS+5 days
10	Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11	Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12	Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13	**Tower Assembly**	**158 days**	**Tue 9/6/16**	**Thu 4/13/17**	
14	WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15	Assemble Cells on the Ground (10 cells)	100 days	Fri 9/30/16	Thu 2/16/17	14SS+18 days
16	Setting cells (2-9)	110 days	Fri 10/21/16	Thu 3/23/17	15SS+15 days
17	Setting Cell 10 and 3 Steel Sections , Build and Set Rotor, and Nacelle and move to another tower location	110 days	Fri 11/4/16	Thu 4/6/17	16SS+10 days
18	Vertical PT	100 days	Fri 11/11/16	Thu 3/30/17	17SS+5 days
19	Mechanical Completion and Tower Wiring	100 days	Fri 11/18/16	Thu 4/6/17	18SS+5 days
20	Summary Tower Assembly Complete	0 days	Thu 4/6/17	Thu 4/6/17	19
21	Substantial Completion	0 days	Thu 4/13/17	Thu 4/13/17	20FS+5 days

Figure 1 Bar chart scheduling for HT2a (Most likely scenario)

Table 7 provides the overall schedule of wind farm construction for various types of wind towers under three different scenarios.

Wind tower type	Worst scenario (calendar day)	Most likely scenario (calendar day)	Best scenario (calendar day)
HT3a	428	272	236
HT3a hybrid	369	242	224
HT2a	383	246	229
HT2a hybrid	334	239	222

4.4.2 Probabilistic analysis

There are three possible scenarios for each type of wind towers. There is not any certain answer guaranties the occurrence of these possible scenarios. Therefore, the research team decided to run triangular distribution to reach an approximate probability distribution representing the outcome of future events (Figure 14). At the top of this figure, there is a probability axis. A vertical line was drawn from 95% point to the time axis. This line meets time line at 385. This means that the contractor has 95% of chance to complete the entire construction within 385 days.

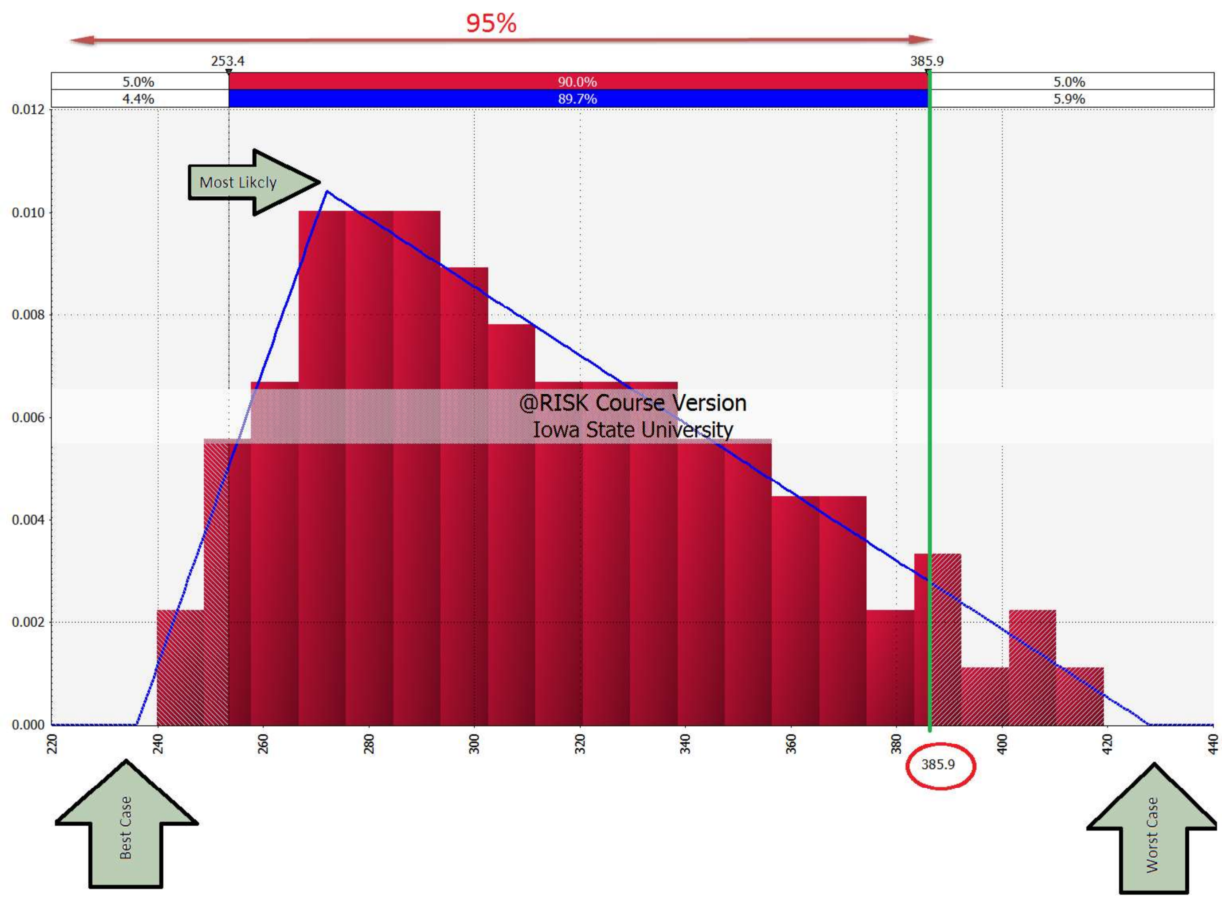


Figure 2 Triangular distribution analysis for total project duration

Table 7. Estimated project duration

Wind tower type / Reliability percentage	90%	80%	70%	60%	50%
HT3a	372	351	333	318	306
HT3a Hybrid	325	309	295	283	273
HT2a	336	318	303	291	280
HT2a Hybrid	302	288	278	269	261

4.5 Cost Estimation

The WBS outlined in Section 3 as well as crew information and scheduling details in Section 5 are benefitted from for estimating the cost of each activity. A number of 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 mile, c) the cost of the labor work is assumed to be $75/man-hour, and d) the transportation distance from precast manufacturing plant to the project site is 200 miles. Furthermore, the overall construction process will need to utilize four different types of crawler cranes with auxiliary equipment including rough terrain cranes, telehandlers, and man lifts. Table 8 presents the crane mobilization costs and monthly rental costs.

Table 8. Assumptions regarding the cost of the cranes

Crane	Monthly Bare Rate, 200 Hours	Mobilization cost
LR 11350	$ 275,000.00	$ 500,000.00
M16000	$ 115,000.00	$ 150,000.00
200 ton mobile crane	$ 36,000.00	$ 48,000.00
RT 130	$ 28,000.00	$ 33,000.00

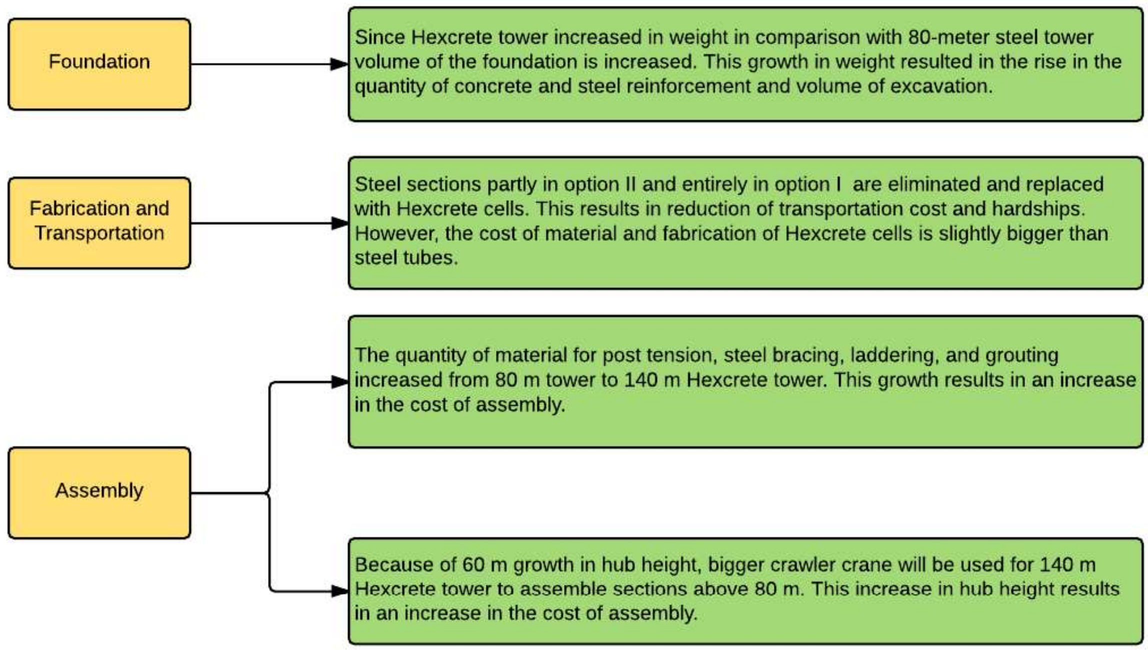


Figure 15. Cost differences between 80 m steel tower and 140-m Hexcrete tower

4.5.1 Fabrications and Delivery of Hexcrete columns and panels

The precast concrete columns are High-Strength Concrete (HSC) and the panels are Ultra High-Performance Concrete (UHPC). The cost of High Strength Concrete (HSC) per cubic yard is assumed to be $900/CY and UHPC is estimated to be $2,800/CY with the site delivery option – free on board (F.O.B). These unit prices were estimated reasonably by a precast concrete Mid-west-based manufacturing company. Table 9 summarizes precast concrete costs for various tower options. The cost of steel top is also included for hybrid options. Appendix D presents detailed cost estimation for development and transportation of hexcrete components.

Table 9. Estimated cost for Hexcrete columns and panels in each wind towers

Type of tower	Hexcrete columns cost($)	Hexcrete panels cost($)	Steel Top ($)	Total cost ($)
HT3a	403,200	129,600	N/A	538,800
HT3a hybrid	346,500	84,500	143,667	431,000
HT2a	518,700	66,150	N/A	613,350
HT2a hybrid	459,900	94,650	175,350	526,050

4.5.2 Foundations

The construction cost of wind tower foundation can be easily estimated with available practices as it does not need any new process or technology. The costs of concrete and reinforcing steel are assumed to be $100/C.Y and $750/ton (F.O.B), respectively. Appendix F provides detailed cost estimation and required equipment and labor work for this activity. The total cost of construction of foundation for each type of wind tower is revealed in Table 10.

Table 10. Estimated cost of foundation

Type of wind tower	Estimated foundation cost
HT3a	$351,847
HT3a Hybrid	$290,380
HT2a	$252,784
HT2a Hybrid	$252,784

4.5.3 Assembling tower component

The assembly will be categorized into three major assembly work activities e.g. cell assembly, cell erection and post-tensioning, and erection of the steel top (for hybrid models), nacelle, and rotor.

Assembling cells on ground can be achieved by making use of a 200-ton crawler crane. For adjusting hexcrete cells below 80-m height, Manitowoc 16000 will be benefitted from. Further, LR11350 will be used to install segments above 80 meters and rotor and nacelle. Also, the time estimated to partially dissemble LR11350 and transfer it to another tower location and reassemble it again is assumed to be one day. In addition, Specific equipment, crew size, crew production, and material employed for each activity are specified (Appendix I).

The principal materials required for completion of assembling tower components consist of temporary/permanent bracing and platforms, epoxy grout, and post tension cables. Further, one of the primary cost driving items from 120-m Hexcrete tower (HT I) to 140-m Hexcrete tower is the materials required for post-tensioning, grouting and bracing materials. For the HT3a, specifically 3.2 MW turbines are utilized instead of the 2.3 MW turbines which were employed for the HT1 tower. The larger turbine raises the loads on the tower by a factor of 1.3-1.5. This leads to a larger base diameter tower (28 feet) for HT3a Option I when compared with 22.5 (feet) for HT1, thus requiring more horizontal post-tensioning strands. The number of vertical strands needed for the tower is a function of the overturning moment exerted to the tower. As the moment is almost 1.5 times greater than that of the HT1 tower, the number of strands in each column grows from 74 strands (HT1) to 92 strands (HT3a option I). This change causes a significant development in materials compared to 120-m Hexcrete tower. Quantities and estimation of the cost of the materials for every wind tower type are provided in appendix G.

For HT2a-most likely scenario, detailed cost estimation of the assembly is provided in Table 11. Appendix H also presents a detailed cost estimate for each scenario.

Table 11. Detail cost estimation for the assembly HT2a (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	include in assembling cells on ground			$110,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$39,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$75,864	include in assembly
Grout Tower Sections	include in assembling cells on ground			$155,200	include 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
Vertica post tension		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				

Table 12 indicates the final estimated assembly cost of the worst, best, and most likely scenarios for each type of wind tower.

Table 12. Estimated assembly cost for each scenario

Type of wind tower / Scenario	Worst case	Most likely	Best case
HT3a	$873,333	$784,226	$748,844
HT3a Hybrid	$680,640	$616,352	$590,168
HT2a	$830,903	$753,238	$722,462
HT2a Hybrid	$639,396	$584,723	$562,090

4.5.4 Probabilistic analysis:

There are three possible scenarios for each type of wind towers. There is not any certain answer guaranties the occurrence of these possible scenarios. Therefore, the research team decided to run triangular distribution to reach an approximate probability distribution representing the outcome of future events (Figure 16). At the top of this figure, there is a probability axis. A vertical line was drawn from 90% point to the cost axis. This line meets cost axis at 656,500. This means that the contractor has 90% of chance to complete the entire assembly with 656,500$.

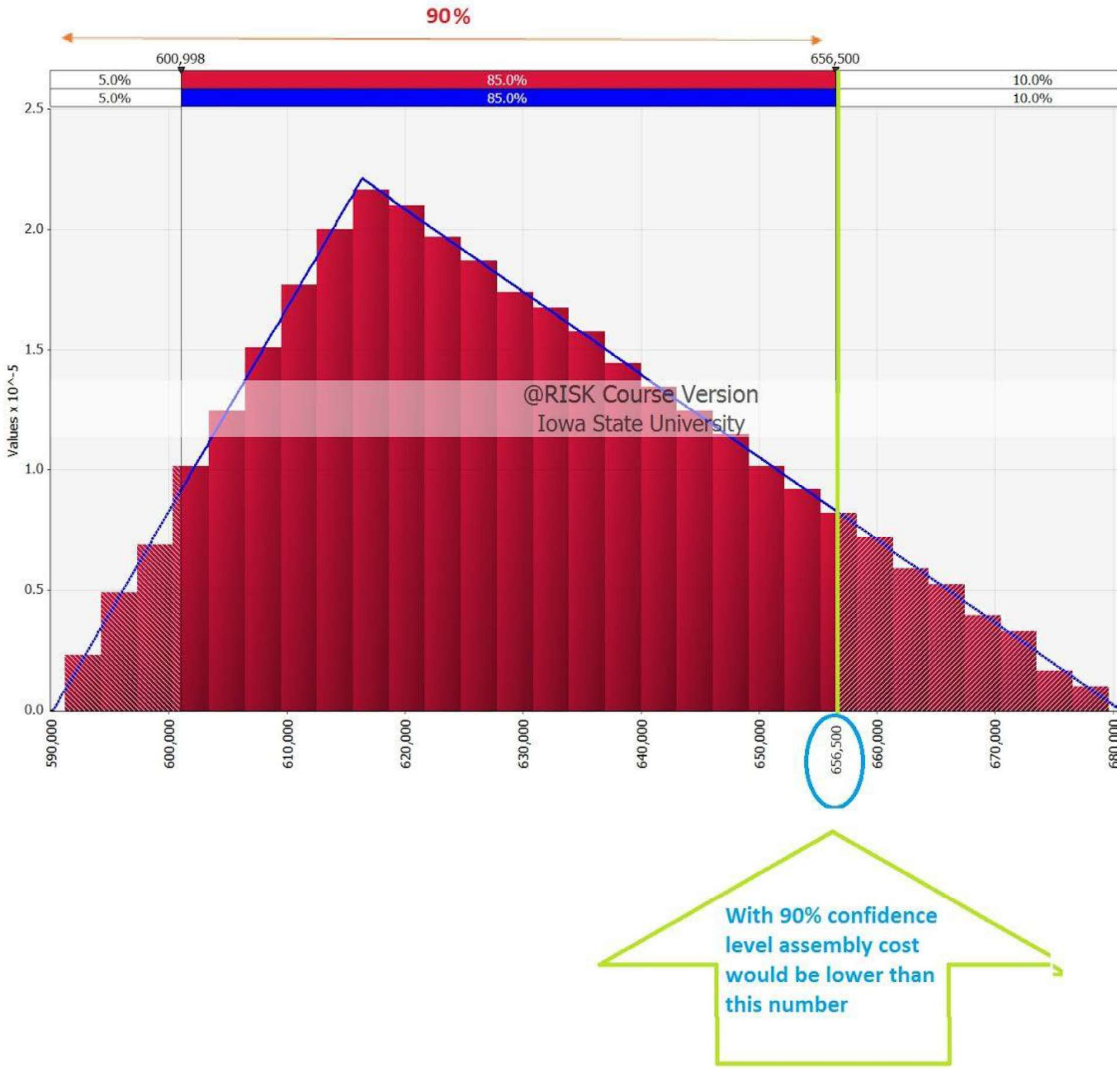


Figure 3 Cost analysis for assembly HT3a Hybrid

Table 13. represents total estimated assembly cost with the different reliability percentages.

Wind tower type / Reliability percentage	90%	80%	70%	60%
HT3a	$ 839,000	$ 825,000.00	$ 815,000	$ 807,000
HT3a Hybrid	$ 656,500	$ 647,000	$ 639,000	$ 633,000
HT2a	$ 802,000	$ 790,000	$ 780,000	$ 773,000
HT2a Hybrid	$ 619,500	$ 610,500	$ 604,000	$ 589,500

4.6 LCOE (Levelized cost of energy) comparison

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.).

The evaluation process will be using the LCOE model developed by the National Renewable Energy Laboratories (NREL) as referenced by Tegen 2013. Per Tegen there are four basic inputs into the LCOE equation. The first three – installed capital cost (ICC), annual operating expense (AOE), and annual energy production (AEP) – enable this equation to capture system-level impacts from design changes (e.g., taller wind turbine towers). 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 capturing expected plant life. (Tegen 2013) For this analysis, the life of a wind project is assumed to be 20 years.

Figure 17 (Tegen 2013) illustrates the breakdown of ICC for the NREL land-based reference project.

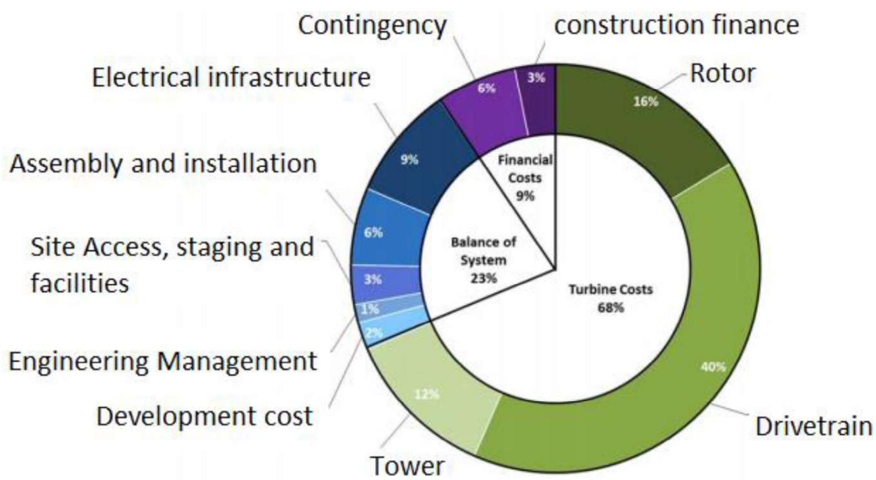


Figure 17. Installed Capital Costs for Land Based Wind Power Projects (NREL 2013)

Annual operating expenses (AOE) typically include land-lease costs, operation maintenance (O&M) wages and materials; and levelized replacement costs. O&M costs are generally expressed in two categories: 1) Fixed O&M, which includes known operations costs (e.g., scheduled maintenance, rent, leasing, taxes, utilities, or insurance payments) and 2) Variable O&M, which includes unplanned maintenance and other costs that may vary throughout the project life depending on how much electricity is generated (Tegen 2013).

Annual energy production (AEP) for this analysis is computed using the NREL wind turbine design cost and scaling model. The model computes annual energy capture and other related factors, such as capacity factor, for a wind project that is specified by generic input parameters. Turbine parameters are characteristics that are specific to the turbine and independent of wind characteristics. These consist not only of turbine size (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. Although some losses can be affected by turbine design or wind characteristics, losses are treated as independent of any other input in this simplified analysis. Types of losses accounted for in this analysis include array losses, collection and transmission losses, soil losses, and availability. Net annual energy production (AEPnet) is calculated by applying all losses to the gross AEP (Tegen 2013).

Throughout 2011, the financing environment remained relatively steady for land-based wind development. The cost of capital for both term debt and tax equity investment in 2011 did not depart significantly from 2010 levels. Because of the lack of large fluctuations in the cost and availability of debt and equity capital from 2010 to 2011, the financing assumptions were held constant from the previous land-based wind LCOE analysis (Tegen 2013).

The theoretical project that used in this research to compare the LCOE of Hexcrete towers with an 80 m steel tower consists of 100 each, 2.3 MW wind turbines located on a site in the “Heartland” of America, i.e. Iowa. The LCOE model will assume a wind resource generating an AEP from a low wind speed, high shear site in the US.

NREL’s LCOE model is utilized as a baseline to specify the LCOEs of various 140m hexcrete tower options. Out of various LCOE components, this study only assessed the following four components; a) Tower module, b) Assembly and installation, c) Foundation, and d) operation and maintenance. The other components are assumed to be the same across different tower options.

		Siemens - 2.3MW - 80m Hub Height - Rolled Steel Tower	Siemens - 3.2MW - 140m Hub Height - HT3a (best Case)
3	Nacelle Module	755	749
3	Tower Module	192	168
3	Rotor Module	335	334
2	Balance of Station	379	734
3	Development	32	32
3	Engineering Management	19	19
3	Electrical Infrastructure	150	150
3	Plant Commissioning		
3	Site Access and Staging	48	48
3	Assembly & Installation	75	371
3	Foundation	52	110
3	Operations and Maintenance Infrastructure	4	4

Figure 4 LCOE spreadsheet

The Annual energy production (AEP) for different hub heights was achieved from NREL's values estimated in calculation of LCOEs. Table 14 provides the LCOEs calculated for various types of 140-m Hexcrete towers.

Table 13. LCOE of different options

Type of wind tower / Scenario	Worst	Most likely	Best
HT3a	0.1142	0.1129	0.1124
HT3a Hybrid	0.1073	0.1064	0.1060
HT2a	0.1162	0.1148	0.1143
HT2a Hybrid	0.1084	0.1074	0.1070

4.7 Sensitivity analysis

Sensitivity analysis is the investigation of how the uncertainty in a system can be rationed to different sources of uncertainty in its inputs (Chau 1994). In order to find the effects of the range of production rates of two key assembly activities and the AEP changes, a sensitivity analysis was conducted.

A Monte Carlo simulation was utilized to better understand and quantify the cost uncertainties within the theoretical estimate. The Monte Carlo simulation allowed the research team to both quantify the range of possible LCOE values and to perform a sensitivity analysis to identify how each of the input variables effects the overall LCOE model. The NREL LCOE model was used as a baseline as previously described and random variables were identified. Any input variables that differed from the 80 m Steel Tower baseline to the 120 m and 140 m Hexcrete Tower proposed were considered random variables within the Monte Carlo simulation.

"In a stochastic model, a range of possible values for each variable is used and each value range has an associated probability density function (pdf)" (Gransberg et. al 2006).

In order to determine an accurate range for each random variable, three point estimating was utilized. "Due to the problem of availability of historical data, the pdf is often estimated based on subjective data" (Chau 1994). The research team in collaboration with the SME's established a maximum, minimum, and most likely value for each random variable. These values were determined through reasonable expert judgement of each SME in their area of specialization. "The triangular pdf simplifies the computational aspect of the modelling process and subjective estimates of the parameters of the triangular distribution (i.e. minimum, most likely, and maximum) are relatively easy to extract from estimators" (Chau 1994).

In this analysis Table 15, which presents estimated assembly cost for each scenario, is used as the input for the cost of assembly and installation. Further, based on the information that NREL's experts have provided, AEP for Siemens 2.3 MW and 3.2 MW turbines were estimated to be 623,500 MWh/year and 769,700 MWh/year per turbine, respectively. For running sensitivity analysis numbers in the following table are used as the worst, most likely and best case scenario for AEP.

Table 14 AEP inputs for sensitivity analysis

Turbine type / AEP (MWh/year)	Worst case (15% less than NREL's prediction)	Most likely (NREL's prediction)	best case (15% more) than NREL's prediction
Siemens 2.3 MW	529,975	623,500	717,025
Siemens 3.2 MW	654,245	769,700	855,155

Figure 19 is the tornado graph that provides the results of the sensitivity analysis for HT2a. The analysis indicates the relationship between LCOE and input variables and also states that how LCOE is sensitive to AEP and cost of installation and assembly. Figure 19 reveals that LCOE depends on AEP approximately 3.5 times more than assembly and installation. The sensitivity analysis demonstrates that the random variable with the highest potential impact on the overall LCOE is the annual energy production (AEP).

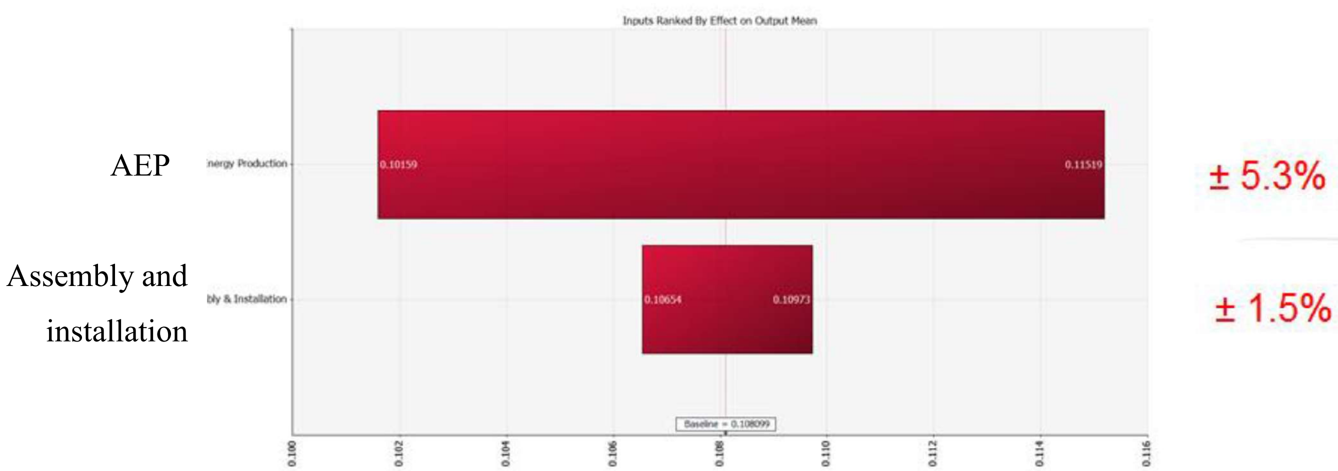


Figure 5. Sensitivity analysis

The aim of this research project is to discover a constructible, financially feasible option wind tower configuration to the 80-m steel tower stage that can reduce the general Levelized expense of vitality. The study finishes up the objective can be achieved by employing of the 140-m Hexcrete tower stage on specific wind sites in the United States.

Based on the effect of AEP on LCOE, this huge increase from 80 m steel tower to 140-m Hexcrete tower in annual energy generation compensates for the potential risk of deploying 140-m Hexcrete towers prototype.

5 LCOE ANALYSIS MAPS

The overall goal of this study is create maps to evaluate LCOE of different wind tower construction options. The specific objectives to accomplish this are collecting weather information from the local weather station, estimating AEP at different hub height, and finally creating wind maps using Arc GIS.

5.1 Weather data collection

The first phase will consist of finding accurate data weather for last ten years and use them to reach wind maps in GIS. Wind speed usually measured at weather stations in 5/0, 2, 6, 8 or 10 meters of the surface. Using Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS) data base the wind speed data were collected for different locations in Iowa (Figure 20).

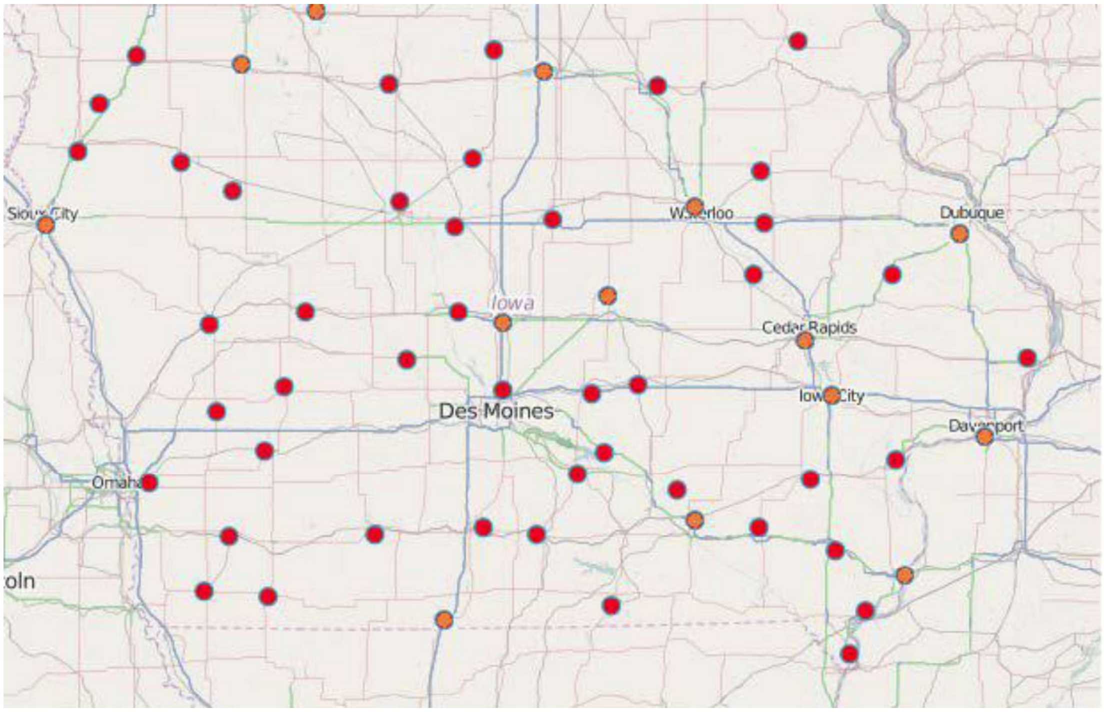


Figure 20. Weather stations used for data collection

5.2 Annual energy output calculations

In the higher altitudes, there is a direct measure wind speed can be estimated from the following experimental formula (Augusti 1984):

$$V(h) = V_{10} \cdot (h/h_{10})^{\alpha}$$

Where:

$V(h)$ = Velocity of the wind (mph/s) at height h

V_{10} = Velocity of the wind (mph/s), at height h_{10} = 10 meters

α = Hellmann exponent

Renee 2013 said "The Hellmann exponent depends upon the coastal location and the shape of the terrain on the ground, and the stability of the air. Therefore considering one constant number for α for all weather stations is a poor estimate. Using the α which is obtained in the previous study

(Renee A. et all 2013) wind speeds were estimated for different hub heights. Hellmann exponent data that are used in this study shown in Appendix J.

Wind power turbine manufacture use a calculation based on the wind turbine power. the average annual wind speed at your site, the height of the tower that you plan to use, and the frequency distribution of the wind–an estimate of the number of hours that the wind will blow at each speed during an average year. Annual energy output is estimated using following formula (Wind power engineering development 2009) :

AEO = k . Cp . ½ . ρ . A . V3

Where:

AEO = Annual energy output, kWh/year
P = Power output, kilowatts
Cp = Maximum power coefficient, ranging from 0.25 to 0.45, dimension less (theoretical maximum = 0.59)
ρ = Air density, lb/ft3
A = Rotor swept area, ft2 or π D2/4 (D is the rotor diameter in ft, π = 3.1416)
V = Wind speed, mph
k = 0.000133 A constant to yield power in kilowatts. (Multiplying the above kilowatt answer by 1.340 converts it to horse- power [i.e., 1 kW = 1.340 horsepower]).

5.3 LCOE mapping

ArcMap is geographic information software for developing maps and visualizing geographic information. The software was used to draw LCOE maps for different wind tower options. ArcMap provides a variety of deterministic interpolation methods to estimate variables at unstamped locations including inverse distance weighting IDW), local polynomial (LP), thin plate spline and Kriging. The research team tried to use the most reliable deterministic interpolation among ones mentioned above. According to (Lou et.al 2008) “Kriging to be superior to other conventional interpolation techniques such as LP and IDW, which is by the observations of this study. Overall, the differences of RMSE between ordinary kriging and universal kriging were very small, but universal kriging tended to have higher errors. One of the advantages of kriging is that it provides." Therefore Kriging interpolation was used in this study.

Cressie, 1985 said “Kriging is a stochastic technique similar to IDW, in that it uses a linear combination of weights at known points to estimate the value at an unknown point. In contrast with deterministic methods, Kriging provides a solution to the problem of estimation of the surface by taking account of the spatial correlation. “

Ordinary Kriging. Its predictor for the ‘new’, unobserved (non-simulated) input X $_{n+1}$ denoted by Y(X_{n+1}) is a weighted linear combination of all the *n* ‘old’, already observed outputs x_i :

$$\hat{Y}(\mathbf{x}_{n+1}) = \sum_{i=1}^{n} \lambda_i \cdot Y(\mathbf{x}_i) = \boldsymbol{\lambda}' \cdot \mathbf{Y}$$

This Kriging assumes a single output per input combination; in case of multiple outputs, the predictor may be computed per output. (Van Beers 2004).

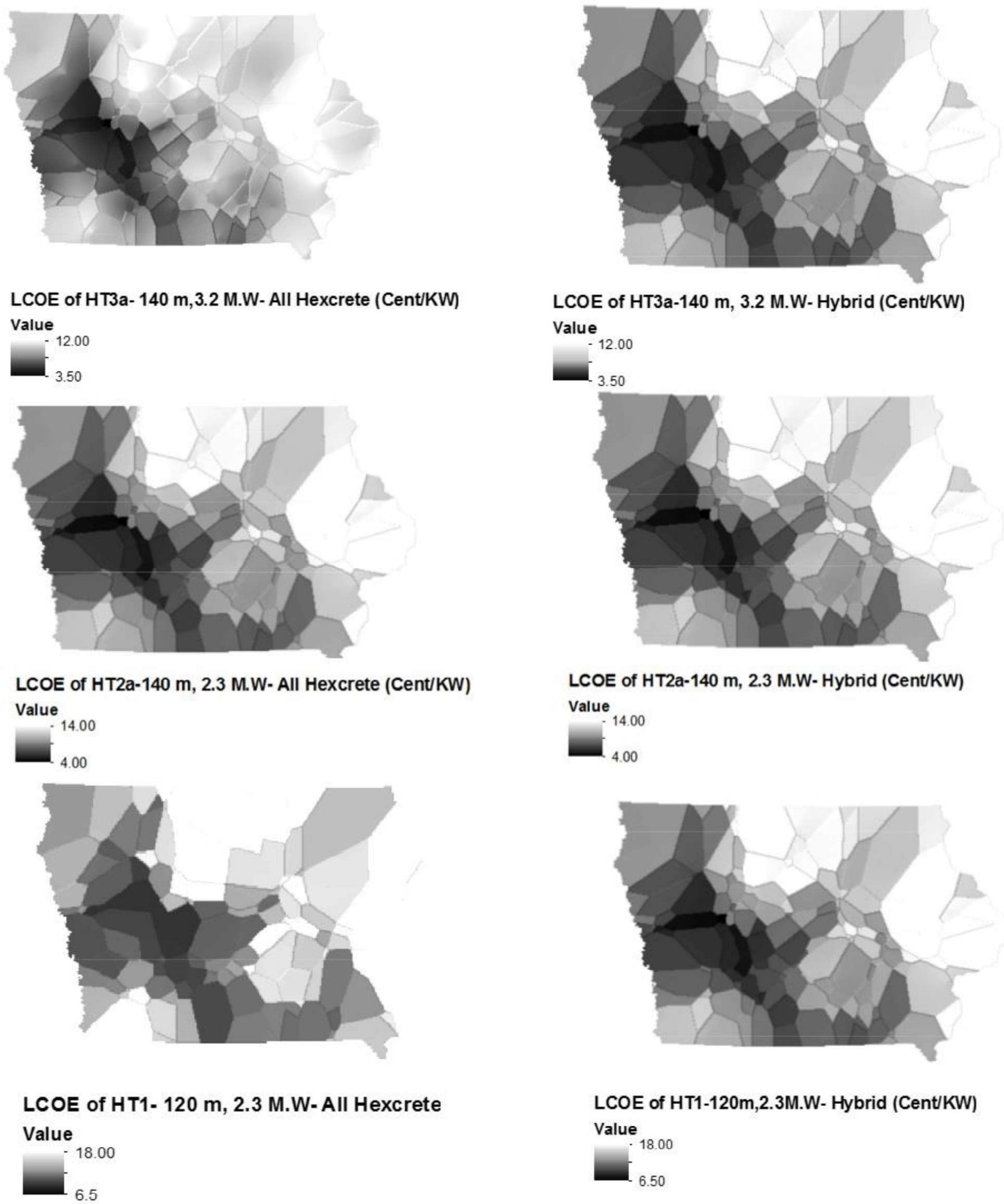


Figure 21. LCOE maps for different wind tower options

Figure 21 shows LCOE in different regions in the State of Iowa. The dark areas indicate lower LCOE. As Figure 21 reveals deploying hybrid towers is more beneficial from the economic perspective. Also, central and western part of Iowa because of having stronger and steadier winds is better places to install such technologies.

LCOE at one particular point, CVK weather station (-93.7593, 42.743) is shown in the table below. As it indicated in Table 15 HT3a hybrid has the lowest LCOE for this specific station. Also, HT1a has the highest LCOE dues to shorter hub height.

Table 15. LCOE at CVK station

Type of tower	**LCOE (Cents)**
HT3a (3.2MW)	6.1
HT3a hybrid (3.2MW)	5.6
HT2a (2.3MW)	6.6
HT2a hybrid (2.3MW)	6.9
HT1a (2.3MW)	11.1
HT1a hybrid (2.3MW)	10.6

6 CONCLUSION

The goal of the research project is to find a constructible, financially feasible alternative wind tower design to the 80 m steel tower platform that has the potential to reduce the overall Levelized cost of energy. By use of taller towers the wind turbine generator now can harvest stronger, steadier, more numerous wind resources for increased wind power production. Taller wind turbines are desired to increase AEP of a wind energy site, but the current tower design does not allow the tower to reach heights of 140 m due to transportation and logistics constraints. The Hexcrete tower design allows wind towers to be built more than 120 m to harvest a better wind resource. LCOE is used as a metric to compare the life cycle costs and benefits of using an 80 m steel tower design with a 140 m Hexcrete tower design. The study concludes there are potential LCOE savings with the utilization of a 140 m Hexcrete versus an 80 m steel tower on individual wind sites in the United States.

According to the DOE (2014), "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 an equal generator and rotor sizes with only changing the height of the tower and the material used to support the tower, 80 m steel versus 140 m Hexcrete tower. In addition to harvesting stronger winds at 140 m, the Hexcrete concrete tower also facilitates a platform that will allow a larger generator and bigger rotor size that will allow the WTG to have an increased electrical capacity and production. The research recommends to further study how this Hexcrete platform can be used in conjunction with other wind energy technological advances such as a bigger generators and larger rotors to lower the cost of wind power production further.

At the end, this study concludes that central and western part of Iowa because of having stronger and steadier winds is better places to install such technologies because of stronger and steadier wind.

7 REFERENCES

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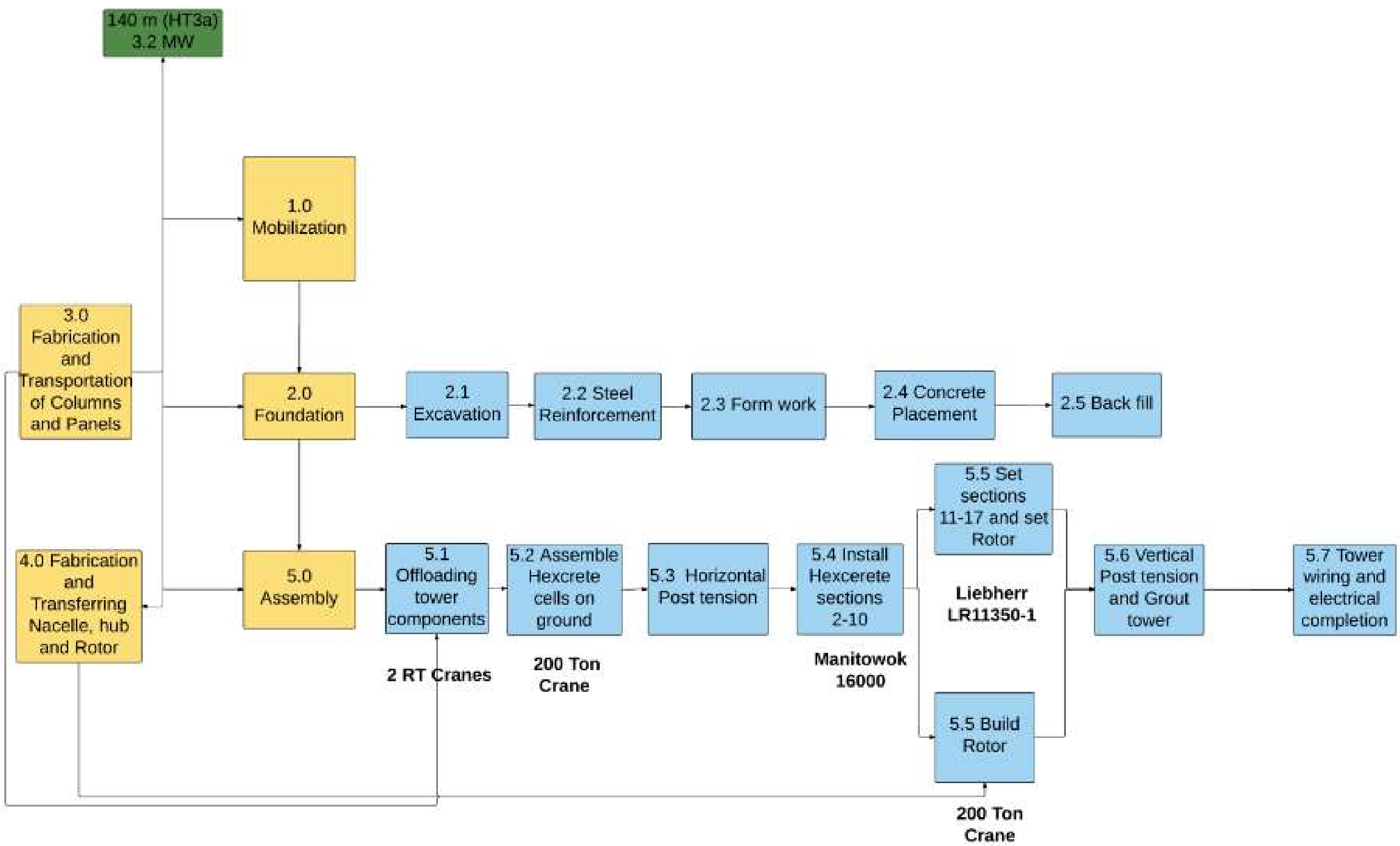
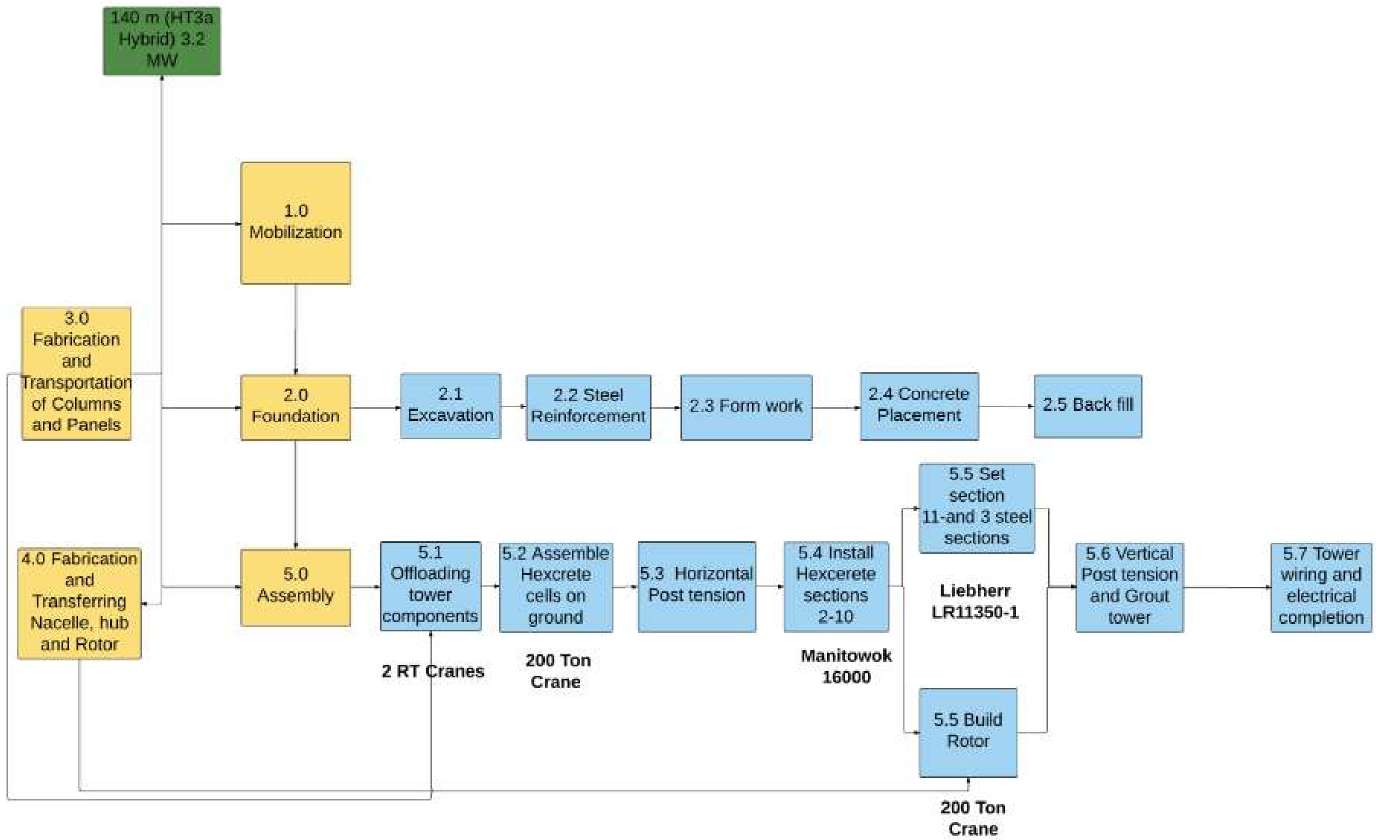
8 APPENDIX

Appendix A: Work break down structure

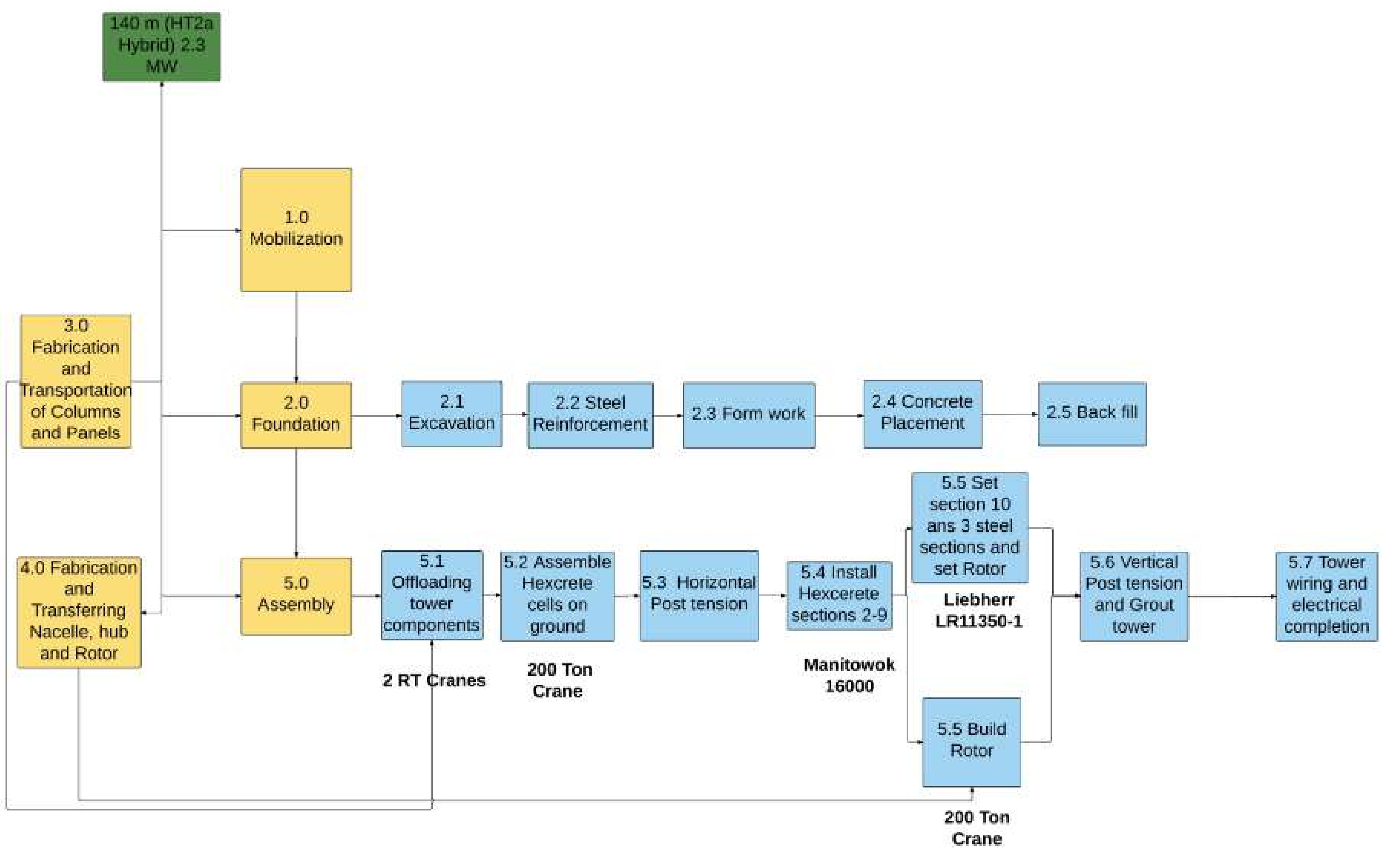
HT3a Work break down structure



HT3a Hybrid Work breaks down structure



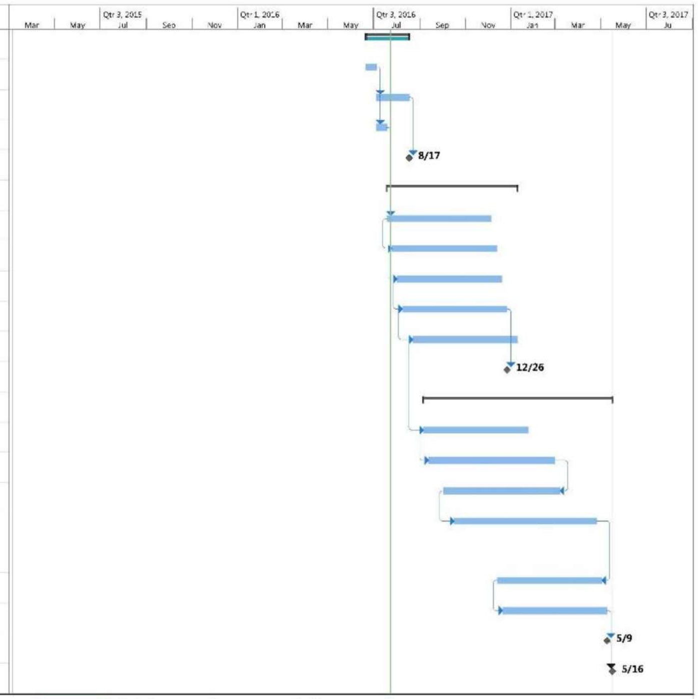
HT2a Hybrid Work breaks down structure



Appendix B : Bar chart scheduling

Bar chart scheduling HT3a worst case scenario

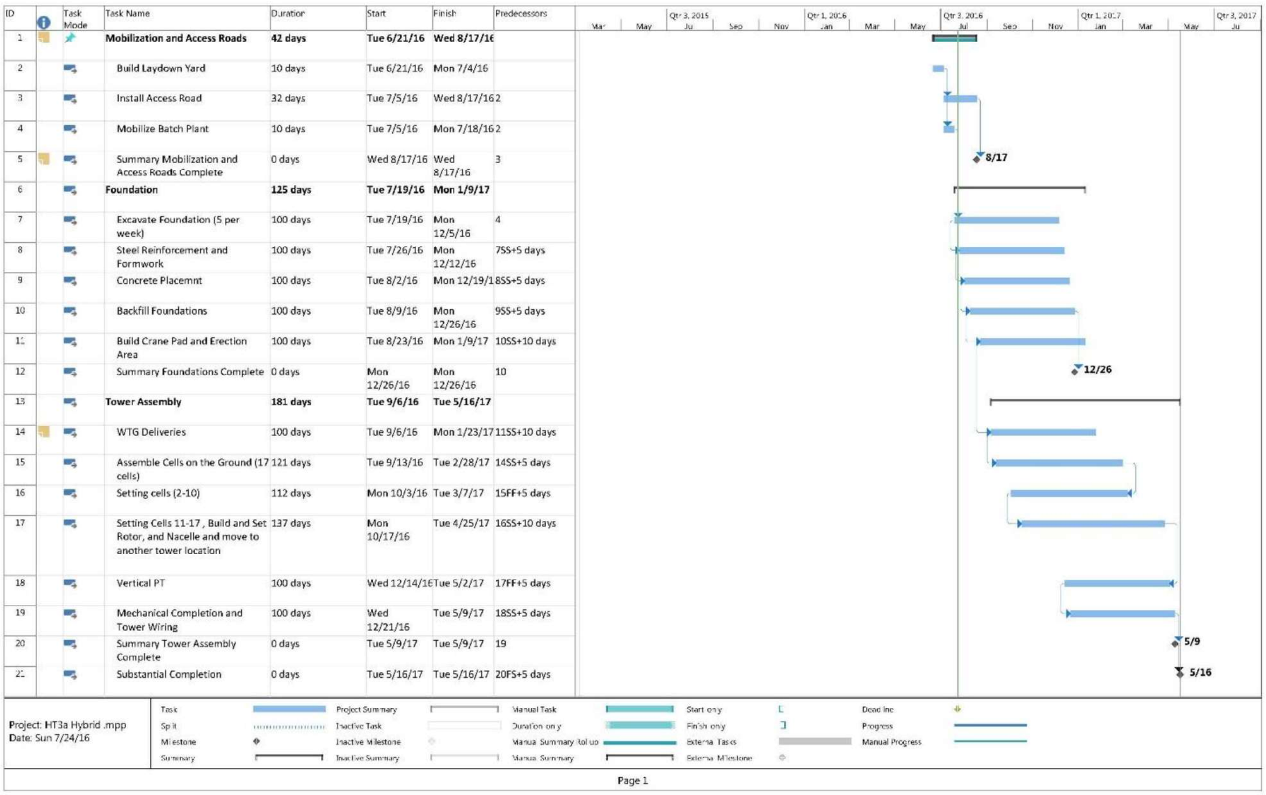
ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**181 days**	**Tue 9/6/16**	**Tue 5/16/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (17 cells)	121 days	Tue 9/13/16	Tue 2/28/17	14SS+5 days
16		Setting cells (2-10)	112 days	Mon 10/3/16	Tue 3/7/17	15FF+5 days
17		Setting Cells 11-17 , Build and Set Rotor, and Nacelle and move to another tower location	137 days	Mon 10/17/16	Tue 4/25/17	16SS+10 days
18		Vertical PT	100 days	Wed 12/14/16	Tue 5/2/17	17FF+5 days
19		Mechanical Completion and Tower Wiring	100 days	Wed 12/21/16	Tue 5/9/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Tue 5/9/17	Tue 5/9/17	19
21		Substantial Completion	0 days	Tue 5/16/17	Tue 5/16/17	20FS+5 days



Project: HT3a Hybrid .mpp
Date: Sun 7/24/16

Task | Split | Milestone | Summary | Project Summary | Inactive Task | Inactive Milestone | Inactive Summary | Manual Task | Duration-only | Manual Summary Rollup | Manual Summary | Start-only | Finish-only | External Tasks | External Milestone | Deadline | Progress | Manual Progress

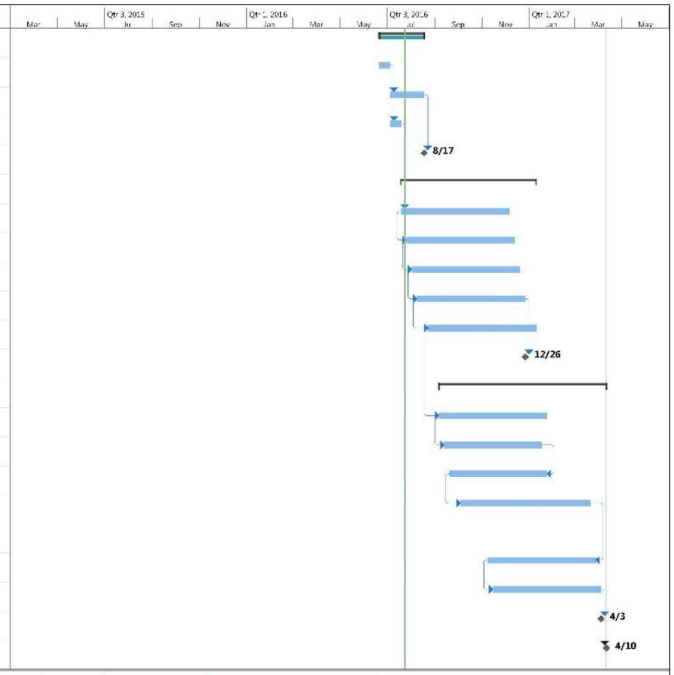
Bar chart scheduling HT3a most likely case scenario



ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**181 days**	**Tue 9/6/16**	**Tue 5/16/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (17 cells)	121 days	Tue 9/13/16	Tue 2/28/17	14SS+5 days
16		Setting cells (2-10)	112 days	Mon 10/3/16	Tue 3/7/17	15FF+5 days
17		Setting Cells 11-17 , Build and Set Rotor, and Nacelle and move to another tower location	137 days	Mon 10/17/16	Tue 4/25/17	16SS+10 days
18		Vertical PT	100 days	Wed 12/14/16	Tue 5/2/17	17FF+5 days
19		Mechanical Completion and Tower Wiring	100 days	Wed 12/21/16	Tue 5/9/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Tue 5/9/17	Tue 5/9/17	19
21		Substantial Completion	0 days	Tue 5/16/17	Tue 5/16/17	20FS+5 days

Bar chart scheduling HT3a best case scenario

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**155 days**	**Tue 9/6/16**	**Mon 4/10/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (17 cells)	90 days	Tue 9/13/16	Mon 1/16/17	14SS+5 days
16		Setting cells (2-10)	90 days	Tue 9/20/16	Mon 1/23/17	15FF+5 days
17		Setting Cells 11-17 , Build and Set Rotor, and Nacelle and move to another tower location	120 days	Tue 10/4/16	Mon 3/20/17	16SS+10 days
18		Vertical PT	100 days	Tue 11/8/16	Mon 3/27/17	17FF+5 days
19		Mechanical Completion and Tower Wiring	100 days	Tue 11/15/16	Mon 4/3/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Mon 4/3/17	Mon 4/3/17	19
21		Substantial Completion	0 days	Mon 4/10/17	Mon 4/10/17	20FS+5 days



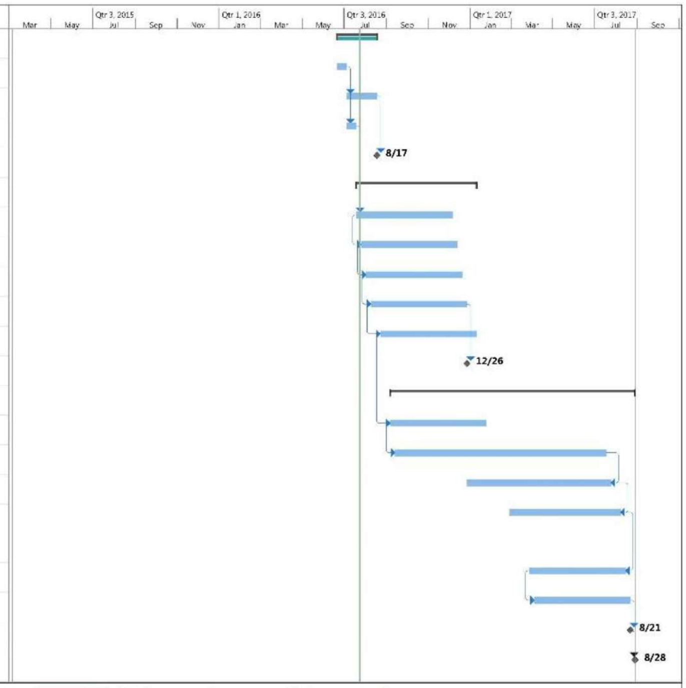
Project: HT3a Hybrid .mpp
Date: Sun 7/24/16

Task | Split | Milestone | Summary | Project Summary | Inactive Task | Inactive Milestone | Inactive Summary | Manual Task | Duration-only | Manual Summary Rollup | Manual Summary | Start-only | Finish-only | External Tasks | External Milestone | Deadline | Progress | Manual Progress

Page 1

Bar chart scheduling HT3a Hybrid worst case scenario

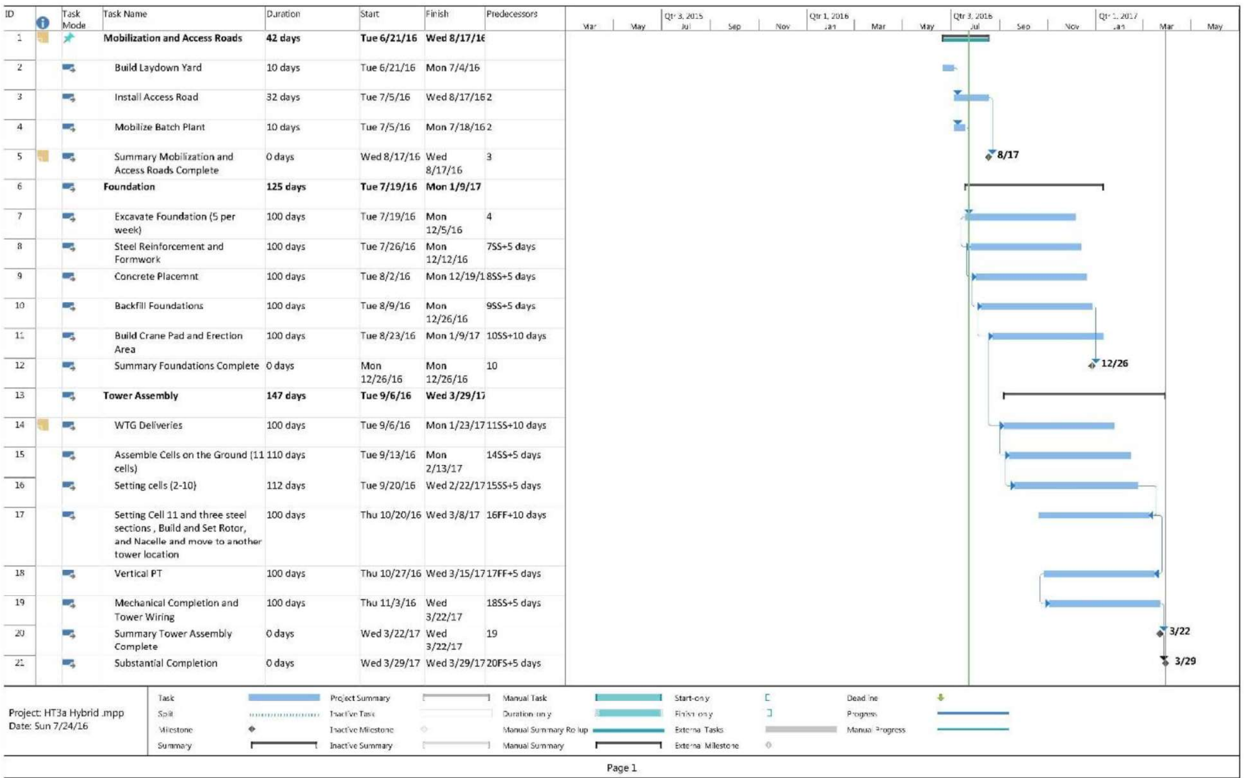
ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/16	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**255 days**	**Tue 9/6/16**	**Mon 8/28/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (11 cells)	220 days	Tue 9/13/16	Mon 7/17/17	14SS+5 days
16		Setting cells (2-10)	150 days	Tue 12/27/16	Mon 7/24/17	15FF+5 days
17		Setting Cell 11 and three steel sections , Build and Set Rotor, and Nacelle and move to another tower location	116 days	Mon 2/27/17	Mon 8/7/17	16FF+10 days
18		Vertical PT	100 days	Tue 3/28/17	Mon 8/14/17	17FF+5 days
19		Mechanical Completion and Tower Wiring	100 days	Tue 4/4/17	Mon 8/21/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Mon 8/21/17	Mon 8/21/17	19
21		Substantial Completion	0 days	Mon 8/28/17	Mon 8/28/17	20FS+5 days



Project: HT3a Hybrid .mpp
Date: Sun 7/24/16

Task, Split, Milestone, Summary, Project Summary, Inactive Task, Inactive Milestone, Inactive Summary, Manual Task, Duration-only, Manual Summary Rollup, Manual Summary, Start-only, Finish-only, External Tasks, External Milestone, Deadline, Progress, Manual Progress

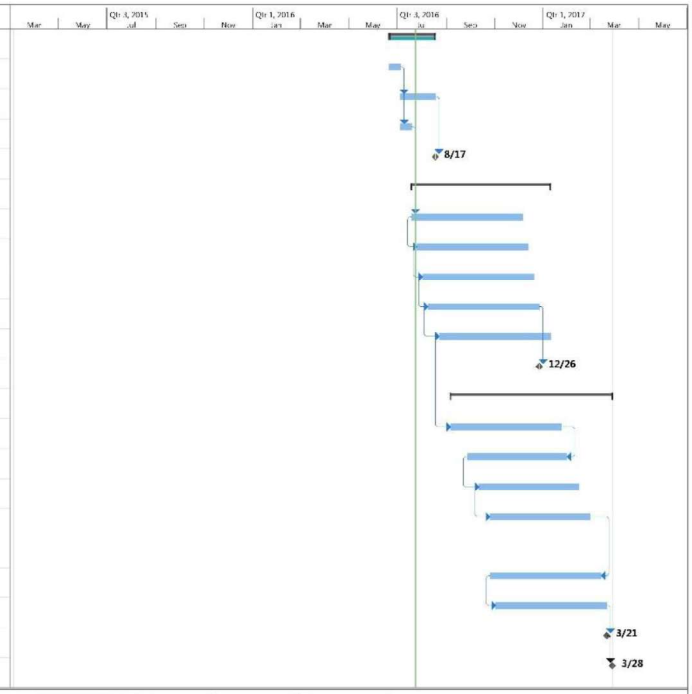
Bar chart scheduling HT3a Hybrid most likely case scenario



ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/1[illegible]**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1[illegible]	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**147 days**	**Tue 9/6/16**	**Wed 3/29/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (11 cells)	110 days	Tue 9/13/16	Mon 2/13/17	14SS+5 days
16		Setting cells (2-10)	112 days	Tue 9/20/16	Wed 2/22/17	15SS+5 days
17		Setting Cell 11 and three steel sections , Build and Set Rotor, and Nacelle and move to another tower location	100 days	Thu 10/20/16	Wed 3/8/17	16FF+10 days
18		Vertical PT	100 days	Thu 10/27/16	Wed 3/15/17	17FF+5 days
19		Mechanical Completion and Tower Wiring	100 days	Thu 11/3/16	Wed 3/22/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Wed 3/22/17	Wed 3/22/17	19
21		Substantial Completion	0 days	Wed 3/29/17	Wed 3/29/17	20FS+5 days

Bar chart scheduling HT3a Hybrid best case scenario

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**146 days**	**Tue 9/6/16**	**Tue 3/28/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (11 cells)	90 days	Tue 9/27/16	Mon 1/30/17	14FF+5 days
16		Setting cells (2-10)	90 days	Wed 10/12/16	Tue 2/14/17	15SS+11 days
17		Setting Cell 11 and three steel sections , Build and Set Rotor, and Nacelle and move to another tower location	90 days	Wed 10/26/16	Tue 2/28/17	16SS+10 days
18		Vertical PT	100 days	Wed 10/26/16	Tue 3/14/17	17FF+10 days
19		Mechanical Completion and Tower Wiring	100 days	Wed 11/2/16	Tue 3/21/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Tue 3/21/17	Tue 3/21/17	19
21		Substantial Completion	0 days	Tue 3/28/17	Tue 3/28/17	20FS+5 days



Project: HT3a Hybrid .mpp
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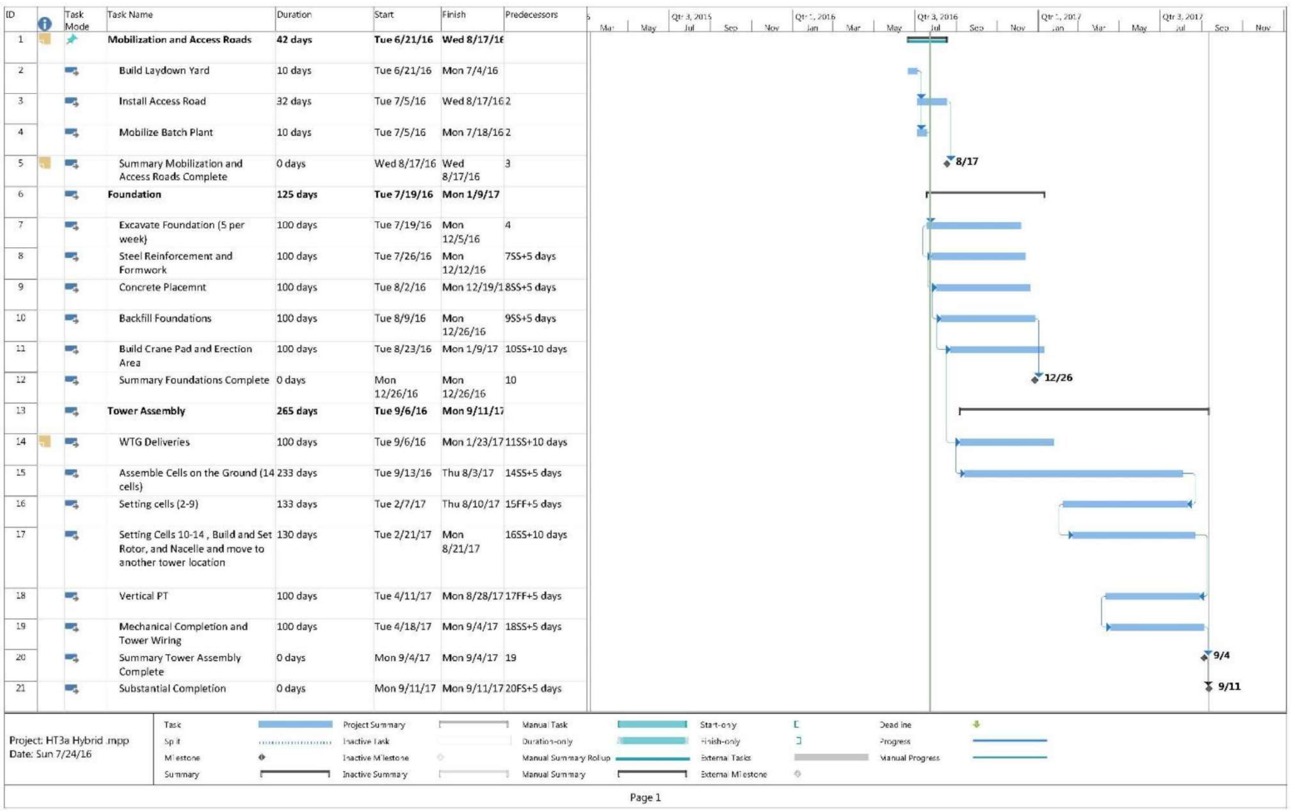
Task | Split | Milestone | Summary | Project Summary | Inactive Task | Inactive Milestone | Inactive Summary | Manual Task | Duration-only | Manual Summary Rollup | Manual Summary | Start-only | Finish-only | External Tasks | External Milestone | Deadline | Progress | Manual Progress

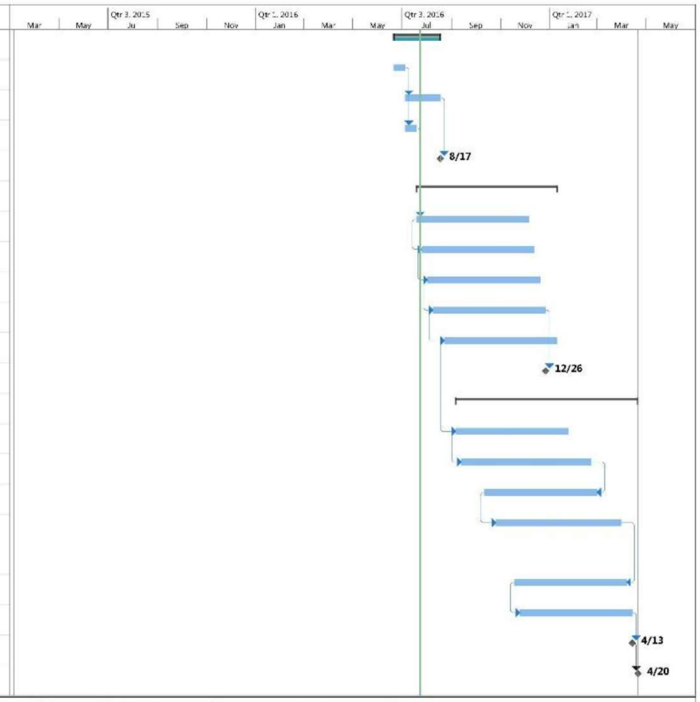
Bar chart scheduling HT2a worst case scenario



ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**265 days**	**Tue 9/6/16**	**Mon 9/11/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (14 cells)	233 days	Tue 9/13/16	Thu 8/3/17	14SS+5 days
16		Setting cells (2-9)	133 days	Tue 2/7/17	Thu 8/10/17	15FF+5 days
17		Setting Cells 10-14 , Build and Set Rotor, and Nacelle and move to another tower location	130 days	Tue 2/21/17	Mon 8/21/17	16SS+10 days
18		Vertical PT	100 days	Tue 4/11/17	Mon 8/28/17	17FF+5 days
19		Mechanical Completion and Tower Wiring	100 days	Tue 4/18/17	Mon 9/4/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Mon 9/4/17	Mon 9/4/17	19
21		Substantial Completion	0 days	Mon 9/11/17	Mon 9/11/17	20FS+5 days

Bar chart scheduling HT2a most likely case scenario

ID	Task Name	Duration	Start	Finish	Predecessors
1	**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2	Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3	Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4	Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5	Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6	**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7	Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8	Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9	Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1	8SS+5 days
10	Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11	Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12	Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13	**Tower Assembly**	**163 days**	**Tue 9/6/16**	**Thu 4/20/17**	
14	WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15	Assemble Cells on the Ground (14 cells)	116 days	Tue 9/13/16	Tue 2/21/17	14SS+5 days
16	Setting cells (2-9)	100 days	Wed 10/12/16	Tue 2/28/17	15FF+5 days
17	Setting Cells 10-14 , Build and Set Rotor, and Nacelle and move to another tower location	112 days	Wed 10/26/16	Thu 3/30/17	16SS+10 days
18	Vertical PT	100 days	Fri 11/18/16	Thu 4/6/17	17FF+5 days
19	Mechanical Completion and Tower Wiring	100 days	Fri 11/25/16	Thu 4/13/17	18SS+5 days
20	Summary Tower Assembly Complete	0 days	Thu 4/13/17	Thu 4/13/17	19
21	Substantial Completion	0 days	Thu 4/20/17	Thu 4/20/17	20FS+5 days



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Task | Split | Milestone | Summary | Project Summary | Inactive Task | Inactive Milestone | Inactive Summary | Manual Task | Duration only | Manual Summary Rollup | Manual Summary | Start only | Finish only | External Tasks | External Milestone | Deadline | Progress | Manual Progress

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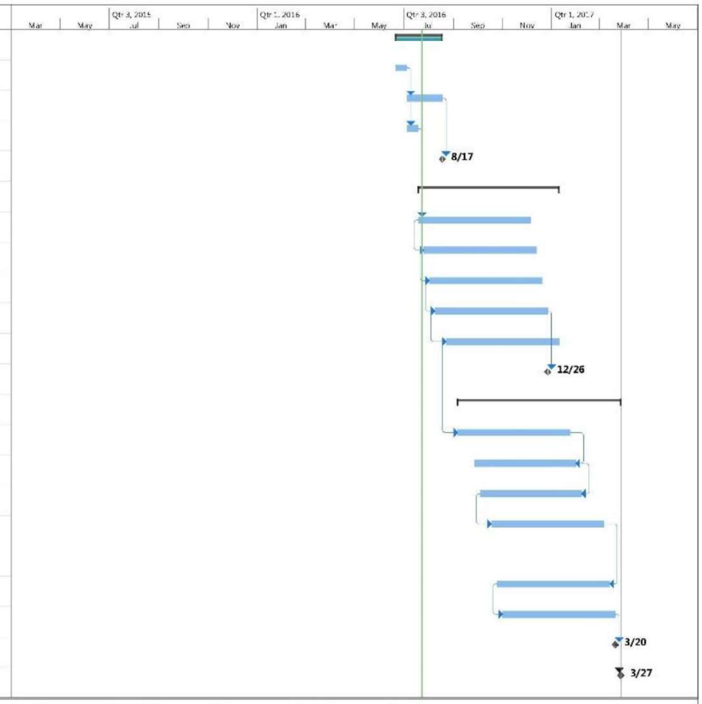
Bar chart scheduling HT2a best case scenario

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**145 days**	**Tue 9/6/16**	**Mon 3/27/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (14 cells)	90 days	Tue 9/27/16	Mon 1/30/17	14FF+5 days
16		Setting cells (2-9)	90 days	Tue 10/4/16	Mon 2/6/17	15FF+5 days
17		Setting Cells 10-14 , Build and Set Rotor, and Nacelle and move to another tower location	100 days	Tue 10/18/16	Mon 3/6/17	16SS+10 days
18		Vertical PT	100 days	Tue 10/25/16	Mon 3/13/17	17FF+5 days
19		Mechanical Completion and Tower Wiring	100 days	Tue 11/1/16	Mon 3/20/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Mon 3/20/17	Mon 3/20/17	19
21		Substantial Completion	0 days	Mon 3/27/17	Mon 3/27/17	20FS+5 days

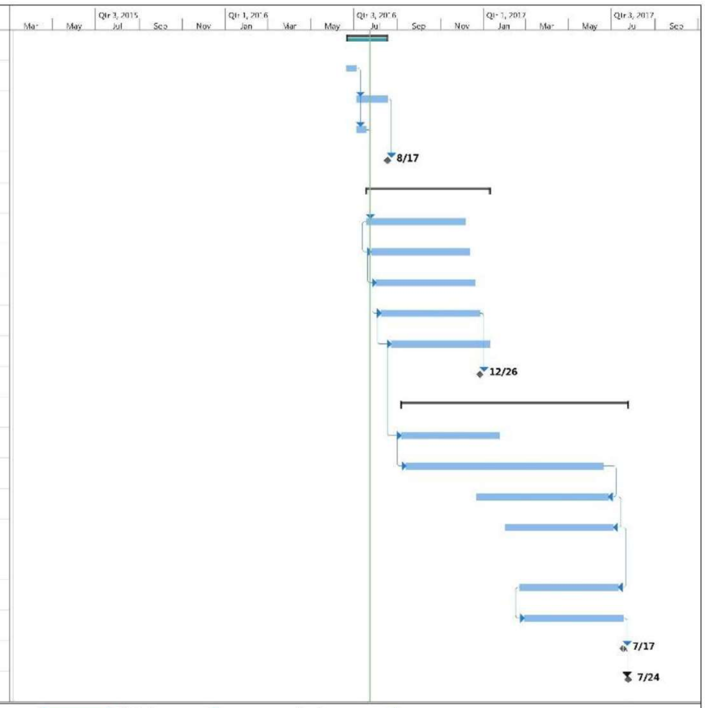


Project: HT3a Hybrid .mpp
Date: Sun 7/24/16

Task, Split, Milestone, Summary, Project Summary, Inactive Task, Inactive Milestone, Inactive Summary, Manual Task, Duration-only, Manual Summary Rollup, Manual Summary, Start-only, Finish-only, External Tasks, External Milestone, Deadline, Progress, Manual Progress

Bar chart scheduling HT2a Hybrid worst case scenario

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**230 days**	**Tue 9/6/16**	**Mon 7/24/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (10 cells)	200 days	Tue 9/13/16	Mon 6/19/17	14SS+5 days
16		Setting cells (2-9)	133 days	Thu 12/22/16	Mon 6/26/17	15FF+5 days
17		Setting Cell 10 and 3 Steel Sections , Build and Set Rotor, and Nacelle and move to another tower location	110 days	Tue 1/31/17	Mon 7/3/17	16FF+5 days
18		Vertical PT	100 days	Tue 2/21/17	Mon 7/10/17	17FF+5 days
19		Mechanical Completion and Tower Wiring	100 days	Tue 2/28/17	Mon 7/17/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Mon 7/17/17	Mon 7/17/17	19
21		Substantial Completion	0 days	Mon 7/24/17	Mon 7/24/17	20FS+5 days



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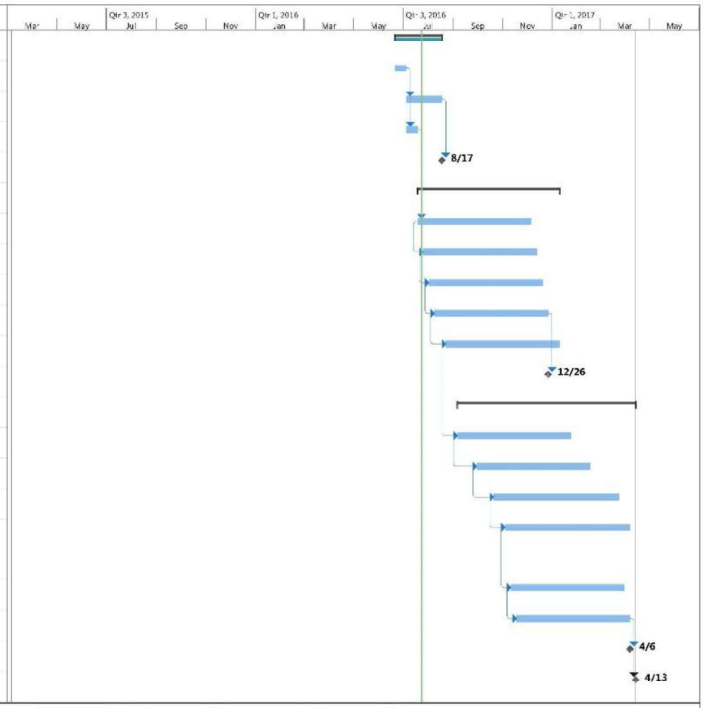
Bar chart scheduling HT2a Hybrid most likely case scenario

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/1	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**158 days**	**Tue 9/6/16**	**Thu 4/13/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (10 cells)	100 days	Fri 9/30/16	Thu 2/16/17	14SS+18 days
16		Setting cells (2-9)	110 days	Fri 10/21/16	Thu 3/23/17	15SS+15 days
17		Setting Cell 10 and 3 Steel Sections , Build and Set Rotor, and Nacelle and move to another tower location	110 days	Fri 11/4/16	Thu 4/6/17	16SS+10 days
18		Vertical PT	100 days	Fri 11/11/16	Thu 3/30/17	17SS+5 days
19		Mechanical Completion and Tower Wiring	100 days	Fri 11/18/16	Thu 4/6/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Thu 4/6/17	Thu 4/6/17	19
21		Substantial Completion	0 days	Thu 4/13/17	Thu 4/13/17	20FS+5 days



Project: HT3a Hybrid .mpp
Date: Sun 7/24/16

Task		Project Summary		Manual Task		Start-only		Deadline	
Split		Inactive Task		Duration-only		Finish-only		Progress	
Milestone		Inactive Milestone		Manual Summary Rollup		External Tasks		Manual Progress	
Summary		Inactive Summary		Manual Summary		External Milestone			

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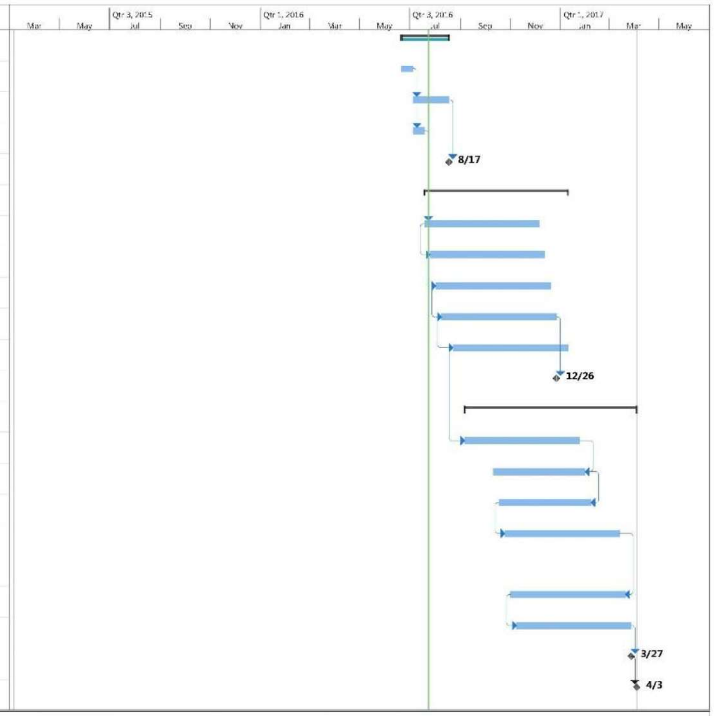
Bar chart scheduling HT2a Hybrid best case scenario

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Tue 6/21/16**	**Wed 8/17/16**	
2		Build Laydown Yard	10 days	Tue 6/21/16	Mon 7/4/16	
3		Install Access Road	32 days	Tue 7/5/16	Wed 8/17/16	2
4		Mobilize Batch Plant	10 days	Tue 7/5/16	Mon 7/18/16	2
5		Summary Mobilization and Access Roads Complete	0 days	Wed 8/17/16	Wed 8/17/16	3
6		**Foundation**	**125 days**	**Tue 7/19/16**	**Mon 1/9/17**	
7		Excavate Foundation (5 per week)	100 days	Tue 7/19/16	Mon 12/5/16	4
8		Steel Reinforcement and Formwork	100 days	Tue 7/26/16	Mon 12/12/16	7SS+5 days
9		Concrete Placemnt	100 days	Tue 8/2/16	Mon 12/19/16	8SS+5 days
10		Backfill Foundations	100 days	Tue 8/9/16	Mon 12/26/16	9SS+5 days
11		Build Crane Pad and Erection Area	100 days	Tue 8/23/16	Mon 1/9/17	10SS+10 days
12		Summary Foundations Complete	0 days	Mon 12/26/16	Mon 12/26/16	10
13		**Tower Assembly**	**150 days**	**Tue 9/6/16**	**Mon 4/3/17**	
14		WTG Deliveries	100 days	Tue 9/6/16	Mon 1/23/17	11SS+10 days
15		Assemble Cells on the Ground (10 cells)	80 days	Tue 10/11/16	Mon 1/30/17	14FF+5 days
16		Setting cells (2-9)	80 days	Tue 10/18/16	Mon 2/6/17	15FF+5 days
17		Setting Cell 10 and 3 Steel Sections , Build and Set Rotor, and Nacelle and move to another tower location	100 days	Tue 10/25/16	Mon 3/13/17	16SS+5 days
18		Vertical PT	100 days	Tue 11/1/16	Mon 3/20/17	17FF+5 days
19		Mechanical Completion and Tower Wiring	100 days	Tue 11/8/16	Mon 3/27/17	18SS+5 days
20		Summary Tower Assembly Complete	0 days	Mon 3/27/17	Mon 3/27/17	19
21		Substantial Completion	0 days	Mon 4/3/17	Mon 4/3/17	20FS+5 days



Project: HT3a Hybrid .mpp
Date: Sun 7/24/16

Task | Split | Milestone | Summary | Project Summary | Inactive Task | Inactive Milestone | Inactive Summary | Manual Task | Duration-only | Manual Summary Rollup | Manual Summary | Start-only | Finish-only | External Tasks | External Milestone | Deadline | Progress | Manual Progress

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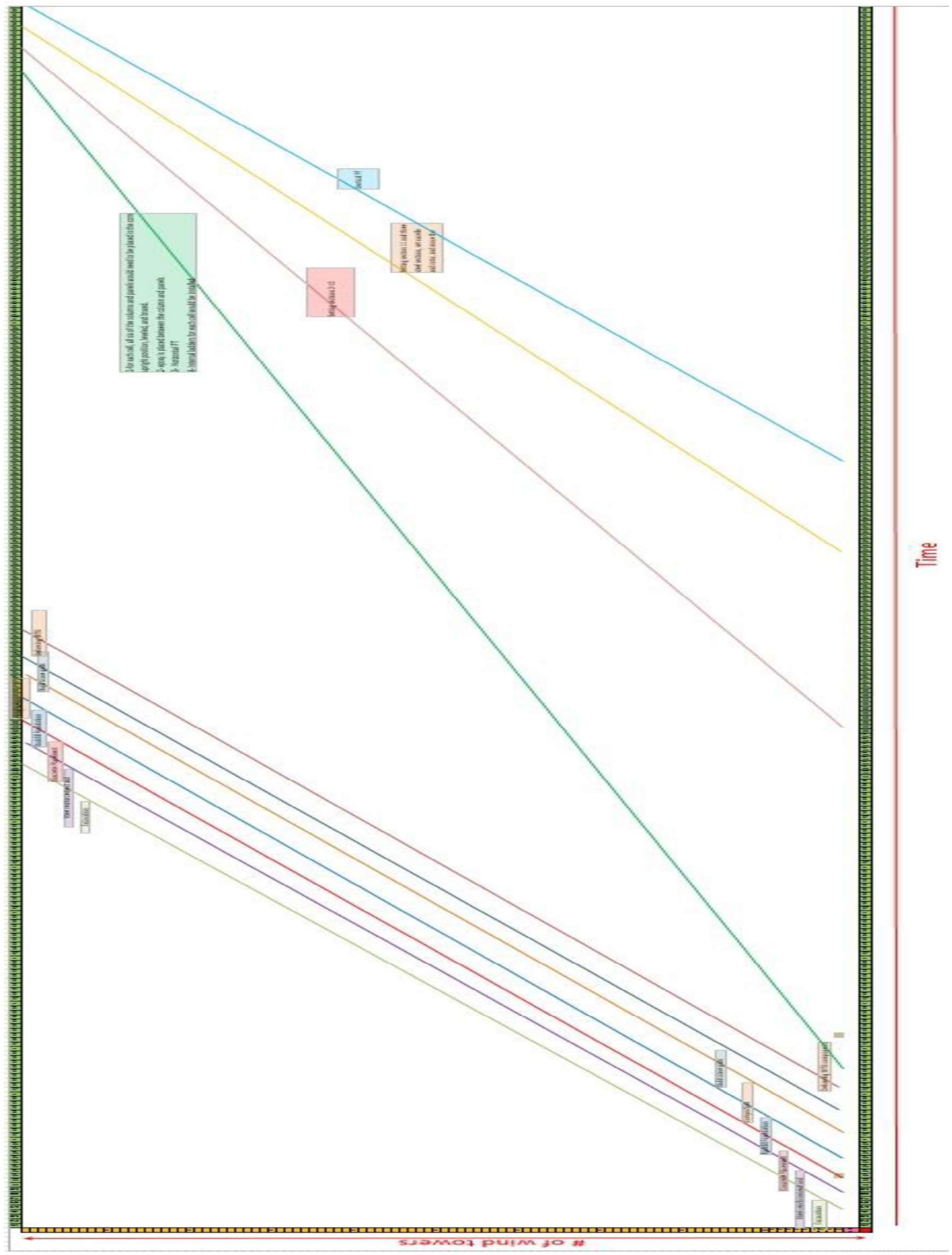
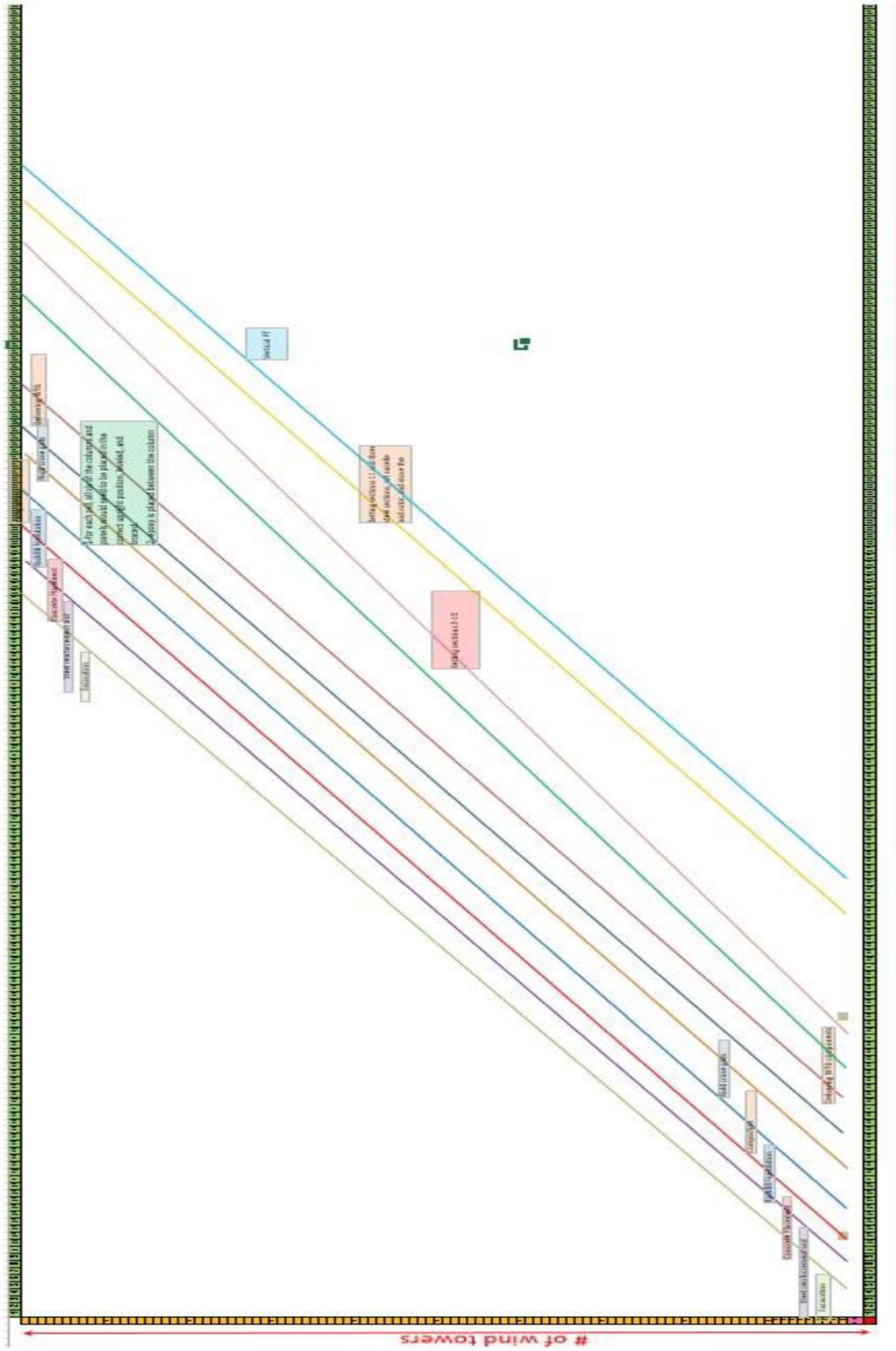
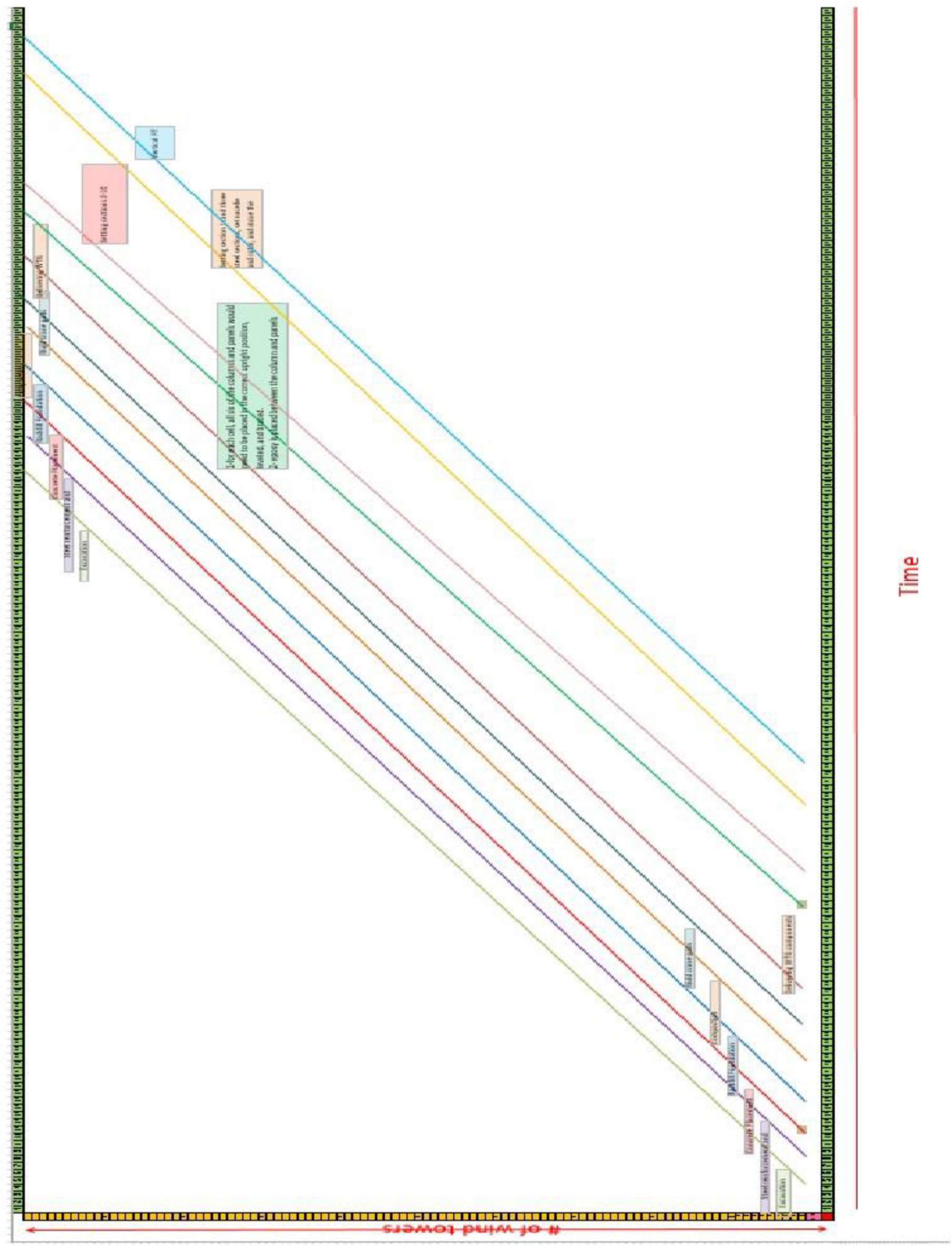
Appendix C: Linear scheduling method



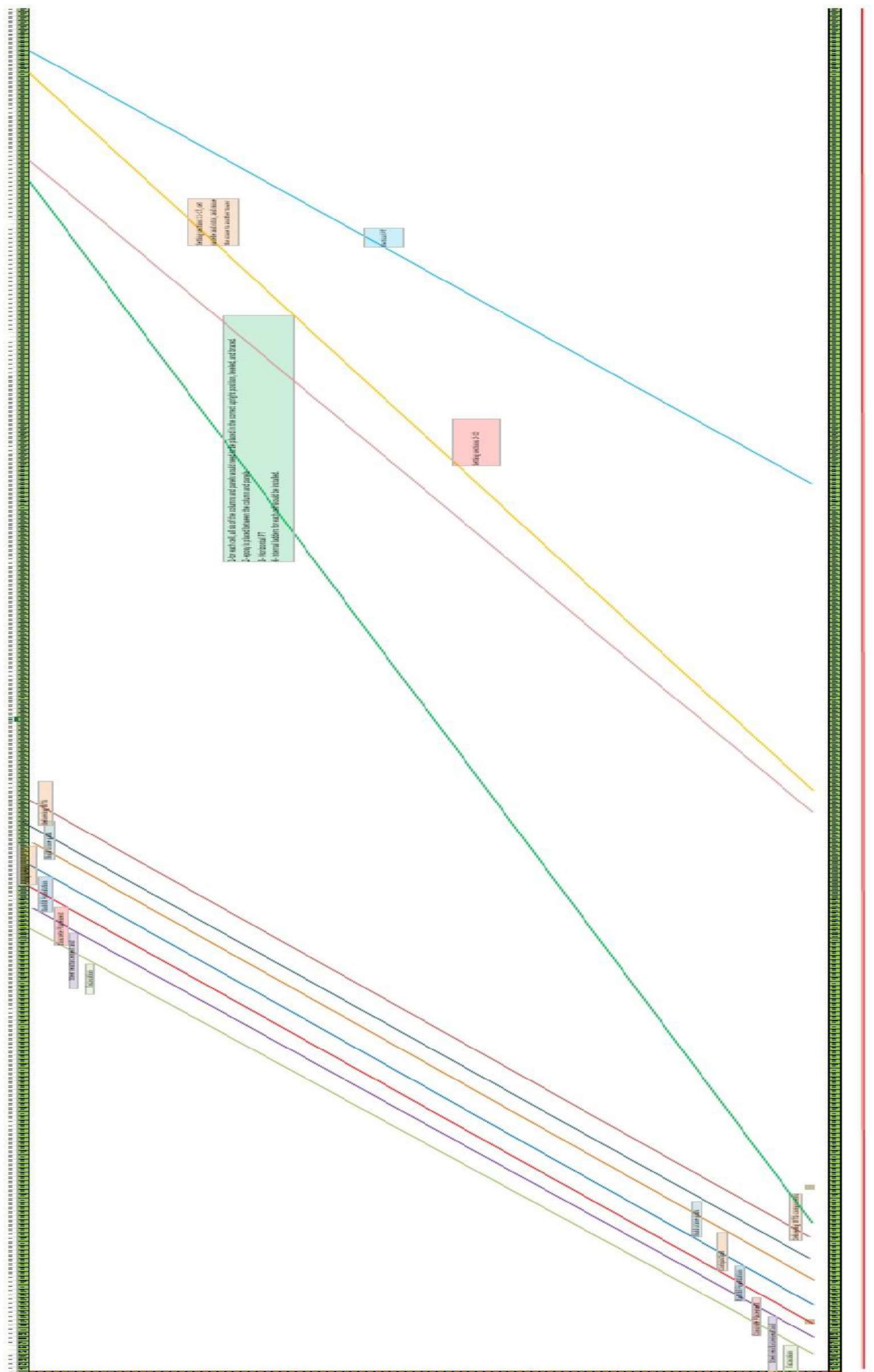
HT3a Hybrid –Scenario 1-



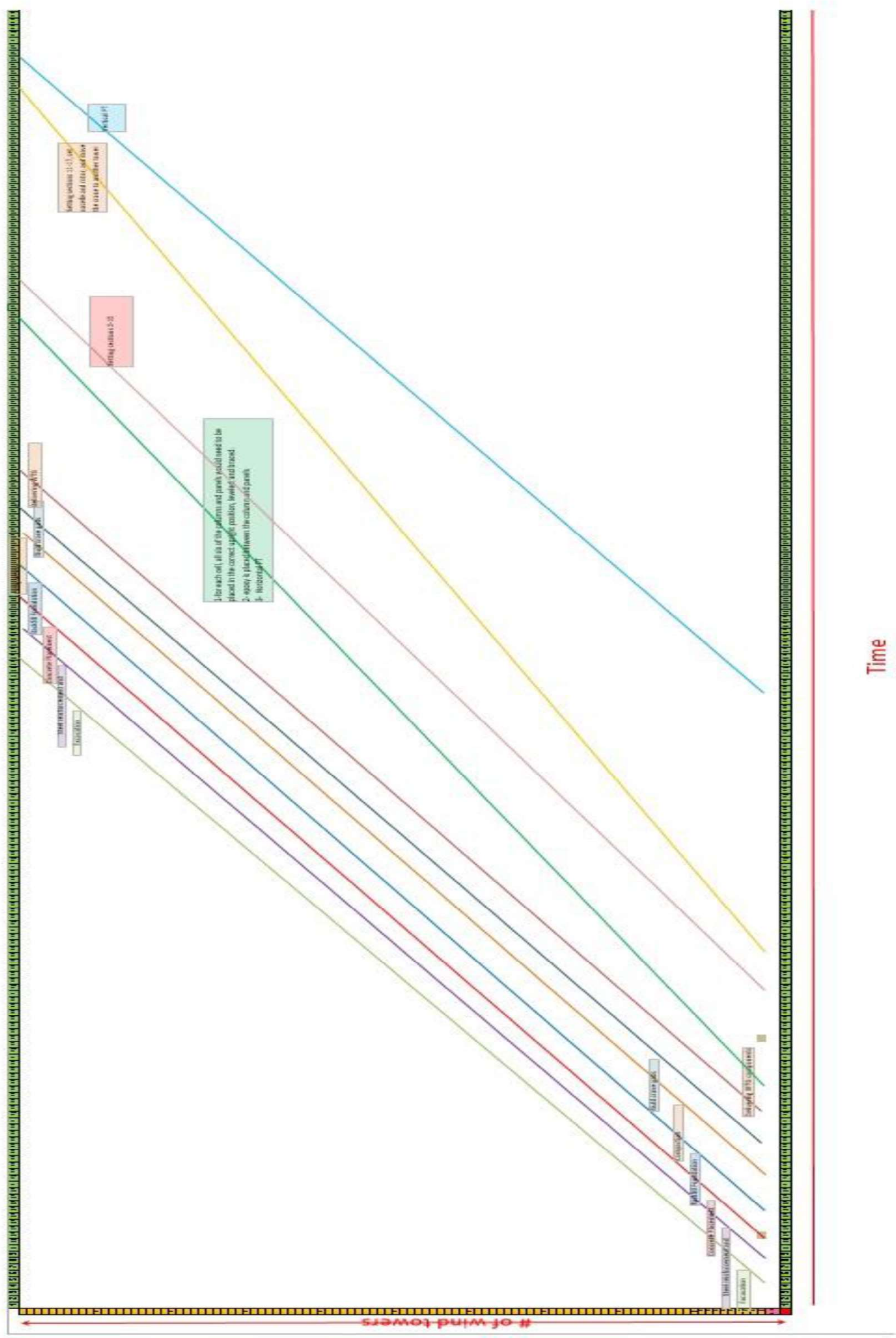
HT3a Hybrid –Scenario 2-



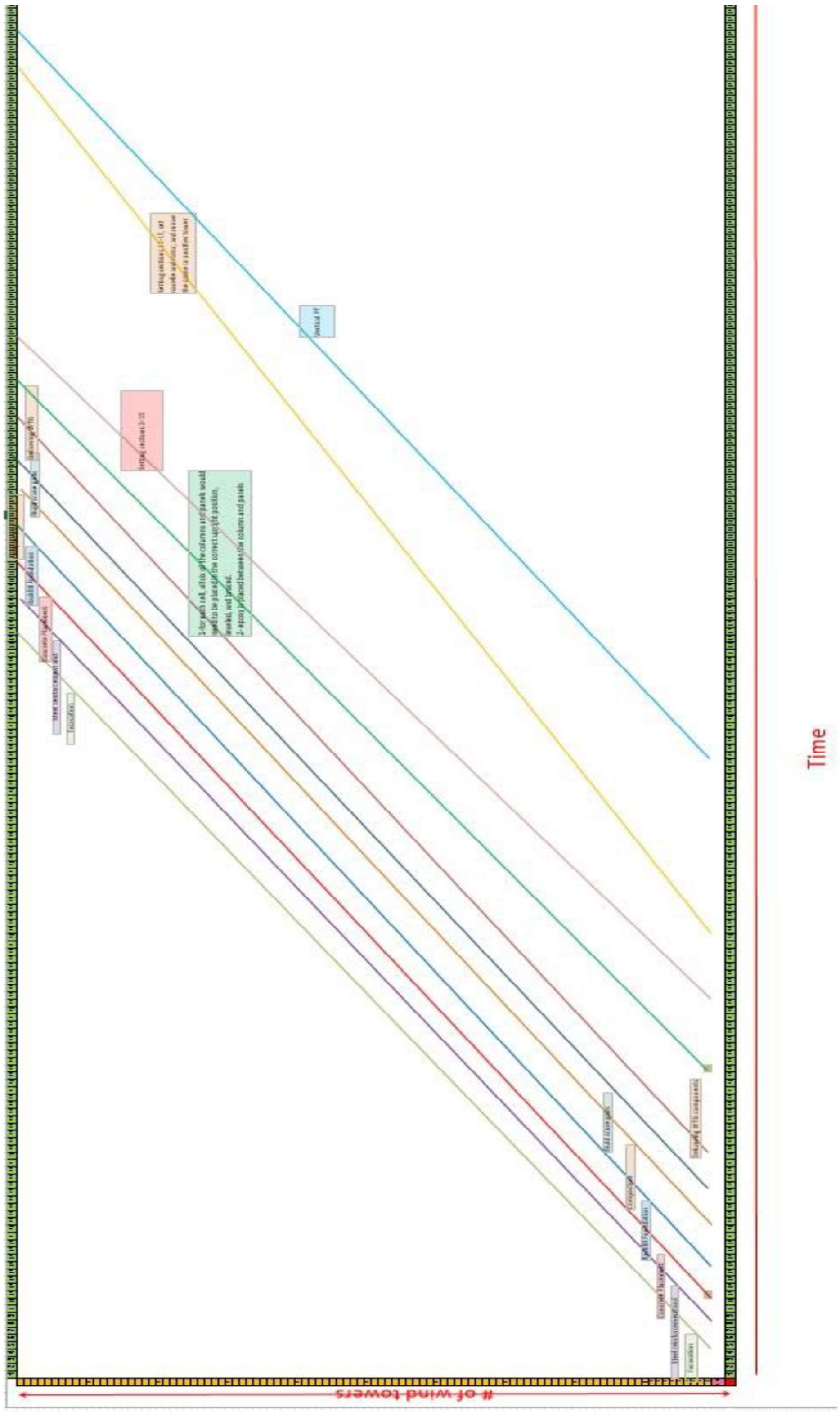
HT3a Hybrid –Scenario 3-



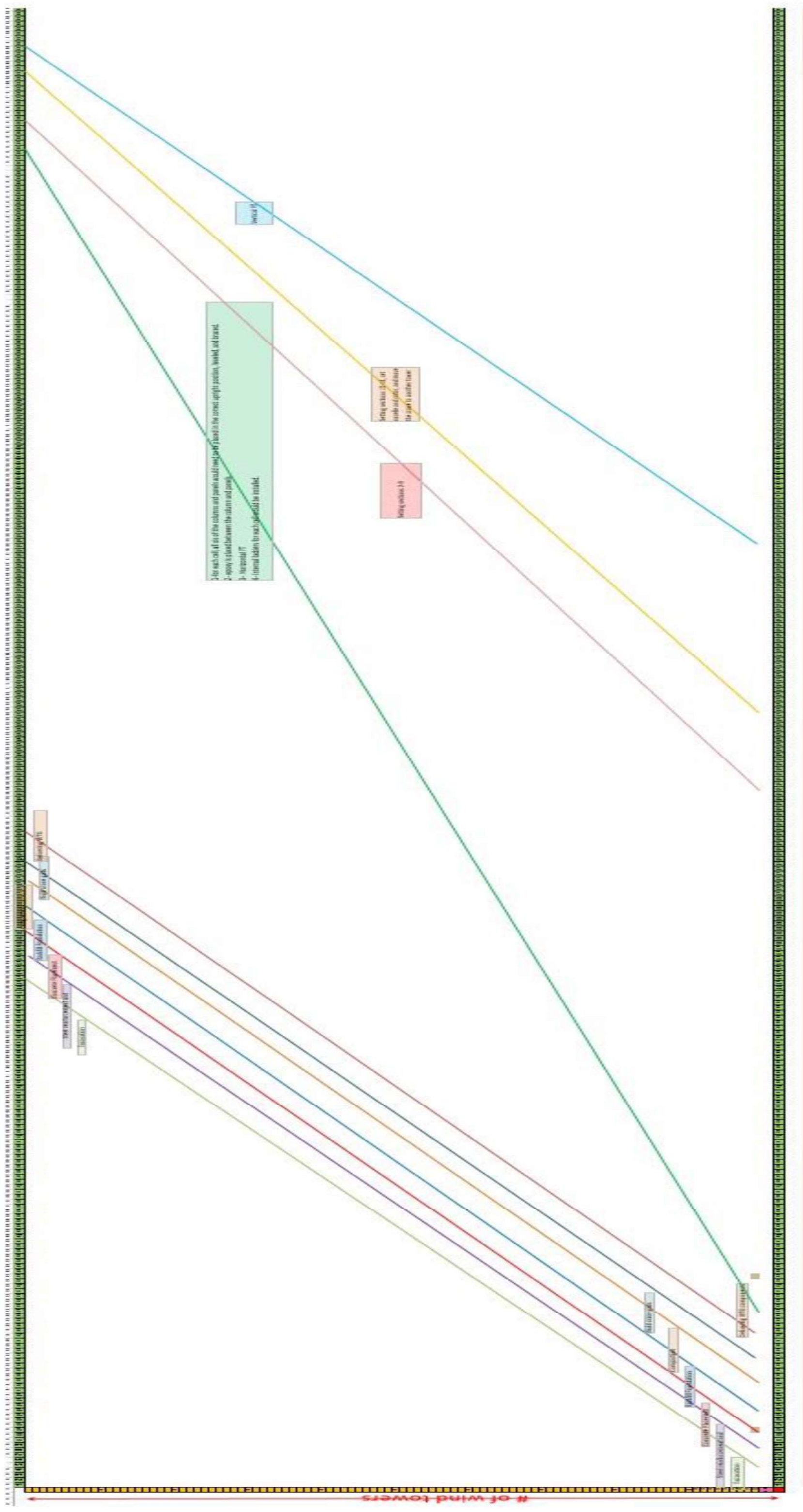
HT3a- Scenario 1-



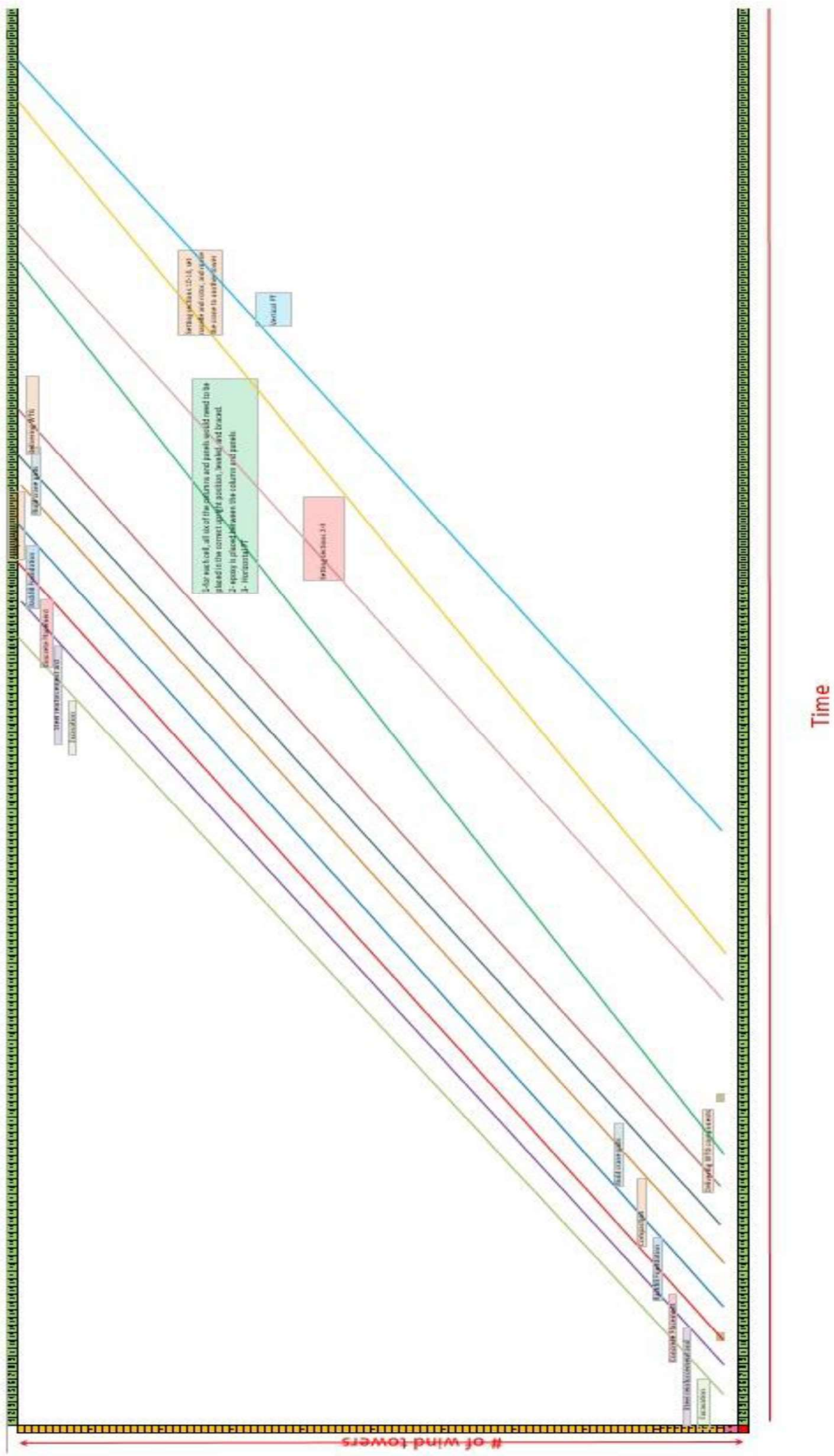
HT3a- Scenario 2-



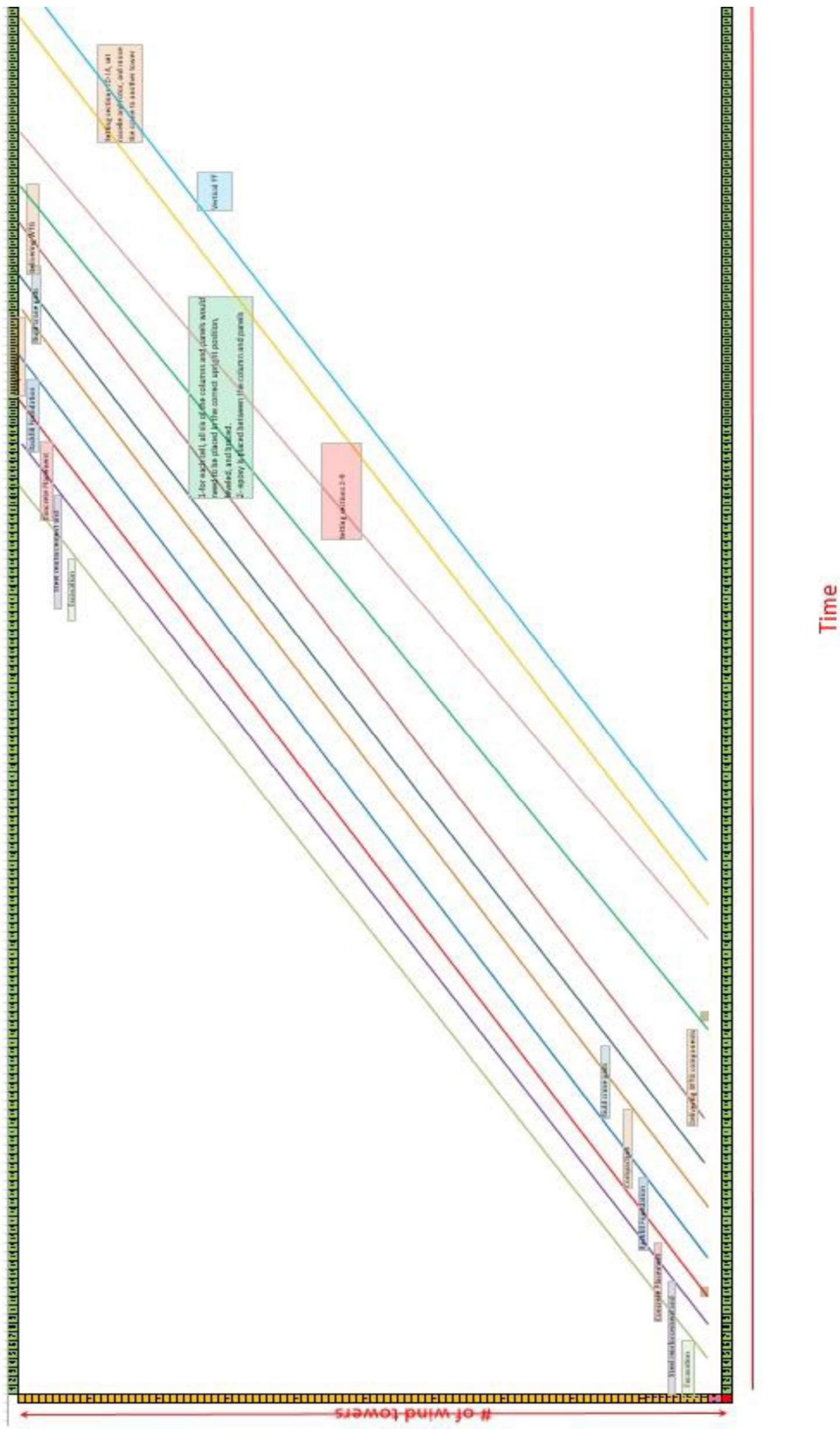
HT3a- Scenario 3-



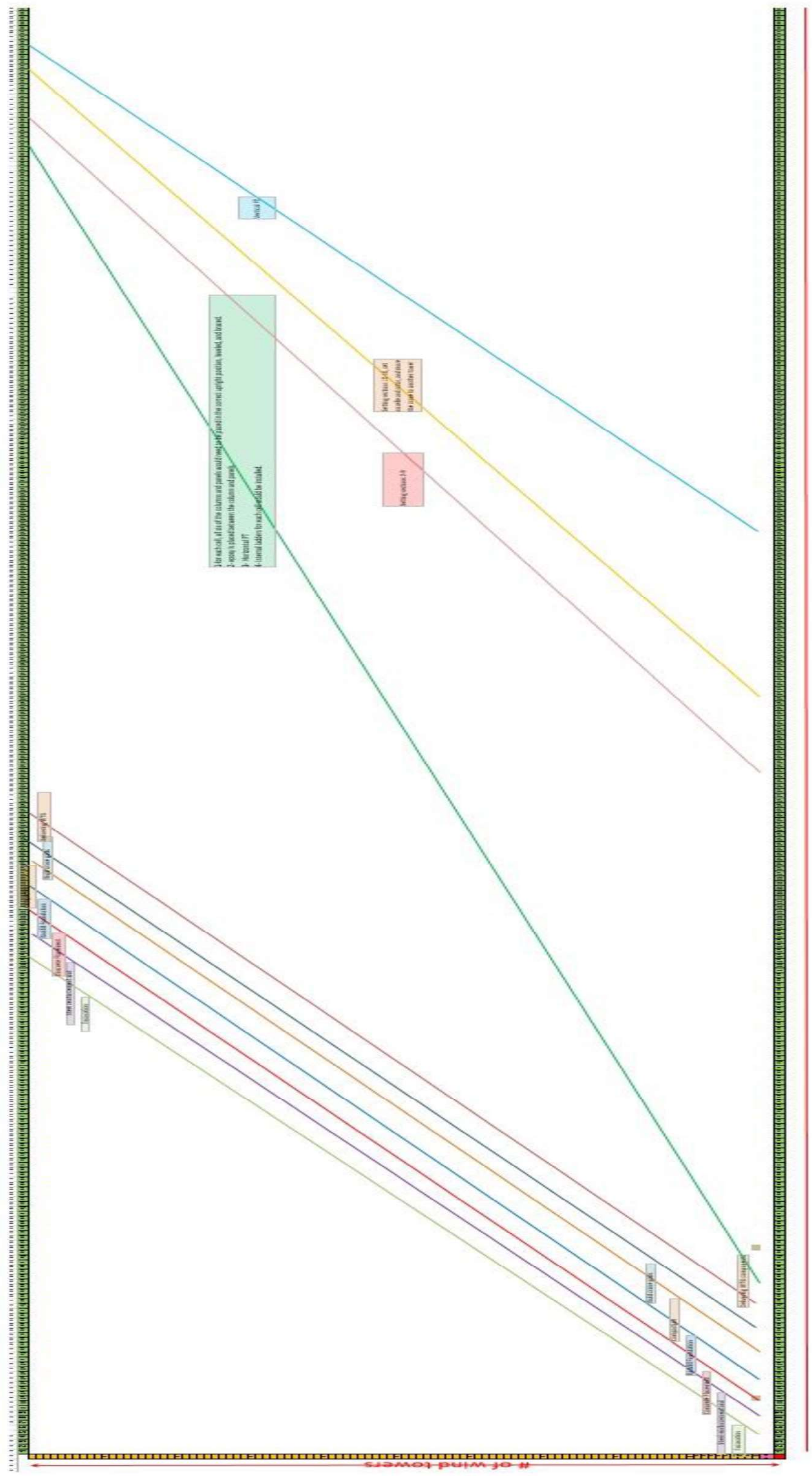
HT2a- Scenario 1-



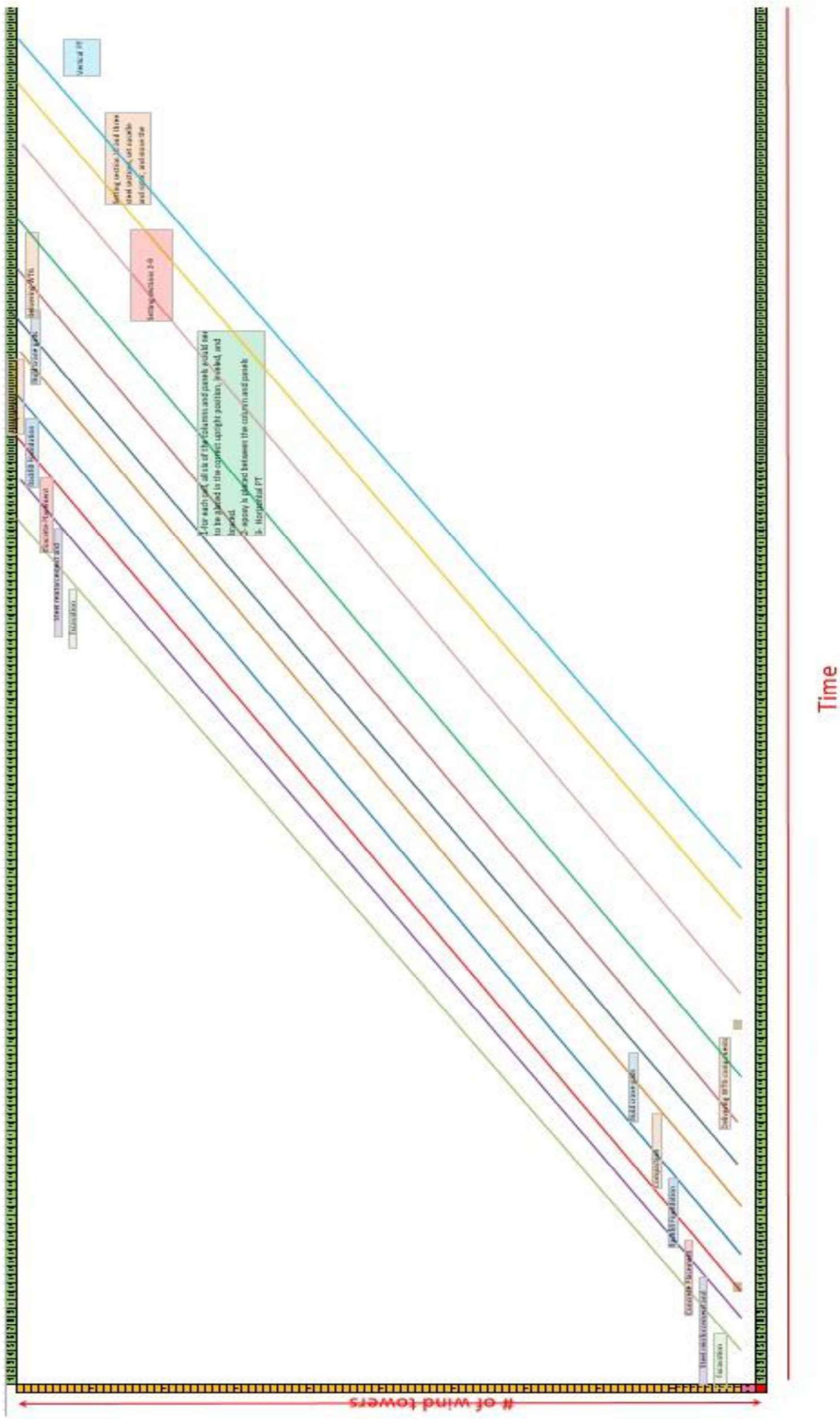
HT2a- Scenario 2-



HT2a- Scenario 3-



HT2a Hybrid- Scenario 1-



HT2a Hybrid- Scenario 2-

Appendix D: Detailed cost estimation for fabrication and transportation

Detailed cost estimation for fabrication and transportation of Hexcrete columns and panels to job site for HT3a

Item	**Material**	**Volume in C.Y**	**Painting cost per C.Y($)**	**Unit cost per CY($)**	**Total cost per C.Y($)**	**Transportation cost**
Precast concrete four columns	High Strength Concrete	664	10	900	597,600	F.O.B
Precast concrete for panels	Ultra-High Performance Concrete	232	10	2800	649,600	F.O.B

Detailed cost estimation for fabrication and transportation of Hexcrete columns and panels to job site for HT3a hybrid

Item	**Material**	**Volume in C.Y**	**Painting cost per C.Y($)**	**Unit cost per CY($)**	**Total cost per C.Y($)**	**Transportation cost**
Precast concrete four columns	High Strength Concrete	561	10	900	504,900	F.O.B
Precast concrete for panels	Ultra-High Performance Concrete	165	10	2800	462,000	F.O.B

Detailed cost estimation for fabrication and transportation of Hexcrete columns and panels to job site for HT2a hybrid

Item	**Material**	**Volume in C.Y**	**Painting cost per C.Y($)**	**Unit cost per CY($)**	**Total cost per C.Y($)**	**Transportation cost**
Precast concrete four columns	High Strength Concrete	441	10	900	396,900	F.O.B
Precast concrete for panels	Ultra-High Performance Concrete	219	10	2800	613,200	F.O.B

Detailed cost estimation for fabrication and transportation of Hexcrete columns and panels to job site for HT2a

Item	**Material**	**Volume in C.Y**	**Painting cost per C.Y($)**	**Unit cost per CY($)**	**Total cost per C.Y($)**	**Transportation cost**
Precast concrete four columns	High Strength Concrete	631	10	900	567,900	F.O.B
Precast concrete for panels	Ultra-High Performance Concrete	247	10	2800	691,600	F.O.B

Detailed cost estimation for foundation

Detailed cost estimation for foundation for HT3a

Item	Volume	Unit	Cost of material per unit($)	Material($)	Labor per unit($)	Total labor cost($)	Rental cost of equipment ($)	Total cost of equipment($)	Production rate	Total($)
Excavation	2108	C.Y.	N/A	N/A	0.32/C.Y	675	2.7/C.Y	5,692	2080 B.C.Y/Day	6,366
Steel reinforcement	234	Ton	750	175,500	750/ton	28,800	N/A	N/A	50 T/Day	204,300
Formwork	650	L.F.	1.47	955	3.65/L.F	2,372	N/A	N/A	Half day/WTG	3,327
Concrete placement	1084	C.Y.	100	133,400	16/C.Y	21,344	5/C.Y	6,670	700 C.Y/Day	161,414
Backfill	1024	C.Y.	N/A	N/A	0.53/C.Y	825	350/WTG	350	1500 B.C.Y/Day	1,175
Compaction	870	C.Y.	N/A	N/A	0.15/C.Y	130	135/WTG	135	1 Day/WTG	265
Total										**$351,847**

Detailed cost estimation for foundation for HT3a hybrid

Item	Volume	Unit	Cost of material per unit($)	Material($)	Labor per unit($)	Total labor cost($)	Rental cost of equipment ($)	Total cost of equipment($)	Production rate	Total($)
Excavation	1827	C.Y.	N/A	N/A	0.32/C.Y	585	2.7/C.Y	4,935	2080 B.C.Y/Day	5,518
Steel reinforcement	182	Ton	750	136,500	750/ton	28,800	N/A	N/A	50 T/Day	165,300
Formwork	650	L.F.	1.47	955	3.65/L.F	2,372	N/A	N/A	Half day/WTG	3,327
Concrete placement	884	C.Y.	100	88,400	16/C.Y	21,344	5/C.Y	4,420	700 C.Y/Day	114,164
Backfill	943	C.Y.	N/A	N/A	0.53/C.Y	500	350/WTG	350	1500 B.C.Y/Day	850
Compaction	870	C.Y.	N/A	N/A	0.15/C.Y	130	135/WTG	135	1 Day/WTG	1,222
Total										**$290,380**

Detailed cost estimation for foundation for HT2a

Item	**Volume**	**Unit**	**Cost of material per unit($)**	**Material($)**	**Labor per unit($)**	**Total labor cost($)**	**Rental cost of equipment ($)**	**Total cost of equipment($)**	**Production rate**	**Total($)**
Excavation	1623	C.Y.	N/A	N/A	0.32/C.Y	520	2.7/C.Y	7,800	2080 B.C.Y/Day	8,319
Steel reinforcement	159	Ton	750	211,200	750/ton	21,600	N/A	N/A	50 T/Day	145,620
Formwork	650	L.F.	1.47	955	3.65/L.F	2,372	N/A	N/A	Half day/WTG	3,327
Concrete placement	806	C.Y.	100	133,400	16/C.Y	7,200	5/C.Y	6,670	700 C.Y/Day	94,470
Backfill	817	C.Y.	N/A	N/A	0.53/C.Y	450	350/WTG	350	1500 B.C.Y/Day	785
Compaction	870	C.Y.	N/A	N/A	0.15/C.Y	130	135/WTG	135	1 Day/WTG	265
Total										**$252,784**

Detailed cost estimation for foundation for HT2a hybrid

Item	**Volume**	**Unit**	**Cost of material per unit($)**	**Material($)**	**Labor per unit($)**	**Total labor cost($)**	**Rental cost of equipment ($)**	**Total cost of equipment($)**	**Production rate**	**Total($)**
Excavation	1623	C.Y.	N/A	N/A	0.32/C.Y	520	2.7/C.Y	7,800	2080 B.C.Y/Day	8,319
Steel reinforcement	159	Ton	750	211,200	750/ton	21,600	N/A	N/A	50 T/Day	145,620
Formwork	650	L.F.	1.47	955	3.65/L.F	2,372	N/A	N/A	Half day/WTG	3,327
Concrete placement	806	C.Y.	100	133,400	16/C.Y	7,200	5/C.Y	6,670	700 C.Y/Day	94,470
Backfill	817	C.Y.	N/A	N/A	0.53/C.Y	450	350/WTG	350	1500 B.C.Y/Day	785
Compaction	870	C.Y.	N/A	N/A	0.15/C.Y	130	135/WTG	135	1 Day/WTG	265
Total										**$252,784**

Appendix E: Equipment and labor work for foundation

Item	**Equipment**	**Labor**
Excavation	1 Hyd Excavator 3 C.Y	1 Eqiup.oper and 3 workers
Reinforcing Steel		12 rodmen
Form work		6 workers
Concrete Placement	concrete pump truck/ gas engine vibrators	1 operator for truck/ 5 laborers/ 1 labor foreman
Backfill	1 Dozer 80 H.P.	1 Equip.oper (med)/ 5 Laborer
Compacting Foundation	Double Drum Ride-On Roller Diesel	1 operator

Appendix F: Cost estimation for material in post-tensioning, grouting and bracing

Cost estimation for material in post-tensioning, grouting and bracing, HT3a

HT3a		Total LF	Weight	Total weight	Cost per Unit ($)	Total cost
Post-tension						
Vertical PT		304000	0.74	185814 lb.	0.8	$169,127
Horizontal PT		37900	0.74	45627 lb.	0.8	$22,437
Anchors		901			50	$46,500
Duct		14446			2	$28,892
Total PT Cost						$266,956
Grout		**Total CY**			**Cost per CY ($)**	**Total cost**
Non-shrink Grout		3.4			1000	$3,400
Epoxy Grout		6.75			18000	$121,500
Total Tower Grouting Cost						$124,900
Bracing and Platforms		**Total Weight**	**Unit cost ($)**	**Installation Cost**		**Total Cost**
Structural steel bracing		96000	0.625	0.625		$120,000
Ladders and platforms	16	each	3000 ($/each)			$48,000
Total bracing and platforms						$168,000
Total Material Cost						$ 525,679.00

Cost estimation for material in post-tensioning, grouting and bracing, HT3a Hybrid

HT3a Hybrid		Total LF	Weight	Total weight	Cost per Unit ($)	Total cost
Post-tension						
Vertical PT		173052	0.74	128058.48	0.8	$102,447
Horizontal PT		49461	0.74	36601.14	0.8	$29,281
Anchors		570			50	$28,500
Duct		9226			2	$18,452
Total PT Cost						$178,680
Grout		**Total CY**			**Cost per CY ($)**	**Total cost**
Non-shrink Grout		2.75			1000	$2,750
Epoxy Grout		4			18000	$72,000
Total Tower Grouting Cost						$74,750
Bracing and Platforms		**Total Wei**	**Unit cost (**	**Installation Cost**		**Total Cost**
Structural steel bracing		72000	0.625	0.625		$90,000
Ladders and platforms	13	each	3000 ($/each)			$39,000
Total bracing and platforms						$129,000
Total Material Cost						$382,430

Cost estimation for material in post-tensioning, grouting and bracing, HT2a

HT2a		Total LF	Weight	Total weight	Cost per Unit ($)	Total cost
Post-tension						
Vertical PT		251100	0.74	185814 lb.	0.8	$148,651
Horizontal PT		61659	0.74	45627 lb.	0.8	$36,501
Anchors		901			50	$45,050
Duct		13082			2	$26,164
Total PT Cost						$223,515
Grout		**Total CY**			**Cost per CY ($)**	**Total cost**
Non-shrink Grout		2.2			1000	$2,200
Epoxy Grout		8.5			18000	$153,000
Total Tower Grouting Cost						$155,200
Bracing and Platforms		**Total Weight**	**Unit cost ($)**	**Installation Cost**		**Total Cost**
Structural steel bracing		88000	0.625	0.625		$110,000
Ladders and platforms	13	each	3000 ($/each)			$39,000
Total bracing and platforms						$149,000
Total Material Cost						527,715

Cost estimation for material in post-tensioning, grouting and bracing, HT2a Hybrid

HT2a Hybrid		Total LF	Weight	Total weight	Cost per Unit ($)	Total cost
Post-tension						
Vertical PT		153490	0.74	113582.6	0.8	$90,866
Horizontal PT		46425	0.74	34354.5	0.8	$27,484
Anchors		551			50	$27,550
Duct		10081			2	$20,162
Total PT Cost						$166,062
Grout		**Total CY**			**Cost per CY ($)**	**Total cost**
Non-shrink Grout		1.33			1000	$1,330
Epoxy Grout		5.7			18000	$102,600
Total Tower Grouting Cost						$103,930
Bracing and Platforms		**Total Wei**	**Unit cost (**	**Installation Cost**		**Total Cost**
Structural steel bracing		64000	0.625	0.625		$80,000
Ladders and platforms	13	each	3000 ($/each)			$39,000
Total bracing and platforms						$119,000
Total Material Cost						$388,992

Appendix G: Detailed cost estimation for assembly

Detailed cost estimation for assembly, HT3a worst case 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	$20,851.09	144	$10,800		3
Assembling Hexcrete Cells on Ground	$42,979.26	1,280	$96,000		16
Steel Bracing	include in assembling cells on ground			$120,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$48,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$71,000	include in assembly
Grout Tower Sections 1-16	include in assembling cells on ground			$117,552	include in assembly
Set Tower Sections	$78,023.81				
Set sections 2-10		312	$23,400		3
Set sections 11-16		208	$15,600		2
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension	$800	96	$7,200	$169,127	2
Project management cost	$47,200				N/A
Total	$143,854		$203,800	$525,679	
Total Assembly Cost	$873,333				

*WTG: Wind turbine generator

Detailed cost estimation for assembly, HT3a 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	$20,851.09	144	$10,800		3
Assembling Hexcrete Cells on Ground	$23,169.73	640	$48,000		8
Steel Bracing	include in assembling cells on ground			$120,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$48,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$71,000	include in assembly
Grout Tower Sections 1-16	include in assembling cells on ground			$117,552	include in assembly
Set Tower Sections	$66,476.19				
Set sections 2-10		234	$17,550		2.25
Set sections 11-16		156	$11,700		1.5
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension	$800	96	$7,200	$169,127	2
Project management cost	$47,200				N/A
Total	$112,497		$146,050	$525,679	
Total Assembly Cost	$784,226				

Detailed cost estimation for assembly, HT3a best case 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	$20,851.09	144	$10,800		3
Assembling Hexcrete Cells on Ground	$16,566.56	427	$32,000		5.333333333
Steel Bracing	include in assembling cells on ground			$120,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$48,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$71,000	include in assembly
Grout Tower Sections 1-16	include in assembling cells on ground			$117,552	include in assembly
Set Tower Sections	$59,547.62				
Set sections 2-10		187	$14,040		1.8
Set sections 11-16		125	$9,360		1.2
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension	$800	96	$7,200	$169,127	2
Project management cost	$47,200				N/A
Total	$98,965		$124,200	$525,679	
Total Assembly Cost	$748,844				

***WTG: Wind turbine generator**

Detailed cost estimation for assembly, HT3a Hybrid worst case 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	$23,297.14	144	$10,800		3
Assembling Hexcrete Cells on Ground	$27,238.22	880	$66,000		11
Steel Bracing	include in assembling cells on ground			$90,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$39,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$76,233	include in assembly
Grout Tower Sections	include in assembling cells on ground			$74,750	include in assembly
Set Tower Sections	$76,674.60				
Set sections 2-10		312	$23,400		3
Set section 11 and 3 steel sections		139	$10,400		1.333333333
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension		96	$7,200	$102,447	2
Project management cost	$48,400				N/A
Total	$128,410		$121,400	$382,430	
Total Assembly Cost	$680,640				

Detailed cost estimation for assembly, HT3a Hybrid 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	$23,297.14	144	$10,800		3
Assembling Hexcrete Cells on Ground	$13,619.17	440	$33,000		5.5
Steel Bracing	include in assembling cells on ground			$90,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$39,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$76,233	include in assembly
Grout Tower Sections	include in assembling cells on ground			$74,750	include in assembly
Set Tower Sections	$67,428.57				
Set sections 2-10		234	$17,550		2.25
Set section 11 and 3 steel sections		104	$7,800		1
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension		96	$7,200	$102,447	2
Project management cost	$48,400				N/A
Total	$105,545		$79,950	$382,430	
Total Assembly Cost	$616,325				

***WTG: Wind turbine generator**

Detailed cost estimation for assembly, HT3a Hybrid best case 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	$23,297.14	144	$10,800		3
Assembling Hexcrete Cells on Ground	$9,079.49	293	$22,000		3.666666667
Steel Bracing	include in assembling cells on ground			$90,000	include in assemb
Misc. Ladders and Platforms	include in assembling cells on ground			$39,000	include in assemb
Horizontal post tension	include in assembling cells on ground			$76,233	include in assemb
Grout Tower Sections	include in assembling cells on ground			$74,750	include in assemb
Set Tower Sections	$61,880.95				
Set sections 2-10		187	$14,040		1.8
Set section 11 and 3 steel sections		83	$6,240		0.8
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension		96	$7,200	$102,447	2
Project management cost	$48,400				N/A
Total	$95,458		$63,880	$382,430	
Total Assembly Cost	$590,1				

Detailed cost estimation for assembly, HT2a best case scenario

Work Breakdown Structure Activity	Equipment cost($)	Quantity (Man-	Labor($)	Material Costs($)	Production Rates(days/WTG)
Offloading Hexcrete cells, Tower Components, Nacelle, Hub, and Blades	$23,297.14	144	$10,800		3
Assembling Hexcrete Cells on Ground	$37,066.67	1,120	$84,000		14
Steel Bracing	include in assembling cells on ground			$110,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$39,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$74,864	include in assembly
Grout Tower Sections	include in assembling cells on ground			$155,200	include in assembly
Set Tower Sections	$53,023.81				
Set sections 2-9		277	$20,800		3
Set sections 10-14		173	$13,000		2
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension		96	$7,200	$148,651	2
Project management cost	$49,200				N/A
Total	$114,588		$139,400	$527,715	
Total Assembly Cost	$830,903				

***WTG: Wind turbine generator**

Detailed cost estimation for assembly, HT2a 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	$23,297.14	144	$10,800		3
Assembling Hexcrete Cells on Ground	$19,733.33	560	$42,000		7
Steel Bracing	include in assembling cells on ground			$110,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$39,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$74,864	include in assembly
Grout Tower Sections	include in assembling cells on ground			$155,200	include in assembly
Set Tower Sections	$43,142.86				
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
Vertica post tension		96	$7,200	$148,651	2
Project management cost	$49,200				N/A
Total	$87,373		$88,950	$527,715	
Total Assembly Cost	$753,238				

Detailed cost estimation for assembly, HT2a best case 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	$23,297.14	144	$10,800		3
Assembling Hexcrete Cells on Ground	$13,955.56	373	$28,000		5
Steel Bracing	include in assembling cells on ground			$110,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$39,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$74,864	include in assembly
Grout Tower Sections	include in assembling cells on ground			$155,200	include in assembly
Set Tower Sections	$37,214.29				
Set sections 2-9		166	$12,480		2
Set sections 10-14		104	$7,800		1
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension		96	$7,200	$148,651	2
Project management cost	$49,200				N/A
Total	$75,667		$69,880	$527,715	
Total Assembly Cost	$722,462				

***WTG: Wind turbine generator**

Detailed cost estimation for assembly, HT2a Hybrid worst case scenario

Work Breakdown Structure Activity	Equipment cost($)	Quantity (Man-hour)	Labor($)	Material Costs($)	Production Rate days/WTG)
Offloading Hexcrete cells, Tower Components, Nacelle, Hub, and Blades	$23,297.14	144	$10,800		3
Assembling Hexcrete Cells on Ground	$22,285.83	720	$54,000		9
Steel Bracing	include in assembling cells on ground			$80,000	include in assem
Misc. Ladders and Platforms	include in assembling cells on ground			$39,000	include in assem
Horizontal post tension	include in assembling cells on ground			$75,196	include in assem
Grout Tower Sections	include in assembling cells on ground			$103,930	include in assem
Set Tower Sections	$48,420.63				
Set sections 2-9		277	$20,800		3
Set section 10 and 3 steel sections		139	$10,400		1
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension		96	$7,200	$90,866	2
Project management cost	$48,400				N/A
Total	$95,204		$106,800	$388,992	
Total Assembly Cost	$639,3				

Detailed cost estimation for assembly, HT2a Hybrid 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	$23,297.14	144	$10,800		3
Assembling Hexcrete Cells on Ground	$11,142.98	360	$27,000		5
Steel Bracing	include in assembling cells on ground			$80,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$39,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$75,196	include in assembly
Grout Tower Sections	include in assembling cells on ground			$103,930	include in assembly
Set Tower Sections	$39,690.48				
Set sections 2-9		208	$15,600		2
Set section 10 and 3 steel sections		104	$7,800		1
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension		96	$7,200	$90,866	2
Project management cost	$48,400				N/A
Total	$75,331		$72,000	$388,992	
Total Assembly Cost	$584,723				

*WTG: Wind turbine generator

Detailed cost estimation for assembly, HT2a Hybrid best case 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	$23,297.14	144	$10,800		3
Assembling Hexcrete Cells on Ground	$7,428.69	240	$18,000		3
Steel Bracing	include in assembling cells on ground			$80,000	include in assembly
Misc. Ladders and Platforms	include in assembling cells on ground			$39,000	include in assembly
Horizontal post tension	include in assembling cells on ground			$75,196	include in assembly
Grout Tower Sections	include in assembling cells on ground			$103,930	include in assembly
Set Tower Sections	$34,452.38				
Set sections 2-9		166	$12,480		2
Set section 10 and 3 steel sections		83	$6,240		1
Build Rotor, Set Nacelle, and Rotor	$1,200	48	$3,600		1
Vertica post tension		96	$7,200	$90,866	2
Project management cost	$48,400				N/A
Total	$66,378		$58,320	$388,992	
Total Assembly Cost	$562,090				

*WTG: Wind turbine generator

Appendix H: Needed Equipment and labor for each task

Activity	Equipment	Labor
Offload		
Offload Top, Nacelle, Hub, and Blades	3 Forklifts	6 Riggers
Offload Hexcrete Tower Components	3 Forklifts	6 Riggers
Assemble Hexcrete Cells on Ground	200 Ton Crawler Crane	1 operator/ 4 labors
Grout Tower Sections 1-18	Grout Mixer	two for mixing and four for installation along panel joints
Horizontal post tension	0.6" Monostrand Ram with OTC Pump.	four people for tendon installation and three for tensioning
Set Base Mid / Tower Sections 1-18		
Set Tower Sections (sections are below 80 meter)	Manitowak 16000, rough terrain crane for assisting with the tower and rotor tandem picks, 2-fork lifts, an articulated man lift, 4-light plants, 4-suitcase generators, a flatbed semi, 100-crane mats, 15-pickup trucks with 2-trailers, light plants, power washers, a dozer for unload assist and fixing ruts, hydraulic torqueing and tensioning equipment	8-workers (1-connectors, 3-riggers, 2-laborers, 1-equipment operators and 1-superintendent).
Set Tower Sections (sections are above 80 meters)	LR 1135-1 Crane , LR 1135-1 Crane rough terrain crane for assisting with the tower and rotor tandem picks, 2-fork lifts, an articulated man lift, 4-light plants, 4-suitcase generators, a flatbed semi, 100-crane mats, 15-pickup trucks with 2-trailers, light plants, power washers, a dozer for unload assist and fixing ruts, hydraulic torqueing and tensioning equipment	8-workers (1-connectors, 3-riggers, 2-laborers, 1-equipment operators and 1-superintendent).
Build rotor	200 Ton Crawler Crane	1 operator/ 4 labors
Set Nacelle, and Rotor	LR 1135-1 Crane	8-workers (1-connectors, 3-riggers, 2-laborers, 1-equipment operators and 1-superintendent).
Vertica post tension	VSL ZPE-1000 Hydraulic jack/ gasoline Enerpac Pump	four people for tendon installation and three for tensioning

Appendix J: Hellman exponent in State of Iowa

	Altoona					Homestead					Mason City					Palmer				
Hour	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
0	0.3806	0.3689	0.3449	0.3842	0.4233	0.3123	0.3200	0.3092	0.2854	0.3253	0.2998	0.2732	0.2663	0.3203	0.3506	0.2312	0.2464	0.1886	0.2565	0.2532
1	0.3861	0.3618	0.3501	0.4039	0.4243	0.3265	0.3175	0.3108	0.3263	0.3566	0.2952	0.2653	0.2681	0.3172	0.3447	0.2367	0.2417	0.1894	0.2594	0.2882
2	0.3928	0.3599	0.3507	0.4090	0.4451	0.3184	0.2881	0.3151	0.3231	0.3730	0.2979	0.2685	0.2833	0.3143	0.3396	0.2339	0.2491	0.1899	0.2719	0.2417
3	0.3812	0.3553	0.3530	0.3890	0.4224	0.3129	0.2783	0.3068	0.3167	0.3718	0.3006	0.2809	0.2968	0.2928	0.3341	0.2406	0.2492	0.1947	0.2811	0.2596
4	0.3860	0.3515	0.3536	0.4065	0.4252	0.3140	0.2745	0.3184	0.3127	0.3787	0.2881	0.2840	0.2647	0.2847	0.3137	0.2542	0.2523	0.2199	0.3031	0.2575
5	0.3978	0.3520	0.3642	0.4387	0.4264	0.3342	0.3219	0.3285	0.3116	0.3793	0.2823	0.2956	0.2494	0.2528	0.3063	0.2403	0.2384	0.2178	0.2581	0.2630
6	0.4069	0.3642	0.3658	0.4550	0.4334	0.3252	0.3339	0.2946	0.3179	0.3658	0.2816	0.2921	0.2451	0.3027	0.2844	0.2636	0.2496	0.2259	0.3181	0.2876
7	0.3875	0.3590	0.3366	0.4350	0.4127	0.3289	0.3398	0.2494	0.3732	0.3710	0.2837	0.2897	0.2483	0.3239	0.2816	0.2660	0.2402	0.2351	0.3343	0.2787
8	0.3155	0.3486	0.2525	0.2505	0.4205	0.2527	0.3157	0.1854	0.1739	0.3361	0.2405	0.2789	0.1836	0.1637	0.2757	0.2150	0.2264	0.1558	0.2114	0.3132
9	0.2297	0.3682	0.1469	0.0924	0.3513	0.1416	0.2207	0.1104	0.0175	0.1769	0.1585	0.2442	0.1091	0.0376	0.1496	0.1286	0.1769	0.1018	0.0719	0.1721
10	0.1564	0.3002	0.1044	0.0585	0.2024	0.0804	0.1172	0.0696	0.0064	0.0706	0.1156	0.2067	0.0893	0.0373	0.0573	0.0830	0.1419	0.0591	0.0494	0.0729
11	0.1146	0.2150	0.0880	0.0540	0.1265	0.0605	0.0651	0.0752	0.0173	0.0360	0.0970	0.1656	0.0832	0.0462	0.0443	0.0644	0.1033	0.0442	0.0537	0.0506
12	0.0969	0.1664	0.0846	0.0619	0.0917	0.0607	0.0560	0.0727	0.0287	0.0454	0.0763	0.1220	0.0593	0.0586	0.0384	0.0668	0.1127	0.0411	0.0555	0.0526
13	0.0960	0.1447	0.0894	0.0619	0.0994	0.0599	0.0464	0.0845	0.0393	0.0281	0.0653	0.0904	0.0558	0.0527	0.0463	0.0621	0.1022	0.0391	0.0489	0.0549
14	0.0935	0.1314	0.0909	0.0638	0.0972	0.0650	0.0457	0.0923	0.0453	0.0452	0.0609	0.0800	0.0637	0.0304	0.0498	0.0662	0.0963	0.0446	0.0608	0.0632

15	0.0980	0.1265	0.0916	0.0696	0.1113	0.0867	0.0900	0.0890	0.0546	0.0916	0.0844	0.1047	0.0817	0.0592	0.0732	0.0681	0.0924	0.0421	0.0622	0.0836
16	0.1210	0.1645	0.1132	0.0766	0.1400	0.1171	0.1350	0.0995	0.0757	0.1457	0.1147	0.1393	0.0833	0.0773	0.1261	0.0874	0.1290	0.0509	0.0680	0.1102
17	0.1664	0.2319	0.1449	0.1097	0.1931	0.1724	0.1995	0.1220	0.1329	0.2308	0.1619	0.1882	0.0928	0.1164	0.2041	0.1224	0.1700	0.0718	0.0901	0.1786
18	0.2372	0.2951	0.2054	0.1814	0.2799	0.2264	0.2386	0.1769	0.2180	0.2584	0.2092	0.2219	0.1508	0.1877	0.2482	0.1646	0.2219	0.1175	0.1331	0.1969
19	0.3128	0.3584	0.2865	0.2778	0.3399	0.2595	0.2762	0.2253	0.2360	0.2929	0.2457	0.2472	0.1902	0.2648	0.2750	0.1976	0.2478	0.1514	0.1754	0.2280
20	0.3357	0.3796	0.3108	0.3069	0.3563	0.2928	0.2983	0.2404	0.2199	0.2868	0.2704	0.2680	0.2088	0.2915	0.3088	0.2033	0.2500	0.1465	0.1869	0.2519
21	0.3482	0.3785	0.3362	0.3232	0.3621	0.2864	0.3223	0.2601	0.2437	0.3041	0.2802	0.2689	0.2369	0.2972	0.3191	0.2249	0.2359	0.1923	0.2295	0.2615
22	0.3610	0.3794	0.3529	0.3469	0.3693	0.3056	0.3294	0.2867	0.2805	0.3071	0.2854	0.2705	0.2459	0.2959	0.3298	0.2320	0.2375	0.1925	0.2597	0.2605
23	0.3689	0.3592	0.3508	0.3647	0.3994	0.3119	0.3218	0.2815	0.3167	0.3137	0.2956	0.2717	0.2492	0.3455	0.3360	0.2379	0.2528	0.1988	0.2688	0.2455

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