May 2001 • NREL/SR-500-29493

Subcontractor Report

WindPACT Turbine Design Scaling Studies Technical Area 3–Self-Erecting Tower and Nacelle Feasibility

March 2000–March 2001

Global Energy Concepts, LLC
Kirkland, Washington

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Executive Summary

The United States Department of Energy (DOE), through the National Renewable Energy Laboratory (NREL), has implemented the Wind Partnerships for Advanced Component Technologies (WindPACT) program to explore advanced technologies for improving the reliability and cost-effectiveness of wind energy technology. Global Energy Concepts (GEC) prepared this report on self-erecting towers as part of the WindPACT program. The objectives of the work were to identify potential methods for erecting wind turbine towers without the use of large conventional cranes, establish the most promising methods, and compare the costs of the most promising methods to the costs of conventional cranes.

Approach

To meet the objectives of this project, GEC explored methods used in the engineering and construction industries that could be used for on-site assembly and self-erection of wind turbines. Experts were consulted from various industries including onshore and offshore oil industries, the crane and rigging industry, heavy construction industry, and other manufacturing sectors. The use of multiple experts from diverse industries enabled GEC to leverage a wide range of technical expertise to maximize the probability of identifying a successful, cost-effective self-erection concept. The concepts identified were then ranked based on a criteria developed by GEC and NREL personnel. The top-ranked concepts were more fully developed to compile preliminary design and costing work. These results were then compared to conventional turbine erection techniques. In the course of the investigation, GEC became aware of four organizations with ideas for self-erection techniques outside of the GEC study. To the extent permitted by confidentiality agreements and resource constraints, these ideas are described in this report.

Concepts Identified and Selected

GEC identified 10 different concepts for self-erection of wind turbines. These concepts were sorted into the following categories:

- Telescoping
- Tower-climbing devices
- Jack-up devices
- Lifting through secondary structures, Such as A-Frame's and gin-pole's.

The ranking process resulted in one of the tower-climbing concepts and one of the secondary-structure concepts being selected for further consideration. Two of the three independent concepts also fall into the tower-climbing category, and one uses a telescoping approach.

Findings

The two methods selected for further evaluation were compared to conventional crane techniques. The results of this comparison indicated that one of the two techniques compared favorably to conventional cranes for 1.5 megawatts MW and larger turbines but was more expensive than conventional cranes for smaller turbines. See (Figure i). These results assume relatively benign

terrain. The costs of operating the large crane for a large turbine will increase significantly in more complex terrain, making self-erection a more favorable option.

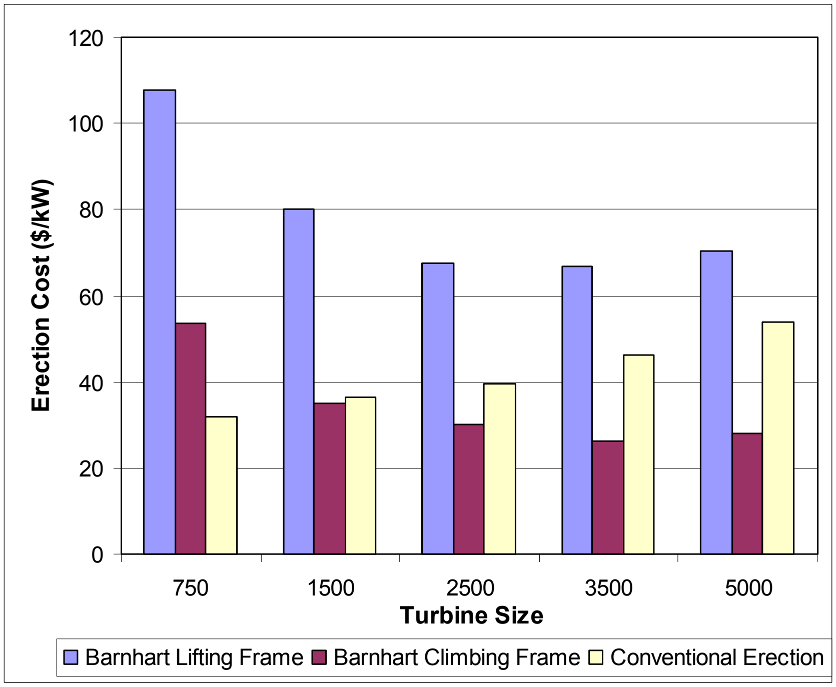

Figure i Comparison of Self-Erection with Conventional Erection

GEC's investigation of conventional cranes indicated that the costs of cranes were heavily influenced by the height to which the turbines needed to be lifted. In addition, it became apparent that the three independent firms developing self-erection techniques were targeting the installation of 750 kilowatt (kW) to 1.5-MW turbines on taller towers. To better understand this development, a simple cost of energy (COE) model was developed that considered the impact of taller towers on energy capture as well as the costs of towers, foundations, and erection. The results of this study are summarized in Figure ii.

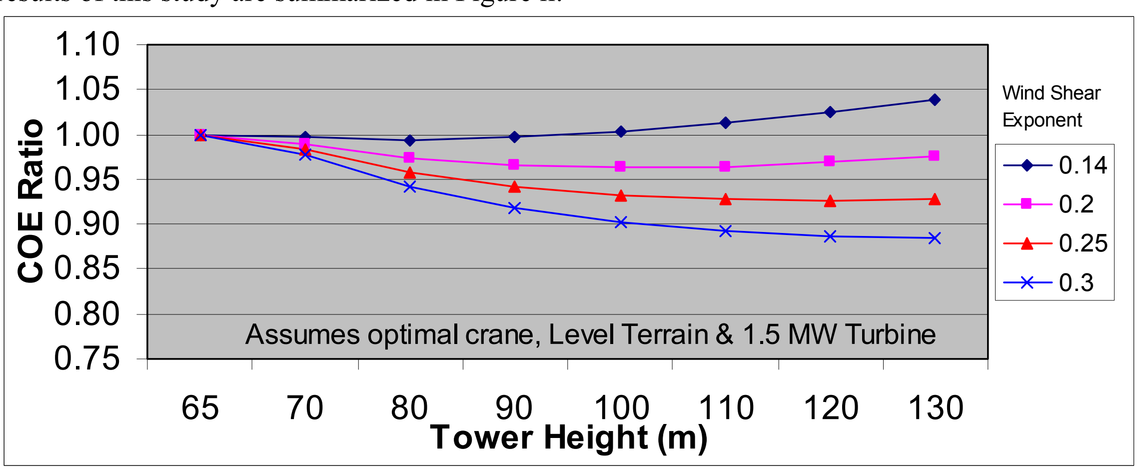

Figure ii Impact of Tower Height on COE

GEC also used this model to evaluate the value associated with self-erection relative to conventional cranes. The results of this analysis are shown in Figure iii. To account for the effect of complex terrain, GEC's estimated the added cost for disassembling and reassembling the crane after a prescribed number of turbines are installed. More complex terrain results in fewer turbines between crane disassemblies. As shown in Figure iii, the cost advantage of self-erection increases as the terrain becomes more complex. In addition, optimal tower height decreases as terrain complexity increases.

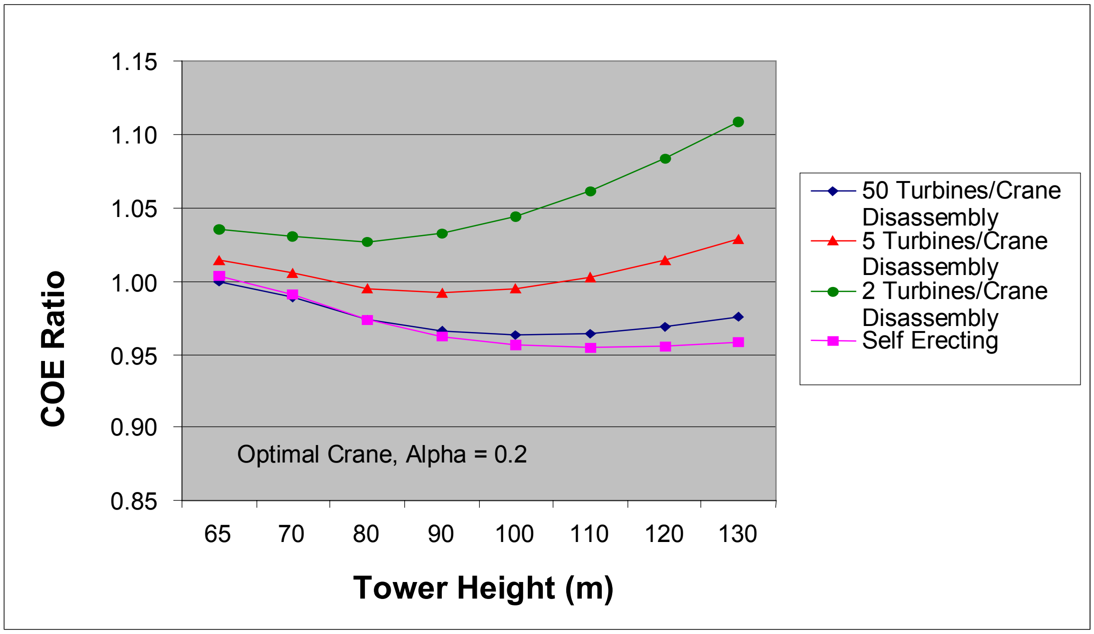

Figure iii COE Impact of Self-Erection

Conclusions

This study identified several viable self-erection techniques. The economics of self-erection are sensitive to the wind shear exponent, the complexity of the terrain, crane cost and availability, and many other factors. According to a preliminary analysis, these factors have the potential to reduce the COE for larger turbines, particularly in complex terrain where significant disassembly of the large conventional cranes will be required to change turbine locations. In addition, the use of self-erection techniques has the potential to reduce the costs of installing smaller turbines on taller towers, thus reducing the cost of energy.

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1. Introduction

The United States Department of Energy (DOE), through the National Renewable Energy Laboratory (NREL), has implemented the Wind Partnerships for Advanced Component Technologies (WindPACT) program. This program explores advanced technologies for improving the reliability and cost-effectiveness of wind energy technology. The initial step in the WindPACT program is a series of preliminary scaling studies to bound the optimum sizes for future turbines, help define sizing limits for certain critical technologies and explore the potential for advanced concepts as turbine scales increase. We identified four technical areas for study under this phase of the program: Composite Blades (Technical Area 1), Turbine Rotor and Blade Logistics (Technical Area 2), Self-Erecting Towers and Nacelle Feasibility (Technical Area 3), and Balance-of-Station Cost (Technical Area 4).

Global Energy Concepts (GEC) prepared this report under Technical Area 3 of the WindPACT scaling studies with the following objectives: to identify potential methods for erecting wind turbine towers without the use of large conventional cranes, and establish the most promising methods and compare the costs of the most promising methods to the costs of conventional cranes. To meet this objective, GEC explored methods used in the engineering and construction industries that could be used for on-site assembly and self-erection of wind turbines. Experts were consulted from various industries including onshore and offshore oil industries, the crane and rigging industry, heavy construction industry, and other manufacturing sectors. The use of multiple experts from diverse industries enabled GEC to leverage a wide range of technical expertise to maximize the probability of identifying a successful, cost-effective self-erection concept.

1.1 Project Organization and Approach

The general approach to the project was to identify a large number of potential self-erection concepts, evaluate all the concepts to identify the most promising, and then complete further analysis on the selected concepts to permit cost comparisons with conventional turbine erection techniques.

The WindPACT scaling studies generally address turbines between 1 and 5 megawatts (MW) in size. With NREL's concurrence, GEC focused on the upper end of the range (5 MW) and then examined how costs might change for smaller turbines.

GEC's project team included T&T Engineering of Houston, Texas; Barnhart Crane & Rigging of Memphis, Tennessee; Ederer of Seattle, Washington; and BCL & Associates of Palm Springs, California. Each subcontractor was asked to identify lifting techniques used in their respective industries that they felt could be used for erecting large wind turbines. The concepts that were identified were evaluated and ranked according to their likelihood for successful utilization in wind turbine erection. The most promising concepts were then developed further to identify logistic concerns, scaling relationships, and more detailed costs.

GEC executed this approach in the following steps:

1. Developed turbine weights and dimensions and other relevant input assumptions.

2. Met with industry partners to identify concepts that could be used for self-erection of wind turbines.
3. Evaluated the concepts that were identified to select the most promising.
4. Had wind industry and construction industry consultants review the selected concepts for reasonableness.
5. Developed the selected concepts to the extent possible, identifying technological constraints, transportation constraints, site constraints, labor constraints, and safety constraints. The concepts were developed sufficiently to allow preliminary costs to be estimated.

1.2 Turbine Assumptions

To study methods for self-erection of wind turbines, it was first necessary to define the weights and dimensions of the turbines to be constructed. Because current wind technology data generally only cover the lower end of the 1-5 MW range, it was necessary here to extrapolate turbine specifications from current industry sizes of 1.5 to 2.5 MW, to as much as 5 MW.

As part of its study of WindPACT Technical Area 2 (Turbine, Rotor, and Blade Logistics), GEC estimated the dimensions and weights of major components for different turbine sizes.. The results of this analysis were used for this study and are summarized in Tables 1 and 2.

Table 1. WindPACT Turbine Tower Data

Tower	Units	Turbines					Notes, References, Assumptions
	kW	750	1500	2500	3500	5000	
Number of Sections	each	3	4	5	6	7	
Tower Mass	kg	59,510.6	136,788.9	292,034.5	475,359.5	821,091.8	GEC Tower Mass m = $0.4802D^{2.9978}$
Section 1 (Base)							
Length	m	21.7	21.5	22.1	21.7	22.3	
Base Diameter	m	3.7	4.9	6.4	7.5	9.0	GEC Tower Base Dia (mm) = 74.708D+5.6748
Diameter 2	m	3.1	4.3	5.7	6.9	8.3	
Mass	kg	28,642	51,574	90,403	124,764	187,016	
Section 2							
Length	m	21.7	21.5	22.1	21.7	22.3	
Diameter 1	m	3.1	4.3	5.7	6.9	8.3	
Diameter 2	m	2.5	3.7	5.1	6.2	7.7	
Mass	kg	19,199	38,757	72,389	104,022	160,349	
Section 3							
Length	m	21.7	21.5	22.1	21.7	22.3	
Diameter 1	m	2.5	3.7	5.1	6.2	7.7	
Diameter 2	m	1.9	3.1	4.4	5.6	7.0	GEC Tower Top Diameter (mm) = 37.354D+2.8374
Mass	kg	11,646	27,771	56,377	85,166	135,732	
Section 4							
Length	m		21.5	22.1	21.7	22.3	
Diameter 1	m		3.1	4.4	5.6	7.0	
Diameter 2	m		2.5	3.8	5.0	6.4	GEC Tower Top Diameter (mm) = 37.354D+2.8374
Mass	kg		18,615	42,366	68,196	113,167	
Section 5							
Length	m			22.1	21.7	22.3	
Diameter 1	m			3.8	5.0	6.4	
Diameter 2	m			3.2	4.4	5.8	GEC Tower Top Diameter (mm) = 37.354D+2.8374
Mass	kg			30,357	53,111	92,653	
Section 6							
Length	m				21.7	22.3	
Diameter 1	m				4.4	5.8	
Diameter 2	m				3.7	5.1	GEC Tower Top Diameter (mm) = 37.354D+2.8374
Mass	kg				39,912	74,191	
Section 7							
Length	m					22.3	
Diameter 1	m					5.1	
Diameter 2	m					4.5	GEC Tower Top Diameter (mm) = 37.354D+2.8374
Mass	kg					57,780	

Table 2. WindPACT Turbine Characteristics

	Units	Turbines					Notes, References, Assumptions
Facility							
Rating	kW	**750**	**1500**	**2500**	**3500**	**5000**	
Calculated Rating	kW	864	1505	2497	3456	4976	Back calculated from rotor diameter using 0.44 kW/m^2
No. of Turbines	each	50	50	50	50	50	
Facility Capacity	MW	37.5	75	125	175	250	Local 115 kV line can handle up to 150 MW per WAPA survey
Rotor							
Diameter (D)	m	50	66	85	100	120	Selected rotor diameter, back-calculated turbine power using 0.44 kW/m^2
Swept Area	m^2	1,963	3,421	5,675	7,854	11,310	
No. of Blades	each	3	3	3	3	3	Assumes 3-bladed, upwind rotor configuration.
Hub Height	m	65	86	111	130	156	Used ratio of tower height/rotor diameter of 1.3.
Rotor Mass	kg	12,635	30,819	58,061	88,727	142,783	No. of blades x blade mass + hub mass
Solidity	-	0.05	0.05	0.05	0.05	0.05	Assumed typical for 3-bladed rotors.
Hub							
H x Dia.	m	2.25 x 2.25	3.2 x 3.8	3.8 x 4	3.8 x 4	4.2 x 4.5	
Mass	kg	3,816	12,516	22,457	34,136	54,604	Hub mass for 2.5 MW+ turbines based on Hub Mass Graph. $m = 0.24D^{2.5765}$
Blade (each)							
Length	m	24.5	32.3	41.7	49.0	58.8	Assumes 2.0% of blade length is comprised of the hub.
Projected Area	m^2	98	171	284	393	565	Calculated based on assumed solidity.
Maximum Cord	m	2.5	3.3	4.3	5.0	6.0	Value based on 5% of rotor diameter.
Mass	kg	2,940	6,101	11,868	18,197	29,393	European Commission document. Figure 4.5.2 $m = 0.1D^{2.63}$
Nacelle							
Overall L x W x H	m	6 x 3 x 3	9 x 3.5 x 3.5	10 x 4 x 4	12 x 4 x 4	15 x 4.5 x 4.5	
Total Nacelle Mass	kg	31,081	60,517	111,065	164,049	254,102	European Commission document. Figure 4.6.3 $m = 2.60D^{2.4}$
Rated Nacelle Mass	kg/kW	41	40	44	47	51	
Gearbox L x W x H	m						
Gearbox Mass	kg						Information pending
Generator Length	m						
Generator Diameter	m						
Generator Mass	kg	2,792	5,267	8,567	11,867	16,817	University of Sunderland Equ. 5.54 for induction gen in USA
Transformer L x W x H	m	-					
Transformer Mass	kg	-	3600				Information pending
Tower Head Mass							
Mass	kg	45,428	91,747	174,091	262,708	416,815	NREL and TVP Turbines Head Mass Graph, $m = 2.2692(D^{2.5318})$
Rated Mass	kg/kW	61	61	70	75	83	
Specific Mass	kg/m^2	23	27	31	33	37	

For details of how these values were developed, see Reference 1. In addition to the baseline dimensions and weights that were developed for Technical Area 2, the centers of gravity for various turbine components were also estimated. For the center of gravity locations, it was assumed that the WindPACT turbine's mass distribution was similar to that of existing wind turbines. The results of this analysis for the 5 MW turbine are provided in Appendix A.

GEC also developed estimated design loads for the 5 MW turbines, which were used for comparison with the loads associated with raising the tower. The loads estimation was based on baseline predicted loads from the Advanced Research Turbine (ART) Loads Specification [2]. Some of the design loads scaled from the ART loads specification are experienced during normal operating conditions, whereas others are experienced during extreme environmental conditions and still others result from malfunctioning of the controls or safety system. The loads were scaled from the 600 kW ART to the 5 MW WindPACT turbines by applying approximate scaling laws. Some of the loads, such as tower top shear, were scaled with the rotor diameter squared. Others, such as tower top bending moments, were scaled with the rotor diameter cubed. Axial tower loads are a function of the tower head weight and scale approximately with the rotor diameter to the 2.5 power. A summary of the loads is given in Table 3.

Table 3 Operating Load Estimates

Peak Design Load	**600 kW Load**	**5 MW Scaled Load**	**Scaling Relationship**
	Diameter = 42 m	**Diameter = 120 m**	**D2/D1 = 2.85**
Tower top shear	275 kN	2,244 kN	$= k D^2$
Tower top axial	504 kN	6,954 kN	$= k D^{2.5}$
Tower top rolling mt.	491 kNm	11,451 kNm	$= k D^3$
Tower top pitching mt.	1,213 kNm	28,291 kNm	$= k D^3$
Tower top yaw mt.	768 kNm	18,332 kNm	$= k D^3$
Tower base shear	290 kN	2,367 kN	$= k D^2$
Tower base axial	843 kN	11,632 kN	$= k D^{2.5}$
Tower base bending mt.	10,908 kNm	350,064 kNm	= top shear * 156 m

1.3 Baseline Costs

To provide a benchmark against which various self-erection schemes could be compared, we developed baseline lifting costs using conventional crane technology.

Baseline crane costs were also needed for the Technical Area 2 (Turbine, Rotor, and Blade Logistics) study completed by GEC. The baseline costs used in Section 2 of this report were developed as part of GEC's Technical Area 2 study. Reference 1 documents this work.

2. Industry Research and Concept Evaluation

In the following sections, we document the research conducted by GEC to identify potential concepts for self-erecting wind turbines and towers, describe the concepts identified, and the process by which the identified concepts were evaluated to select concepts for more detailed analysis and cost assessment.

2.1 Sources of Information

In an effort to leverage a variety of technologies to maximize the chance of identifying a usable concept, a literature search and a variety of subcontractors were used. The results of these investigations are discussed in the following sections.

2.1.1 Industry Literature Review

After reviewing literature that included conference proceedings, trade publications, and governmental reports, we determined that several wind turbines had been previously deployed using self-erecting concepts. These included the several large experimental European turbines, the Wind Eagle, and the WG MS4-600.

2.1.1.1 Growian

The Growian wind turbine was a large experimental test turbine installed at the Kaiser-Wilhelm-Koog test site in Germany in 1982. The nacelle of the Growian turbine was assembled around the base of the tower after the tower was erected and pulled up the tower with a winch. Photographs of the Growian's erection process can be found on pages 268 and 429 of Reference 3.

2.1.1.2 WTS-3

The WTS-3 was a large experimental Swedish turbine. It was erected using a pair of large lifting towers. The towers were placed on opposite sides of the nacelle and tower and used to lift the nacelle and tower into place. A photograph of the WTS-3 erection can be found on page 427 of Reference 3.

2.1.1.3 Aeolus II

The Aeolus II was a large experimental wind turbine installed near Wilhemshaven, Germany. It incorporated a set of tracks into the tower and the nacelle was adapted to ride up the tracks to the top of the tower. The nacelle raising process required 20 hours and the inclusion of the tracks to lift the large nacelle up the concrete tower had a significant adverse impact on the turbine's economics. Information about the Aeolus II can be found on page 426 of Reference 3.

2.1.1.4 Wind Eagle

The Wind Eagle – a flexible, lightweight, two-bladed turbine -- was recently developed in the United States [4]. It was a flexible. The turbine had a tall, slender, guyed tower and was completely assembled on the ground and erected by tilting up. A gin-pole was used to assist in the tilting and a winch pad was temporarily installed at the appropriate location to allow the turbine to be lowered for maintenance whenever necessary. The machine could be raised or lowered in approximately 30 minutes. It had a 27 meter (m) rotor and was rated at 300 kilowatts (kW).

2.1.1.5 WEG MS4-600

One self-erecting tower concept that was identified from a review of industry literature was the WEG MS4-600 turbine [5]. It was developed in the mid-1990s by the Wind Energy Group in Great Britain and included many advanced features such as a flexible downwind rotor, a center-balanced tilting nacelle, torsionally flexible drivetrain mounting, and active-stall power regulation. The WEG MS4-600 included a tilt-up tower and a winch system to lift the nacelle and rotor into place atop the tower. One of the features of the turbine was a horizontal offset between the rotor centerline and the yaw axis. Although the offset was primarily intended to facilitate yaw stability, it was also a key feature enabling the nacelle to be winched to the top of the tower (see Figure 1). The WEG concept was not evaluated as part of this study, but is referred to here for reference purposes.

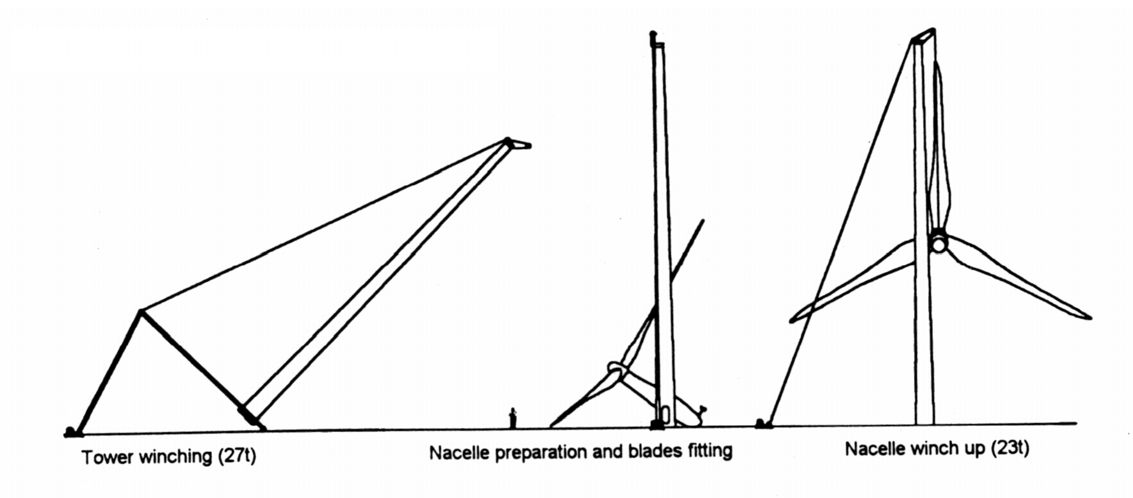


Figure 1. WEG MS4-600

2.1.2 T&T Engineering

T&T Engineering specializes in design of drilling rigs for the oil industry. They work with both onshore and offshore applications and are familiar with a broad range or strategies for installing oil drilling rigs and towers. Based on their experience with the oil industry, they recommended four concepts that might be applicable to wind turbines.

2.1.2.1 Tilt-Up Method with Self-Supporting Frame

The first concept that T&T Engineering described was a tilt-up structure similar to some that are used in the oil and gas industry that utilize self-contained frames to support a gin-pole and a winch. The frame has a toe that extends underneath the tower to the combined center of gravity of the tower and tower head mass. By using this frame, it is not necessary to install a foundation for a lifting winch. (SeeFigure 2).

After examining the loads associated with a frame for lifting a 5-MW wind turbine, however, the concept was quickly revealed to be impractical. For a 5-MW turbine, the bending moment in the frame near the pivot point at the base of the tower would be approximately 1,140,000 kNm, thereby requiring a beam with a section modulus of 5.6 m^3. To achieve this section modulus, it would be necessary to use a pair of rectangular girders, each 9-m tall, were with top and bottom flange sections that were 0.5-m thick and 1.25-m wide. Assuming the girders were tapered to reduce weight in areas where there was no bending moment, the girders would have a combined weight of approximately 925,000 kg. This is more than 10% heavier than the wind turbine tower itself. A quick examination of scaling laws showed the lifting frame to scale approximately with the rotor diameter to the 3.5 power. Therefore, this concept might be useful for smaller turbines but is impractical for large-scale machines.

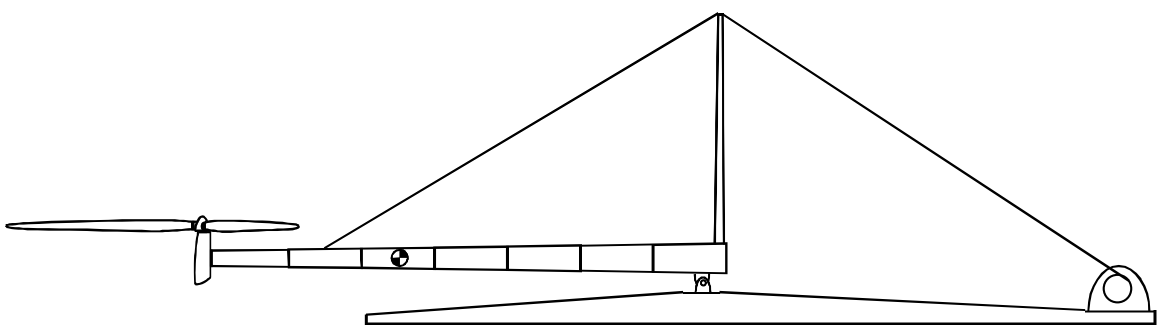


Figure 2. Tilt-up Concept with No Winch Foundation Required

2.1.2.2 Jack-Up with Offshore Platform Towers for Lifting

T&T Engineering also identified lifting technology from offshore drilling platforms that could possibly be modified for wind turbine erection. Offshore oil-drilling platforms are supported by several (usually three or four) legs that are anchored at the ocean floor. The drilling platform is mounted on the legs with rack and pinion mechanisms that allow the platform to move up and down.

This technology could potentially be used for wind turbine erection: the wind turbine would be assembled lying on its side. A set of lifting towers that are similar in design to the support legs of an offshore drilling platform would be erected with two towers on each side of the wind turbine tower. The lifting towers would be located near the center of gravity for the entire wind turbine, including the tower, nacelle, and rotor. A frame would be connected to a pair of trunnions built into the wind turbine tower just above the center of gravity and the frame would be raised up the lifting towers using a rack-and-pinion mechanism. The bottom of the wind turbine tower would be guided by a trailing frame as the tower is lifted. In this way, the entire wind turbine could be lifted in one piece. Figure 3 illustrates this concept.

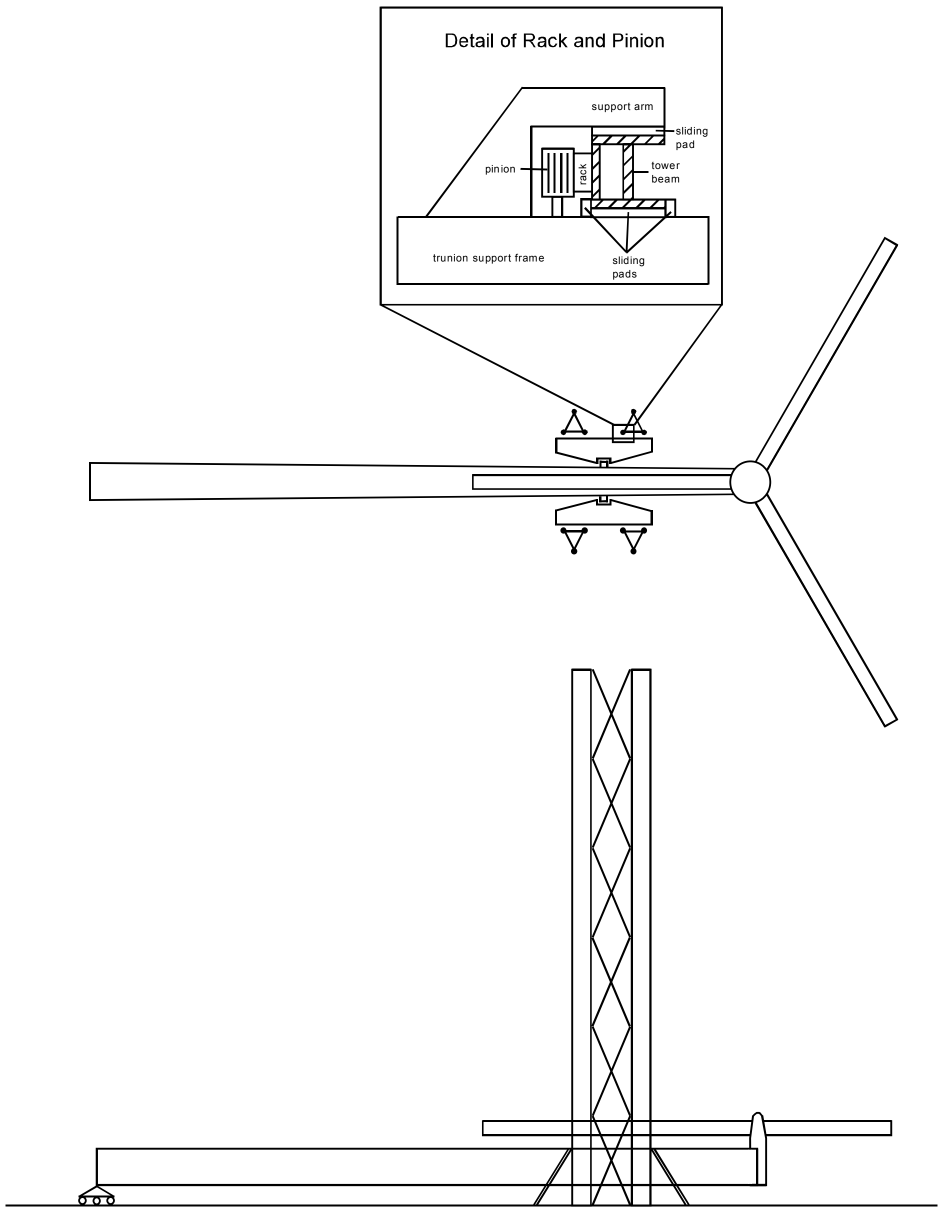


Figure 3. Jack-up Concept Using Offshore Platform Towers

The design of the lifting towers and the rack-and-pinion mechanism would be taken directly from an offshore drilling platform, although they could be scaled down somewhat given that the 5-MW wind turbine is much smaller than an offshore platform. The towers are each triangular-shaped truss structures, and each corner of the triangle is made from an I-beam. The rack of the rack and pinion mechanism would be mounted to one I-beam on the lifting tower. A frame would have to be designed that could attach to trunnions on the side of the wind turbine tower to lift the wind turbine. The frame would include some support structure that would wrap around the I-beam on the lifting tower and include some sliding pads for guiding the entire mechanism as it travels up and down the lifting tower.

According to an analysis of loads conducted during turbine erection, the bending load on the wind turbine tower at the location where the frame attaches would be higher than typical turbine hurricane-survival loads. GEC estimates that the center of gravity for the entire wind turbine system would be approximately 93 m from the tower base or 63 m from the nacelle and that the peak bending moment at that location due to tower top shear times 63 m plus tower drag would be approximately 172,000 kNm. The bending moment caused by lifting would be approximately 315,000 kNm (or greater if a dynamic load factor is included). Therefore, the loads associated with turbine erection would govern the tower design. The lifting loads could be reduced by picking the turbine at a point closer to the nacelle, although that would require taller lifting towers. Further investigation would be required to determine if lifting loads posed a serious limitation to this concept.

Another disadvantage to this lifting concept is that it requires trunnions to be built into the wind turbine tower to provide a lifting-hoist attachment point. The inclusion of trunnions in the tower would add some extra complexity and expense to the wind turbine tower. It is possible that the trunnions could be designed as a removable frame that would clamp onto the wind turbine tower; however the T&T assumed that the trunnions would be fabricated as part of the tower.

2.1.2.3 Slip-Form Approach

According to T&T Engineering, some drilling rigs in the oil industry are erected using a slip-form-type approach in which the top of the tower is lifted first and the lower sections of the tower are subsequently placed under the top sections. In this way, the tower is constructed from the top down. This technology is only used on relatively small drilling rigs (50 m tall or less). However, T&T indicated that using a frame to support the lowest-two tower sections, it should be possible to strengthen the structure to enable it to lift a 5-MW turbine. Those two sections are then lifted in the frame so that only the bottom section is supported, however, there is room below it to insert the next section. The next-lower section is then moved into position next to the frame in a horizontal position, latched into a hinge-type structure, and rotated down to the bottom of the frame. The key to the oil-drilling-rig method is that the lifting frame has a section with bearing surfaces that provide a horizontal couple at the tower base to keep the tower from tipping over as it is being raised. These bearing surfaces would have to be very strong to support a large wind turbine with assumed wind loads, but they should be technically feasible. The biggest drawback to this design is that it only works with towers that are non-tapered because the tower must maintain a constant cross section in order for the bearing surfaces to brace it as it is raised. Figure 4 illustrates this concept.

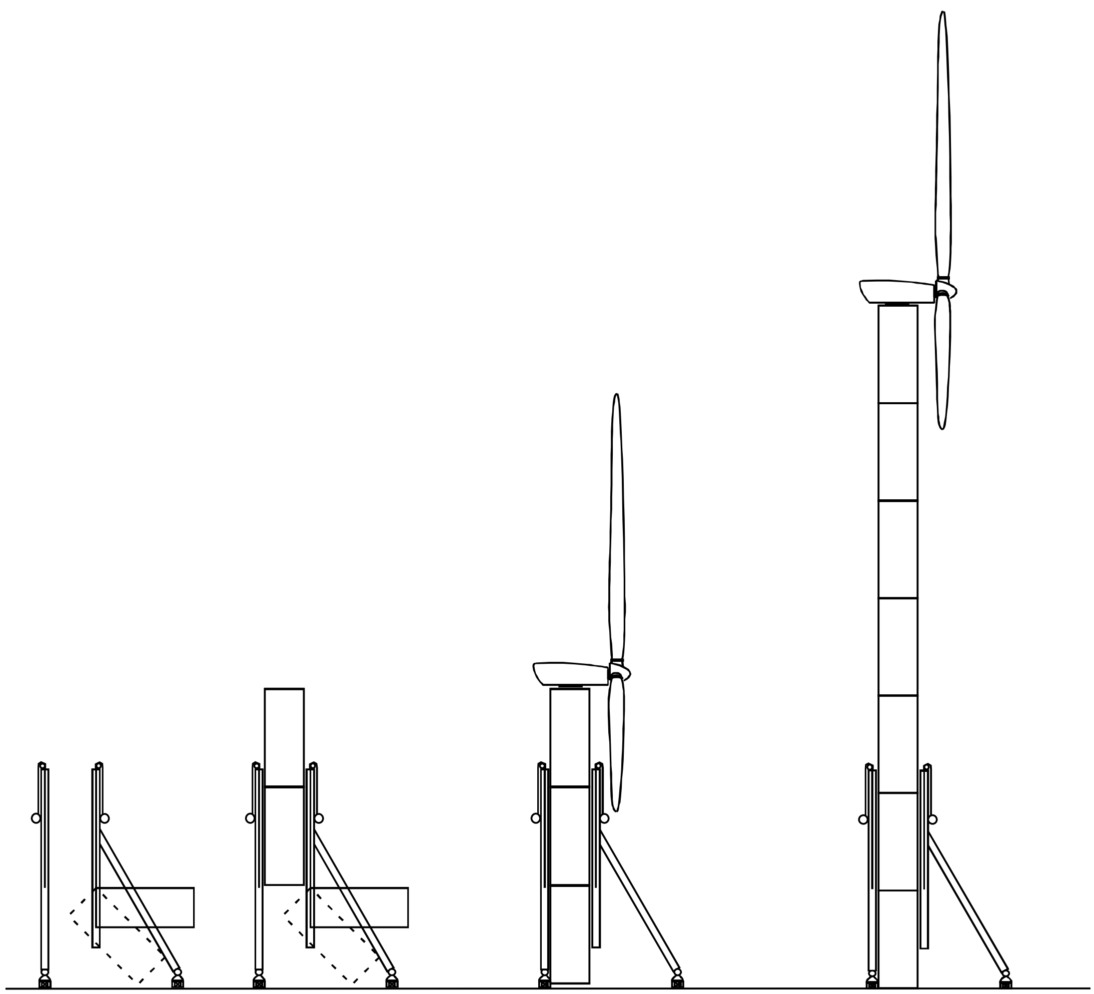


Figure 4. Slip-Form Construction for Non-Tapered Towers

2.1.2.4 Telescoping Tower

T&T Engineering developed a concept for raising a tower by telescoping the tower sections. To install a turbine, the tower sections would nest inside of one another, standing vertically in the foundation. The top tower section would be slightly taller than the other tower sections so that the nacelle could be attached to it while it is nested inside of the other sections. After attaching the nacelle, the tower would be raised sufficiently to mount the rotor. With the nacelle and rotor in place, the tower would be raised to its full height. The lifting mechanism would consist of cable and pulleys or a jacking system. It was not immediately apparent how the lifting would be arranged on each tower section. This problem would have to be solved before this concept could be practical. Another unsolved problem is the method of connecting tower sections together. Because a conventional flange connection would not work for the nested tower sections, another connection method would be needed. Figure 5 illustrates this concept.

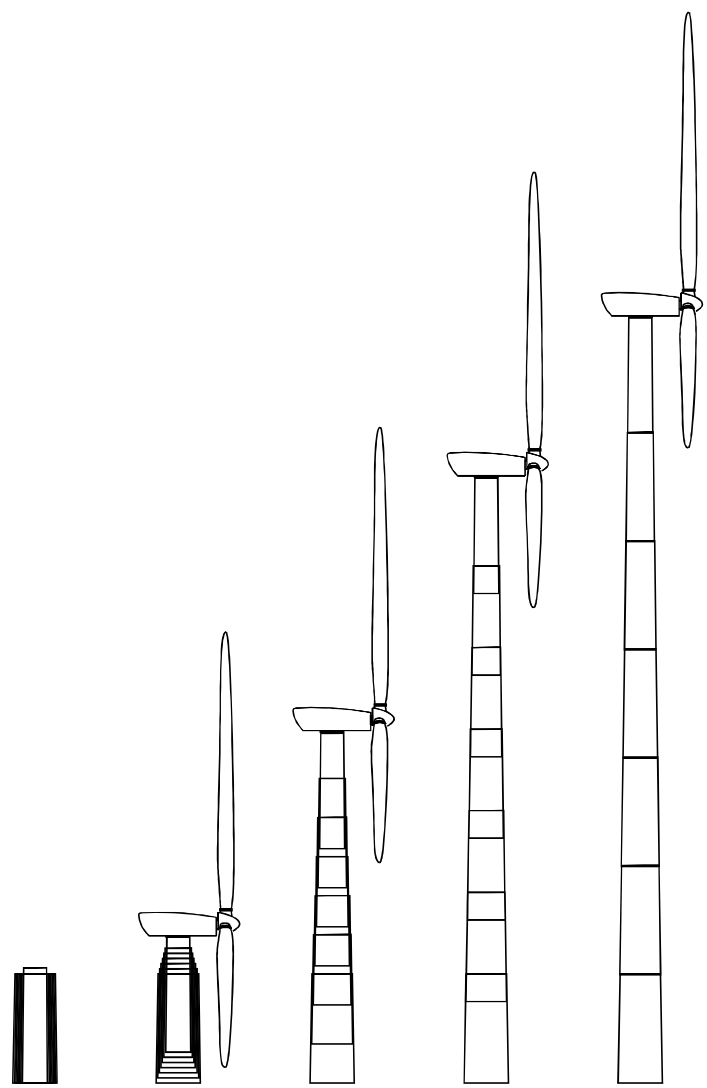


Figure 5. Telescoping Tower

2.1.3 Barnhart Crane & Lifting

Barnhart Crane & Lifting (Barnhart) is a full-service heavy-lift and heavy-transport company with engineers that design innovative lifting and rigging systems. They have experience lifting and moving a broad range of objects in all sizes and weights. Barnhart has been awarded the “Rigging Job of the Year” award by the Specialized Carriers and Riggers Association in seven of the past eight years. The company has offices throughout the United States.

2.1.3.1 Lifting Tower

Barnhart uses a method for erecting large chimneys that may be adaptable for wind turbine erection. They have a lifting tower that they assemble to straddle the chimney; next, they lift the chimney by connecting a lifting frame to a set of trunnions just above the chimney’s center of gravity. The chimney is raised with a set of strand jacks. Although a 5-MW wind turbine would be much larger and heavier than a chimney, Barnhart is confident that their lifting frame can be scaled up to lift a wind turbine. Their lifting frame is modular and comes with girders that fasten together at “nodes” with pinned connections so that the setup of the frame is expedited. Also, their frames are designed for easy shipping via sea container when disassembled. This concept has all of the same limitations as the T&T Jack-up concept. However, it has additional appeal in that it is made entirely of components that already exist and that Barnhart uses regularly to erect heavy objects, such as a frame for holding the trunnions on the wind turbine tower. Figure 6 shows a large chimney being lifted using this method.

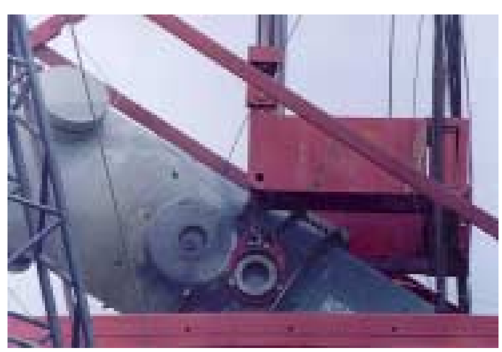
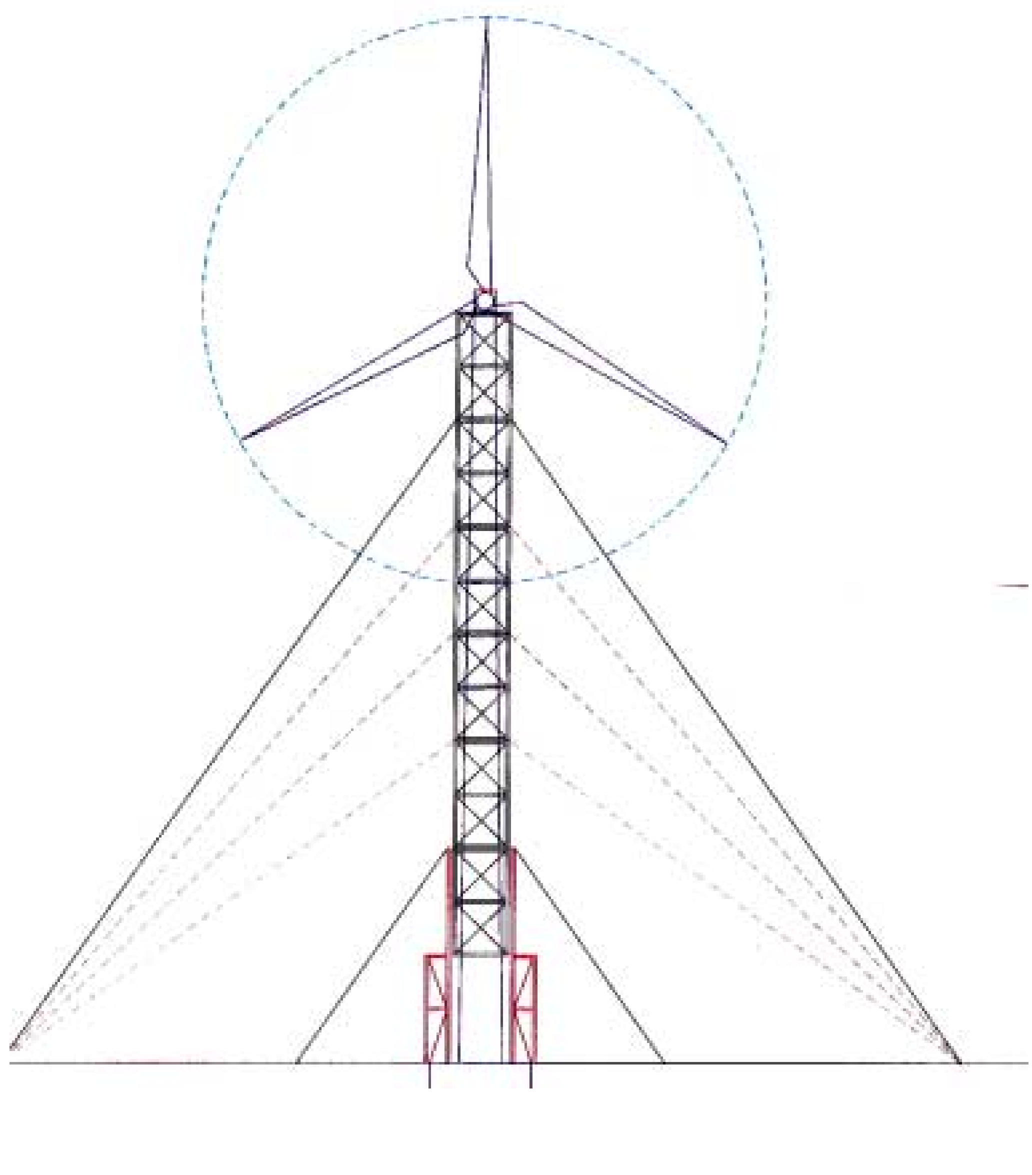


Figure 6. Barnhart Lifting Frame

2.1.3.2 Slip-Form Adapted for Non-Tapered Towers

Barnhart also developed a slip-form concept for erecting wind turbines. The Barnhart method encases each wind turbine tower section in a truss-type modular-frame structure. The frame structures are constant cross section but they can attach to tower pieces of varying geometry. This allows a tapered tower to be installed with a slip-form technique, whereas T&T Engineering's method required the tower itself to be non-tapered. Because of serious concerns about the tipping stability of such a design Barnhart proposed using guy cables attached to the frame structures to prevent tipping. The guys would have to be let out as the tower is raised and the adjustment of the guys would have to be coordinated with the raising of the tower. Also, temporary anchors or foundations would have to be provided for the guy cables. Figure 7 illustrates this concept.

Figure 7. Slip-Form Construction with a Frame to Support Tapered Towers



2.1.3.3 Climbing Frame with Boom and Mast

Barnhart presented a concept for a lifting frame that climbs the tower as it goes. The frame would have a crane boom and mast mounted on it and the boom would be tall enough to allow it to lift a tower section and place it above the frame. Once that tower section is in place, the frame would climb the section using a set of strand jacks connected with lifting cables that would attach to a set of eyes on the top of the tower section. The lifting frame would then be reattached to the top of the new tower section and the process would be repeated. The crane's boom and mast would have cables between them and a separate cable would extend from the mast to an attachment point on the ground at the base of the tower. The ground cable would provide a moment to the crane to reduce the moment applied at the tower top. This cable would have to be extended each time the lifting frame advances to the top of a new tower section. This concept is illustrated in Figure 8.

One of the challenges of this concept is developing a method for attaching the lifting frame to the tower so as to allow for tapering of the wind turbine tower. Barnhart proposes to attach the frame to the tower with a set of pivoting attachment arms. As the tower diameter decreases on the top tower sections, the arms would be oriented at a larger angle when they are attached to the tower.

The biggest problem with this concept is the loads that would be applied to the wind turbine tower as the nacelle is raised. GEC performed some preliminary calculations for the loads that would be exerted on the tower top as the nacelle is raised. Although the moment applied to the tower top is minimized because of the ground cable, there is still some moment applied.
The tower top moment occurs because the pivot point for the crane is not coincident with the tower centerline. The eccentricity between the tower centerline and the crane pivot point creates a moment on the tower top equal to the downward reaction force at the crane's pivot multiplied by the eccentricity. GEC estimated that the tower top moment could be as high as 38,910 kNm while lifting the nacelle, which is 1.4 times the estimated design moment for the tower top. This could be improved by varying the geometry of the crane or by lifting nacelle components individually to reduce the total weight in any single lift.

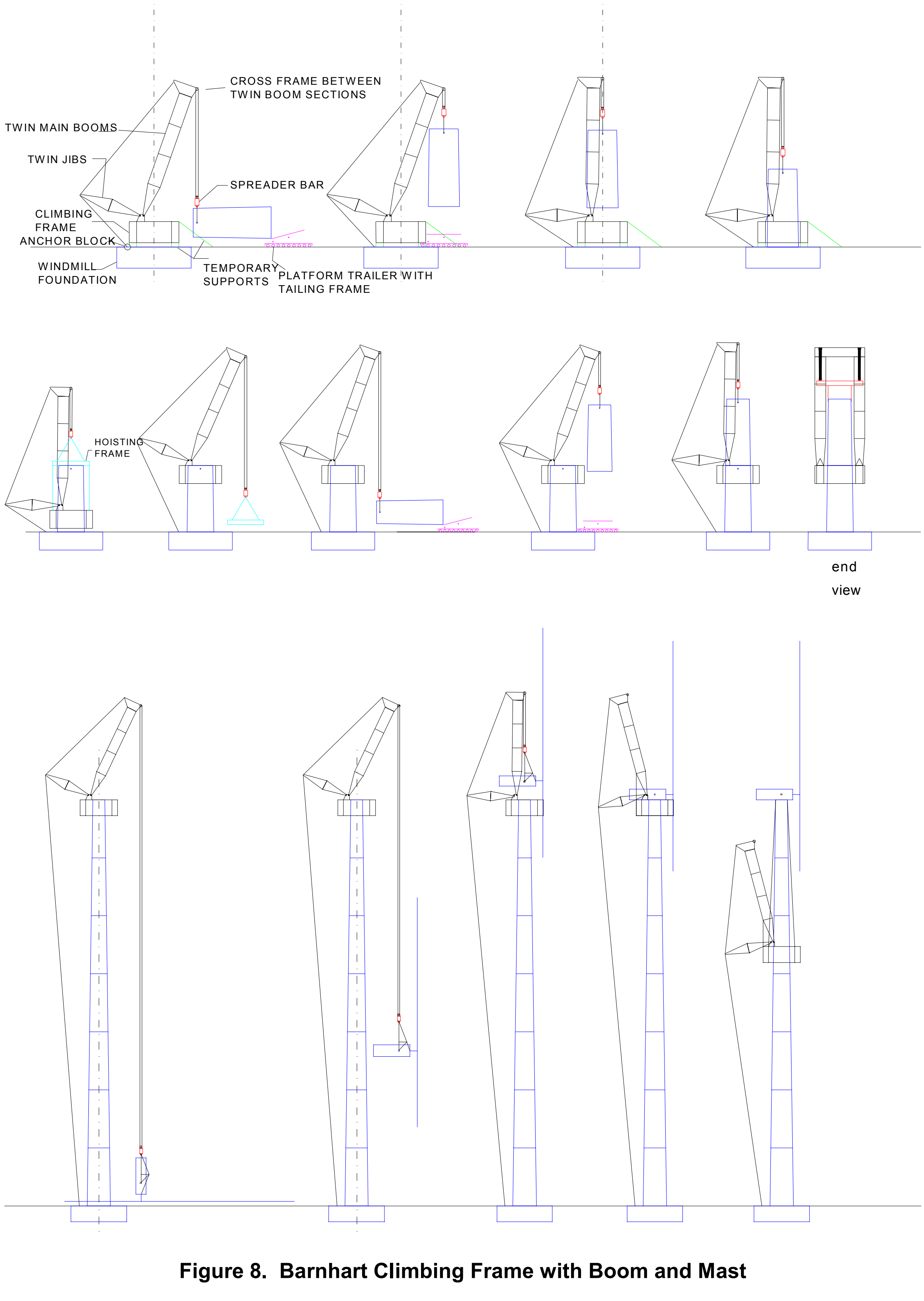


Figure 8. Barnhart Climbing Frame with Boom and Mast

2.1.3.4 Climbing Frame with Boom, Mast, and Counterweight

Because of the limitations associated with loads on the tower top, Barnhart developed a modified version of the climbing-frame concept. In the modified concept, the cable between the mast and an anchor point connects to the climbing frame itself instead of to the ground. Because the cable does not provide a moment to balance the weight of the load, a counterweight is added to the frame. The counterweight is movable on the frame so that it can be positioned at the correct location to provide the exact amount of counterbalancing moment for the load being lifted. This would reduce or eliminate the moments on the wind turbine tower top. It also simplifies the logistics because the cable that secures the jib to the frame would not have to be adjusted every time the frame climbs to a new level on the turbine. Figure 9 illustrates this concept.

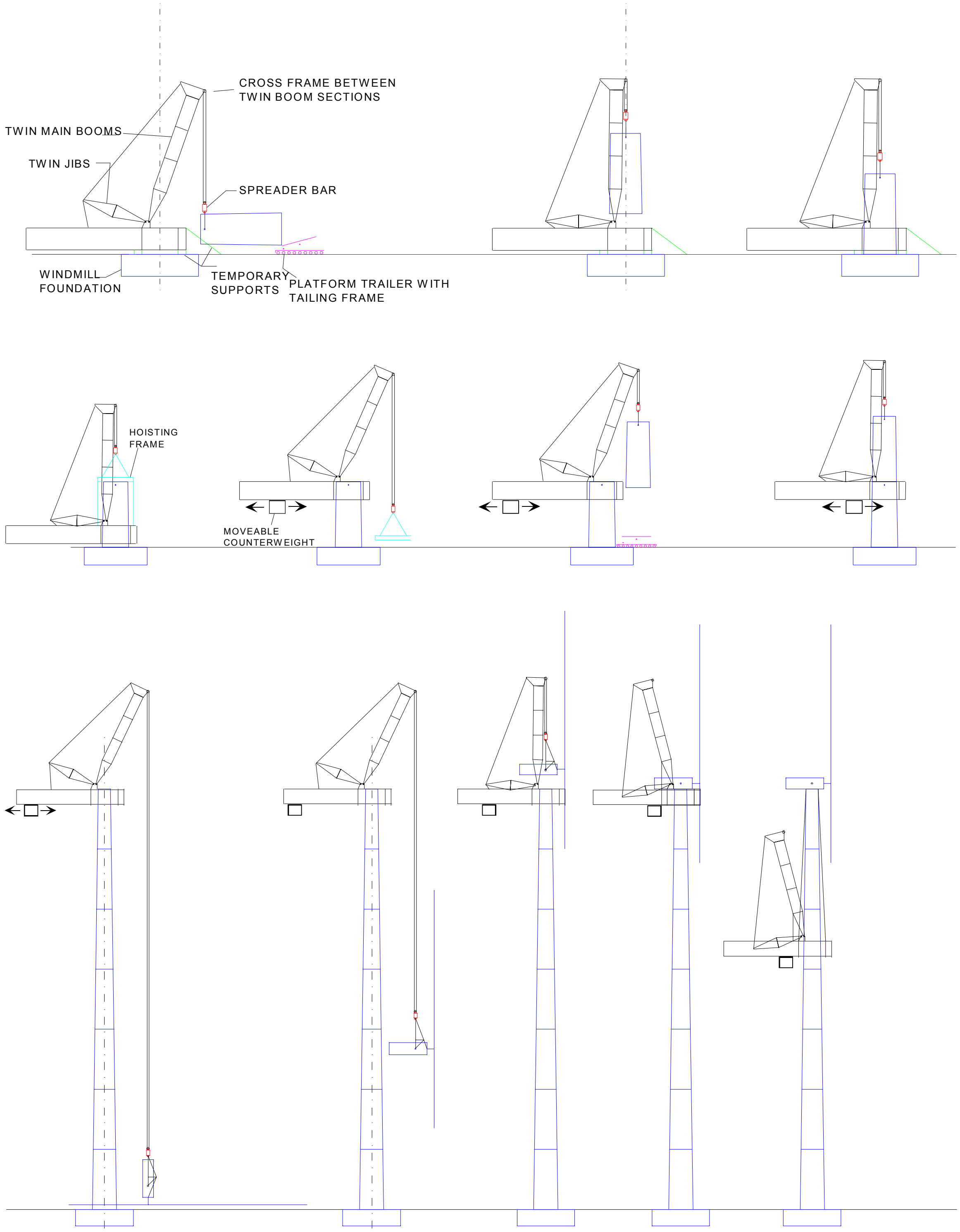


Figure 9. Barnhart Climbing Frame with Boom, Mast, and Counterweight

2.1.3.5 Climbing Frame with Lifting Tower and Strand Jacks

A variation on the climbing frame concept from Barnhart uses a truss tower that stands on top of the frame and incorporates a strand jack for lifting components. Barnhart has modular truss towers in stock that they regularly use for heavy-lifting operations, so that part of the design represents lower risk than the concept with a boom and jib on the climbing frame. The strand jack that is used for lifting is also a familiar item to Barnhart; they use it regularly for all of their very heavy lifting. Strand jacks have extremely high weight-lifting capacities and they are relatively inexpensive. The problem is that strand jacks are very slow. They can lift items at a rate of approximately 12 inches per minute. Lowering the cable is somewhat slower and occurs at a rate of approximately 9 inches per minute. At that rate, the top tower section, nacelle, and rotor would each take approximately 8 1/2 hours to lift and it would take more than 11 hours to lower the cable between lifts. It might be possible to replace the strand jacks with a hoist or other lifting device that would raise components into place more quickly, although the Barnhart design would only use the strand jacks. This concept is illustrated in Figure 10.

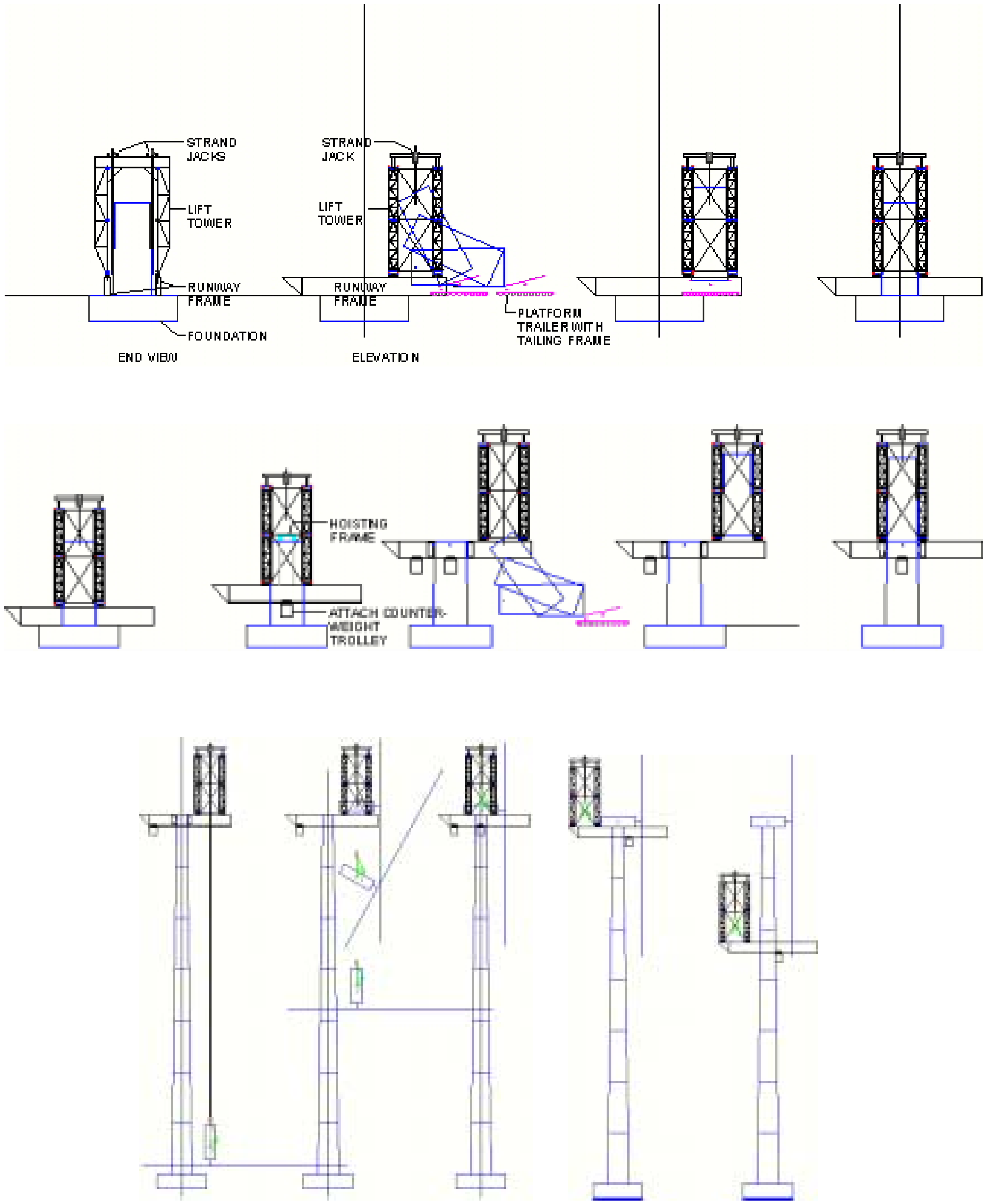


Figure 10. Barnhart Climbing Frame with Lifting Tower and Strand Jacks

2.1.4 Ederer

Ederer identified several promising concepts for self-erection of wind turbine towers. They also provided feedback and comment on the previously identified concepts. In addition, Ederer proposed a concept that essentially used two of Barnhart's concepts. This is further described below.

Ederer has a telescoping lifting tower, shown in Figure 11, that they use for certain lifting jobs. The tower is mounted on a mobile platform so that it can be driven into place and set up quickly. The mobile platform can be driven on wheels as shown in Figure 11, or it can be equipped with caterpillar tracks for use on rough terrain. The tower boom tilts up from a storage position on the mobile base to a vertical position for use. The tower is then telescoped to the desired height and secured with guy wires. The guy wires are held into place with temporary moveable anchors so that foundations are not needed.

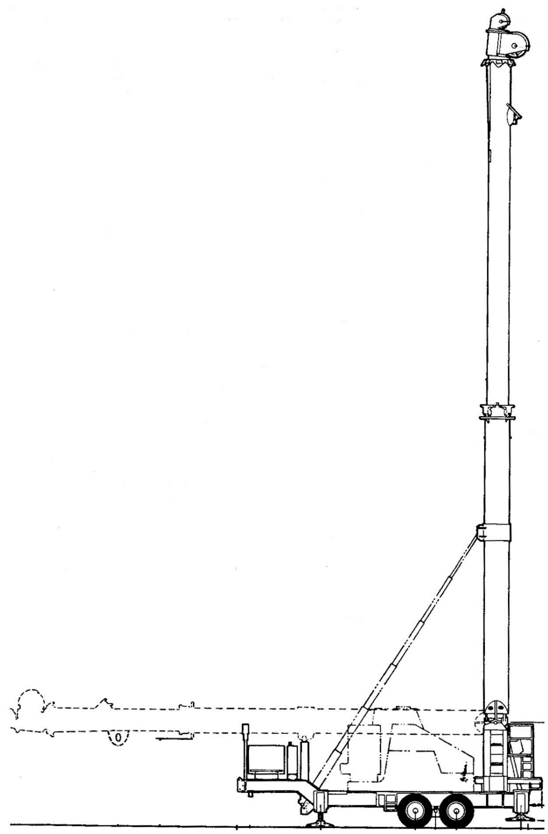


Figure 11. Ederer's Telescoping Lifting Tower

For raising a wind turbine tower, Ederer proposes to use two telescoping lifting towers placed on opposite sides of the pre-assembled wind turbine tower (see Figure 12). Lifting lines would be attached to the tower at a location just above the tower's center of gravity and the tower would be tilted up. The telescoping lifting towers could not reasonably be made to raise the entire wind turbine including the nacelle and rotor, so the tower would be lifted without any other equipment installed at the tower top. Without the nacelle or rotor installed the tower can be lifted at a pick point just above the tower's center of gravity, which is at approximately 40% of the tower height.

This allows for significantly shorter towers than would be required if the entire wind turbine were lifted at once.

In order to raise the nacelle and rotor after the tower has been tilted up, a frame with a crane boom would be preinstalled at the top of the tower while the tower is still on the ground. The frame and boom would be similar to the Barnhart climbing frame except that it would not have the capability to climb the tower. After the nacelle and rotor are lifted into place, the crane would lower itself back down the tower.

Ederer's concept was not included in the list of candidate self-erection methods for further evaluation because they had scheduling constraints that prevented them from developing the concept any further.

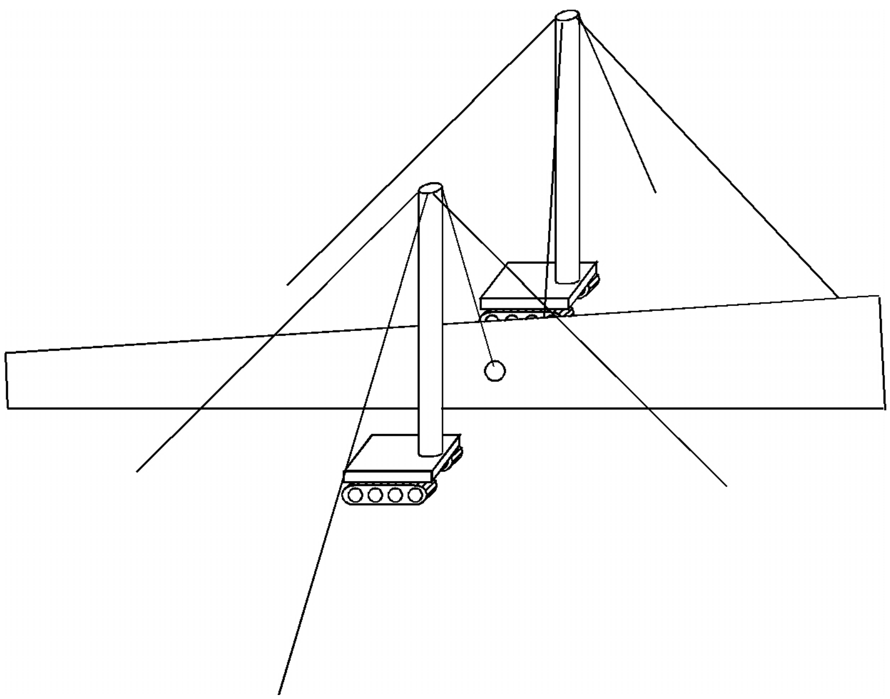


Figure 12. Ederer Towers Set Up to Lift Wind Turbine Tower

2.1.5 Valmont Industries

During the course of this study, GEC identified several self-erecting tower designs that were being developed independently of the WindPACT program. One of those designs was developed by Valmont Industries, Inc. (Valmont). Valmont is an international manufacturing company with 27 manufacturing plants located on five continents. They specialize in design and manufacture of irrigation system as well as poles, towers, and structures for lighting, utility transmission lines, and communication applications. They also specialize in galvanizing and custom coatings.

Through their experience with poles for lighting and utility transmission lines, Valmont has developed specialized procedures and facilities for manufacture of break-formed steel poles. They have developed a wind turbine tower design that leverages their strength in breakform steel-pole fabrication that reportedly reduces the tower weight and cost compared to conventional monopole tubular steel towers.

The Valmont tower is formed as a 12-sided break-formed pole that does not taper. The main mast is supported by two stanchion legs which attach to the tower somewhere below the lower tip of the wind turbine rotor and form a tripod together with the tower. A pair of guide rails are formed integrally with the tower structure, allowing a platform sled device to be pulled up the tower for erection of the turbine.

Valmont has designed a sled specifically for use with their tower to allow erection of the turbine without using a large crane. The sled, (see Figure 13) has wheels that guide it to move vertically on the rails that are formed into the tower. A cable system lifts the sled up the tower. The sled includes a power supply for the hoist that controls the cable-lifting system so that external power connections are not needed. The sled also includes a frame that can support the wind turbine nacelle. The frame moves laterally on the sled to position the nacelle over the top of the tower. When in use, the nacelle would be affixed to the sliding frame on the sled and the sled is raised part way up the tower. The rotor is then attached to the nacelle once the sled has been raised high enough to accommodate ground clearance of the blades. With the blades in place, the entire nacelle and rotor are raised to the top of the tower on the sled. The sliding frame then translates until the nacelle can be lowered and attached to the yaw bearing on top of the tower.

Tower sections are installed using a gin-pole device that is raised using the same set of rails on which the sled is guided. The gin-pole is a relatively simple device that Valmont uses frequently for installing communication towers.

The Valmont tower is intended to solve a variety of problems associated with tall wind turbines besides self-erection. Because of the stancions, the tower may be significantly lighter than a conventional tubular tower. For very tall towers, the tower weight and cost become dominant; therefore, Valmont views their design as an advantage for tall turbines. Also, because Valmont's tower has a relatively small diameter and consistent length sections, it is easier to transport than a conventional tubular tower. Tubular towers with a base diameter larger than 4.4 m are difficult to transport unless the tower sections are divided into pieces. The Valmont tower has a diameter lower than 4.4 m, so transportation is not a problem.

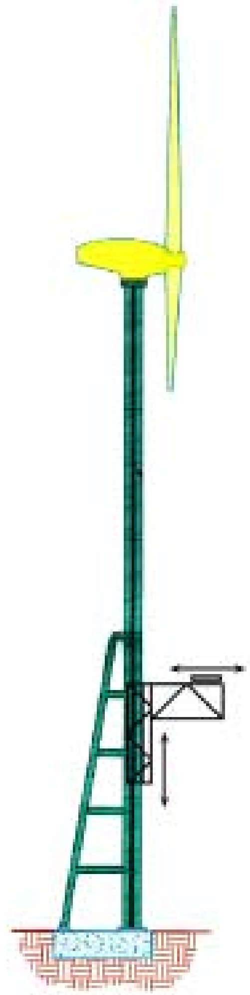


Figure 13. Valmont Tower with Self-Erection Sled

2.1.6 Chicago Bridge & Iron

Chicago Bridge & Iron (CB&I) is one of the world's leading engineering and construction companies. They design and build a variety of steel-plate structures ranging from water tanks to tunnel liners. Their Corporate Construction Technology group has developed several techniques to self-erect water tanks: they believe that their methods can be applied to wind turbine installation.

CB&I has developed the "See-Saw" derrick for use in installing water tanks. (See Figure 14). They have used this equipment for more than 40 years for self-erection of water tanks, and the equipment and method have been updated recently to reflect the latest safety standards. The See-Saw derrick attaches to the tower at two locations. One of the two attachment mechanisms can be released, raised, and then reattached to the tower. At that point, the second attachment mechanism is released, raised, and then reattached. In this way, the derrick is able to climb the tower in a stepwise manner. The derrick includes a boom to which cable can be secured for lifting objects onto the tower. The lifting hoist is typically located at ground level and a cable is routed from the hoist to a pulley on the derrick and then down to the load being lifted. CB&I has used their See-Saw derrick to lift as much as 50 tons, which may be adequate for erecting a 1.5 MW turbine. CB&I believes they can modify the derrick for wind turbine self-erection.

Another potential advantage that CB&I can provide for self-erection of wind turbines is a wealth of experience with field welding of steel structures. They routinely weld water tanks and other steel-plate structures, and they have developed high-quality procedures for both manual and machine welding. CB&I's welding lab is known worldwide for their research and training in welding all types of materials in difficult field conditions. The company believes that it can successfully fabricate a tower in the field, thereby relieving transportation as well as erection problems associated with large wind turbines.

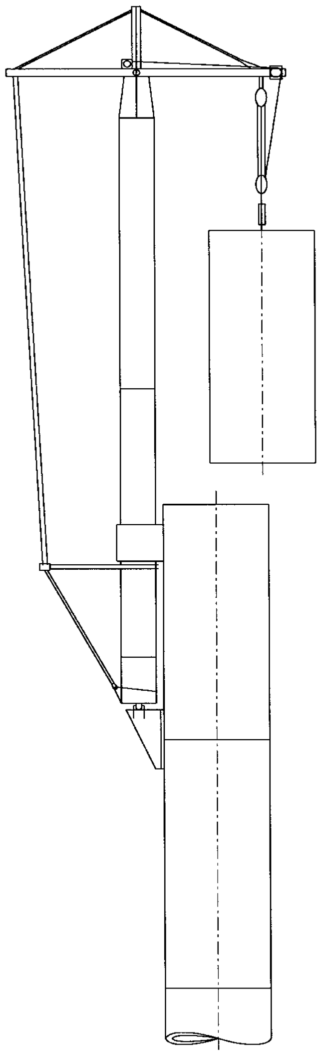


Figure 14. Chicago Bridge & Iron "See-Saw" Derrick

2.1.7 Blattner-Elgood/Mayo Concept

The team of D.H. Blattner and Sons and Elgood/Mayo has developed a turbine self-erection concept, which they believe can significantly reduce the costs of assembly and erection, particularly in complex terrain. The Blattner-Elgood/Mayo concept includes a conventional tubular tower and may eventually be used on a 1.5-MW wind turbine.

The Blattner-Elgood/Mayo concept, (see Figure 15) uses a pair of rails that are temporarily affixed to each tower section. A climbing frame is attached to the rails and used to raise subsequent tower pieces. The climbing frame includes a gripper that holds onto the tower section that is being lifted. When the entire tower is erected, the nacelle is placed on the climbing frame and lifted into place atop the tower. For gripping the nacelle, a small section of tower is fastened onto the bottom of the yaw bearing to provide a convenient attachment point for the climbing frame. After the nacelle is installed, the rotor is supported on the climbing frame and raised into place at the top of the tower. The nacelle must be yawed around to align the shaft with the rotor hub. At that time, the rotor is translated horizontally until the hub can be attached to the shaft.

The climbing frame is able to move up and down the rails by using a hydraulically powered slider. The slider is extended, at which time a pair of pins in the slider are fastened to fastening holes in the rails. The slider is then retracted and the climbing frame is raised as the slider shortens. A pair of pins on the climbing frame are then attached to the rails, the pins on the slider are removed, and the slider can be extended again to repeat the process. In this manner, the climbing frame is capable of moving approximately 10 feet per cycle of extending and retracting the slider.

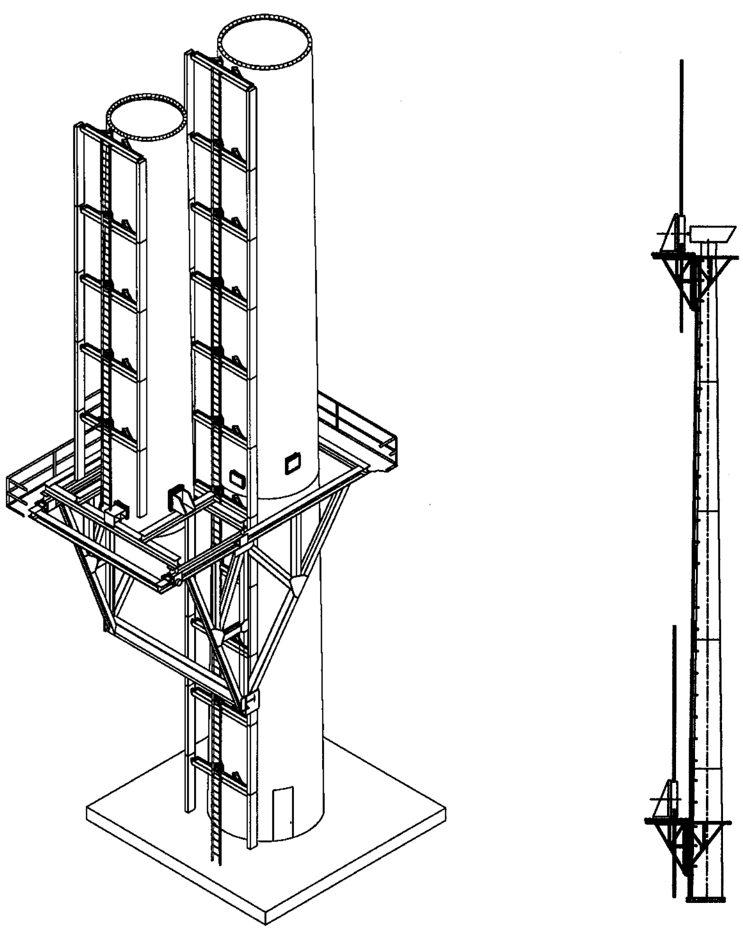


Figure 15. Blattner-Elgood/Mayo Self-Erection System

Blattner-Elgood/Mayo estimated costs for using their self-erection technique to install a wind turbine compared to costs for using a conventional crane. For their estimate they assumed a turbine size of 1.5 MW. The number of turbines in a project was a variable parameter in their analysis, as was the number of turbines that could be installed per crane mobilization, an approximate indicator of terrain roughness. The results of their analysis are shown in Figure 16 for the case of a crane mobilization every 16 turbines. Only those costs that would change between the Blattner-Elgood/Mayo concept and the conventional crane approach are covered. Therefore, assembly labor and material costs are excluded from the Blattner-Elgood/Mayo estimates. The costs shown in Figure 16 agree well with GEC's cost estimates for erection using conventional cranes, and using the Barnhart climbing frame if turbine assembly labor and materials costs are excluded from GEC's costs.

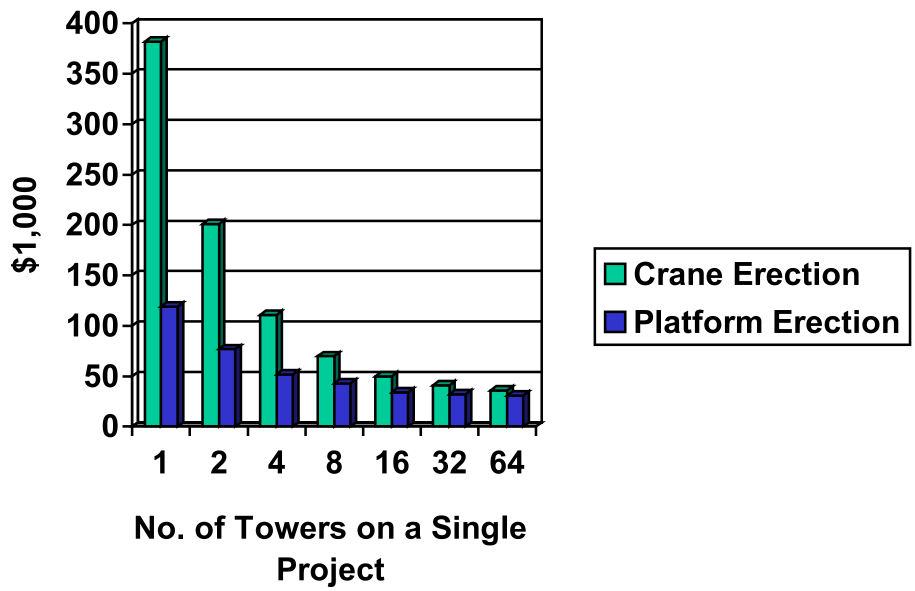


Figure 16. Blattner-Elgood/Mayo Cost Estimates

2.1.8 Patrick & Henderson

Patrick & Henderson (P&H) is a civil engineering firm that has been extensively involved in the wind industry. They are well known for their innovative foundation design. According to this design, tensioned rods are embedded in a cylinder of concrete, resulting in a significant cost savings compared to traditional foundation designs. P&H is currently developing a self-erecting wind turbine tower system. However, confidentiality concerns preclude a discussion of their tower concept in this report.

2.2 Evaluation of Concepts

Once all of the concepts were identified, they were ranked according to their likelihood for success using a quantitative method. To rank the concepts, GEC prepared a scorecard, shown in Appendix B, that GEC and NREL engineers filled out for each concept. The scores from all of the engineers were averaged for each concept and the highest-ranking concepts were selected for further analysis. The concepts developed independently by Blattner, Valmont, CB&I, and Patrick & Henderson were not included in this process because GEC was either not aware of them at the time the scoring was done or insufficient information was available to consider them in the process.

The score sheet used to rank the concepts included nine categories on which the concepts were evaluated. The categories included the technical feasibility of each concept, the level of technical innovation required, the perceived labor cost of each concept, the perceived capital cost, the speed with which a turbine could be erected, the structural loads imparted on the turbine structure during erection, the suitability of the technique for ongoing maintenance work, and the flexibility that the concept would allow for changes in the wind turbine design.

Some concepts scored very highly in certain categories, but scored poorly in others. For instance, the T&T tilt-up method ranked highly in terms of the speed with which a turbine could be erected; however, it scored very badly in the technical-feasibility category. The slip-form techniques scored well for structural loads that would be imparted on the wind turbine during construction, but did not fare well when it came to labor cost and applicability to maintenance tasks.

For all of the criteria a weighted average was calculated for each concept; the concepts were then ranked. The results are shown in Figure 17 in non-dimensional form. Two of Barnhart's concepts--the lifting frame and the climbing frame with a counterbalance weight--scored the highest. The next-best score went to T&T's lifting frame, which uses towers from offshore oil-drilling platforms.

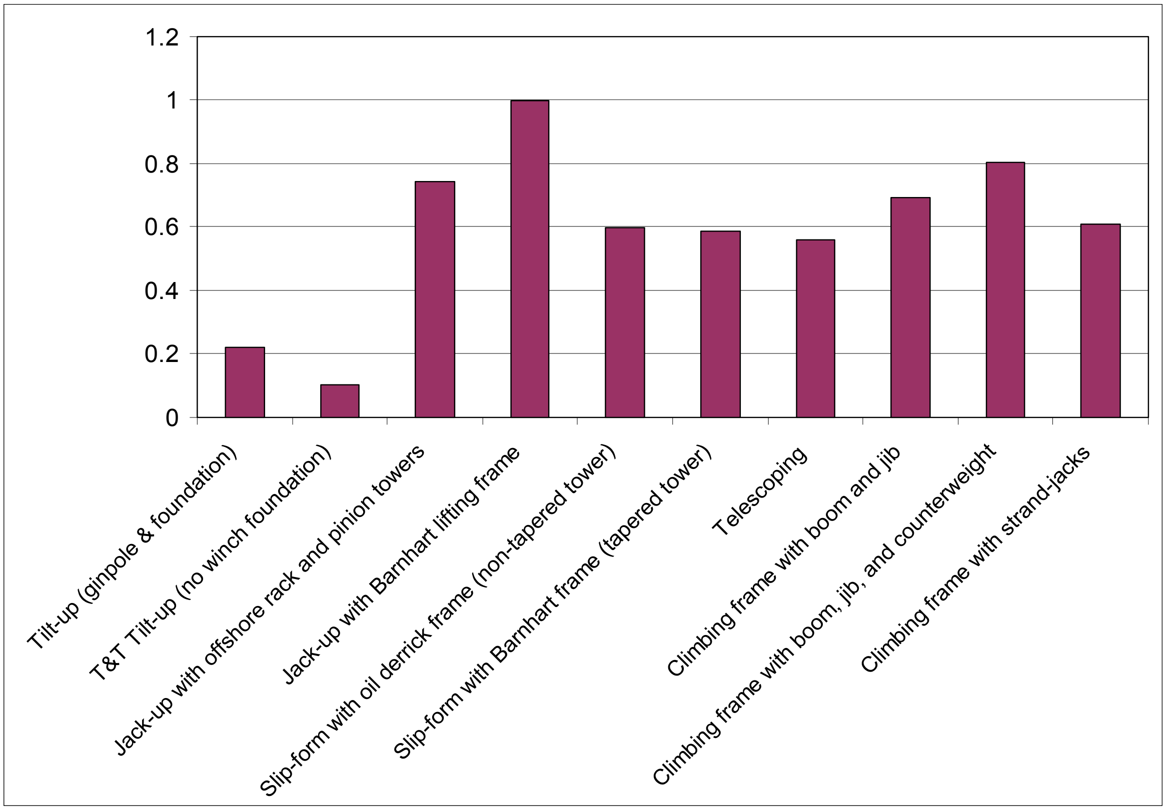


Figure 17. Concept Score Sheet

In addition to evaluating the concepts using the score sheet method, GEC also solicited input from several construction experts. Clare Lees from BCL & Associates and Sean Roberts from RMC both provided valuable input on the designs based on their extensive field experience with wind turbine construction. T&T Engineering gave feedback on Barnhart's concepts. Also, Ederer provided their comments on all of the concepts that were identified.

Each of the experts raised similar concerns. They encouraged further thought about the amount of land that had to be cleared around the wind turbine foundation, side loading of the system, labor costs involved in using the designs, and the time required for setting up specialized equipment such as the Barnhart lifting frame.

Based on the results of this evaluation, GEC requested Barnhart to proceed with further design analysis and costing of the lifting frame and the climbing frame with a counterbalance weight. Barnhart was specifically asked to consider the points raised by the various expert subcontractors.

3. Description of Selected Concepts

Barnhart developed the two concepts selected for further development sufficiently to identify design and logistic issues, and to estimate the costs of components. They did not create a detailed design for either of the erection methods.

Barnhart has extensive experience designing customized techniques for heavy rigging and lifting. They maximize the efficiency of their design process by using standardized parts and components. They have a storage yard with a variety of girders, truss frames, crane booms, strand jacks, and other components. To the extent possible, they attempt to use the parts that they have in storage for new designs. This speeds the design process, increases their confidence in the capabilities and performance of the components that they use, and saves on material costs by reusing components for multiple jobs. They used a similar approach in designing the self-erecting wind turbine hardware, thus allowing them to arrive at a relatively detailed level of design in a short period of time. It also allowed them to estimate costs for the hardware with relatively high confidence.

3.1 Barnhart Lifting Frame

The first concept that Barnhart developed was the lifting frame, which is used to tilt up the pre-assembled wind turbine in a single lift. The lifting frame is made out of truss tower sections called bents, which can be pinned together to create a tall frame. The frame is made out of 11 bents, each of which is 9.1 m (30 ft) tall, for a total height of 101 m (330 ft). This allows the wind turbine tower to be lifted at a location just above the center of gravity, which is at 92.3 m (303 ft).

The bents are each made as truss structures with 4 I-beams as corner members. The I-beams in the lower two-thirds of the tower are W12 x 96 beams. In the upper one-third of the tower they are W12 x 72 beams. The I-beams are connected to each other with a series of cross braces. The weight of each tower is approximately 744 kg/m (500 lb/ft) or 75,000 kg (165,000 lb) in total. The combined weight of all four tower structures is 300,000 kg (660,000 lb).

The wind turbine is raised using strand jacks, which are mounted on a support frame that is attached to the top of the towers. The support frame is made from rectangular girders that Barnhart has as standard stock items. Each girder is suspended between two towers and supports two strand jacks; each of the latter has a 360-ton capacity. The strand jacks are standard items that Barnhart has in stock and is familiar with using.

Erection of the lifting tower requires a 600-ton Transi-Lift or equivalent crane. This compares to a 1200-ton Transi-Lift or equivalent that would be required to erect the 5-MW turbine with standard crane methods. The lifting frame can be designed to include a built-in lifting crane. (See Figures 18a and 18b) so that the lifting tower itself becomes a self-erecting structure.

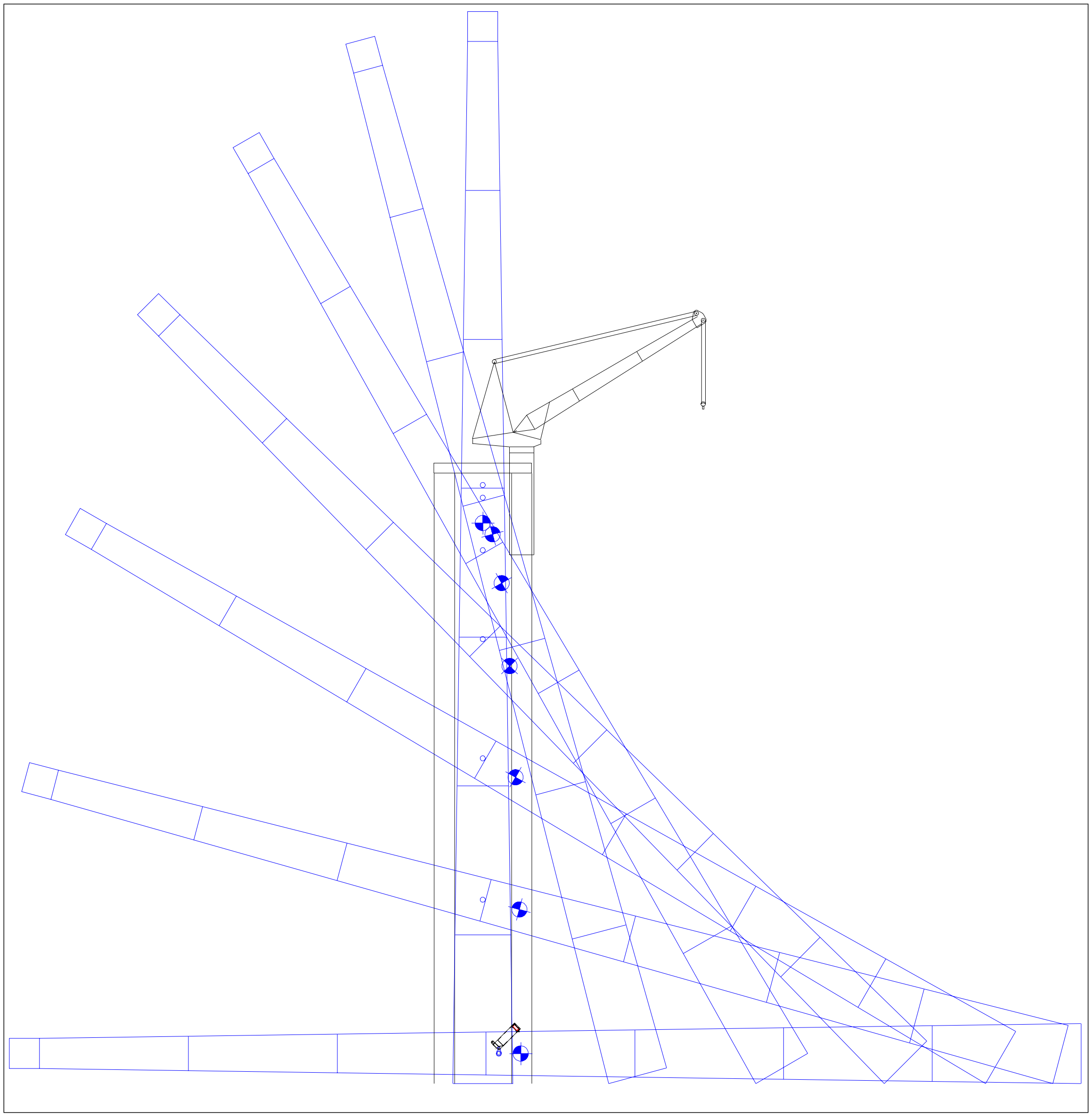


Figure 18a. Barnhart Lifting Frame—Lift Sequence

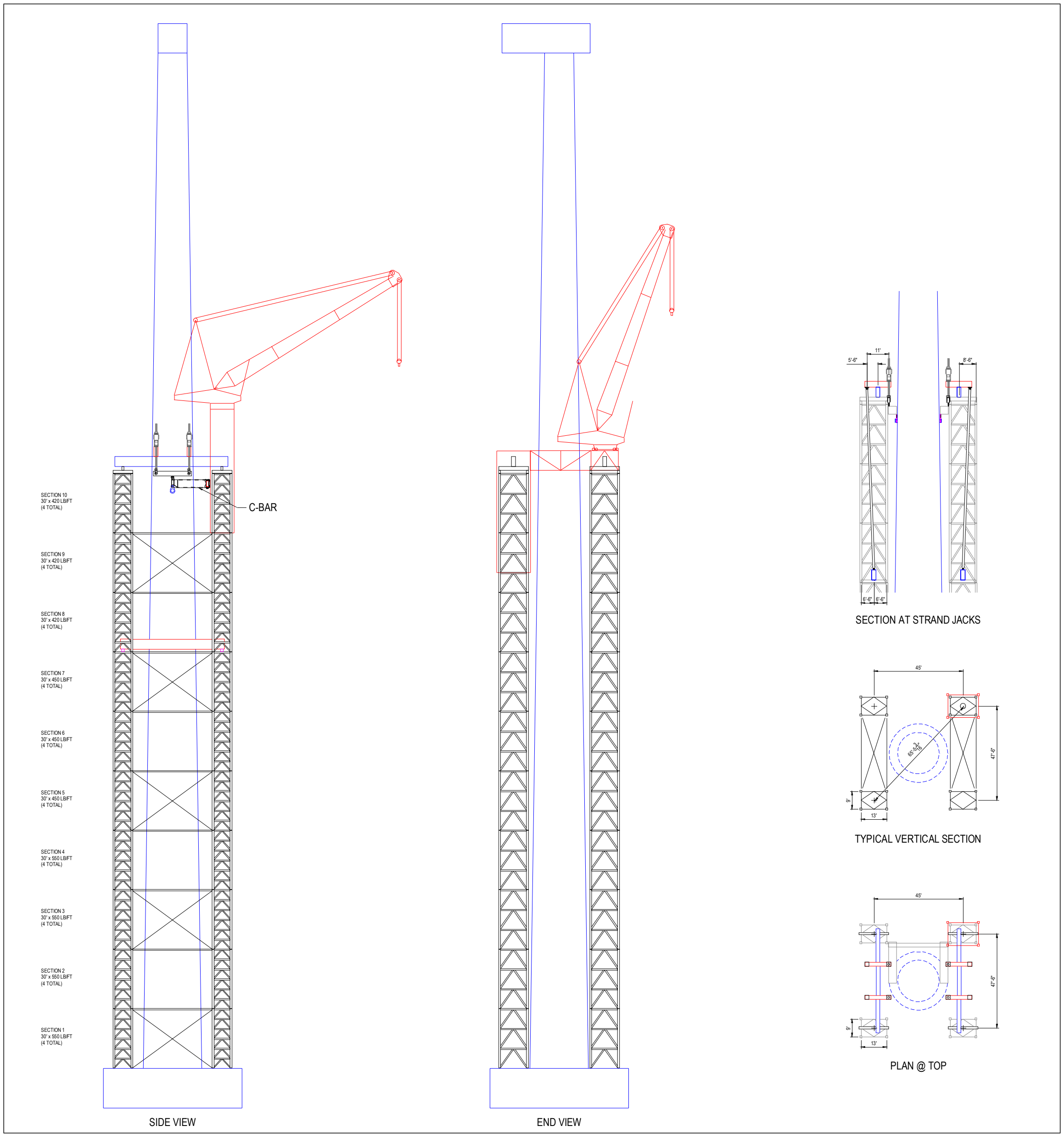


Figure 18b. Barnhart Lifting Frame

3.2 Barnhart Climbing Frame with a Boom, Mast, and Counterweight

Barnhart also performed an analysis of their climbing frame with a moveable counterweight. Drawings of the frame, and a schematic demonstrating its use, are shown in Figures 19a and 19b. The climbing frame consists of a pair of longitudinal truss members, with one member on each side of the wind turbine tower. A second pair of truss members are secured between the longitudinal trusses to form a box that encloses the wind turbine tower. Each truss member is made from a pair of I-beams on the top and bottom, with cross bracing inserted between them. The I-beams are 14-inch-wide flange members that weigh approximately 150 kg/m (100 lb/ft). They are each 24.4 m (80 ft) in length and have a total weight of 3660 kg (8000 lb). The cross members are made from similar beams as the longitudinal trusses and are 10 m (33 ft) in length, weighing 1500 kg (3300 lb). The total weight of all of the I-beams in the various truss members is 20,640 kg (45,200 lb). A pair of chain-driven, movable counterweights are attached to the frame with an additional weight of 96,000 kg (212,000 lb) each.

The boom, mast, and jib are standard crane structures with at least a 300-ton lifting capacity. The boom is 30 m (98 ft) in length and the jib is 15 m (49 ft) in length. The total lifting height capacity of the boom and jib is approximately 38 m (126 ft).

An engine and hoist are mounted on the climbing frame to provide power for lifting turbine parts. The engine and hoist are situated in the aft end of the frame near the counterbalance weights. The engine and hoist have a combined weight of 41,000 kg (90,000 lb).

In order to raise the climbing frame to the top of each tower section after that section has been installed, the frame is equipped with a pair of strand jacks. The cables from the strand jacks are secured to a set of eyes at the top of a tower section, and the strand jacks pull the cable in so as to raise the climbing frame to the top of the tower. The strand jacks are 132-ton Enerpac units that are capable of lifting the frame at a rate of 0.3 m/min (1 ft/min). Further description of the strand jacks can be found on Enerpac's Web site (www.enerpac.com). They can lift the frame the height of one tower section in approximately 1 hour and 15 minutes. After the frame has been raised, a set of tension rods is connected to the eyes to secure the frame in place.

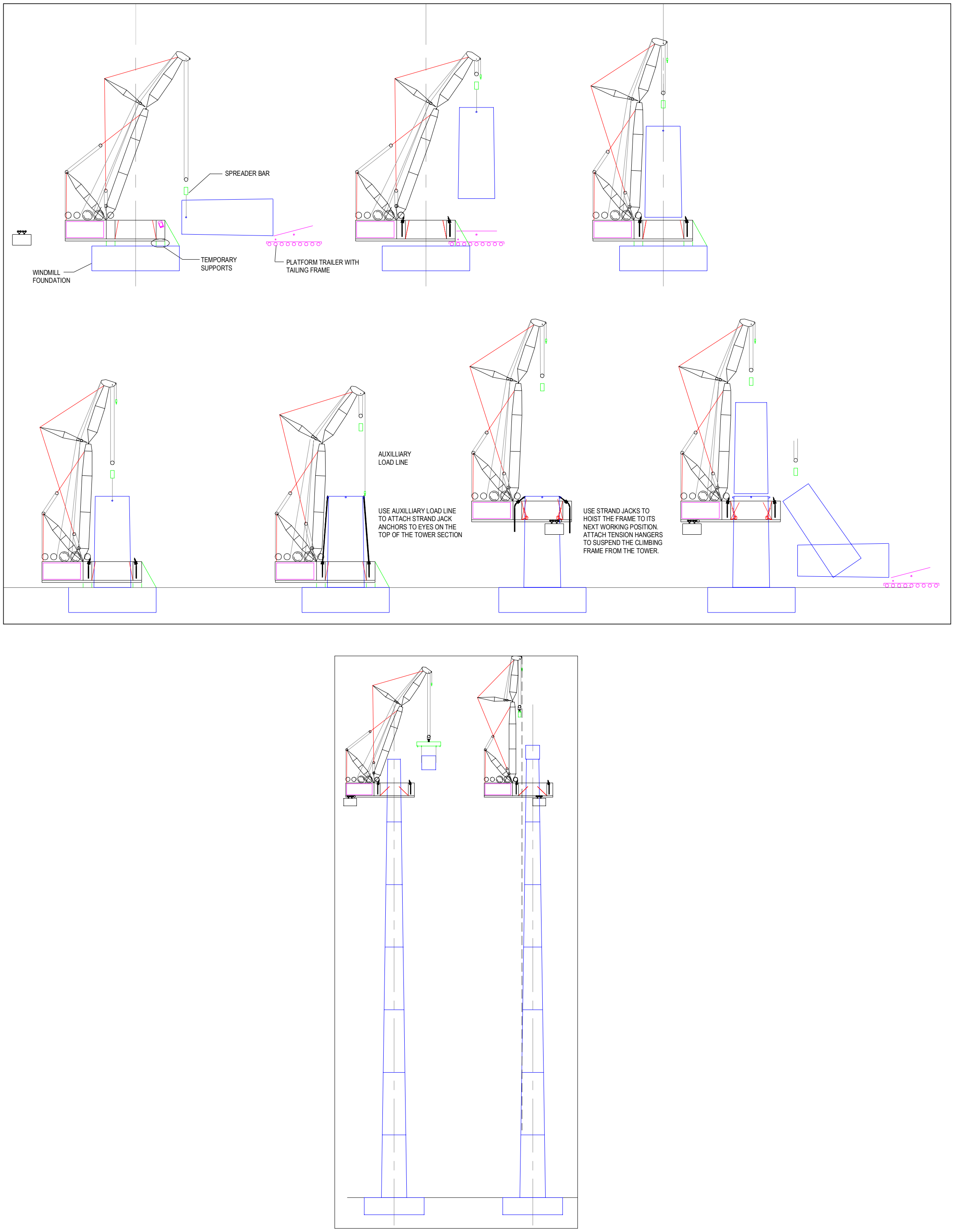


Figure 19a. Barnhart Climbing Frame—Lift Sequence

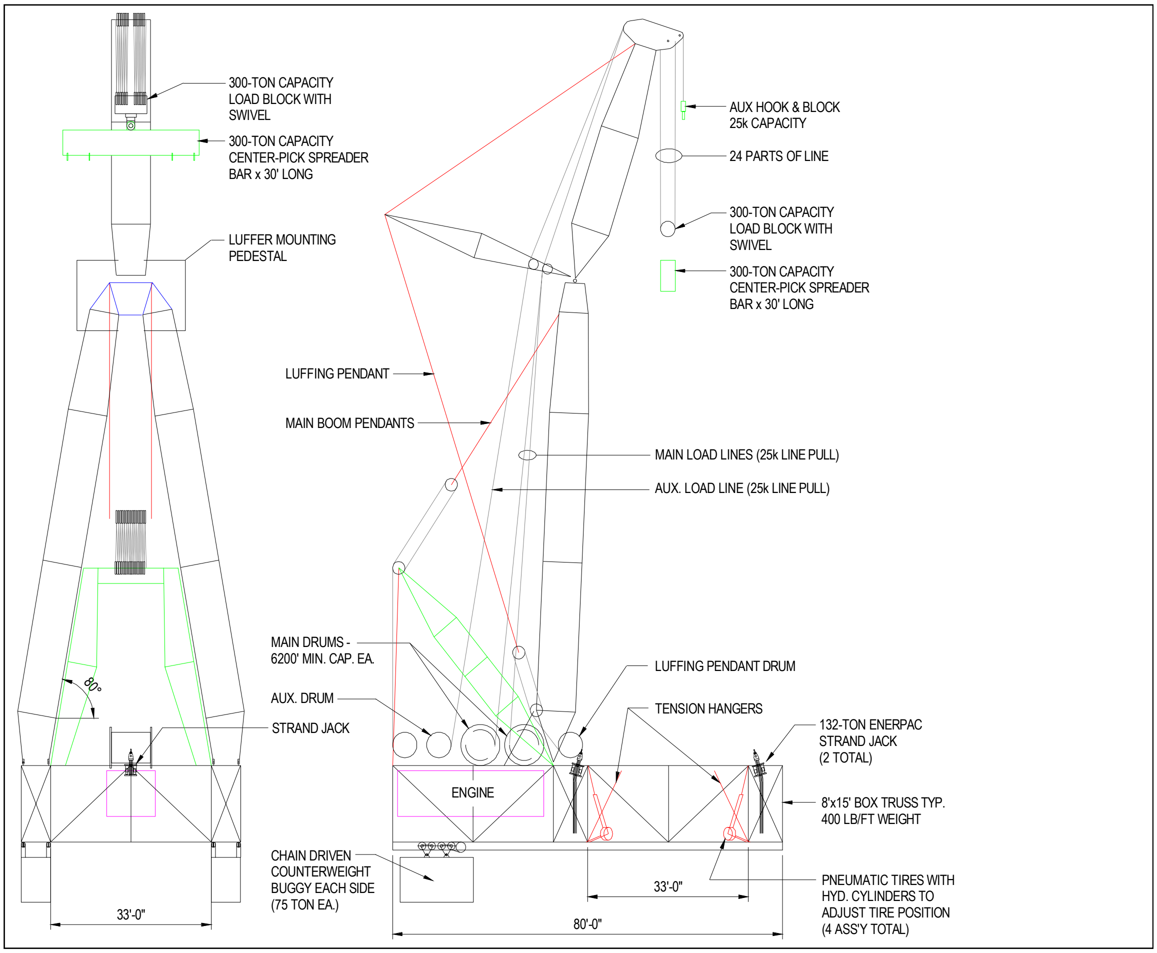


Figure 19b. Barnhart Climbing Frame

3.3 Design Constraints

Although technically feasible, these self-erection concepts have certain limitations, drawbacks, and constraints posed by site and environmental conditions. The preliminary design analysis uncovered some of the constraints of the techniques. A complete understanding of all of the constraints and limitations however, would require further analysis and a detailed design.

GEC considered the following constraints and limitations on turbine loads: erection, required modifications to the wind turbine, environmental conditions, site conditions and transportation logistics, and costs.

3.3.1 Turbine Loads

The loads imposed on the turbine during the erection process must be evaluated to determine whether they will exceed the loads for which the turbine is designed. If the erection loads exceed the design loads, then the costs of any turbine design changes must be considered in the economic analysis.

For the Barnhart lifting frame, the maximum bending load introduced into the turbine occurs in the turbine's tower just at the moment when the tower is lifted but is still in a horizontal position. The bending moment is equal to the weight of the nacelle and the top tower sections multiplied by a moment arm equal to the distance between the centers of gravity of those components and the lifting point. For the 5-MW turbine the total bending moment due to erection was calculated to be 317,925 kNm, (see Figure 20). The maximum load during turbine operation at the tower lift point was calculated to be 174,136 kNm. Therefore, the bending load associated with tower erection is substantially higher than the load experienced during turbine operation. It is possible to reduce the bending moment on the tower by lifting the tower at a location closer to the nacelle. However, that would require taller lifting frames, which would increase costs.

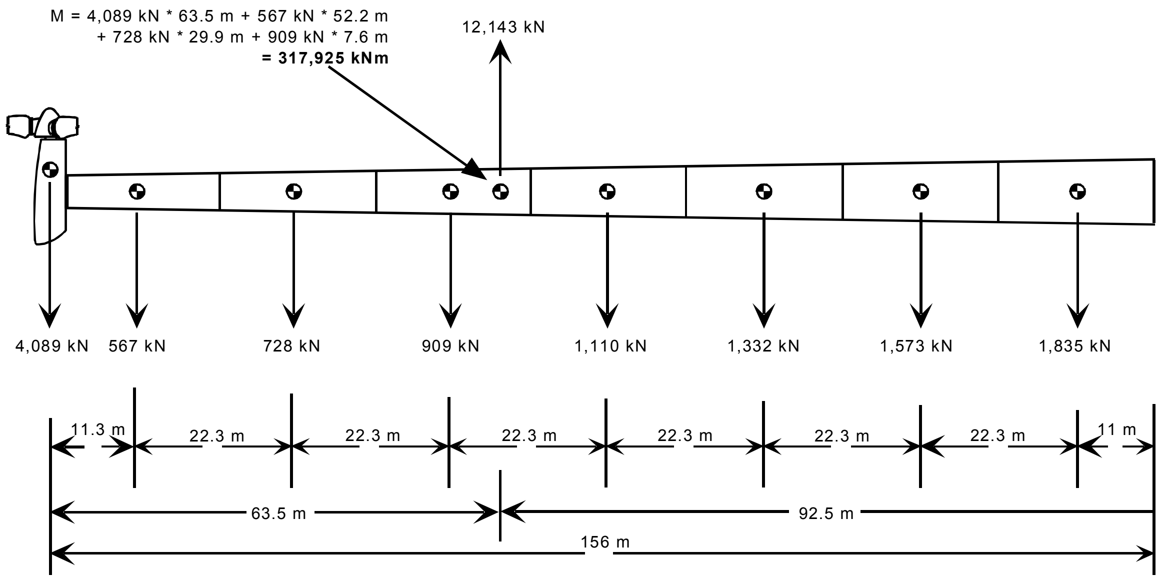


Figure 20. Turbine Loads Associated with the Barnhart Lifting Frame

For the Barnhart climbing frame, the primary loads during erection will be compression forces in the tower due to the weight of the climbing frame, (see Figure 21). The gravity load from the weight of the climbing frame and the turbine component being lifted is transferred to the wind turbine tower through the tension rods that connect to a set of lugs at the top of a tower section. The exact load that is transmitted depends on the weight of the part being lifted, although the worst-case scenario is when the nacelle is being lifted. The total mass of the climbing frame is 158,000 kg and the mass of the nacelle is 254,000 kg. Therefore, the gravity load of the frame and the nacelle combined is 4,042 kN. Bending moments exerted on the tower will be minimal because of the counterweight, which has been designed to eliminate any bending moments. In terms of loading, the climbing frame would probably not have any adverse effect on the wind turbine design.

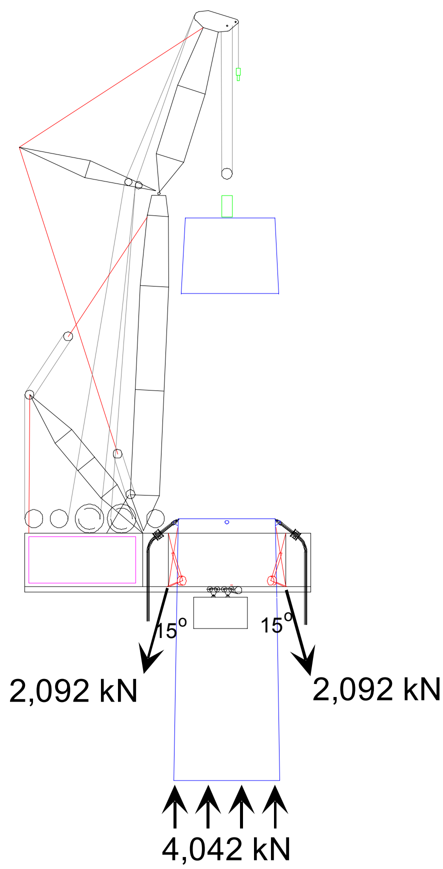


Figure 21. Turbine Loads Associated with the Barnhart Climbing Frame

3.3.2 Modifications to the Wind Turbine Design

The Barnhart lifting frame would require several modifications to a typical wind turbine tower design. These might include mounting trunnions on the tower to serve as attachment points for the lifting frame, and increasing tower strength in the area of the trunnions to accommodate the high lifting loads.

The Barnhart climbing frame would require lugs or other fittings mounted to the tower near the top of each tower section to allow attachment of the climbing frame. The fittings would be potential stress risers and could compromise the fatigue life of the wind turbine tower unless carefully designed. The cost impact of these changes should not be significant if they are considered in the design process.

3.3.3 Environmental Conditions

Another potential limitation of the two Barnhart concepts is wind speed. The lifting frame is particularly susceptible to side winds. GEC's calculations indicate that the frame alone can easily withstand the one-year return wind for an International Electrotechnical CommissionIEC Class 1 site of 52.5 m/s. However, during a lifting operation, the frame is also subject to wind loading imparted by the turbine itself. This loading will be most severe when the turbine is lifted to a nearly vertical position. Barnhart intended the frame to withstand a side load equal to 2% of the weight being lifted, standard practice in the crane industry. GEC calculations show that the 2% side load would be developed in a wind of 6.9 m/s. However, because there is excess margin in the lifting frame, it can withstand higher side loads than the 2% for which Barnhart designed it. The excess margins allow the tower to withstand winds approximately 9.2 m/s. This is a marginal wind speed for use on a wind farm and could significantly reduce the days on which turbine erection could be performed. The climbing frame on the other hand, has sufficient strength to withstand very high winds.

3.3.4 Transportation and Site Requirements

Transportation does not impose a serious logistic burden on either of Barnhart's concepts. One of Barnhart's guiding design philosophies is that all of their systems are built to be placed into 40-foot shipping containers for easy transportation. Therefore, there should be no problems getting the hardware into even the most remote site. The turbines themselves would represent a more significant transportation challenge than the self-erection equipment.

The lifting-frame concept requires a relatively large clearing around the base of the turbine. The footprint of the lifting frame is approximately 17.7 m (58 ft) square. The area under the footprint of the lifting frame needs to be relatively level. In addition to the flat, clear area that is required for the lifting frame's footprint, a large pad is required to allow assembly of the turbine on its side. The larger area for turbine assembly would not necessarily need to be level, because blocking can be provided for the turbine. However, in wooded or complex terrain, to clearing significant amounts of land would be expensive and have significant environmental impact.

The climbing frame, which is 15 m (49 ft) by 24 m (80 ft), does not require a significant amount of clear or level land around the base of the turbine, because temporary blocking can be provided for the frame. The only other space that is needed around the base of the turbine is for a small support crane, and some room to lay out turbine parts. This area would be required independent of the turbine erection techniques developed.

3.4 Costs

Cost-effectiveness is one of the keys to the feasibility of these self-erection concepts. In this section, we present preliminary cost estimates for the two Barnhart concepts analyzed in detail.

The primary costs for each of the self-erection concepts are development cost, capital cost for equipment, transportation cost to get the equipment to the site, labor cost associated with setting up and removing the equipment at each turbine, and labor and material cost for turbine erection. Some of these costs scale with turbine size; however, many of them remain relatively fixed, such as development and equipment capital costs which were amortized over five-years of use. The number of turbines installed in five years varies for the turbine size and for the lifting concept based on full-time use of the equipment over the five-year period. For instance, the Barnhart climbing frame is capable of erecting a 5-MW wind turbine every 10 days, including setup and tear-down time, so it could be used to install 130 turbines over five years. If the development costs were spread out over a larger number of wind turbines, or over a longer period of time, then the cost of self-erection per turbine, or per kW, would drop. We assumed an 18% return on capital investments.

3.4.1 Barnhart Lifting Frame

For the Barnhart lifting frame, the cost of installation is approximately $352,368 per turbine for a wind farm of 50 turbines rated at 5 MW each (see Figure 22). This breakdown to $3,000 per turbine in amortization of development costs; $51,800 per turbine for amortization of capital equipment; $2,800 per turbine for transportation of the lifting equipment from Memphis, Tennessee, to South Dakota; $68,400 for labor costs associated with setting up and dismantling the frame at each turbine; $8,400 for labor costs to operate the equipment during the turbine erection; and $78,100 for labor and materials during turbine installation. A relatively large support crane is required to erect the lifting frame. Based on the height of the lifting frame, it was determined that a Lampson LTL-600 crane or the equivalent is needed for the 5-MW turbine, at a cost of $139,800 per turbine. Smaller support cranes can be used for smaller turbines. The cost of self-erection using the lifting frame is approximately $70.47/kW for a 5-MW turbine. The cost per kW decreases for smaller turbines due to lower support crane costs until a minimum cost is reached at $66.75/kW for the 3.5-MW machine. The cost per kW then increases again for smaller turbine sizes until it reaches a maximum of $107.80/kW for a 750-kW turbine. The major cost component associated with using the lifting frame is the support crane. Barnhart indicated that the lifting frame could be made to be self-erecting. This would significantly reduce the cost of the support crane and make this erection technique more attractive, potentially lowering the costs to a level close to those estimated in the figure below for the Barnhart climbing frame.

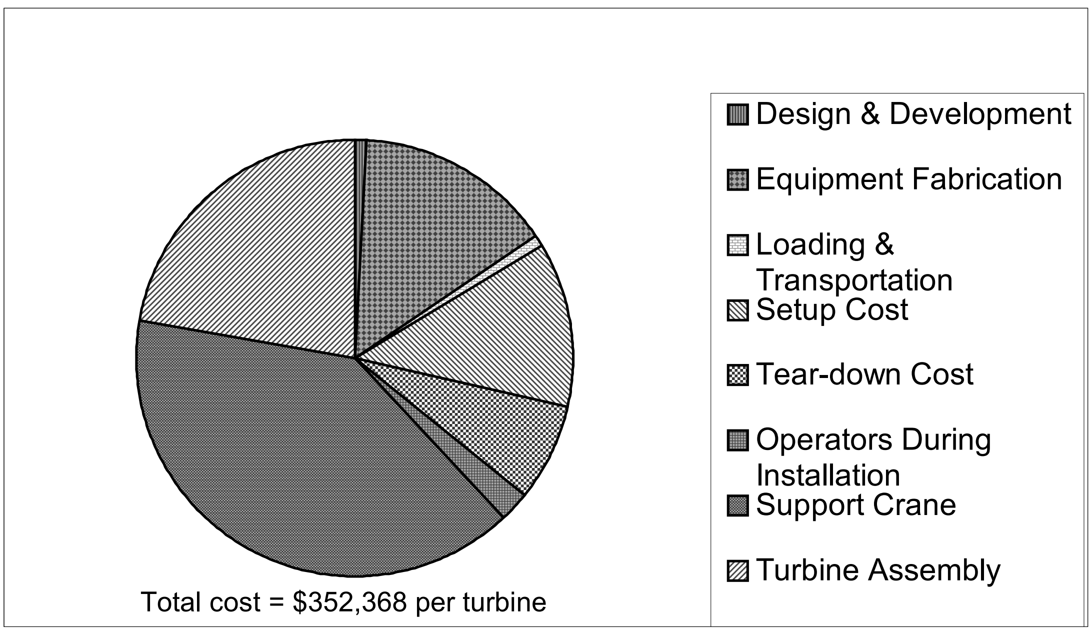


Figure 22. Cost Breakdown for Barnhart Lifting Frame

3.4.2 Barnhart Climbing Frame

The cost of using the Barnhart climbing frame is approximately $139,200 per turbine for a windfarm of 50 turbines rated at 5 MW each (see Figure 23). This breaks down to $1,800 per turbine in amortization of development costs; $10,000 per turbine for amortization of capital equipment; $1,500 per turbine for transportation from Memphis, Tennessee, to South Dakota; $3,600 for labor costs associated with setting up and dismantling the frame at each turbine;

$10,800 for labor costs to operate the equipment during the turbine erection; and $107,600 for labor and materials during turbine installation. The support crane required for the climbing frame is relatively modest in size and costs $3,900 for the 5-MW turbine. The cost of self-erection using the lifting frame is approximately $27.84/kW for a 5-MW turbine. The cost per kW increases for smaller turbines to a maximum of $53.41/kW for a 750-kW turbine.

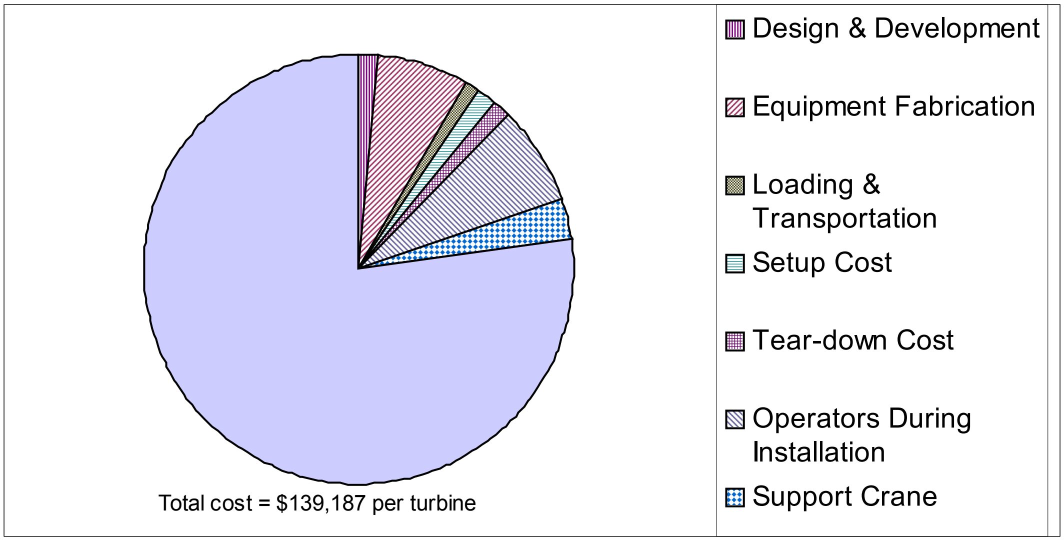


Figure 23. Cost Breakdown for Barnhart Climbing Frame

Barnhart developed the cost elements for the 5-MW turbines,. Some of the cost items, such as development, were estimated based on past experience. Other cost items, such as transportation, were easily quantifiable by Barnhart. Labor rates used are the standard rates that Barnhart charges for construction crews. The number of people in the construction crew and the amount of time needed to accomplish a task were based on past experience, but are subject to significant uncertainty. Barnhart estimated that it would require a total of six days to set up and dismantle their climbing frame. However, they also indicated that the frame could be designed with wheels so that it could potentially be rolled between turbines without being completely dismantled. Therefore, GEC assumed that the climbing frame could be reengineered to be moved between turbines in over 1 day. GEC selected the support cranes based on information gathered in Technical Area 2 of the WindPACT study based on the maximum height and weight required. We present details of the costs for these two concepts in Appendix C.

4. Comparison with Baseline Costs

The costs of using the Barnhart climbing frame were competitive with those of conventional cranes for 1.5-MW through 5-MW turbines, whereas the Barnhart lifting frame was not competitive with conventional crane technology for any of the turbine sizes examined for a 50 turbine project (see Figure 24). The data for conventional cranes were developed from Reference 1 (Technical Area 2 - Turbine, Rotor, and Blade Logistics). GEC expects that the uncertainties in the self-erection costs, variation in terrain and other conditions, and change in turbine hub height, will change the size at which the climbing frame concept is cost effective. GEC does not expect the lifting frame concept to be cost effective under any foreseeable scenario. In general, conventional erection techniques are more cost effective for smaller turbine sizes, whereas self-erection is less expensive for large turbines because the costs for conventional cranes rise sharply as the size increases. Conversely, the cost of self-erection equipment does not rise sharply with turbine size; therefore, the cost per kW decreases with larger turbine size.

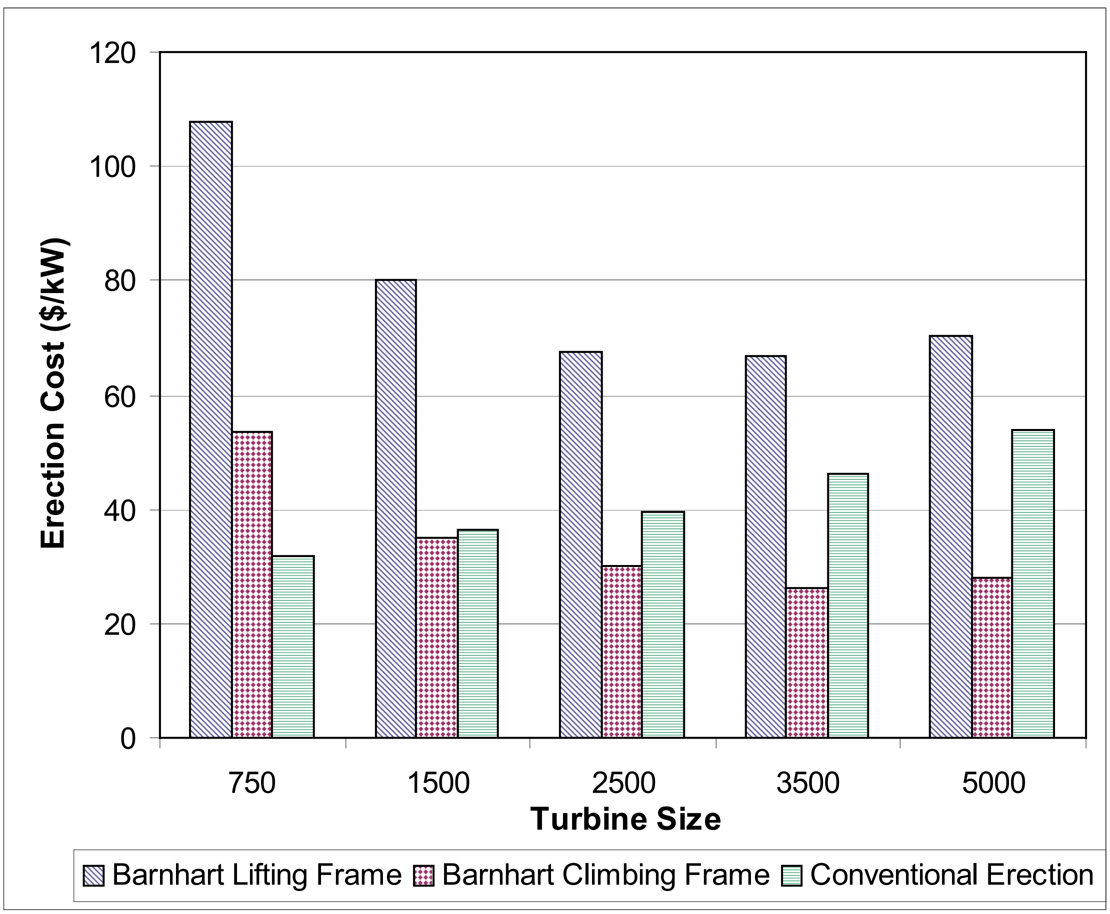


Figure 24. Comparison of Self-Erection and Conventional Erection Costs

According to the results of the Technical Area 2 (Turbine, Rotor, and Blade Logistics) study (even for the largest turbine considered), the cost of erection was less than $60/kW, which is a relatively small fraction of the total system installed cost. For 3.5-MWand 5-MW turbines, there are other costs that grow to dominate the overall installed cost, thus lowering crane and installation prices in comparison. For instance, the transportation cost grows to approximately $242 per kW, even if the towers are sectioned and the gearbox and generator are removed from the nacelle for transport. Therefore, the savings that self-erection can provide for very large wind turbines may be small relative to the overall system cost.

As part of the baseline turbine definition, tower sizes and weights were estimated for turbines up to 5 MW. The sizes and weights were estimated using a spreadsheet-based calculation tool that GEC developed for the WindPACT studies. The tower calculation tool calculates the tower dimensions required to provide sufficient strength to withstand a 50-year extreme gust in an IEC Class 2 wind regime with the blades pitched to their non-feathered position. Figure 25 illustrates the costs of the resulting towers assuming a tower cost of $1.65/kg. The tower costs can be seen to more than double on a capacity basis as the turbine size grows from 750 kW to 5 MW. This increase is a result of both increased tower height and rotor diameter. The growth in tower cost is significantly larger than the cost per kW of cranes and installation. Clearly, the tower design is an area worthy of further consideration when identifying areas for increasing the cost-effectiveness of large wind turbines. The taller towers do however, result in the turbine being exposed to higher wind speeds and thus increased energy capture. The extent to which this is significant is further discussed in the next section of this report.

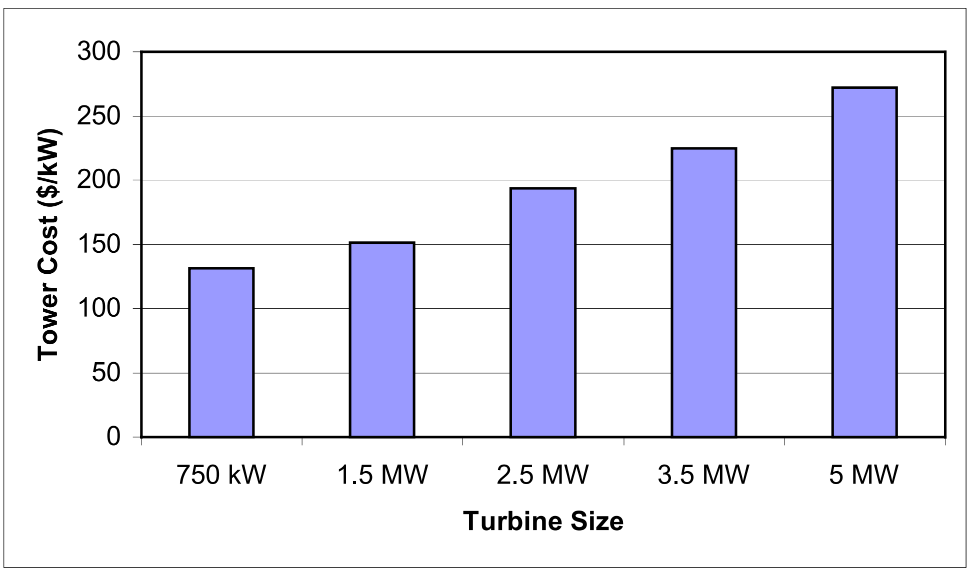


Figure 25. Tower Costs as a Function of Turbine Size

Although the potential cost savings from self-erection are relatively small in flat terrain compared to increases in other costs such as transportation cost or tower cost, the cost savings can become significant in rough terrain. As shown in Figure 26, crane costs can increase dramatically more than $80/kW for a 5-MW turbine if the terrain varies enough to cause the crane to be dismantled and reassembled several times during installation (see Reference 1). Because the Barnhart climbing frame can easily be transported between turbines, regardless of terrain, the cost of self-erection is not expected to vary significantly with rough terrain. This adds significantly to the value of self-erection at rough terrain sites.

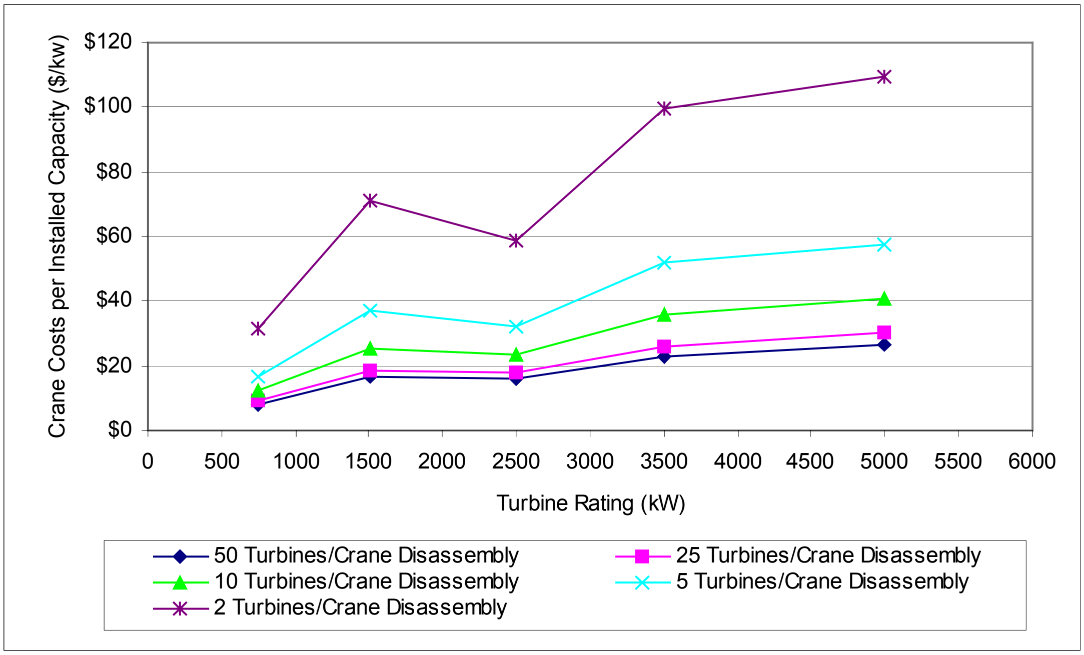


Figure 26. Crane Cost Increase in Rough Terrain

In addition to the added crane costs incurred due to rough terrain, the total amount of time required to install a turbine also increases in rough terrain. Additional finance, insurance, and other costs may accrue during project construction. Figure 27 shows a comparison of installation time for various types of terrain. The effect of rough terrain is a decrease in the number of turbines that can be installed between crane disassemblies. For conventional cranes, the effect of rough terrain is to dramatically increase the installation time. In contrast, the installation time for self-erection is unaffected by terrain because the climbing frame can be quickly and easily broken down into small pieces that are easily transported between turbines in almost any terrain.

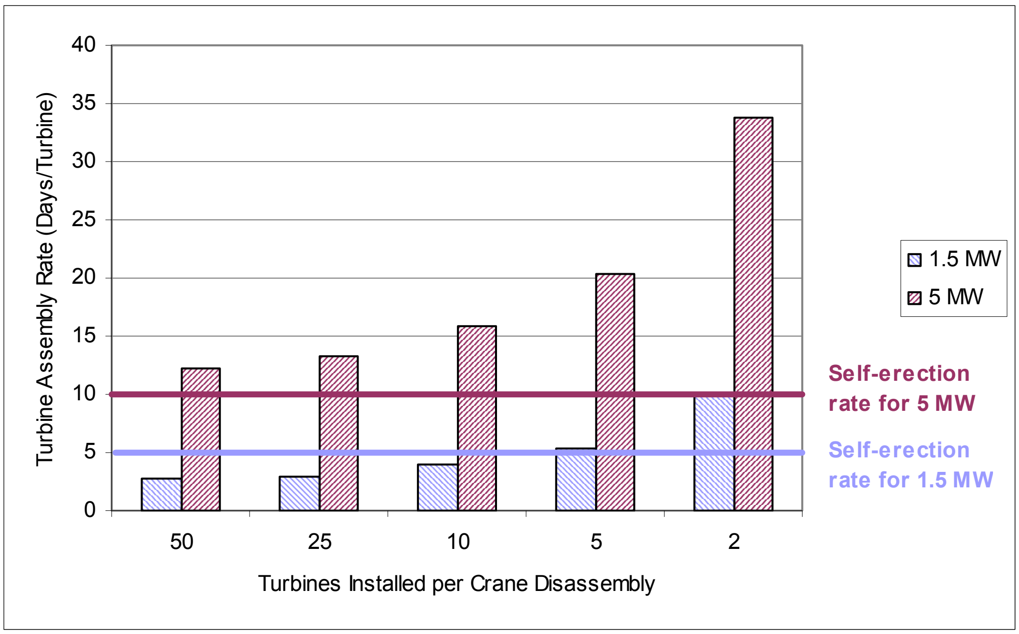


Figure 27. Assembly Time Increase in Rough Terrain

5. Value of Self-Erection

In the previous section, we examined the value of self-erection in regard to erecting the five turbine sizes initially selected for the WindPACT studies. During the course of this study, it became apparent that the wind industry was interested in better understanding the value of self-erection for 750-kW to 1.5-MW turbines. (Particularly, on taller towers than assumed in the WindPact configurations). Anyone wishing to analyze this relatively complex issue, should consider the increase in energy production achieved from the taller tower, as well as the additional costs of the towers and foundations and the additional height's impact on erection and operations and maintenance costs. Although the scope of this study limited the extent to which this issue could be examined, we did complete the following simplified analysis.

First we built a spreadsheet model was built which estimated the cost of energy (COE) from a 1.5-MW wind turbine installed on a 65-meter tower. This estimate was made using a simplified version of the Electric Power Research Institute (Technical Advisory Group) COE equation. The weight, cost, and performance characteristics of this turbine were estimated based on industry information. The model was constructed to permit scaling of the relevant parameters for a second tower height. The second tower height was an input variable. We made the following key assumptions in the scaling analysis:

- Tower cost scales in proportion to tower mass.
- Tower mass scales with height raised to the 1.67 (see Appendix D).
- Wind speeds for higher hub heights were estimated using power law. The exponent (alpha) is a variable in the model.
- Percent increase in energy production with height is twice the percent increase in wind speed, based on an analysis of a typical low wind turbine's output across a range of wind speeds.
- Foundation costs scale linearly with tower height. This assumes the foundation will scale with overturning moment.
- (O&M) Operation and Maintenance costs are a constant $0.008/kilowatt-hour(kWh).
- Conventional-crane costs are proportional to the tower height ratio raised to the 1.6. This is based on the analysis of data developed in WindPACT Technical Area 2 and provided in Appendix C.
- Self-erection costs will be proportional to tower height.

Typical model inputs and outputs are shown in Table 4.

Table 4. Typical Model Inputs and Outputs

INPUTS					
Upper Height (m)	80	65 m Foundation Costs	$60,000		
Lower Height (m)	65	Foundation Cost Exponent	1		
Lower Wind Speed (m/s)	8	Tower Cost exponent	1.67		
Alpha	0.2	BOS cost per kW	$350		
Energy Mult.on Wind Speed Ratio	2	Assembly & Erection /kW 65 m	$40		
Turbine Cost per kW	$650	Assembly & Erection Exponent	1.60		
Turbine Rating (kW)	1,500	CF at Lower Height	0.35		
65 m Tower Costs	$125,000	Discount Rate	0.11		
		O&M per kWh	0.008		
OUTPUTS					
Turbine Cost	$975,000	Assembly & Erection 65 m	$60,000	COE w/o O&M Lower	$0.042
Upper Wind Speed (m/s)	8.34	Assembly & Erection Upper	$83,644	COE w/o O&M Upper	$0.040
Upper/Lower Wind Speed Ratio	1.04	Assembly and Erection Delta	$23,644	Total COE Lower	$0.050
Energy Ratio	1.08	65 m Total Cost	$1,745,000	Total COE Upper	$0.048
Taller-Tower Cost	$176,687	Taller Total Cost	$1,834,177	COE Upper/Lower	$0.974
Taller Tower Foundation Cost	$73,846	65m Total Cost /kW	$1,163	COE Delta	$0.001
BOS Cost	$525,000	Taller Total Cost per kW	$1,223		

We used the model to complete several analyses. In the first analysis, we examined the COE as a function of tower height and wind shear. The results of this study are shown in Figure 28. Note that even in sites with substantial wind shear, the model predicts a minimum in the COE. That is, COE does not continue to decline with tower height. The maximum reduction in COE available from increasing tower height is approximately 12% in a site with a wind speed exponent of 0.3. If the multiplier relating change in energy capture to change in mean wind speed changes from 2 to 2.5, the reduction in COE changes to 17% thus indicating an interesting potential trade between increasing the rotor area per unit rating of a turbine and increasing tower height.

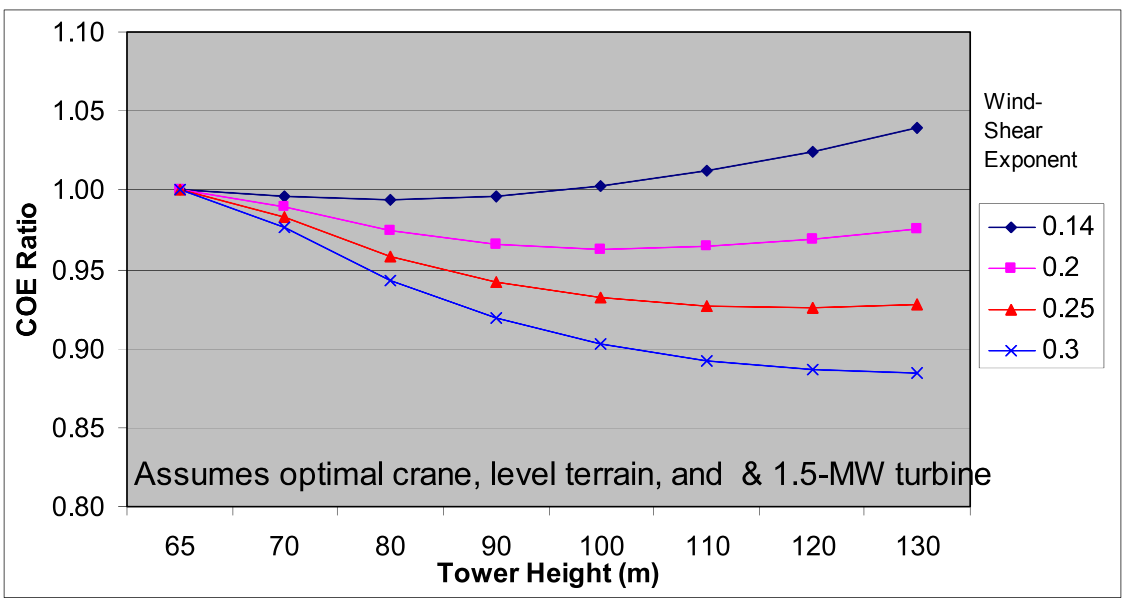


Figure 28. Impact of Tower Height on COE

For the second analysis, we examined the cost of turbine erection as a function of tower height. Figure 29 shows the results of this analysis. This provides the developer of a self-erection system a sense for the value that can be placed on self-erection services. These do not, however, consider the possible benefit of self-erection devices to O &M costs. The results shown in Figure 29 are based on use of a crane that is optimally sized for the weight and height being lifted. Because cranes are available in discrete sizes, the more typical scenario is that the crane is taller than required for the job and one ends up paying for "excess capacity." The excess crane capacity could potentially increase the actual assembly and erection costs slightly compared to those shown in Figure 29. Terrain also has a significant effect on the cost of installation. Rough terrain conditions are represented in Figure 29 by the lines for five or two turbines/crane disassembly. For the case where a crane disassembly is required every 2 turbines, the cost of assembly and erection more than doubles compared to that for benign terrain.

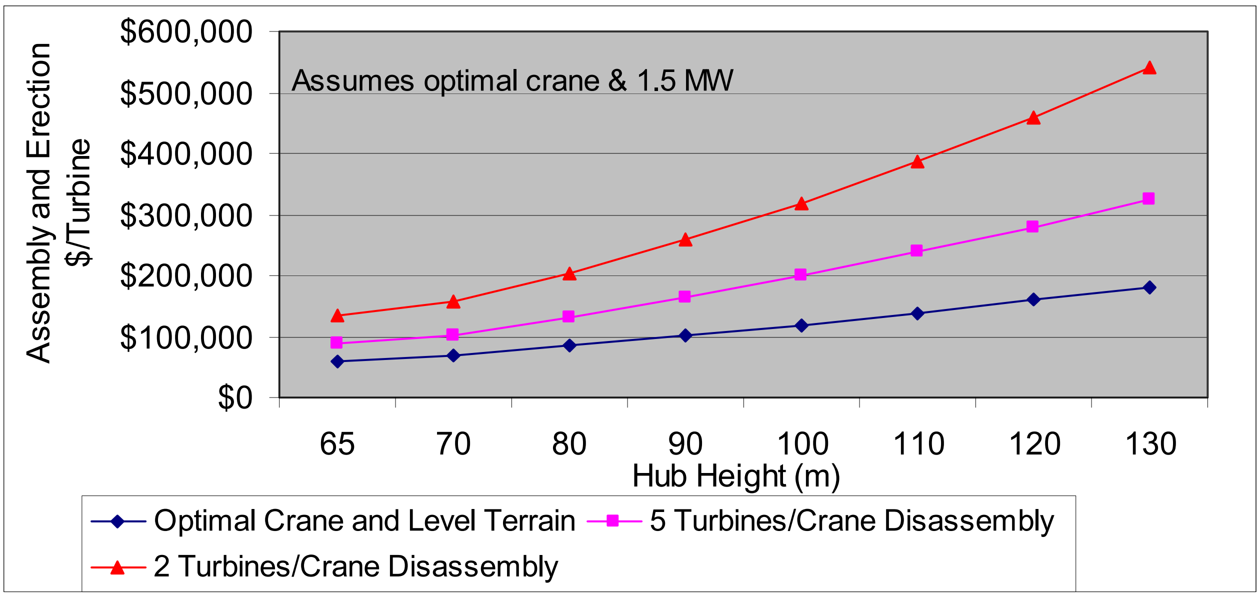


Figure 29. Assembly and Erection Costs as a Function of Hub Height

For the third analysis, we compared the COE obtained with self-erection with the COE obtained using an optimized crane. The results of this analysis are shown in Figure 30. In this analysis, we assumed that the optimal crane is used for the traditional erection process, however, this may not always be the case. In addition, we can see in Figure 30 that the COE significantly increases in complex terrain. The results shown in Figure 30 assume a wind shear exponent of 0.2; however, we expect that the results would change with different values of wind shear.

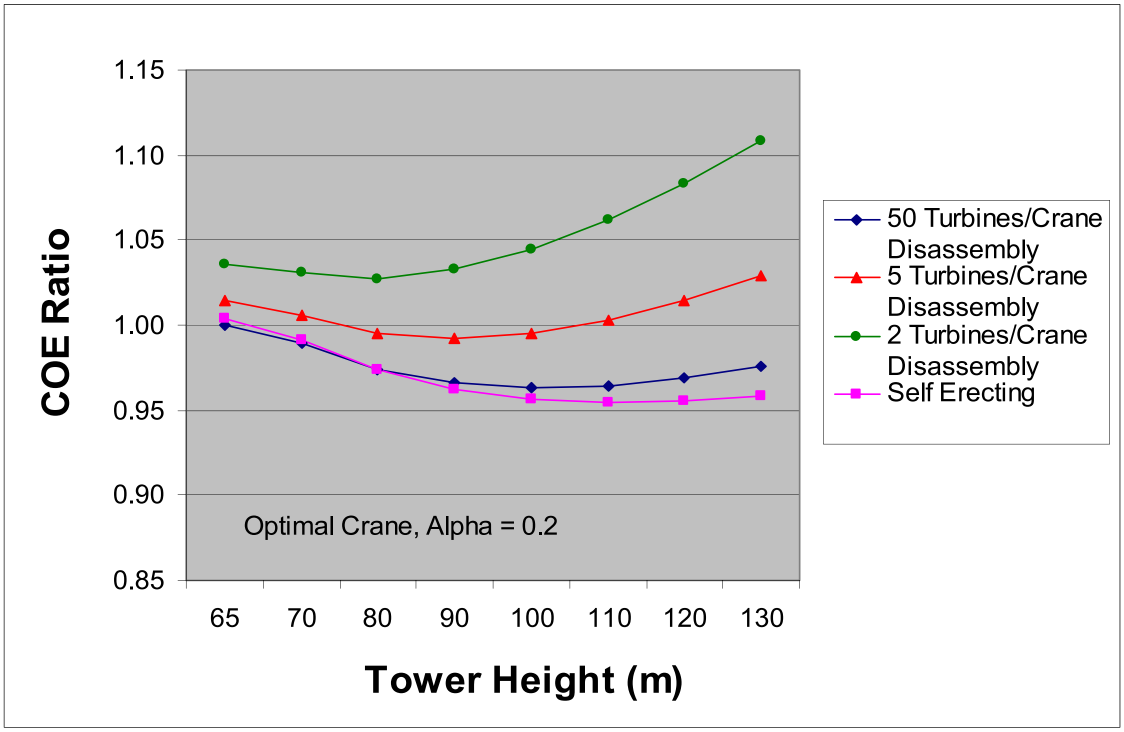


Figure 30. COE Impact of Self-Erection

6. Conclusions

The Barnhart lifting frame that tilts the wind turbine up after the turbine has been fully assembled on the ground was not competitive with conventional crane technologies. This concept has some significant limitations. Specifically, the size, weight, and cost of the frame are large enough that the concept is not economically competitive with conventional lifting methods or other self-erection techniques. The economics are further hurt because a relatively large support crane is required to erect the lifting frame. Barnhart indicated that the lifting frame itself could be made to be self-erecting, which would improve the economics of the scheme. However, there are some logistic problems with the concept that further reduce its attractiveness. A large pad is required around the base of the wind turbine in order to allow the turbine to be assembled on its side, to provide a base for the lifting tower, and for the support crane. The large-pad requirement increases the costs of the lifting tower concept and creates sensitive environmental considerations in complex or wooded terrain.

The Barnhart climbing frame--which raises each tower section into place and then climbs that tower section using strand jacks so that the subsequent tower section can be lifted--was found to be competitive with conventional cranes for erecting large wind turbines. It appears to be cost-competitive with conventional crane technology for wind turbines of 1.5 MW or larger, and offers significant potential savings for 5-MW turbines. We identified no major technical barriers that would limit the use of this technology. Because it requires only a small pad around the base of the turbine, and because it does not require a large support crane, this self-erection concept appears to be particularly promising for sites in complex terrain. The economic analysis was completed assuming relatively benign terrain. In some complex terrain the self-erection technologies would be even more competitive. One potential concern that must be addressed is the attachment of the climbing frame to the wind turbine tower. Lugs must be added to each tower section to facilitate attachment of the climbing frame. The lugs add stress risers to the tower and could potentially be problematic for the fatigue life of the tower if not designed and fabricated carefully.

The cost of self-erection, as estimated by Barnhart and GEC, is higher than conventional crane lifting for wind turbines smaller than 1.5 MW. Above this size, cost savings are possible from self-erection. The cost estimates were based on a variety of assumptions that affect where the price crossover point is. In our study for example, we assumed that 50 turbines were installed. The cost of self-erection could be reduced if a larger number of turbines were included in the analysis. Self-erection of turbines smaller than 1.5-MW on towers more than 80 meters tall may be cost effective in complex terrain where the use of a large crane is problematic.

Regardless of the turbine size, where self-erection becomes economically feasible it is apparent that in relatively benign terrain, the cost-savings potential is not a major contributor to the overall system cost. Crane and installation costs are relatively small contributors to the total wind turbine system cost for the WindPACT turbine configuration. Crane and assembly costs are only in the range of $30 to $55 per kilowatt compared to total system costs of approximately $1000 per kilowatt. Even if the crane costs could be completely eliminated, that would only represent a savings of approximately1% to 2%. The savings are substantially greater in complex terrain. Assuming a wind shear exponent of 0.2, and an 80-meter tower height, the self-erection can reduce COE approximately 5% compared to conventional cranes.

Although self-erection by itself may not achieve large savings on the overall cost of a wind turbine, it can reduce the cost of energy by allowing the use of taller towers. Taller towers place the wind turbine in higher wind speeds. This can be especially advantageous at sites with high wind shear. However, tower height is often limited by the availability of cranes for installing the turbine, and the costs of the larger cranes needed to erect taller machines are significantly higher. Therefore, self-erection schemes can eliminate the crane limitation, reduce costs, and allow a tall tower, which gets the rotor into the higher winds where it can capture more energy. The overall COE savings available using this approach depends on the terrain and how well optimized the design is for crane use. Assuming a wind shear exponent of 0.2 and complex terrain, we can conclude that moving from a 65-meter to a 100-meter tower will increase COE slightly if a crane is used. If a self-erecting turbine were used, COE would be reduced approximately 8%.

Several companies are developing self-erection schemes independently of the WindPACT program. These companies anticipate a market for self-erecting turbines as small as 660 kW. They believe that self-erection is an attractive option because of the possibility for taller towers. This advantage is particularly important in the Midwest, where wind shear has been measured at some sites to be considerably higher than 0.20. The companies developing self-erection technologies also perceive an advantage in performing operations and maintenance tasks.

Although self-erection offers the potential for reductions in COE, the increase in the costs of towers as turbine size increases is a significantly larger contributor to the cost of energy than increased crane costs. Research into alternate/innovative towers for large turbines, potentially incorporating self-erection features could significantly reduce cost of energy.

7. References

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Appendix A

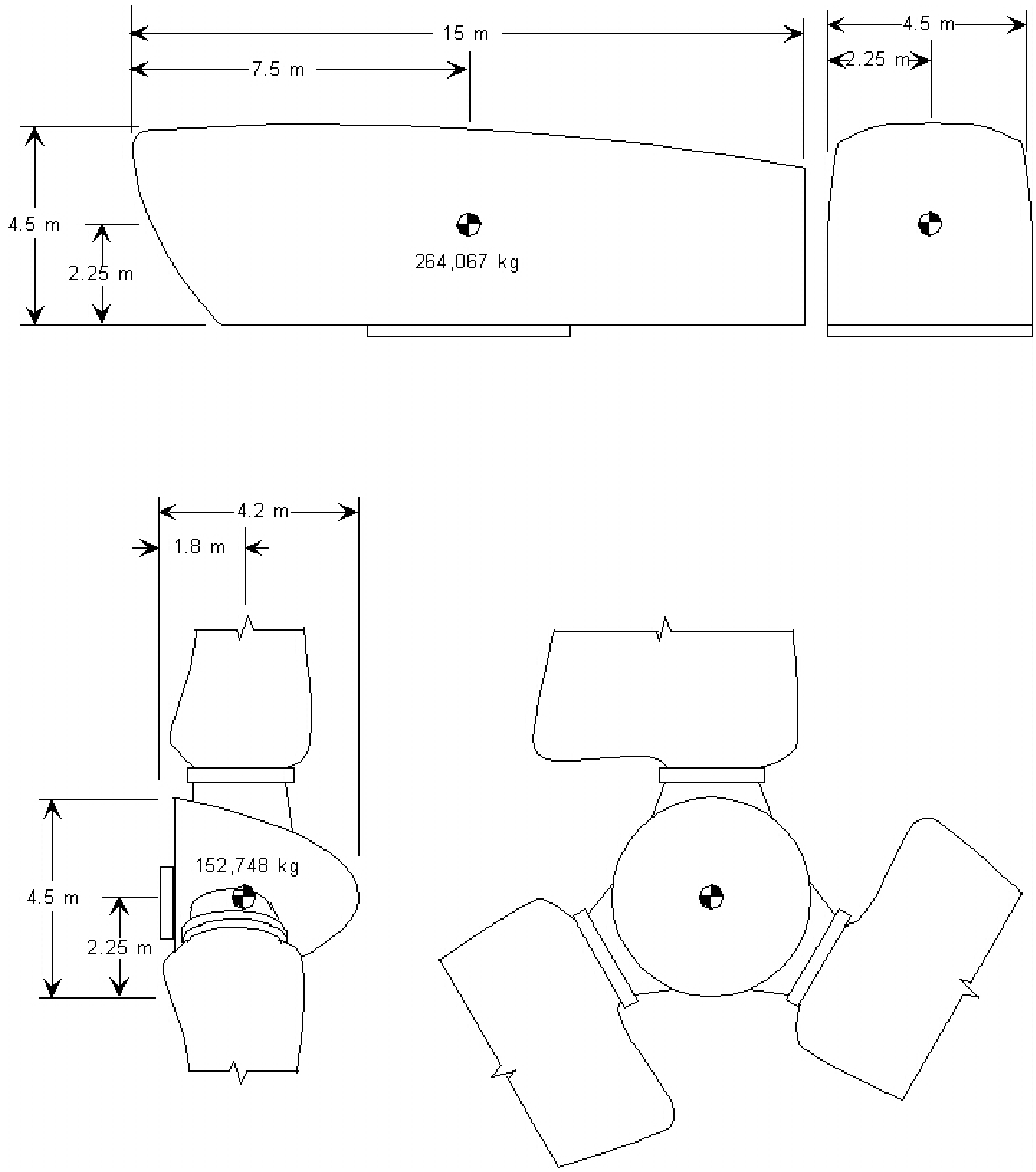


Figure A1. 5-MW Turbine Center of Gravity Data

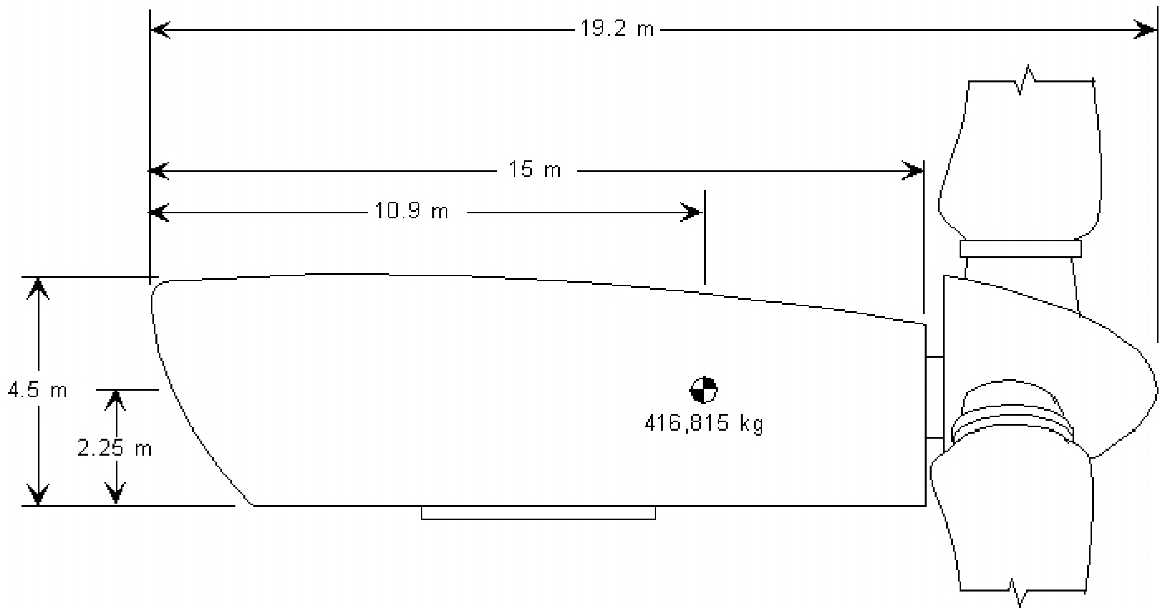


Figure A2. 5-MW Turbine Center of Gravity Data

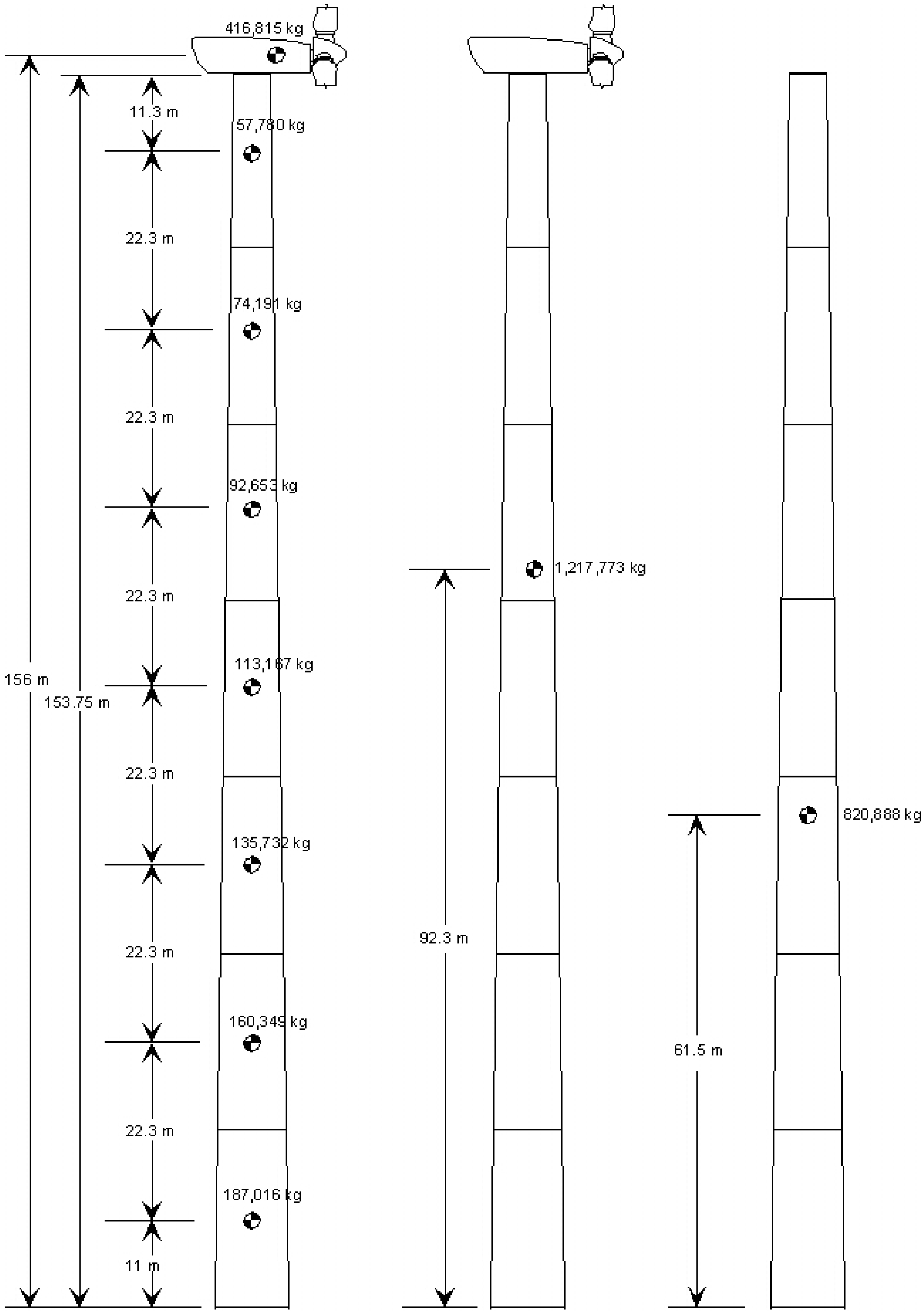


Figure A3. 5-MW Turbine Center of Gravity Data

Appendix B

Concept	Labor Cost	Capital Cost	Innovation Needed	Erection Speed	Loads	Feasibility	Applicability for Maintenance Tasks	Turbine Mods Req'd	Possibility for Alternative Turbine Designs
Tilt-up (ginpole & foundation)									
T&T Tilt-up (no winch foundation)									
Jack-up with offshore rack and pinion towers									
Jack-up with Barnhart lifting frame									
Slip-form with oil derrick frame (non-tapered tower)									
Slip-form with Barnhart frame (tapered tower)									
Telescoping									
Climbing frame with boom and jib									
Climbing frame with boom, jib, and counterweight									
Climbing frame with strand-jacks									

Figure B1. Sample Concept Score Sheet

Appendix C

Table C1. Barnhart Lifting-Frame Cost Estimates

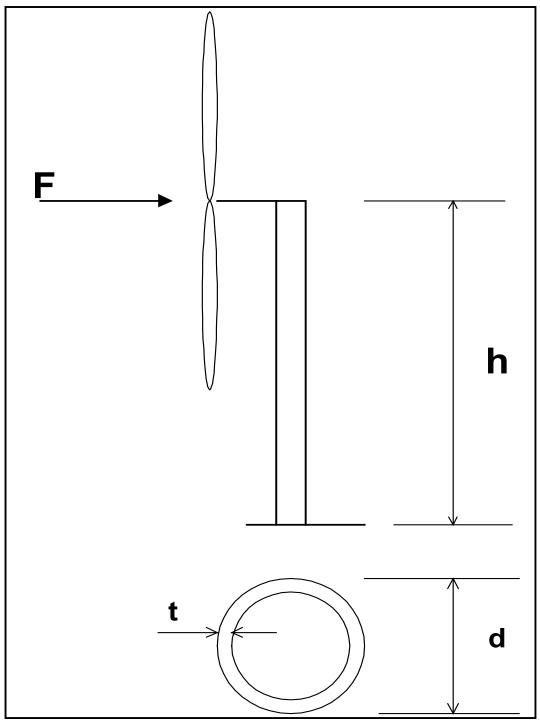
Turbine size (kW)	750	1500	2500	3500	5000	Notes
Equipment development cost	$100,000	$100,000	$100,000	$100,000	$100,000	667 hours at $150/hr
Equipment capital cost	$900,000	$1,100,000	$1,300,000	$1,500,000	$1,700,000	Based on an estimate from Barnhart
Dev. & capital cost per turbine	$10,548	$19,690	$31,175	$45,005	$54,850	Assumes an 18% rate of return on capital costs with investment paid off after five years
Transportation cost/mile	$40	$45	$50	$55	$60	$60/mile transport rate from Barnhart
Miles transported (Memphis to S.D., round trip)	2000	2000	2000	2000	2000	
Transportation cost	$80,000	$90,000	$100,000	$110,000	$120,000	
Loading at Barnhart	$12,000	$14,000	$16,000	$18,000	$20,000	Scaled by weight using climbing frame number
Setup time	5	7	9	11	12	Estimated by Barnhart and GEC. Subject to a large uncertainty
Setup operators	9	9	9	9	9	
Labor rate ($/hr)	$50	$50	$50	$50	$50	$50/hr labor rate from Barnhart
Setup cost	$18,000	$25,200	$32,400	$39,600	$43,200	
Tear-down time	3	4	5	7	7	Estimated by Barnhart and GEC. Subject to a large uncertainty
Tear-down operators	9	9	9	9	9	
Tear-down cost	$10,800	$14,400	$18,000	$25,200	$25,200	
Number of operators required	3	3	3	3	3	Does not include the turbine erection crew
Number of days for turbine installation	1	3	5	6	7	Estimated by Barnhart and GEC. Subject to a large uncertainty
Operator cost	$1,200	$3,600	$6,000	$7,200	$8,400	
Adjustment to tower rig & set labor	$0	-$1,445	-$3,371	-$5,297	-$8,187	Adjustment to assembly cost based on decreased time required
Adjustment to nacelle & rotor rig & set labor	$0	-$1,180	-$2,753	-$4,326	-$6,685	Adjustment to assembly cost based on decreased time required
Adjustment to assembly general conditions	$0	-$406	-$947	-$1,488	-$2,300	Adjustment to assembly cost based on decreased time required
Turbine assembly labor & materials	$17,662	$22,440	$37,179	$43,489	$78,078	Based on costs from Technical Area 2 with adjustment for self-erection assembly times
Support crane used	150-ton truck	M 4100W	M 4100W	M 4600W	LTL-600	Based on height and weight information gathered under Technical Area 2
Hourly support crane cost	$325	$374	$374	$490	$920	Costs are based on information gathered under Technical Area 2
Support crane cost	$20,800	$32,912	$41,888	$70,560	$139,840	The support crane is needed during setup and tear down of the frame. Support crane costs during turbine installation are included in the erection costs under Technical Area 2 and are not included in this number.
Cost per turbine	$80,850	$120,321	$168,962	$233,614	$352,368	
Cost per kW	$107.80	$80.21	$67.58	$66.75	$70.47	
Cost for 5-turbine project	$4,042,504	$6,016,066	$8,448,125	$11,680,684	$17,618,390	

Table C2. Barnhart Climbing Frame Cost Estimates

Turbine size (kW)	750	1500	2500	3500	5000	Notes
Equipment development cost	$150,000	$150,000	$150,000	$150,000	$150,000	1000 hours at $150/hour
Equipment capital cost	$600,000	$650,000	$700,000	$750,000	$850,000	Based on and estimate from Barnhart
Dev. & capital cost per turbine	$4,395	$5,626	$6,973	$9,493	$11,720	Assumes an 18% rate of return on capital cos with investment paid off after five years
Transportation cost/mile	$15	$20	$25	$30	$33	$33/mile transport rate from Barnhart
Miles transported (Memphis to S.D., round trip)	2000	2000	2000	2000	2000	
Transportation cost	$30,000	$40,000	$50,000	$60,000	$66,000	
Loading at Barnhart	$5,000	$6,300	$7,700	$9,000	$10,000	
Setup time (days)	0.5	0.5	0.5	0.5	0.5	
Setup operators	9	9	9	9	9	
Labor rate ($/hr)	$50	$50	$50	$50	$50	$50/hr labor rate from Barnhart
Setup cost	$1,800	$1,800	$1,800	$1,800	$1,800	
Tear-down time	0.5	0.5	0.5	0.5	0.5	
Tear-down operators	9	9	9	9	9	
Tear-down cost	$1,800	$1,800	$1,800	$1,800	$1,800	
Number of operators required	3	3	3	3	3	Does not include the turbine erection crew
Number of days for turbine installation	4	5	6	8	9	Based on 1 day per tower section, plus a little for the nacelle and rotor
Operator cost	$4,800	$6,000	$7,200	$9,600	$10,800	
Adjustment to tower rig & set labor	$3,750	$4,183	$4,760	$5,337	$6,203	Adjustment to assembly cost based on extra time required
Adjustment to nacelle & rotor rig & set labor	$1,667	$1,845	$2,082	$2,319	$2,674	Adjustment to assembly cost based on extra time required
Adjustment to assembly general conditions	$2,000	$2,265	$2,618	$2,971	$3,500	Adjustment to assembly cost based on extra time required
Turbine assembly labor & materials	$25,079	$33,762	$53,709	$65,226	$107,627	Based on costs from Technical Area 2 with adjustment for self-erection assembly times
Support crane used	50 ton hydr.	150 ton truck	150 ton truck	M 4100W	M 4600W	Based on height and weight information gathered under Technical Area 2
Hourly support crane cost	$185	$325	$325	$374	$490	Costs are based on information gathered und Technical Area 2
Support crane cost	$1,480	$2,600	$2,600	$2,992	$3,920	The support crane is needed during setup an tear down of the frame. Support crane costs during turbine assembly are included in the assembly costs and are not included in this number.
Cost per turbine	$40,054	$52,514	$75,237	$92,292	$139,187	
Cost per kW	$53.41	$35.01	$30.09	$26.37	$27.84	
Cost for 50-turbine project	$2,002,703	$2,625,696	$3,761,839	$4,614,582	$6,959,352	

Appendix D

Table D1. Development of Tower Mass Scaling Exponent with Height



Notation:

d = tube diameter
t = tube wall thickness
h = tower height
F = rotor thrust = constant
A = cross-section area
S = section modulus
M = section-bending moment
f = bending stress

Assumptions:

tower is tubular
tower wall thickness is proportional to tube diameter
tower moment is due to rotor thrust only

Approach:
The bending stress at the tower base due to the rotor thrust will be a constant for all designs.

We have

$$M = Fh$$

and

$$S \propto d^2 t \propto d^3$$

$$f = M/S$$

$$\propto \frac{Fh}{d^3}$$

$$\therefore \frac{f}{F} = \text{const.} \propto \frac{h}{d^3}$$

$$\therefore d \propto h^{1/3}$$

Tower cross section is

$$A \propto dt$$

$$\propto d^2$$

$$\propto h^{2/3}$$

Tower mass is

$$\text{mass} \propto \text{volume}$$

$$\propto Ah$$

$$\propto h^{2/3} h$$

$$\propto h^{5/3}$$

Conclusion: The tower mass will be proportional to the height to the power of 5/3.

Table D2. Crane Cost as a Function of Hub Height

	4600 S5	LTL-600	LTL-850	LTL-1100	LTL-1200
Crane Costs	$10,709.00	$24,709.00	$40,817.00	$79,069.00	$133,867.00
Assembly Costs	$20,345.00	$25,555.00	$44,184.00	$53,907.00	$94,794.00
Total Costs	**$31,054.00**	**$50,264.00**	**$85,001.00**	**$132,976.00**	**$228,661.00**
Tower Height (m)	**Cost/Height ($/m)**	**Cost/Height ($/m)**	**Cost/Height ($/m)**	**Cost/Height ($/m)**	**Cost/Height ($/m)**
60	$517.57	$837.73	$1,416.68	$2,216.27	$3,811.02
65	$477.75	$773.29	$1,307.71	$2,045.78	$3,517.86
70	$443.63	$718.06	$1,214.30	$1,899.66	$3,266.59
75	$414.05	$670.19	$1,133.35	$1,773.01	$3,048.81
80	$388.18	$628.30	$1,062.51	$1,662.20	$2,858.26
85	$365.34	$591.34	$1,000.01	$1,564.42	$2,690.13
90		$558.49	$944.46	$1,477.51	$2,540.68
95		$529.09	$894.75	$1,399.75	$2,406.96
100		$502.64	$850.01	$1,329.76	$2,286.61
105			$809.53	$1,266.44	$2,177.72
110			$772.74	$1,208.87	$2,078.74
115			$739.14	$1,156.31	$1,988.36
120			$708.34	$1,108.13	$1,905.51
125			$680.01	$1,063.81	$1,829.29
130				$1,022.89	$1,758.93
135				$985.01	$1,693.79
140				$949.83	$1,633.29
145				$917.08	$1,576.97
150				$886.51	$1,524.41
155					$1,475.23
160					$1,429.13
165					$1,385.82
170					$1,345.06
175					$1,306.63
180					$1,270.34

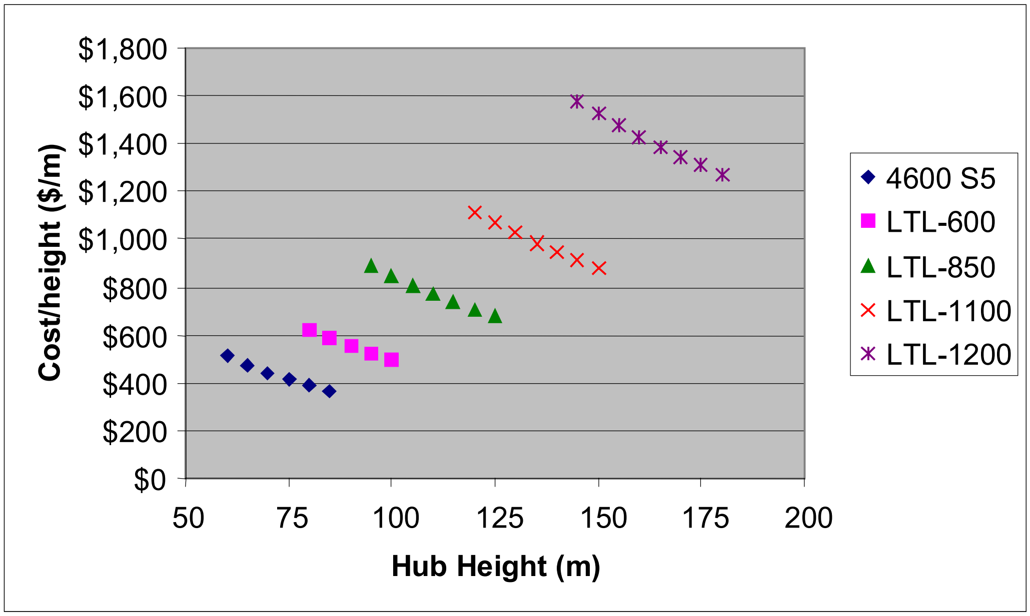


Figure D1. Crane Costs for "Near-Optimal" Cranes

Data is taken from the shaded cells in Table D2.

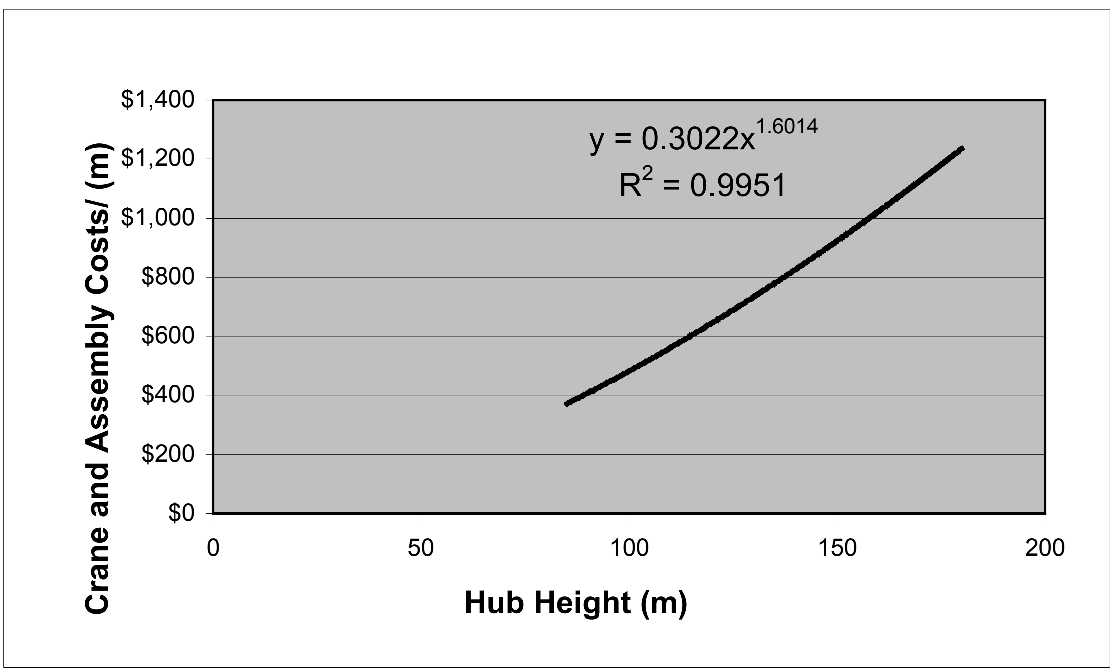


Figure D2. Crane Cost as a Function of Hub Height for Optimal Cranes

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13. ABSTRACT *(Maximum 200 words)*
The United States Department of Energy (DOE), through the National Renewable Energy Laboratory (NREL), has implemented the Wind Partnerships for Advanced Component Technologies (WindPACT) program to explore advanced technologies for improving the reliability and cost-effectiveness of wind energy technology. Global Energy Concepts (GEC) prepared this report on self-erecting towers as part of the WindPACT program. The objectives of the work were to identify potential methods for erecting wind turbine towers without the use of large conventional cranes, establish the most promising methods, and compare the costs of the most promising methods to the costs of conventional cranes.

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