A report concerning

A Self-Erecting Method for Wind Turbines. Phase 1: Feasibility and Preliminary Design.

Submitted to

Xcel Energy Renewable Development Fund
Contract # BW06

By

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1 INTRODUCTION

1.1 Background

The cost of energy from wind turbine installations is now competitive with many conventional sources such as thermal and hydroelectric plants. This is due largely to the improved efficiency and reliability of current wind turbine designs. The trends in wind turbine design are towards larger machines (over 1 MW in rating) and towards taller supporting towers. Both of these trends tax the ability of conventional installation methods which rely on mobile cranes to install all components.

The cost of installation of modern wind turbines was included in a recent study by Global Energy Concepts LLS (GEC) carried out on behalf of the U.S. Department of Energy as part of their Wind Partnerships for Advanced Component Technology (WindPACT) program [3]. One of the barriers to development was identified as the availability of suitable cranes which represent an increasing fraction of the total cost as heights and weights increase. The present maximum tower height of wind turbines is about 260 ft (80 m) while typical installations use towers of about 210 ft (65 m) height. However, in many locations, especially in the Great Plains of the U.S., the wind speed increases considerably with height and a more cost-effective installation is possible if the hub-height can be increased to 330 ft (100 m) or more.

Another study funded by the WindPACT program examined possible methods for installing the tower and wind turbine without the use of cranes [4]. One of the methods selected by that study as showing promise was a system involving a frame which could climb the tower. In an independent study D. H. Blattner & Sons and Elgood Mayo Corp. jointly developed and assessed a specific self-erecting design concept [1].

In December of 2001 D.H. Blattner & Sons, Inc (DHB) submitted a proposal to the Xcel Renewable Development Fund (RDF) for a 3-phase program to develop and commercialize a system for the self-erection of wind turbines. The proposed phases were:

- Phase 1 – Feasibility Assessment and Preliminary Design
- Phase 2 – Detailed Design and Fabrication of Prototype
- Phase 3 – Field Installation and Test of Prototype

Xcel subsequently awarded a contract to DHB for the first of these three phases.

1.2 Scope

This report presents the results of Phase 1 of the program. It includes a description of the statement of work, the approach taken to achieve the goals, the results obtained, and recommendations for further development and demonstration of this technology by proceeding with detailed design, fabrication, and testing

1.3 Objectives

The purpose of the work described in this report was:

- Identify the design peak and fatigue loads on a set of four specified tower/rotor combinations.
- Determine the design loads during the self-erection of the four towers
- Determine what modifications would be required to accommodate the self-erection loads.
- Obtain fabrication costs for two sets of towers: one set for conventional crane erection and one for the self-erection method.
- Determine the total costs of installation for both erection scenarios.
- Determine the cost effectiveness of the self-erection method relative to conventional methods.

2 APPROACH

2.1 Project organization

The main subcontractor, D.H. Blattner & Sons, worked with Elgood Mayo Corp. who carried out some of the steel design, and Global Energy Concepts LLC who are consultants to the wind energy industry and who supplied information on loads and costs. DMI Industries Inc. (DMI) provided information on current tower fabrication methods and supplied cost estimates. Brennan Engineering & Consulting carried out some of the work on behalf of Elgood Mayo Corp. Figure 2-1 shows an organizational chart of the project team.

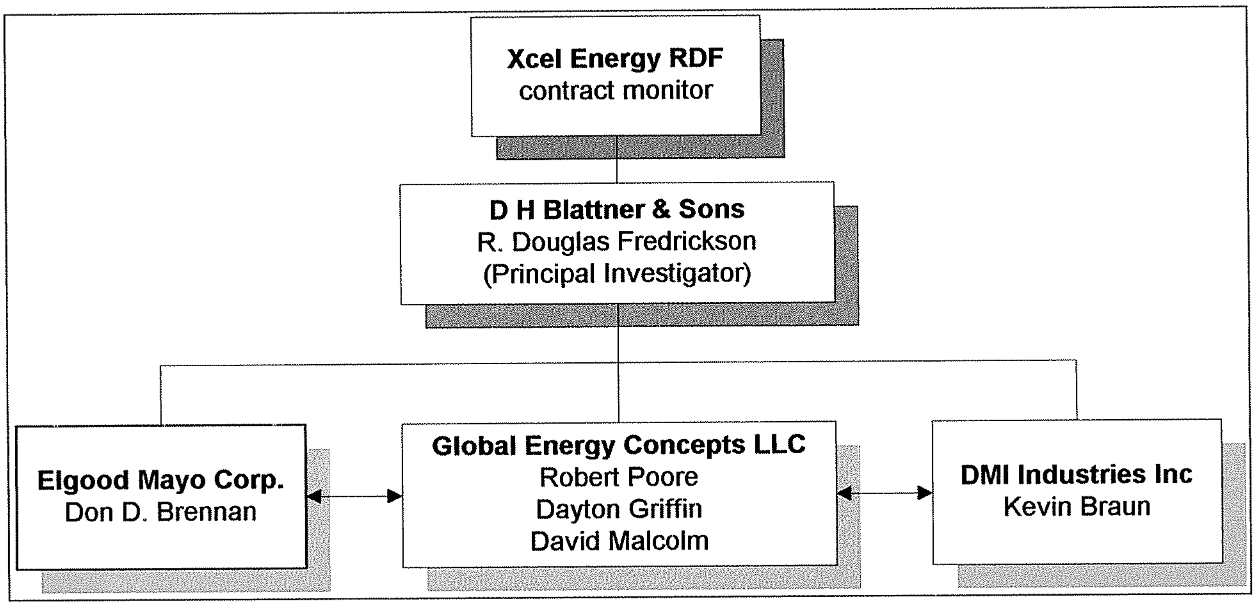


Figure 2-1. Organizational chart of the project team

2.2 Self-erection process

The self-erection process and some details of the climbing platform are shown in Figures 2-2, 2-3, and 2-4. The process consists of the following steps:

- The first tower length (base section) with "guide rails" attached is lifted into place by a medium-capacity crane.
- The climbing platform is connected to the base section.
- The second tower length is lifted onto the climbing platform.
- The climbing platform works its way up to the top of the first tower length.
- The second tower length is moved to be above the first and the connections are made between the two tower lengths.
- The platform descends to pick up the next tower length
- The process is repeated until all the tower sections are in place.
- The turbine nacelle with rotor are lifted into place on the climbing platform and raised to the top of the tower.
- The nacelle, supported by the sling shown in Figure 2-3, is moved over the tower and connected.
- The guide rails are removed and the climbing platform moved to the next tower.

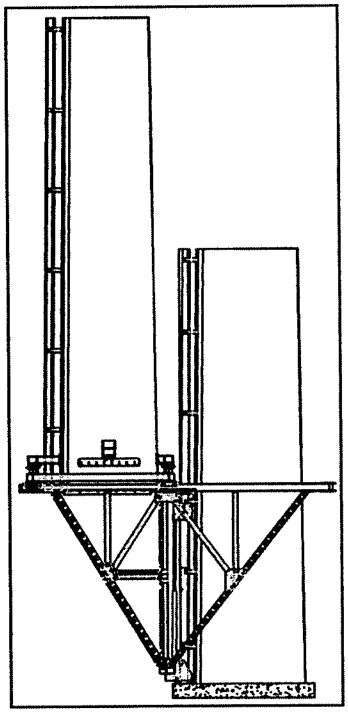


Figure 2-2. Climbing platform with tower length

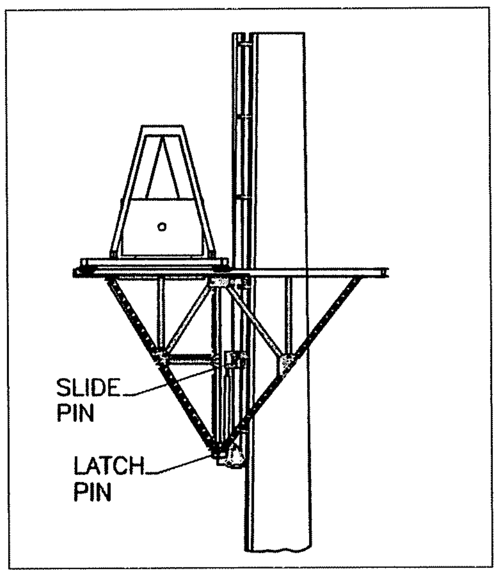


Figure 2-3. Climbing platform carrying nacelle

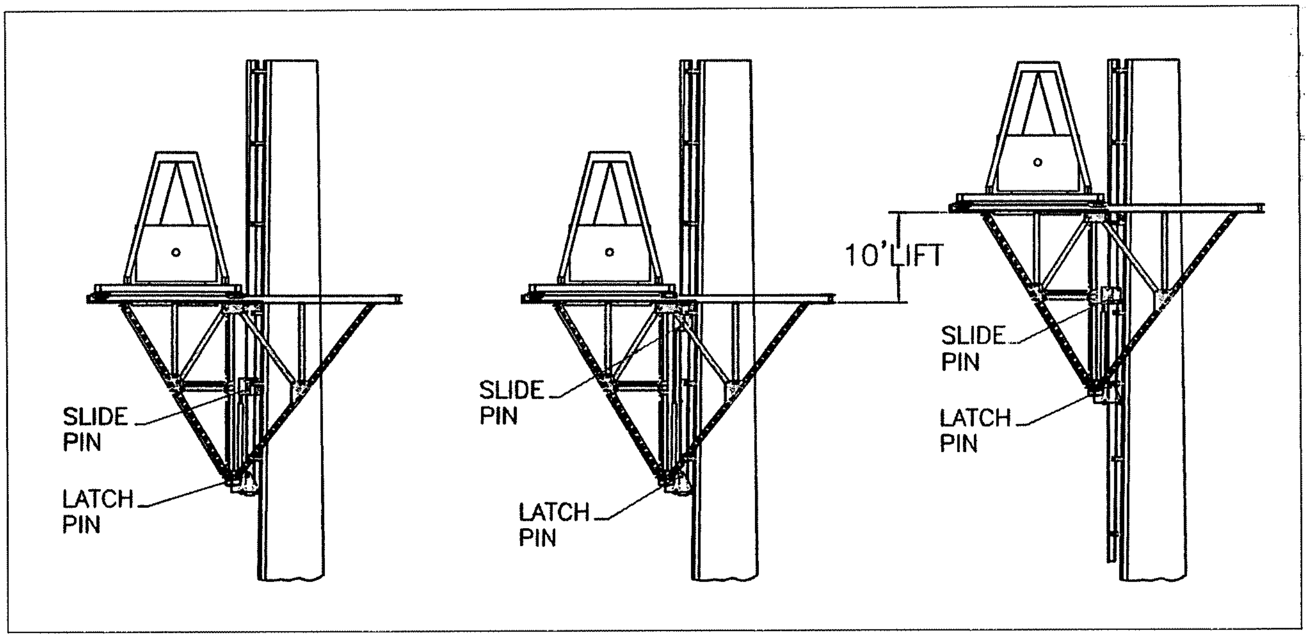


Figure 2-4. Sequence of steps in raising climbing platform

2.3 Selection of towers and turbines

The original statement of work specified four tower/wind turbine combinations:

- A 900 kW wind turbine on a 207-ft (63.1 m) tower.
- A 900 kW wind turbine on a 272-ft (82.9 m) tower.
- A 1500 kW wind turbine on 272-ft (82.9 m) tower.
- A 1500 kW wind turbine on and 323-ft (98.5 m) tower.

Both of these ratings of wind turbines are commonly in commercial use in the United States. 207-ft (63.1 m) is a common tower height since it allows erection by cranes that are normally available and are economic. The 272-ft (82.9 m) and 323-ft (98.5 m) are tower heights that are not common or are beyond the capabilities of most available crane. It is at the taller heights that the self-erecting method may prove more cost-effective.

2.4 Design process

For each of the four configurations it was necessary to determine the design loads during construction so that the modifications to the towers could be designed. In addition, it was necessary to know the fatigue stresses in the walls of the towers during turbine operation so that the effect on the fatigue strength of any modifications could be estimated.

The design loads from the rotors onto the towers were obtained from the WindPACT Rotor Design Study recently completed by GEC for the National Renewable Energy Laboratory [2]. That study modeled a number of different rotor sizes, including 750 kW and 1500 kW, and carried out designs of all major components. In adapting the WindPACT results to this project the tower base loads were linearly adjusted for the tower height and also for the swept area of the rotor. In order to check if this process was compatible with current commercial tower design, the tower designs so obtained were compared with those being used with the Vestas V47 and V80 turbines.

The loads incurred during the self-erection process were also estimated and checks were made to ensure the structural integrity of the towers during that process.

A schematic chart of the process is shown in Figure 2-5.

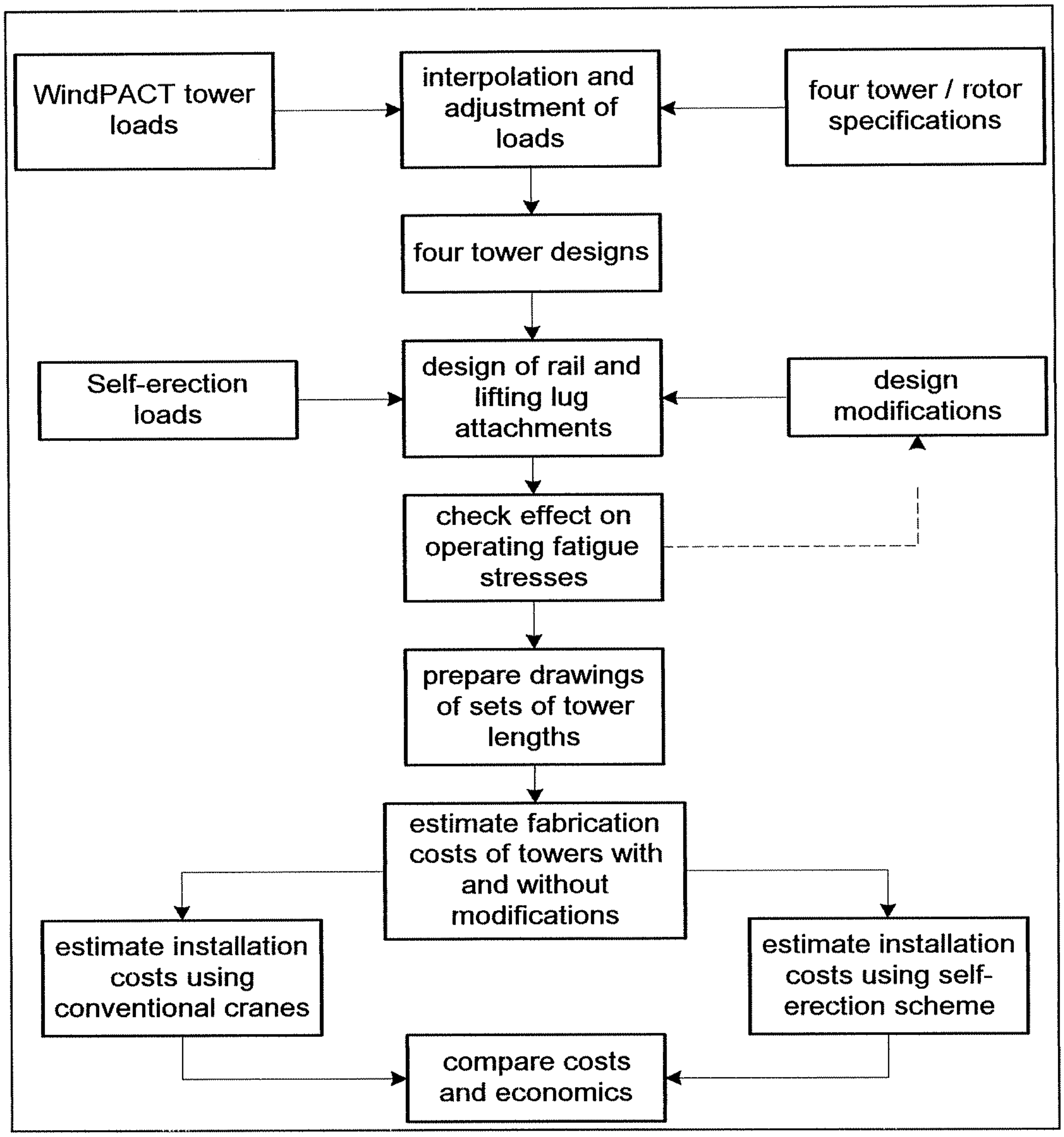


Figure 2-5. Flowchart of approach

2.5 Cost model

All tower fabrication costs were generated by DMI and were for quantities corresponding to a 50 MW windfarm. Costs were FOB at the DMI plant in North Dakota and it was assumed that the windfarm location would be in Minnesota not more than 200 miles from the DMI plant. However, the transportation costs of the two sets of towers (one for conventional crane erection, and the other for use with the self-erecting scheme) were assumed to be the same.

A number of different scenarios for the crane erection scheme were considered. When large cranes are used, a considerable cost is incurred when rough terrain prevents the crane from being moved without full demobilization. Therefore, scenarios were evaluated requiring full demobilization and reassembly for every turbine, every fourth turbine, and every 16th turbine.

3 RESULTS

3.1 Tower assembly design loads

A maximum wind speed of 40 mph (17.9 m/s) was assumed during assembly for the self-erection process. The following peak loads were identified at the attachment points:

Guide rail attachment:
Radial force = 35.6 kip
Lateral force = 5.2 kip

Lifting lug:
Radial force = 5.2 kip
Vertical force = 36.1 kip

Initial designs for the guide rail attachment involved a rectangular plate welded to the tube and carrying a lug to which the rail guide was bolted. It was decided that the weld to the tube would jeopardize the fatigue strength of the tube when the turbine was in operation and that a bolted connection would be more acceptable.

Hand calculations showed that the walls of the tubes would be unable to carry the radial loads from the guide rail connections without some reinforcement of the tube. A configuration incorporating two 6 x 6 inch angles running inside the tube and connecting to the guide rail attachments was proposed and this configuration was subject to finite element analysis through Elgood Mayo. The analysis results indicated that the configuration was acceptable.

However, this configuration was deemed by DMI to incur considerable extra fabricating costs due, in part, to the need to drill the series of additional bolt holes in the tube. The configuration was therefore reconsidered and the final detail was identified. This consists of a single ¾ x 6-inch (19 x 24 mm) bar continuously welded to the length of the tube sections and oriented to fit with the climbing platform attachments. This weld detail was acceptable in fatigue because it is a continuous weld and the ends of the bar can be tapered to lessen stress concentrations.

Another consideration was the number of field connections required. The initial intent for the self-erecting method was to have the uppermost 7 ft of tower to be lifted in place with the nacelle and rotor, which would require an additional tower field connection for that 7-ft length. This additional connection, with the need for accurately machined flanges, increased the total cost and jeopardized the cost-effectiveness of the scheme. Therefore it was decided to eliminate that connection and to lift the nacelle without any accompanying tower length.

The designs that were finally identified from this process are shown in Appendix A.

3.2 Cost estimates

DMI were asked to estimate the costs of fabrication of two sets of designs: one for conventional crane erection and one for the proposed self-erection method. The field connections specified for the self-erecting scheme are shown in Figure 3-1. The corresponding towers for the conventional crane erection were identical to those shown in Figure 3-1.

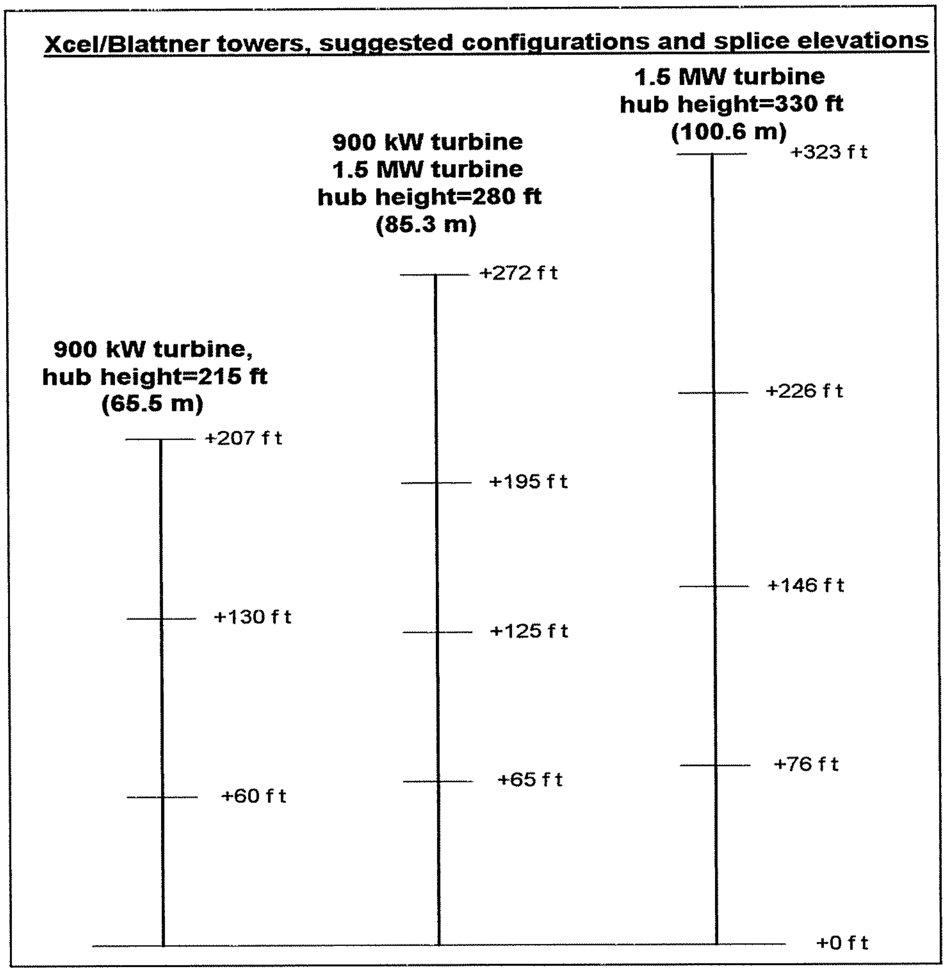


Figure 3-1. Tower section lengths proposed for the self-erecting scheme

The estimated fabrication costs per tower are shown in Table 3-1. Table 3-2 summarizes the costs of assembly for a range of total tower numbers and for various frequencies of crane demobilization. The assembly costs include all cost associated with the erection of the tower and nacelle: delivery of the tower to the site, crane rental costs (with any necessary demobilization costs), delivery and assembly of the self-climbing platform, all labor for both methods, assembly of the tower parts and connection of the nacelle to the tower. Also included are the extra fabrication costs for the self-erecting method. The costs do not include any assembly of the nacelle parts and making it ready for lifting.

Table 3-1. Estimates of tower fabrication costs.

Tower height / turbine rating	Conventional erection, Cost per tower	Self-erecting scheme, Cost per tower
207 ft / 900 kW	$109,000	$118,000
272 ft / 900 kW	$171,000	$183,000
272 ft / 1500 kW	$225,000	$237,000
323 ft / 1500 kW	$297,000	$310,000

Table 3-2. Estimates of tower assembly costs

		costs for installation per tower					
		1 tower / mobilization		4 towers / mobilization		16 towers / mobilization	
total # of towers	Type of erection scheme	1.5MW / 323 ft tower	1.5MW / 272 ft tower	1.5MW / 323 ft tower	1.5MW / 272 ft tower	1.5MW / 323 ft tower	1.5MW / 272 ft tower
1	self-erecting platform	$ 166,629	$ 163,879	$ 166,629	$ 163,879	$ 166,629	$ 163,879
	conventional crane	$ 364,079	$ 326,815	$ 364,079	$ 326,815	$ 364,079	$ 326,815
2	self-erecting platform	$ 108,617	$ 105,867	$ 108,617	$ 105,867	$ 108,617	$ 105,867
	conventional crane	$ 227,767	$ 208,003	$ 192,940	$ 173,176	$ 192,940	$ 173,176
4	self-erecting platform	$ 73,027	$ 70,277	$ 73,027	$ 70,277	$ 73,027	$ 70,277
	conventional crane	$ 218,480	$ 190,217	$ 135,239	$ 115,726	$ 135,239	$ 115,726
8	self-erecting platform	$ 57,147	$ 54,397	$ 57,147	$ 54,397	$ 57,147	$ 54,397
	conventional crane	$ 182,208	$ 158,572	$ 83,467	$ 72,956	$ 74,760	$ 64,249
16	self-erecting platform	$ 49,896	$ 47,146	$ 49,896	$ 47,146	$ 49,896	$ 47,146
	conventional crane	$ 170,259	$ 146,875	$ 71,518	$ 61,259	$ 50,708	$ 42,636
32	self-erecting platform	$ 46,989	$ 44,239	$ 46,989	$ 44,239	$ 46,989	$ 44,239
	conventional crane	$ 161,739	$ 139,449	$ 66,873	$ 56,614	$ 42,188	$ 35,210
64	self-erecting platform	$ 45,177	$ 42,427	$ 45,177	$ 42,427	$ 45,177	$ 42,427
	conventional crane	$ 159,417	$ 137,126	$ 64,551	$ 54,292	$ 42,891	$ 35,367

Shaded cells indicate those conditions in which the climbing platform is more expensive. In all other conditions, the conventional crane is more expensive.

3.3 Economics of assembly schemes

Based on the experience gained by D.H. Blattner & Sons in the wind energy industry, costs were assembled for use of cranes to erect the four wind turbine/tower combinations identified in Section 2.3. For each configuration, costs were estimated for a range of crane demobilization frequencies (once for every turbine, once for every four turbines, etc.)

Those costs were compared with the costs of using the self-erecting platform and Figures 3-2 through 3-5 present some of these comparisons. The costs in those figures do not include the fabrication cost shown in Table 3-1, but the climbing platform costs do include the additional fabrication costs associated with that scheme

Costs associated with the 900 kW turbine are not included for two reasons: the majority of turbines in the future are expected to be rated at 1.5 MW or more; the smaller, lighter turbines are more amenable to erection by conventional crane and the economics of using the climbing platform are less attractive.

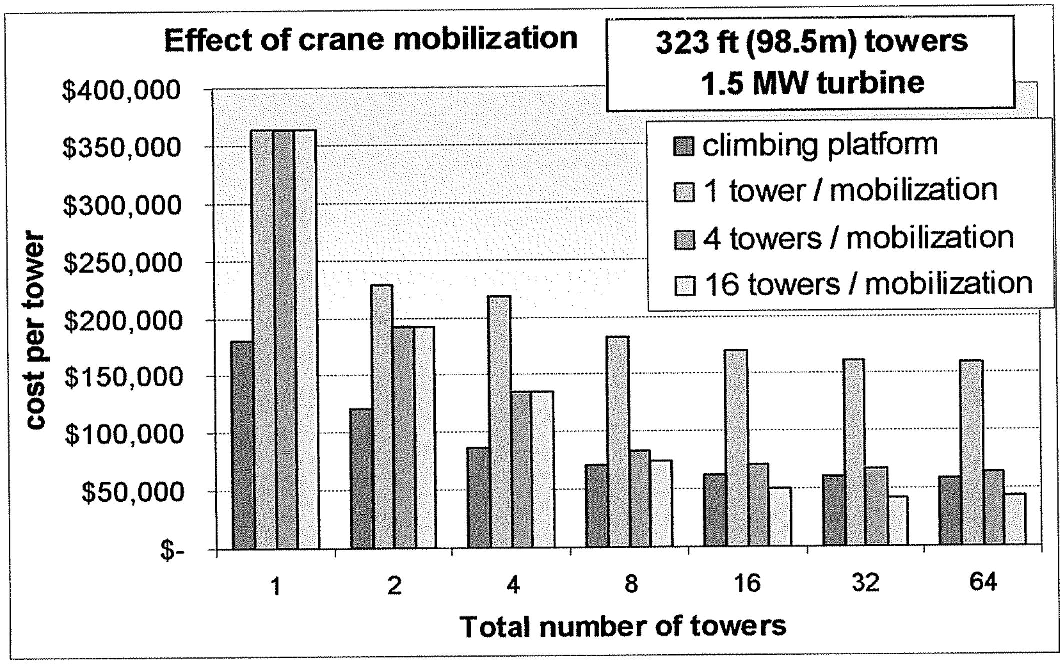


Figure 3-2. Influence of crane demobilization and total turbine number on erection costs. 323 ft tower.

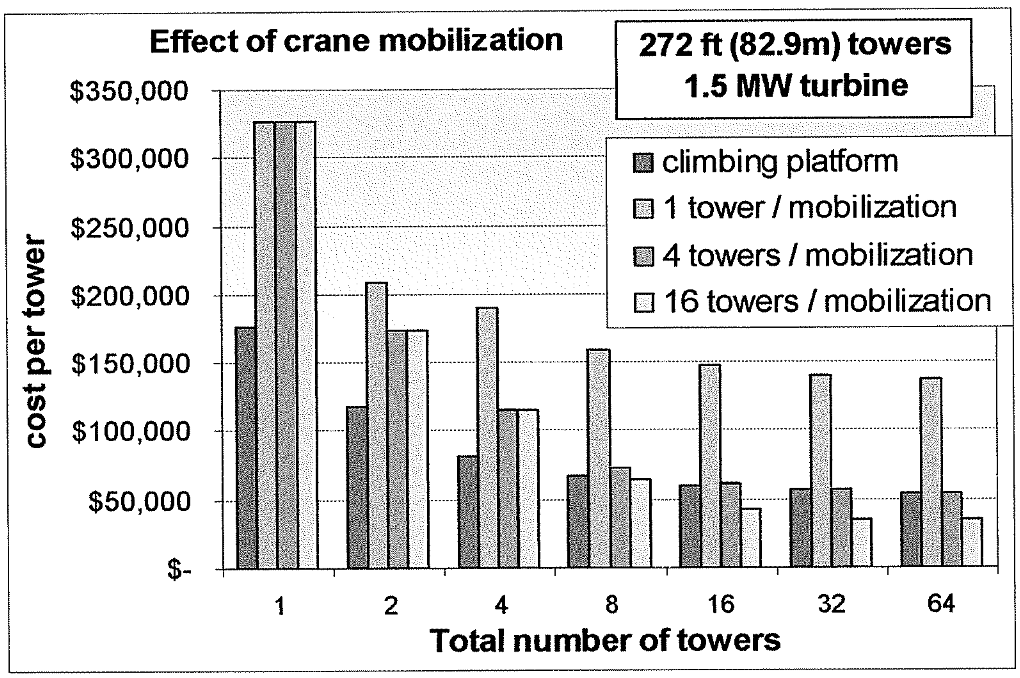


Figure 3-3. Influence of crane demobilization and total turbine number on erection costs. 272 ft tower

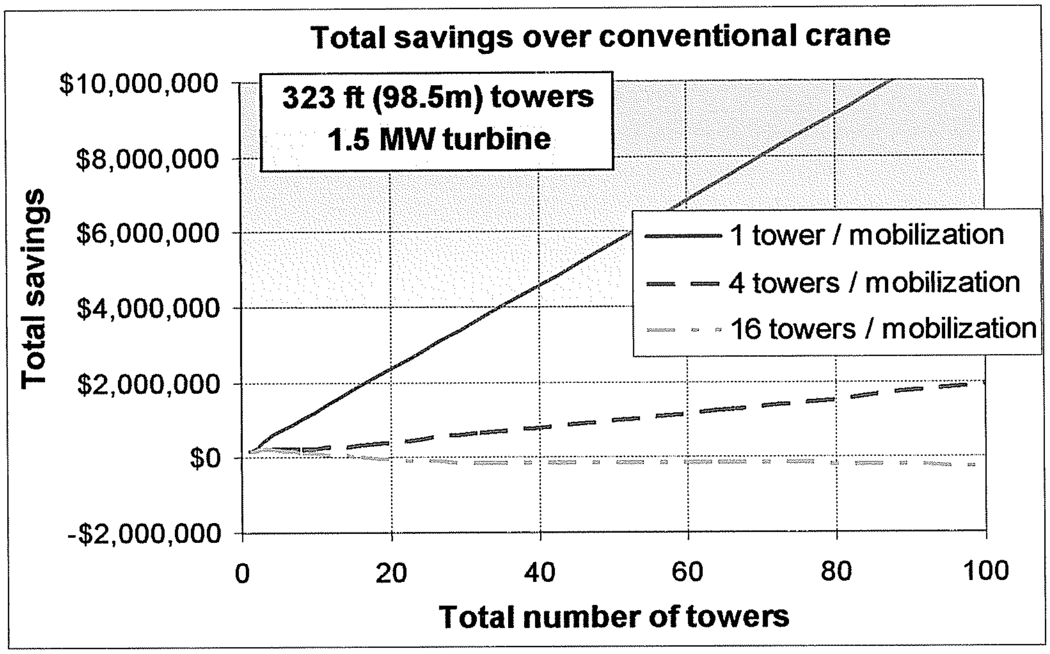


Figure 3-4. Effect of crane demobilization on accumulated savings. 323 ft tower

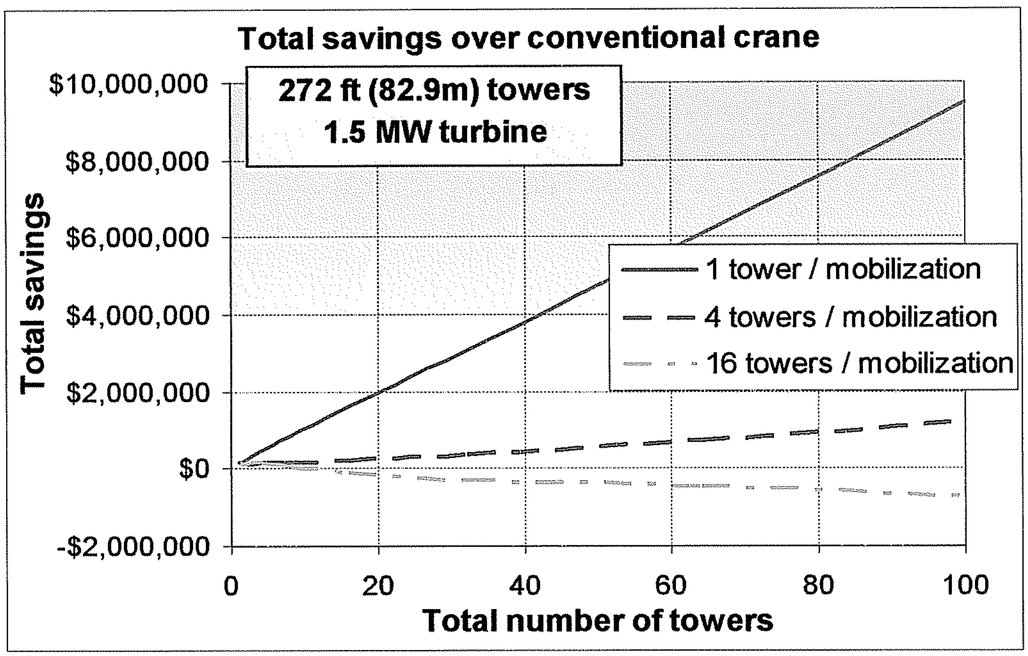


Figure 3-5. Effect of crane demobilization on accumulated savings. 272 ft tower

4 CONCLUSIONS

4.1 Cost effectiveness

The results presented in the previous sections confirm that the self-erecting scheme is particularly cost effective when the alternative involves a high-capacity crane which must be fully demobilized at frequent intervals in the construction of a wind farm. In particular, the results for the tallest towers (a 1.5 MW turbine on a 323-ft, 98.5-m, tower) show that

- The climbing platform shows a cost advantage for all scenarios for developments that involve fewer than 20 turbines. This is due to the high initial mobilization cost of a 500-ton crane and the lower cost of mobilization for the climbing platform
- The climbing platform is advantageous for all developments if the crane must be fully demobilized more often than every 16 turbines (approximately). The self-erecting method is, therefore, advantageous in more mountainous terrain.
- For a single machine installation, the saving of using the climbing platform is equivalent to $130/kW which is approximately 10% of the total installed cost.
- The accumulated savings for a 40-turbine wind farm, in which the crane must be demobilized for every turbine, will amount to about $4.5million.
- The cost saving is sensitive to the added cost of tower fabrication to accommodate the climbing platform. This cost has been minimized by carefully formulating simple modifications.

For a 1.5MW turbine on the intermediate 272-ft (82.9-m) tower, the economics are similar to those for the taller tower. However, for the 900 kW turbine on either of the towers the economics favor the conventional crane installation.

The lifting platform has additional advantages:

- There is no height restriction. Towers of height greater than 100 m can be erected with the same equipment.
- The maximum wind speed in which the climbing platform can work is 40 mph (18 m/s) which is considerably more than the limits for all crane erection methods.
- The climbing platform can also be used for lowering the entire nacelle or major components or in decommissioning. Thus it can lower the maintenance costs where a crane would otherwise be required.

The results presented in this report may not be applicable to all developments. Costs can be affected by the quality and grade of access roads and the number of complete set-up and tear downs required for highway moves. Furthermore, the assembly costs quoted do not cover the complete installation and commissioning.

4.2 Recommendations

It is expected that, in the future, developers will use larger turbines (greater than 1.5 MW) on taller towers (greater than 70 m , 230 ft). For this type of installation, the self-erecting climbing frame has been shown to be cost effective in most circumstances. It is, therefore, recommended that funds be made available for phase II of this project which involves detailed design and fabrication of the climbing platform and planning for on-site testing.

5 REFERENCES

1. Fredrickson, D., Brennan, D.D., Presentation at the 2000 WindPACT Industry Workshop, Golden, CO: National Renewable Energy Laboratory, November 2000.

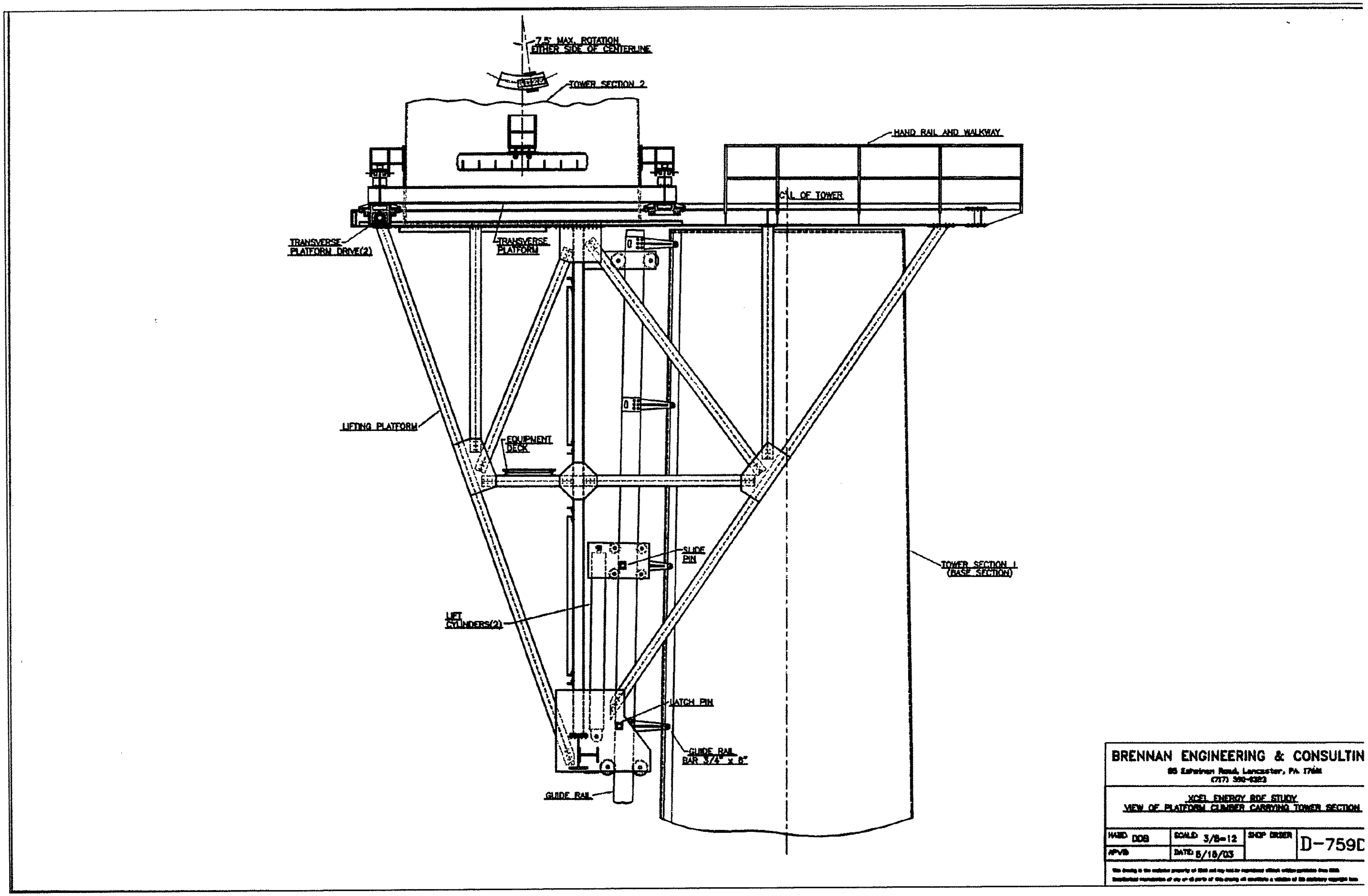
2. Malcolm, D.J. and Hansen, A.C., "WindPACT turbine rotor design study," NREL/SR-500-32495, June 2002.

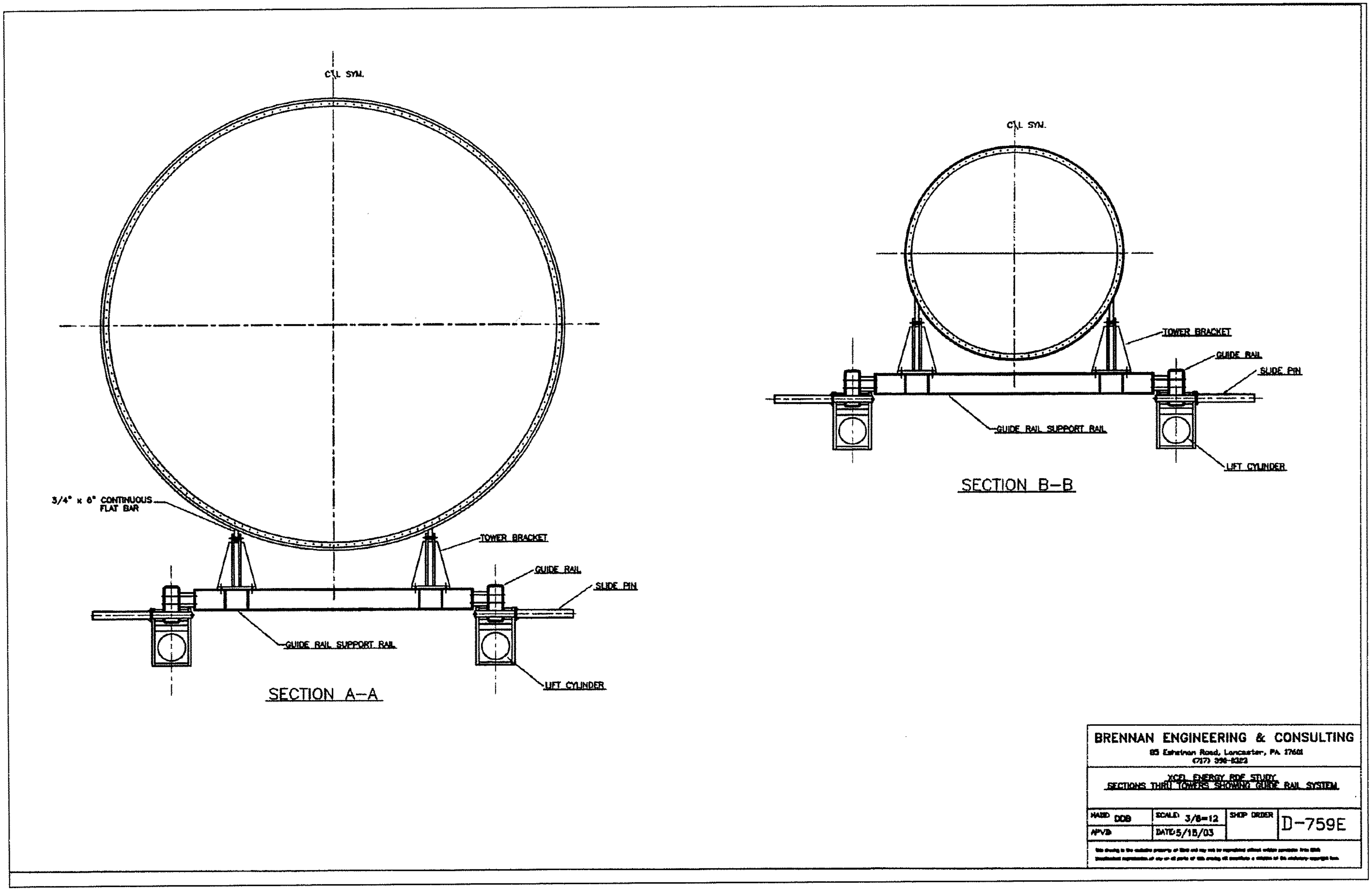
3. Smith, K. (publication pending). WindPACT Turbine Design Scaling Studies Technical Area 2 – Turbine, Rotor and Blade Logistics. Golden, CO: National Renewable Energy Laboratory.

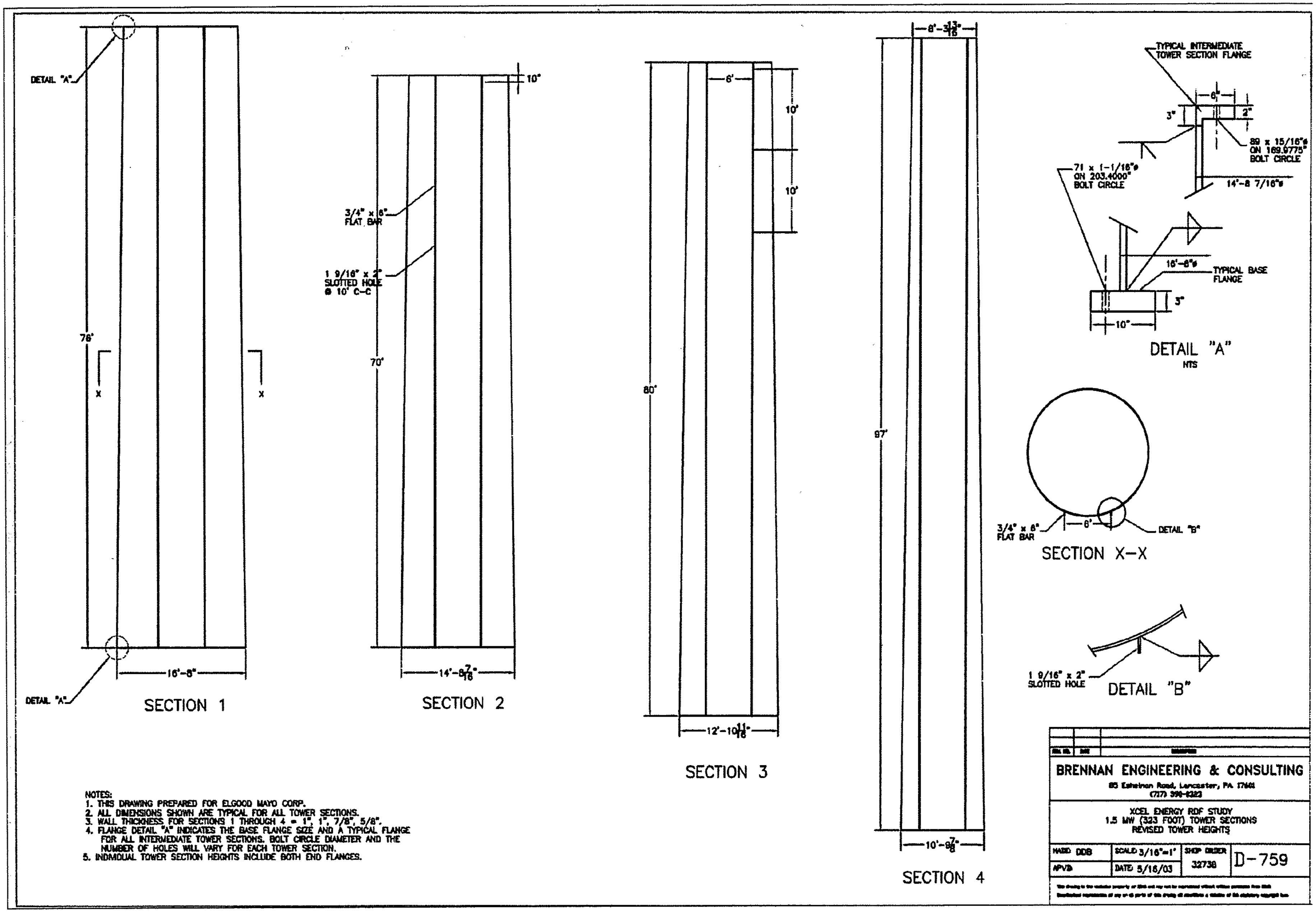
4. Vandenbosche, J. (publication pending). *WindPACT Turbine Design Scaling Studies Technical Area 3 – Self-Erecting Tower Structures*. Golden, CO: National Renewable Energy Laboratory.

Appendix

Drawings of the climbing platform & tower design


7.5° MAX. ROTATION EITHER SIDE OF CENTERLINE
TOWER SECTION 2
HAND RAIL AND WALKWAY
C/L OF TOWER
TRANSVERSE PLATFORM DRIVE(2)
TRANSVERSE PLATFORM
LIFTING PLATFORM
EQUIPMENT DECK
SLIDE PIN
TOWER SECTION 1 (BASE SECTION)
LIFT CYLINDERS(2)
LATCH PIN
GUIDE RAIL BAR 3/4" x 8"
GUIDE RAIL
BRENNAN ENGINEERING & CONSULTIN
XCEL ENERGY RDF STUDY
VIEW OF PLATFORM CLIMBER CARRYING TOWER SECTION
DDB
SCALE 3/8=12
DATE 5/15/03
D-759D


C/L SYM.
3/4" x 6" CONTINUOUS FLAT BAR
TOWER BRACKET
GUIDE RAIL
SLIDE PIN
GUIDE RAIL SUPPORT RAIL
LIFT CYLINDER
SECTION A–A
C/L SYM.
TOWER BRACKET
GUIDE RAIL
SLIDE PIN
GUIDE RAIL SUPPORT RAIL
LIFT CYLINDER
SECTION B–B
BRENNAN ENGINEERING & CONSULTING
XCEL ENERGY RDF STUDY
SECTIONS THRU TOWERS SHOWING GUIDE RAIL SYSTEM
DDB
SCALE: 3/8=12
DATE: 5/15/03
SHOP ORDER
D-759E


SECTION 1
SECTION 2
SECTION 3
SECTION 4
SECTION X–X
DETAIL "A"
DETAIL "B"
TYPICAL INTERMEDIATE TOWER SECTION FLANGE
TYPICAL BASE FLANGE
71 x 1-1/16"⌀ ON 203.4000" BOLT CIRCLE
89 x 15/16"⌀ ON 169.9775" BOLT CIRCLE
3/4" x 6" FLAT BAR
1 9/16" x 2" SLOTTED HOLE @ 10' C-C
NOTES:
1. THIS DRAWING PREPARED FOR ELGOOD MAYO CORP.
2. ALL DIMENSIONS SHOWN ARE TYPICAL FOR ALL TOWER SECTIONS.
3. WALL THICKNESS FOR SECTIONS 1 THROUGH 4 = 1", 1", 7/8", 5/8".
4. FLANGE DETAIL "A" INDICATES THE BASE FLANGE SIZE AND A TYPICAL FLANGE FOR ALL INTERMEDIATE TOWER SECTIONS. BOLT CIRCLE DIAMETER AND THE NUMBER OF HOLES WILL VARY FOR EACH TOWER SECTION.
5. INDIVIDUAL TOWER SECTION HEIGHTS INCLUDE BOTH END FLANGES.
BRENNAN ENGINEERING & CONSULTING
XCEL ENERGY RDF STUDY
1.5 MW (323 FOOT) TOWER SECTIONS
REVISED TOWER HEIGHTS
SCALE 3/16"=1'
DATE 5/16/03
SHOP ORDER 32738
D-759