Technical Assistance from NREL to Wind Tower Technologies

Cooperative Research and Development Final Report

CRADA Number: CRD-17-698

NREL Technical Contact: Annika Eberle

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
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Cooperative Research and Development Final Report

Report Date: September 16, 2019

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Science and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Wind Tower Technologies

CRADA number: CRD-17-698

CRADA Title: Technical Assistance from NREL to Wind Tower Technologies

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$170,000.00
TOTALS	$170,000.00

Abstract of CRADA Work:

This effort will use NREL capabilities in techno-economic analysis to evaluate a technology developed by Wind Tower Technologies (WTT) for an onsite process for building concrete towers using a precast mated mold process. This technology enables tall towers by circumventing transportation limits that constrain the size of conventional steel monopole towers. NREL researchers will provide relevant expertise in techno-economic analysis and assessment of innovative technologies for wind energy applications.

Summary of Research Results:

This report contains Protected CRADA Information, which was produced on June 30, 2018 under CRADA No. 17-698 and is not to be further disclosed for a period of five (5) years from the date it was produced except as expressly provided for in the CRADA.

The purpose of this project was to use NREL's expertise in the evaluation of system impacts of technology innovations to conduct an in-depth economic analysis of the development of a new wind tower construction technology for a small business under the Department of Energy (DOE) Small Business Vouchers Pilot. In this case, WTT sought a techno-economic evaluation of how their innovative self-erecting concrete tower (SECT) system compares to traditional technology. SECT will address challenges around tall wind that are associated with traditional cranes and their limitations in terms of both logistics and costs for installing turbines with hub heights of 140 m and greater.

The objective of this project was to conduct an economic analysis of wind farm construction under traditional technology and SECT and provide WTT with the estimated levelized costs of energy for each construction pathway. This work provided data and analysis to a small business developing advanced energy technologies and helped inform them about the competitiveness of their technology under different scenarios. This project also significantly enhanced the ability for the DOE and NREL to analyze a wide variety of innovations enabling tall wind installations by building tower models based on industry knowledge. Follow-on work led to a software record. SWR-18-43 "LandBOSSE."

Task 1: Review of technical scenarios and detailed work plan definition

We worked with WTT to refine analysis scenarios and define specific modeling needs for tower costs, balance of system costs, and related system impacts. We explored the current status of select alternative tower designs, reviewed the various design considerations and attributes associated with each respective technology, and performed a first-order, bottom-up evaluation of tower costs. Through this process, we identified four hub heights for our analysis:

1. Current wind plants with hub heights of 80-100 m where a representative height of 85 m will be used,
2. State-of-the-art wind plants with hub heights from 100 m-140 m that represent transitional technology with more towers and installation processes. In this case, using two breakpoints of:
   A. 120 m
   B. 140 m
3. Future wind plants with hub heights in excess of 140 m (a 160 m hub height will be used).
4. At each of these four hub heights, we evaluated three tower types:
   A. A baseline conventional tower and turbine installation technology (with large-diameter steel towers for applications above 100 m),
   B. An alternative scenario where only the tower is installed with SECT, and
   C. Another scenario where the tower, nacelle, and rotor are all installed with SECT.

These combinations resulted in a total of twelve different technical analysis scenarios (see Table 1).

We reviewed the modeling requirements for each of these scenarios and performed a cursory assessment of current modeling capabilities to identify areas in need of model development (Table 1). An overview of the key models (for the tower and the balance of system costs) is described in the following report:

Eberle, Annika, Owen Roberts, Alicia Key, Parangat Bhaskar, and Katherine Dykes. 2019. N*REL's Balance-of-System Cost Model for Land-Based Wind*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72201. https://www.nrel.gov/docs/fy19osti/72201.pdf.

We found that three of the models required for this analysis would need to be expanded prior to performing detailed scenario analysis (highlighted in blue in Table 1). The required changes for each of these three models are described below.

Table 1: Project Analysis Scenarios and Model Requirements

(Sections highlighted in blue denote areas that require model development.)

Cost Category	Analysis Scenario and Model Requirements											
	Steel tower				*SECT tower*				*SECT turbine*			
	85 m	*120 m*	*140 m*	*160 m*	*85 m*	*120 m*	*140 m*	*160 m*	*85 m*	*120 m*	*140 m*	*160 m*
Turbine Cost and Loads	TurbineSE & FAST (IEA Wind Task 37 turbine)											
Tower Costs	TowerSE				ConcreteSE (+ WTT input for SECT)							
Annual Energy Production	NREL CSM (IEA Wind Task 37, losses in COE review, sensitivities: hub-height wind speed)											
Operation and Maintenance	Update Land OPEX model using new data and height-dependent crane costs											
BOS: Development	NREL Land BOS model											
BOS: Management	NREL Land BOS model (modify construction time based on weather considerations?)											
BOS: Site	NREL Land BOS model (modify site compound costs?)											
BOS: Erection	NREL Land BOS model (update crane, road costs)				NREL Land BOS model + WTT input for SECT tower				NREL Land BOS model + WTT input for SECT turbine			
BOS: Electrical	NREL Land BOS model (assume simple terrain)											
BOS: Finance	NREL Land BOS model											
Levelized Cost of Energy	NREL CSM simple cost of energy equation + modified equation for construction time											

Abbreviations: TurbineSE = Turbine Systems Engineering module; FAST = an aeroelastic computer-aided engineering (CAE) tool for horizontal axis wind turbines; TowerSE = Tower Systems Engineering module; ConcreteSE = Concrete Systems Engineering module; WWT = Wind Tower Technologies; SECT = Self-Erecting Concrete Turbine; CSM = Cost and Scaling Model; BOS = Balance of System; COE = Cost of Energy; IEA = International Energy Agency; and OPEX = operating expense.

ConcreteSE:

- Description: A reduced-order model that can size a concrete tower based on loads (erection, impact and production).
- Recommendation: First step will be to use WTT data on tower dimensions and properties. Second step will be to develop basic reduced-order model and compare to WTT data. Finally, create capability to size concrete towers for generic turbines of different types and sizes (via surrogate model).

NREL Land Balance of System (BOS):

- Description: Model data collected via a sub-contract with an industry partner during 2011 and reflects all balance of system costs for typical wind plants installed in the US in 2010 and in 2010 USD. Underlying data was used to create curve-fits for various cost components that are tied to a minimum of 10 user inputs. Main concerns with current model are 1) potentially outdated costs and representation of BOS strategies, and 2) data represents conventional towers and hub heights
- Recommendation: Evaluate functional structure of model for critical areas where tower type and height have significant influence (assembly and installation - roads and cranes). Develop strategies for each scenario in the analysis and collect new data to cost out each scenario. Update overall functional structure of model to handle full collection of scenarios. With time, evaluate functional structure and cost data of other model areas, identify any areas of critical need for updates and address as is feasible.

NREL Land OPEX:[1]

- Description: An old model from GEC now DNV was developed in the mid-2000s with costs based on failure rates; newer data was collected under a subcontract but is not yet integrated into model
- Recommendation: Update model with latest available data (review current data with industry as possible). Implement a weather-based model (similar to offshore BOS) to estimate downtime and improved costing on crane usage (mobilization/ demobilization/ daily).

After identifying the analysis scenarios and defining model development needs, we developed a detailed work plan and project schedule (Figure 1).

[1] Given the budget and scope for the project, improvements to the NREL land-based operations and maintenance model were excluded from the WTT SBV project effort.

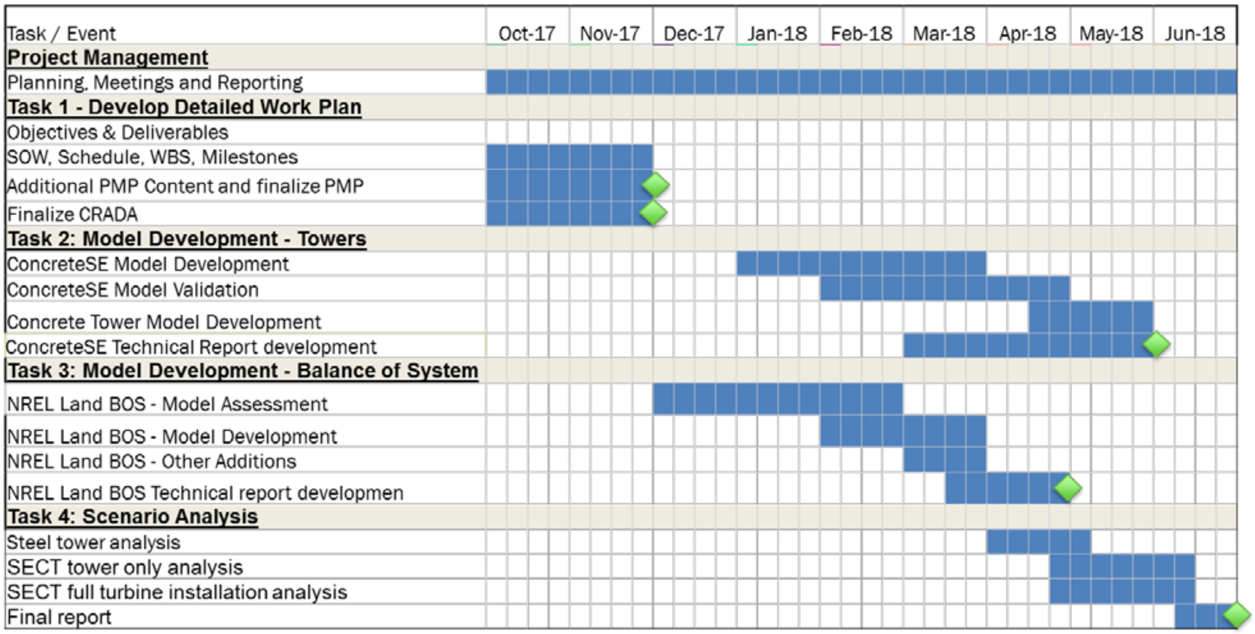

Figure 1: Project schedule, including tasks and timeline (milestones indicated with green diamonds).

Task 2: Develop cost models for both baseline and concrete towers using IEA Wind Task 37 land-based low-wind-speed reference turbine

Reinforced concrete (RC) structures can offer ample versatility in design and construction, can take advantage of local material and labor resources, are virtually maintenance free, offer cost-competitive material (concrete and steel) utilization, have excellent fatigue and dynamic damping properties. The drawbacks of RC towers lie in the extensive time required for activities such as slip-forming, pouring, and especially curing for on-site casting, and in the weight of subcomponents. The associated expensive crane operations and/or requirements for production stacking and scheduling can impose significant economic burdens to the typical wind projects.

It is therefore clear that assessing the benefits of RC towers and the resulting levelized cost of energy (LCOE) requires a systems engineering approach to capture cost relationships that tie in material quantities, geometric parameters, and performance metrics. Additionally, to enable a system-level optimization, physics-based models of all major system components are required to explicitly capture potential trade-offs. For these reasons, a model of a pre-stressed concrete tower (PSCSE or ConcreteSE as it is referred to above under the Task 1 description) was created to capture the fundamental physics governing the strength and dynamics of RC towers for wind power applications.

This model was developed within the wind energy systems engineering toolbox Wind-Plant Integrated System Design & Engineering Model (WISDEM). WISDEM, developed at the National Renewable Energy Laboratory (NREL), integrates a variety of models for the entire wind energy system, including turbine and plant equipment, operation and maintenance (O&M), and cost modeling (Dykes et al. 2011). Although sophisticated load simulations conducted through aero-hydro-servo-elastic tools can account for all ULS and fatigue limit state (FLS) design load cases (design load cases (DLCs)), and for an accurate representation of all physical couplings between component dynamics, these simulations are computationally expensive and time intensive. Simplified tools can guide the preliminary design of components and of the overall system towards a configuration that minimizes the LCOE through multidisciplinary optimization.

Within WISDEM, National Renewable Energy Laboratory (NREL) developed models for the tower and offshore monopile substructure (TowerSE). They are relatively simple and mostly based on modal analysis and buckling verification of the main segments of a steel tubular tower; however, these models do not directly port over to the analysis of a RC structure. PSCSE was developed to allow for the analysis of PSCs support structures.

PSCSE is based on an open-source finite-element analysis (finite-element analysis (FEA)) package (FRAME3DD) that can handle Timoshenko beam elements, and on a set of functions that implement structural code checks (ACI 2014) to verify the SLS and ULS cross-section at various stations along the span. The implemented theory is classic concrete structure design (e.g., MacGregor 2011; Gilbert and Mickleborough 2004) Some of the elements of TowerSE are maintained and expanded, whereas the tower portion of the support structure uses the same set as in TowerSE. Simplified hydrodynamics also is in common with the TowerSE module. Examples of results and preliminary verification of the software can be found in Damiani and Song (2013) and Damiani et al. (2017), but more validation remains necessary.

JacketSE can be used for either stand-alone support-structure analysis and design or as part of a larger wind turbine or wind plant study. In stand-alone mode, JacketSE aids the designer in the search for an optimal preliminary configuration of the substructure and tower, and for given environmental loading conditions, turbine dynamic loading, modal performance targets, and standards design criteria. The optimization criteria (e.g., minimum subcomponent mass or overall total structural mass) are customizable depending on the user's needs. JacketSE also allows for parametric investigations and sensitivity analyses of both external factors and geometric variables that may drive the characteristics of the structure, thereby illustrating their impact on the mass, stiffness, blade/support clearance, strength, reliability, and expected costs.

When used for optimization, the tool can size inner and outer diameters of a tower at a number of span stations, numbers and sizes of tendons, nonprestressing reinforcement and shear reinforcement; another design variable that may be optimized is the tendon prestress value. The design parameters (fixed inputs to the tool) include: tower height, deck and hub height, design wind speed, design wave height and period, and soil characteristics (stratigraphy of undrained shear strength, friction angles, and specific weight). Loads from the rotor nacelle assembly (rotor nacelle assembly (RNA)) are input to the model either from other WISDEM modules or directly from the user. The user must also provide acceptable ranges for the design variables, such as, maximum tower inner and outer diameters; minimum and maximum prestress loading levels; minimum and maximum numbers of rebar within the two or more groups, tendons, and hoop reinforcement, as well as bounds for their respective sizes.

As part of a system study within WISDEM, PSCSE allows for the full gamut of component investigations to arrive at optimum LCOE wind turbine and/or power plant layout. For example, PSCSE can produce a design that meets blade-tower clearance criteria, has sufficient strength to withstand turbine extreme loads, while also meeting mass or cost targets.

Under Task 2 of this project, the team developed a new ConcreteSE model, validated the model, and documented the approach. More details about the ConcreteSE and TowerSE model development can be found in the corresponding technical documentation for each of these WISDEM modules. Details of the final cost model analysis can be found under Task 4 below.

Task 3: Execute NREL Balance of Station Cost Model enhancements required to consider the specified technology scenarios

NREL's Land-based Balance Of System Systems Engineering (LandBOSSE) model was developed to estimate the balance of system (BOS) costs for commercial-scale, land-based wind plants. The model includes the BOS costs for all of the non-hardware aspects of installing a wind plant, including permitting fees, installation labor, and equipment rentals associated with site preparation, foundation construction, tower erection, and the installation of the rotor nacelle assembly.

As part of this project, we evaluated the functional structure of LandBOSSE to determine critical areas where tower type and height have significant influence. We identified assembly and installation and foundation costs as the two major areas for model development and we updated the overall functional structure of model to handle the scenarios of interest.

As described in the LandBOSSE model documentation, the updated version of the LandBOSSE that was used for this analysis was developed using a three-tiered approach. First, the major categories of BOS costs for land-based wind plants were identified and their underlying processes were mapped to input and output variables. Then, the process diagrams were reviewed with industry experts and data were collected for the calculations. In parallel with industry review, the process diagrams were implemented in Python based on the construction of conventional steel tower turbines. Due to data or other limitations, the model implementation of the BOS processes required making some simple assumptions and, as a result, the model differs slightly from the detailed process diagrams outlined in the model documentation. Overall, the model is based on a bottom-up assessment of inputs and outputs associated with each BOS operation and, where needed, it is supplemented by top-down estimates of costs from industry.

The model is populated with default data but is written in a modular manner to allow for the exploration of a variety of plant sizes, locations, and site-specific parameters, along with different types of tower technologies, turbines, and foundation designs. For this analysis, we developed additional model input data and structure and collected new data to cost out each scenario. For example, we used engineering design equations to expand the foundation module and allow foundation size to vary based on tower weight, height, and soil bearing capacity. We also expanded the assembly and installation cost module to account for concrete tower sections, SECT equipment, and weather delays. Please refer to the LandBOSSE model documentation for additional details about the implementation of the model and the functionality associated with each cost module.

We executed the LandBOSSE model for the twelve scenarios outline in Table 1 using wind and soil data for an average site in Iowa. As shown in Figure 2, for all hub heights, we found that the total BOS costs per turbine were greater for concrete towers (installed with either conventional crane or SECT) than for steel towers with conventional cranes. In addition, while the BOS costs for concrete towers installed with conventional cranes was lower than SECT for the 85 m and 120 m hub heights, the BOS costs for concrete towers installed with SECT became less expensive than with conventional cranes at higher hub heights (140 m and 160 m).

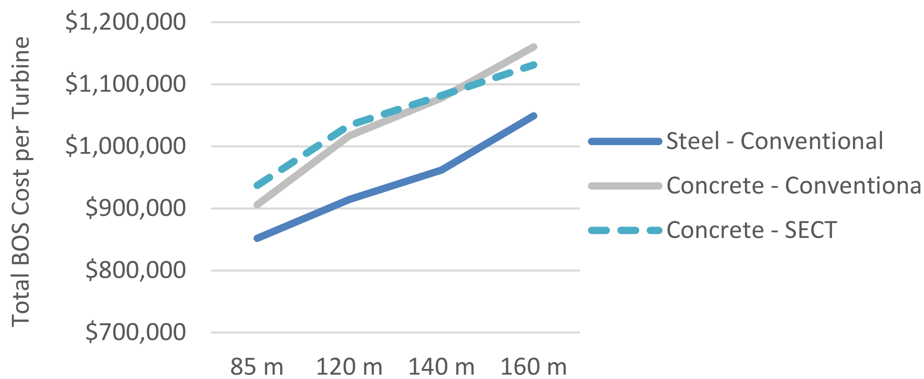

Figure 2: Total Balance of System (BOS) Cost per Turbine (in USD) by Hub Height for Three Tower Construction Methods (steel and concrete towers with conventional cranes, and a self-erecting concrete tower (SECT).

BOS costs for all modules except management, erection, and foundation were the same for all of the scenarios because the model inputs for the other modules remained the same for each scenario (e.g., electrical systems depend on interconnect voltage, rated power, and other factors that did not vary for the scenarios considered). As a result, only three components of BOS costs changed for each scenario: management, foundation, and erection. Although all three of these costs varied, the trends in the total BOS cost per turbine are driven by the differences in erection cost per turbine (see Table 2). Changes in management cost are driven by changes in total BOS cost and do not vary significantly by tower type and construction method and changes in foundation are driven by hub height and tower type (i.e., steel vs. concrete) and are not impacted by tower construction method (conventional cranes vs. SECT). As expected, at higher hub heights, the erection costs for conventional cranes increase more steeply with hub height than they do for SECT (see Figure 3; at higher hub heights, the slope of the SECT curve is smaller than the slope of either the steel or concrete towers with conventional cranes).

Table 2: Balance of System (BOS) Costs (in hundreds of thousands of USD) by Hub Height for Three Tower Construction Methods (steel and concrete towers with conventional cranes, and a self-erecting concrete tower [SECT]).

	Steel - Conventional				Concrete - Conventional				Concrete - SECT			
Hub Height (m)	*85*	*120*	*140*	*160*	*85*	*120*	*140*	*160*	*85*	*120*	*140*	*160*
Collection	**$2.1**	**$2.1**	**$2.1**	**$2.1**	**$2.1**	**$2.1**	**$2.1**	**$2.1**	**$2.1**	**$2.1**	**$2.1**	**$2.1**
Development	**$0.5**	**$0.5**	**$0.5**	**$0.5**	**$0.5**	**$0.5**	**$0.5**	**$0.5**	**$0.5**	**$0.5**	**$0.5**	**$0.5**
Erection	**$1.2**	**$1.5**	**$1.7**	**$2.3**	**$1.6**	**$2.2**	**$2.5**	**$3.1**	**$1.8**	**$2.3**	**$2.6**	**$2.8**
Foundations	**$1.0**	**$1.3**	**$1.5**	**$1.7**	**$1.2**	**$1.5**	**$1.6**	**$1.8**	**$1.2**	**$1.5**	**$1.6**	**$1.8**
Management	**$1.7**	**$1.9**	**$1.9**	**$2.0**	**$1.8**	**$2.0**	**$2.1**	**$2.2**	**$1.9**	**$2.0**	**$2.1**	**$2.2**
Roads	**$0.8**	**$0.8**	**$0.8**	**$0.8**	**$0.8**	**$0.8**	**$0.8**	**$0.8**	**$0.8**	**$0.8**	**$0.8**	**$0.8**
Substation	**$0.7**	**$0.7**	**$0.7**	**$0.7**	**$0.7**	**$0.7**	**$0.7**	**$0.7**	**$0.7**	**$0.7**	**$0.7**	**$0.7**
Transmission	**$0.4**	**$0.4**	**$0.4**	**$0.4**	**$0.4**	**$0.4**	**$0.4**	**$0.4**	**$0.4**	**$0.4**	**$0.4**	**$0.4**
Total	**$8.5**	**$9.1**	**$9.6**	**$10.5**	**$9.1**	**$10.2**	**$10.8**	**$11.6**	**$9.4**	**$10.3**	**$10.8**	**$11.3**

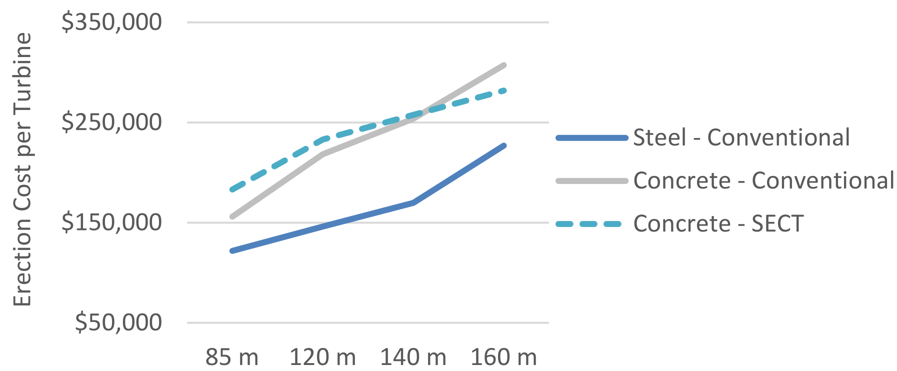

Figure 3: Erection Cost per Turbine (in USD) by Hub Height for Three Tower Construction Methods (steel and concrete towers with conventional cranes, and a self-erecting concrete tower [SECT]).

We explored the relative impact of wind delays on erection costs for all of the scenarios and found that while wind delays increase with hub height for erection using conventional cranes, wind delays for SECT stay relatively constant (Figure 4). These trends result from conventional cranes having lower operational wind speeds than SECT cranes. However, even with double the shear factor for wind speed at higher hub heights, SECT is still not less expensive than steel towers at 160 m (data not shown).

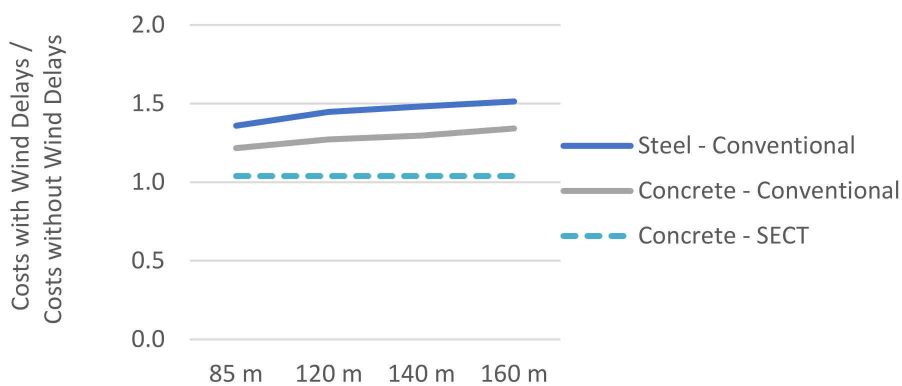

Figure 4: Relative Impact of Wind Delays by Hub Height for Three Tower Construction Methods (steel and concrete towers with conventional cranes, and a self-erecting concrete tower [SECT]).

In addition to examining the impact of wind delays, we investigated the impact of labor rates on total BOS costs (data not shown). We found that even with hourly and per diem rates that were 50% of the default costs in the model, the total BOS costs exhibited similar trends to Figure 2. There was a slightly greater advantage for SECT over conventional crane options but steel towers with conventional cranes still had the lowest total BOS costs for all hub heights.

With regard to foundation costs, we found that the foundation costs for concrete towers is higher than for steel towers. This increase in costs for a concrete tower occurs as a result of the need to increase the foundation size to prevent exceeding the bearing pressure of the soil with a heavier tower (Figure 5). We investigated the impact of soil bearing capacity and found that within a range of reasonable soil conditions (4,000 to 5,000 psf), steel towers maintained a competitive cost advantage over concrete towers due to their lighter weight and reduction in foundation size needed to satisfy the bearing pressure of the soil (i.e., while the costs of concrete tower foundations decreased with increasing bearing capacity, the cost of steel towers also decreased). It is possible that this advantage may differ under stiffer soil conditions.

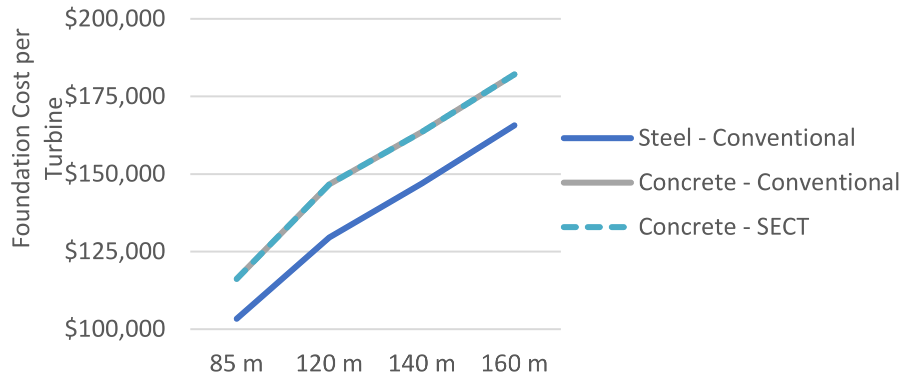

Figure 5: Foundation Cost per Turbine (in USD) by Hub Height for Three Tower Construction Methods (steel and concrete towers with conventional cranes, and a self-erecting concrete tower [SECT]).

Overall, we found that although the total BOS costs associated with constructing concrete towers using SECT decrease with increasing hub height, the decrease is not enough to make them less expensive than constructing steel towers using conventional cranes. However, these results are based solely on the BOS costs; they do not incorporate any potential cost advantages associated with decreased tower costs for concrete towers. Those results will be explored in the next section.

Task 4: LCOE assessment of SECT compared to baseline technology

Finally, we compared the levelized cost of energy (LCOE) each of the technical scenarios outlined under Task 1. Levelized cost of energy (LCOE) combines the technology cost and performance parameters and is given by

$$\text{LCOE} = \frac{(\text{CapEx} \times \text{FCR}) + \text{OpEx}}{(\text{AEP}_{\text{net}}/1{,}000)}$$

Where CapEx is the capital expenditures for the project, FCR is the fixed charge rate, OpEx is the operating expenses for the project, and AEP_{net} is the net annual energy production for the project. The results from this analysis, along with the assumptions used for the calculations, are provided in Table 3 and Figures 6 and 7.

Table 3: Summary of assumptions and results of levelized cost of energy (LCOE) analysis

	Steel - Conventional				Concrete - Conventional				Concrete - SECT			
Hub Height (m)	85	120	140	160	85	120	140	160	85	120	140	160
RNA Cost ($/kW)	800	800	800	800	800	800	800	800	800	800	800	800
Tower Cost ($/kW)	152	257	366	473	125	160	183	211	125	160	183	211
BOS Cost ($/kW)	257	276	290	317	273	307	325	350	283	312	327	342
Financial Costs ($/kW)	157	157	157	157	157	157	157	157	157	157	157	157
Fixed Charge Rate (real) [%]	7.9%	7.9%	7.9%	7.9%	7.9%	7.9%	7.9%	7.9%	7.9%	7.9%	7.9%	7.9%
OpEx ($/kW/yr)	41.1	41.1	41.1	41.1	41.1	41.1	41.1	41.1	41.1	41.1	41.1	41.1
Nameplate (MW)	3.312	3.312	3.312	3.312	3.312	3.312	3.312	3.312	3.312	3.312	3.312	3.312
Losses (%)	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%
IA Annual average wind speed (m/s)	7.46	8.16	8.43	8.67	7.46	8.16	8.43	8.67	7.46	8.16	8.43	8.67
SC Annual average wind speed (m/s)	5.74	6.51	6.75	6.96	5.74	6.51	6.75	6.96	5.74	6.51	6.75	6.96
AEP (Net) (Iowa) (MWh/yr)	12,295	13,837	14,204	14,478	12,295	13,837	14,204	14,478	12,295	13,837	14,204	14,478
AEP (Net) (South Carolina) (MWh/yr)	7,250	9,213	9,692	10,077	7,250	9,213	9,692	10,077	7,250	9,213	9,692	10,077
LCOE (Iowa) ($/MWh)	40.1	38.0	39.3	41.0	39.9	36.8	36.6	36.8	40.1	36.9	36.6	36.7
LCOE (South Carolina) ($/MWh)	68.1	57.1	57.6	58.9	67.7	55.2	53.6	52.9	68.0	55.4	53.6	52.7

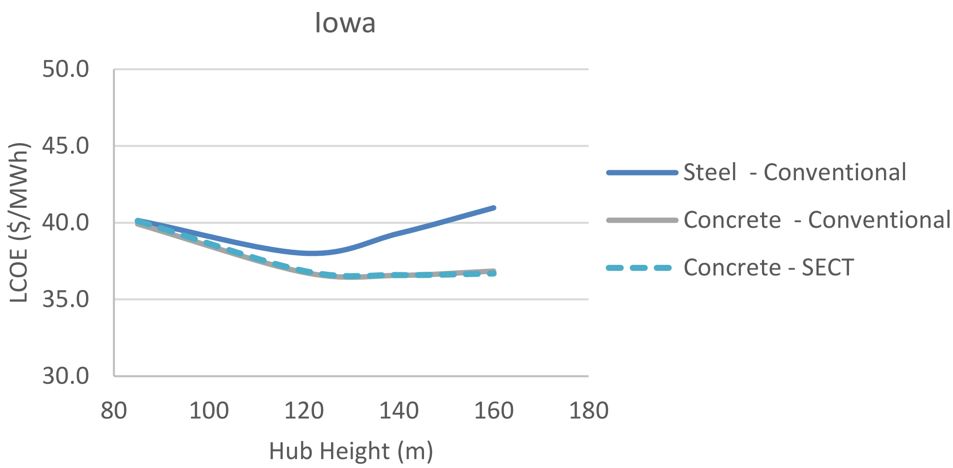

Figure 6: Levelized cost of energy (LCOE) by Hub Height for Three Tower Construction Methods (steel and concrete towers with conventional cranes, and a self-erecting concrete tower [SECT]) using wind and soil data for a site in Iowa.

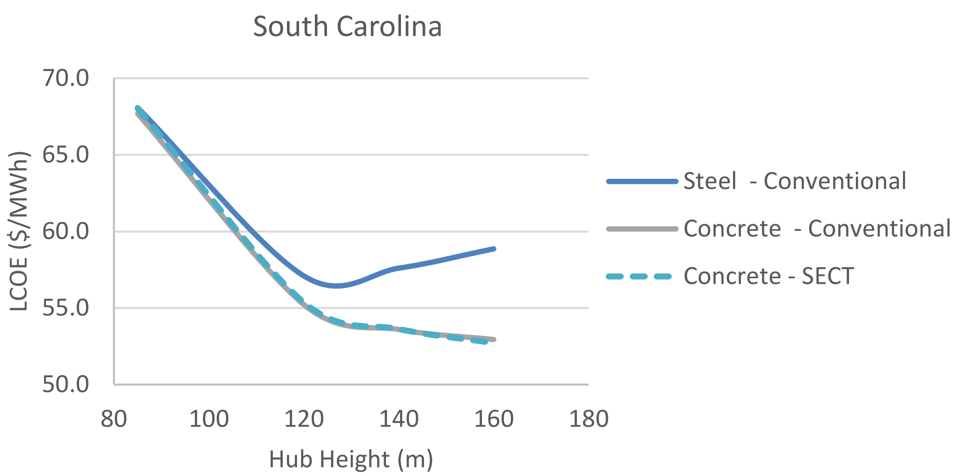

Figure 7: Levelized cost of energy (LCOE) by Hub Height for Three Tower Construction Methods (steel and concrete towers with conventional cranes, and a self-erecting concrete tower [SECT]) using wind and soil data for a site in South Carolina.

The results show that LCOE is comparable for all three tower construction methods at lower hub heights (80-100 m). However, as hub height increases (>100 m), LCOE decreases for concrete towers while it increases for steel towers. In addition, the degree of competitive advantage that concrete towers have over steel towers varies depending on wind resource. This concept is illustrated by the different trends in Figures 6 and 7, which present results from the analysis using wind resource and soil data in Iowa and South Carolina, respectively.

Subject Inventions Listing:

None

ROI #:

None

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