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Analysis of Ideal Towers for Tall Wind Applications

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Innovation in wind turbine tower design is of significant interest for future development of wind power plants. First, wind turbine towers account for a large portion of overall capital expenditures for wind power projects. Second, for low wind–resource regions of the world, the use of low-cost tall-tower technology has the potential to open new markets for development. This study investigates the relative potential of various tower configurations in terms of mass and cost. For different market applications and hub heights, idealized tall towers are designed and compared. The results show that innovation in wind turbine controls makes reaching higher hub heights with current technology economically viable. At the same time, new technologies hold promise for reducing tower costs as these technologies mature and hub heights reach twice the current average.

I. Introduction

The designs for land-based wind turbine towers must satisfy a number of criteria, or constraints, to be viable for deployment. The goal for tower design is to minimize overall tower costs, which normally translates into finding an optimum between material mass and manufacturing costs. The tower, however, must be strong and stiff enough to support the wind turbine under a large variety of operating conditions and extreme events. Additionally, the tower must be manufacturable and transportable. The transportability constraint has become a challenge as turbine designers push towards higher and higher hub heights. For reasons that are discussed in this paper, as tubular towers grow larger, the ideal design approach is to increase the diameter at the tower base and keep the wall thickness minimal. For transportation on land, however, tower diameters are limited to 4.3 m [1] and this, in turn, requires increasing the wall thickness which leads to heavy and costly tower designs when using conventional technology solutions.

To explore the potential benefits of new technology solutions that circumvent the limitations of conventional wind turbine tower technology, an ideal tall towers study was performed. The study compares conventional tower designs at different hub heights alongside idealized tower designs with relaxed constraints around transportation and the maximum tower base diameter. In particular, a conventional technology case is compared to a large-diameter steel tower (LDST) design with a 6.2-m base diameter as well as an on-site manufactured tower design with an unconstrained base diameter. The results for each design show how tower mass and expected material costs change with increasing hub height, and thus provide insight into the potential value of investing in the different technical solutions to enable future, low-cost, tall towers.

II. Methods: Tower Optimization

Tower design looks at minimizing mass and cost through manipulation of the diameter and thickness of the tower along its length. The main constraints on the design are on the tower strength, stiffness and resistance to buckling, which are driven by the loads the tower experiences over its operating lifetime. The loads on the tower stem from aerodynamic, gravitational, and inertial loading from the rotor-nacelle assembly (RNA) at the tower top as well as drag loads from the wind impinging directly on the tower. Detailed discussion of the tower design process is provided, for example, in "Design of Offshore Wind Turbine Towers" [2].

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This study uses a software tool for Tower Systems Engineering (TowerSE) to optimize the wind turbine tower design to minimize mass by adjusting tower diameter and thicknesses. [3] TowerSE is a wind turbine tower conceptual design tool that is part of a larger Wind Plant Integrated Systems Design and Engineering Model (WISDEM). [4] The tower-top diameter is fixed. The main design variables, shown in Table 1, are: the diameter at the base of the tower, the diameter at the set-point elevation, and the set-point itself. The tower outer diameter and wall thickness taper linearly between base and set-point elevation, and between that elevation and the tower top. The assumption of wall thickness taper is a simplification from reality where discrete steel plate thicknesses would be used at the height of the plates along the tower. The wall thickness at the base, top, and elevation set-point also are design variables.

Table 1: Tower Design Variables

Description	Number of Variables
Tower Outer Diameter	2
Tower Wall Thickness	3
Tower Set-Point for Tapering	1

The design variables are optimized for minimum tower mass, since in this case tower cost is a simple multiplier of overall tower mass, and such that the tower designs satisfy constraints under key turbine loads. Resonance avoidance is considered through a constraint on the tower natural frequencies relative to the RNA fundamental forcing frequencies. Depending on the case analyzed, constraints for manufacturability and transportability are applied as well. A user-defined number of analysis stations are created along the tower (in this case 15) to create the full set of stations for evaluation against the strength, shell and global buckling, and fatigue damage constraints. Buckling and strength constraints are evaluated under a user-specified number of load cases (in this study two load cases were used as described below). If applied, manufacturability constraints are evaluated at the tower base, midpoint, and top, whereas transportability is assessed only at the tower base. The full list of constraints is provided in Table 2.

Table 2: Tower Design Constraints

Description	Number of Constraints
Utilization Against Shell and Global Buckling	60
Utilization Against Strength	30
Eigenfrequency Lower Limit	1
Fatigue Damage	15
Diameter to Thickness Ratio (Manufacturability)	3
Base Diameter (Transportability)	1

The methods to calculate the shell buckling, global buckling, fatigue damage, and stresses along the tower for each load case are addressed in several prior studies. [5, 6, 7] There are 15 constraints at each of the defined analysis stations along the tower for each of the buckling, strength and fatigue constraints and these are multiplied by two since each constraint is evaluated for each of the two design load case evaluated – see section III for specifics on the load cases uses in the study. The diameter-to-thickness-ratio constraint ensures weldability of the tower panels. The base diameter upper-bound constraint is adjusted depending on the tower design case—4.3 m for conventional technology, 6.2 m for LDST technology, and unconstrained for on-site manufactured technology.

Finally, the frequency constraint lower bound is adjusted based on the type of tower (present for soft-stiff and absent for soft-soft). The frequency constraint is of interest to the design because it often can be the binding (or design driving) constraint on a soft-stiff design and push the mass up exponentially as towers grow taller and the natural frequencies decrease (for a fixed diameter and thickness profile). The tower designer must ensure that the tower natural frequencies do not overlap with the rotor rotational (1P) and blade passing (3P for a 3-turbine blade) where excitations can lead to resonance and large amplitude loads and increased fatigue damage (see Damiani 2016, for detailed discussion). Conventional tower designs historically were soft-stiff to completely avoid the potential for resonance-induced loading through hardware design. Modern wind turbine controls, however, make it is possible to control through resonance conditions, i.e. ride-through the 1P and 3P frequencies, and thus enable the use of soft-

soft tower designs, which are characterized by very low natural frequencies, are less stiff, and require less thickness despite the use of smaller tower diameters. As shown herein, this has significant implications for the small-diameter towers in tall tower applications.

III. Tower Optimization Case Study

Table 3 shows the cases examined in this study: 6 different combinations of tower designs for each of 6 different turbine hub heights, for a total of 36 optimization cases.

Table 3: Tower Optimization Cases

Tower Configuration	Tower Type	Hub Height
• Conventional (4.3 m base diameter) • LDST (6.2 m base diameter) • On-Site Manufacture (no base diameter constraint)	• Soft-Stiff (constrained to above rated rotor 1P) • Soft-Soft (no frequency constraint)	• 80 m • 100 m • 120 m • 140 m • 160 m • 180 m

The RNA properties and loads for the study are based on a newly designed reference turbine developed by the IEA Wind Task 37 on Wind Energy Systems Engineering. The 3.3 MW reference turbine has a rotor diameter of 130 m and a specific power of roughly 240 W/m^2. [8] Although not as low in specific power as some machines that are in production or are expected to soon be in production, it is an IEC Class 3A turbine design for low-wind-speed applications and closer to current land-based wind turbine technology than other publicly available reference turbine designs. Table 4 provides the fundamental configuration details for the reference turbine used in the study.

Table 4: IEA Wind Task 37 Land-Based Low Wind-Speed Turbine Configuration Data

Wind Turbine Configuration Data	
Lead Developer	Technical University of Munich
Class and Category	IEC Class 3A
Rotor Orientation	Upwind
Number of Blades	3
Control	Variable speed collective pitch
Drivetrain	Geared machine
Rated Power	~3.3 MW
Rotor Diameter	130 m
Hub Height	110 m

The loads for the turbine were provided by the Technical University of Munich (TUM) through a comprehensive analysis of the turbine response to various design load cases (DLCs) as defined by the International Electrotechnical Commission (IEC) design standards for wind turbines. [9] From that analysis, the largest loads for all tower-top forces and moments included DLC 1.1 for operation with normal turbulence, DLC 1.3 for operation with extreme turbulence, and DLC 2.3 for operation with an extreme gust and a simultaneous grid fault. The two load cases with the greatest force and moment components at the tower top were used as input loads to the optimization. These both occurred from DLC 1.3—the first case with a thrust load of 1,000 kN and the second case with a torsion around the vertical axis of 12,500 kNm).[8] Additionally, fatigue loads were applied along the tower based on scaling fatigue damage equivalent loads (DELs) from the NREL 5 MW reference turbine, as the specific DELs for the reference turbine were not available at the time of the analysis. [10]

IV. Results

As would be expected, the tower configuration of soft-stiff or soft-soft had a significant impact on the overall results. Overall, the soft-stiff towers were significantly more massive than their soft-soft counterparts above 100 m. Similarly, there is also a significant decrease in mass moving from transportable to LDST to on-site manufactured technologies. Table 5 summarizes the overall optimized mass results for each of the cases analyzed.

Table 5: Optimized Mass for Tall Towers for Case Configurations (in Metric Tons)

	Transportable		LDST		On-Site Manufactured	
Hub Height	**Soft-Stiff**	**Soft-Soft**	**Soft-Stiff**	**Soft-Soft**	**Soft-Stiff**	**Soft-Soft**
80	180	180	130	130	120	120
100	400	290	200	210	190	190
120	900	440	440	300	290	280
140	1,950	640	860	430	440	380
160	4,400	880	1,600	560	650	470
180	8,900	1,160	2,900	770	960	600

At common hub heights for current installations of 80 m, the frequency constraint is inactive for all the technologies. As hub heights increase to 100 m or above, however, there is a divergence in masses between soft-stiff and soft-soft configurations; but, for all cases, different constraints are active and dictate the overall design. Table 6 summarizes the active constraints for each of the design cases. Constraints include: 1P—frequency constraint, D—fatigue damage, GB—global buckling, SB—shell buckling. Middle (mid), base, or top indicate where along the tower the constraint is active.

Table 6: Design Constraints for Each of the Cases Analyzed

	Transportable		LDST		On-Site Manufactured	
Hub Height	**Soft-Stiff**	**Soft-Soft**	**Soft-Stiff**	**Soft-Soft**	**Soft-Stiff**	**Soft-Soft**
80	D (mid, base), GB (top)	D (mid, base), GB (top)	D (mid, base), SB (mid), GB (top)	D (mid, base), SB (mid), GB (top)	D (mid, base), SB (mid), GB (top, mid, base)	D (mid, base), SB (mid), GB (top, mid, base)
100	1P, GB (top)	D (mid, base), GB (top)	1P, D (mid), SB (mid), GB (top)	D (mid, base), GB (top)	1P, D (mid, base), SB (mid), GB (top, mid, base)	D (mid, base), SB (mid), GB (top, mid, base)
120	1P, GB (top)	D (mid, base), GB (top)	1P, D (mid, base), GB (top)	D (mid, base), GB (top)	1P, D (mid, base), GB (top, mid, base)	D (mid, base), GB (top, mid, base)
140	1P, GB (top)	D (mid, base), GB (top)	1P, D (mid, base), GB (top)	D (mid, base), GB (top)	1P, GB (top, mid, base)	D (mid, base), GB (top, mid, base)
160	1P, GB (top)	D (mid, base), GB (top)	1P, D (mid, base), GB (top)	D (mid, base), GB (top)	1P, GB (top, mid, base)	D (mid, base), GB (top, mid, base)
180	1P, GB (top)	D (mid, base), GB (top)	1P, D (mid, base), GB (top)	D (mid, base), GB (top)	1P, GB (top, mid, base)	D (mid, base), GB (top, mid, base)

In all soft-stiff configurations of 100 m or more the frequency constraint was binding. Fatigue and global buckling constraints also drove the final design, depending on the specific configuration and tower height. Additionally, the global-buckling constraint is active across all cases at the top of the tower at the nacelle interface.

The diameter of the top of the tower was fixed (because the rotor-nacelle design is fixed) and the optimizer thus sought to reduce the thickness of the tower top until the buckling constraint was met. Without the tower constraint being active, both fatigue damage and global buckling are prominent and drive non-linear increases in tower mass with hub height for each of the configurations. Figure 1 show the changes in design driving constraints across the different technology configurations at 120 m.

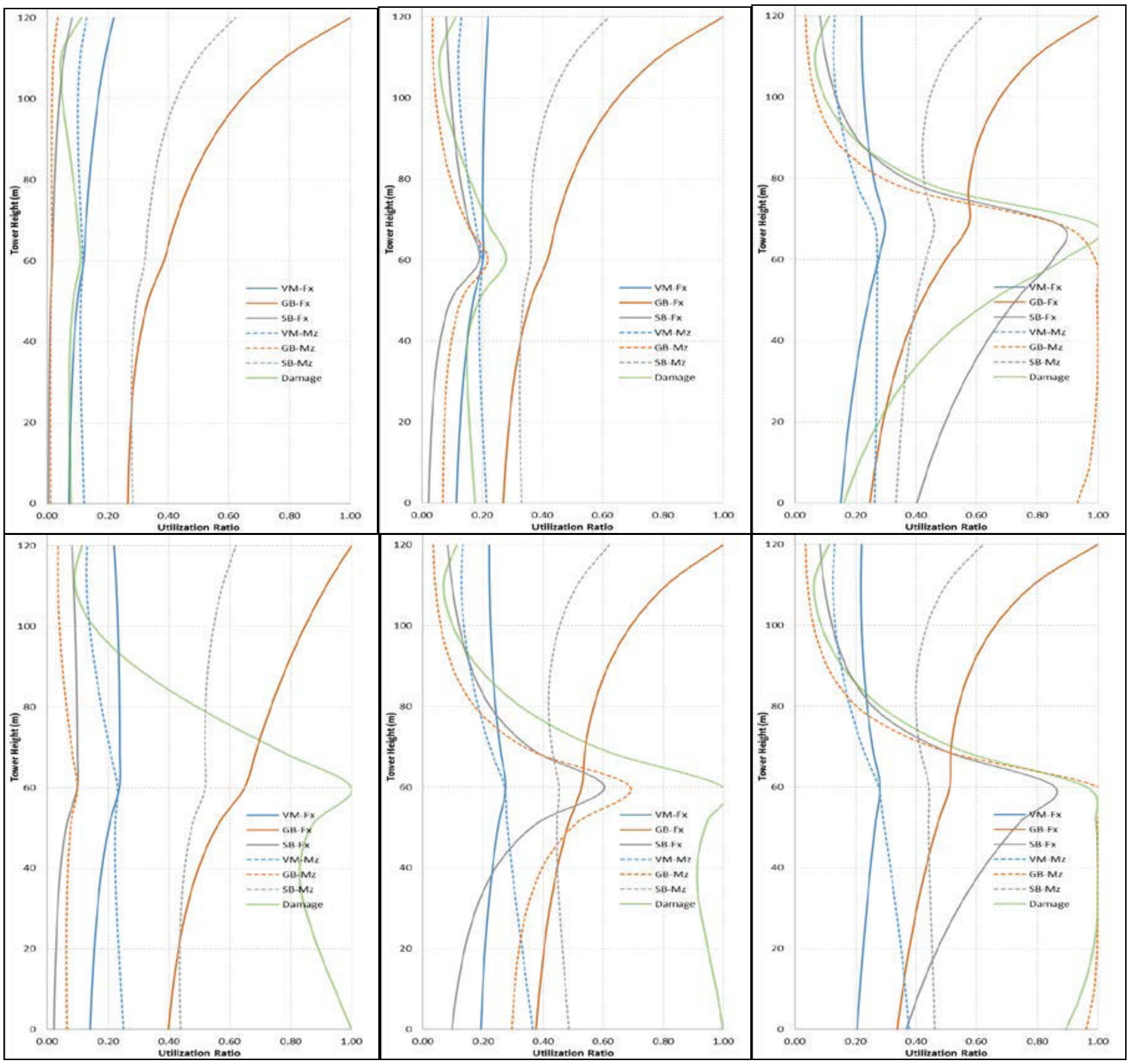

Figure 1: The utilization ratio for all strength, buckling, and damage constraints along the tower for each of the 120 m cases in the soft-stiff configuration (top) and soft-soft configuration (bottom). Moving from left to right: transportable, LDST, and on-site manufactured configurations are plotted. Fx denotes the first DLC 1.3 case with a thrust load of 1,000 kN, and Mz denotes the second case with torsion around the vertical axis of 12,500 kNm. The different design constraints include the von Mises stress (VM), global buckling (GB), shell buckling (SB), and fatigue damage (Damage).

The top plots show the constraint activity for the optimized designs in soft-stiff configurations. Most utilization rates are well below 1.0 because the frequency constraint at 120 m is significantly constraining the design—especially for the transportable and LDST towers. The on-site manufactured design with an unconstrained base diameter is still affected, the frequency constraint is still active, but other design constraints also are active along a significant portion of the tower. Noticeably, global buckling is active along the entire lower section of the tower, which now has a very large diameter of near 10 m at the base. This constraint is active for the soft-soft configuration of the on-site manufactured tower as well, but the lack of a frequency constraint enables the use of a somewhat smaller diameter with about the same wall thickness (15 mm in each case). For both the transportable and LDST towers, where base diameters are constrained to 4.3 m and 6.2 m respectively, global buckling is not a driving constraint for the lower section of the tower, but the fatigue damage constraints are active at both the mid-section of the tower and the tower base.

Figure 2 shows the overall results for soft-stiff tower masses for each of the turbine tower configurations investigated.

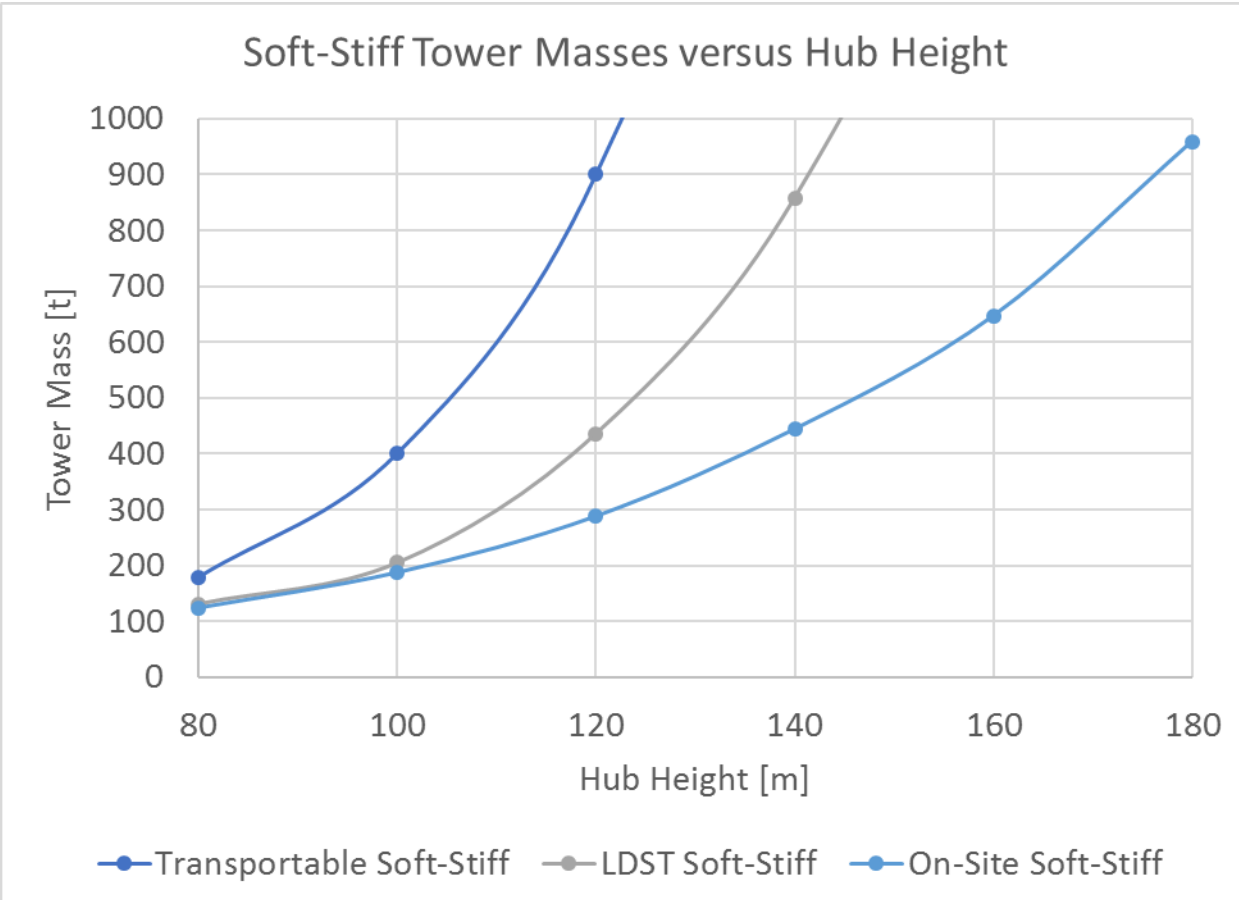

Figure 2: Optimization results for soft-stiff tower design cases from hub heights of 80 m to 180 m

For the transportable towers with maximum diameter of 4.3 m, the optimizer failed to find a feasible solution for hub heights of 140 m or greater. The tower mass can be seen to grow exponentially with tower height, especially past tower heights of 100 m. This result aligns with past analysis that indicates a highly non-linear increase in cost per unit increase of hub height for conventional wind turbine towers at heights of 100 m or more. [11] When the constraint on tower base diameter is relaxed, there are benefits in decreasing mass at all heights. Generally, the need to meet the frequency constraint for soft-stiff towers pushes the wall thickness of smaller-based-diameter towers to large values so that the overall mass increases exponentially. The difference in mass beyond 100 m hub-height between the three design configurations is significant enough to warrant investigation of novel wind turbine tower designs including LDST and on-site manufactured towers. It is important to note, however, that the overall cost could increase due to increased complexity of the manufacturing processes. The results shift when looking not just at traditional soft-stiff towers, but also at soft-soft towers where controls are used to avoid 1P resonance with the rotor (see Figure 3).

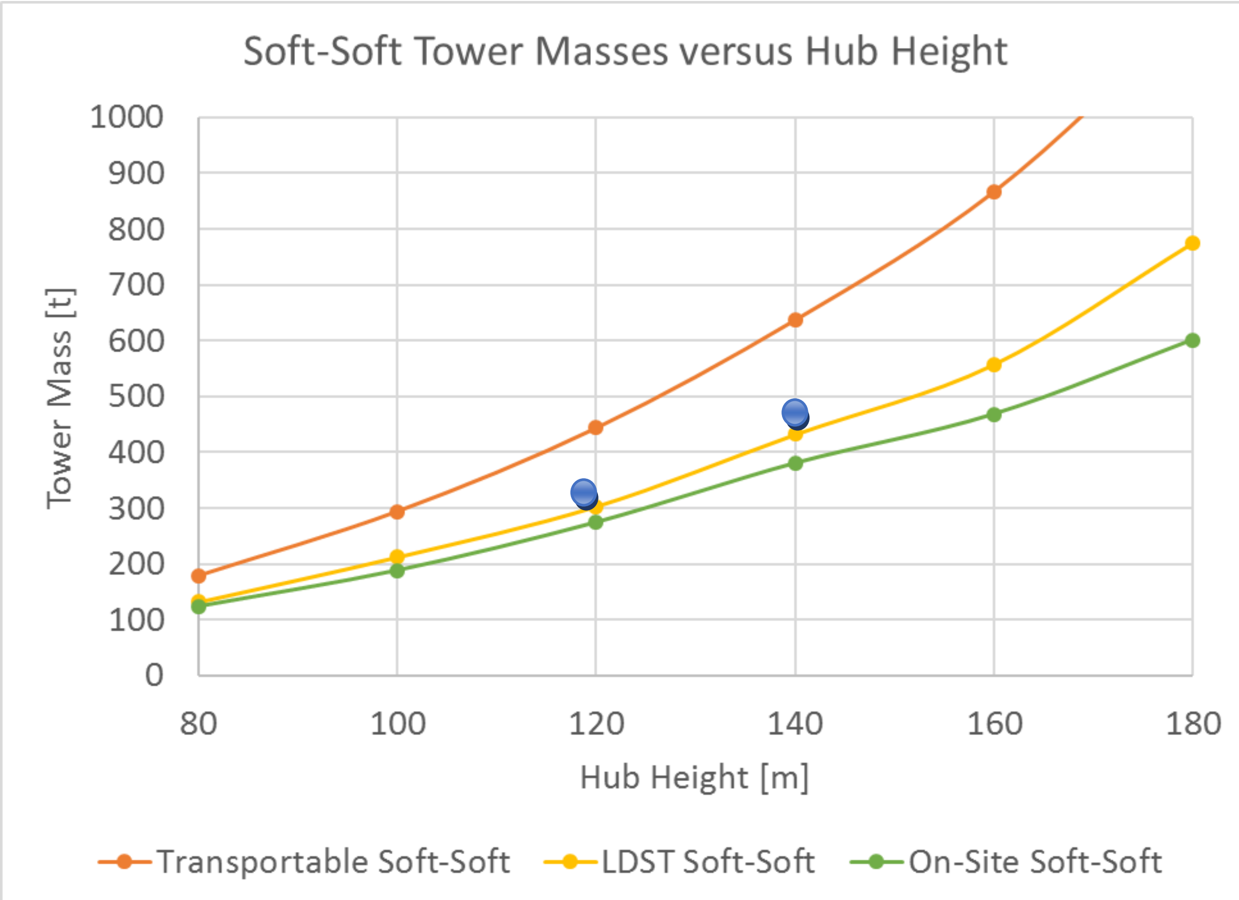

Figure 3: Optimization results for soft-soft tower design cases from hub heights of 80 m to 180 m

For soft-soft towers, the masses are reduced from the soft-stiff tower results for all cases. The difference is most pronounced in the transportable case with maximum base diameter of 4.3 m. The optimizer was able to find feasible solutions for all transportable cases, although the 180-m case yielded an optimized mass of 1,200 tons to meet constraints for global buckling. Similarly, the solutions for the LDST and on-site manufactured cases are all much lower than before—by as much as 200 tons in the on-site manufactured case at a 180-m hub height. Looking across all the towers and considering hub heights of 120 – 160 m which represent near term tall tower opportunities, the LDST and on-site manufactured towers have very similar overall masses (especially between 120 – 140 m). If we were to compare the technologies from an overall cost perspective, it is likely that the LDST technology would outperform on-site manufactured approaches given the additional costs for mobilization and demobilization associated with on-site manufacturing. This would indicate that the use of advanced controls techniques with a soft-soft LDST tower may be a viable solution for enabling tall tower technology compared to on-site manufacturing. However, this study is preliminary and does not adequately model any of the technology scenarios to draw a conclusion.

Additionally, the plots show actual masses for two transportable towers with hub heights of 120 m and 140 m, respectively. These masses are well below the transportable tower masses predicted by the optimization scheme. This is likely due to both the fact that the reference turbine design differs from actual technology in the field potentially with even lower specific power and resulting tower-top loads—and because industry has developed more-sophisticated control systems to enable not just soft-soft tower designs but an overall decrease in design loads experienced by the tower. An example of this is Vestas OptiStop™ and Active Damping™ technologies that reduce the overall loads experienced by the towers and allow for a more efficient, reduced weight, and lower-cost tower design. [12] The industry data demonstrates that although pursuing novel tower technologies holds promise for higher and higher hub heights, innovation around conventional tower designs holds promise and could extend their competitiveness even to the greater hub heights targeted for turbine installations soon. At the same time, when the full suite of controls technologies is applied to LDST and on-site manufactured technologies, their masses can be decreased even further with significant potential to reduce wind cost of energy for tall tower applications.

V. Conclusions and Future Work

This study shows the potential for innovation in wind turbine tower technology (in an idealized form) to reduce tower mass and material costs for a lower cost of energy. The study shows that novel control mechanisms allow for cost-effective traditional tower technology with base diameters of 4.3 m or less to be economic for projects with higher hub heights, and new innovations can even further decrease the relative cost of turbine towers for increasing hub heights. The latter might enable deployment of wind in low-wind-resource regions to expand the overall market for wind energy worldwide. Additionally, the complete paper delves deeper into the design constraints for the different tower technologies at the different hub heights to further investigate the effect of certain design conditions on the viability of the different tower technologies. Additional work will look at these idealized towers from a cost perspective, taking manufacturing cost into account, as well as considering other tower technologies that could use concrete for part or all the tower design.

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