A technical analysis and comparison of tubular and lattice towers for wind turbines

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\textbf{Abstract.} The advancement of wind energy technology brings about an increase in the size and height of the wind turbine towers. As the upscaling of the conventional steel tubular tower is problematic, alternatives are being investigated. In this paper, several configurations were reviewed and the lattice tower was identified as a possible solution. This study analyses and compares the structural performance of the two tower configurations, tubular steel and lattice, of equivalent height, stiffness and mounted rotor, in two sets of tower heights, 120 m and 150 m. The towers are mounted by the baseline 5 MW turbine developed by National Renewable Energy Laboratory (NREL). The results indicate that lattice towers are a suitable alternative to the tubular towers, providing significant material savings for a similar structural behaviour. Comparable bending moments were recorded in the base of the structures. The most demanding operating condition of the wind turbines was identified to be system braking cause by a sudden increase in wind velocity outside of the operating range. The 150 m lattice tower responds with excessive displacement during this abnormal operating condition; this is a potential issue that can cause generator failure if not accounted for in the rotor design.

1. Introduction

Over the past decades, the industry has been focusing on upscaling wind turbine (WT) blades in order to increase the production of energy, from the 50 kw first generation commercial WTs in the 80’s to the current multi megawatt generation. As a result, larger towers are required to provide safe support and reliable performance of the turbines.

Another driving factor of upscaling the towers is the increase of wind speed with altitude. The movement of air mass close to the ground is dominated by friction against the earth’s surface and the velocity increases logarithmically with height [1]. This region, known as Prandtl layer, varies from 20 m to 150 m depending on meteorological conditions. Studies have indicated that a 60 m tower is within this region 30% of the operating hours while 100m towers only 7% [1]. Above the Prandtl layer, in the region called Ekman layer, the airflow is largely friction-free and turbulence is reduced, resulting in an increased wind velocity. This was not considered in the early design of tall WTs and the logarithmic approach was utilised which led to underestimating wind velocities. The energy yield of a turbine increases with the cube of the wind speed. The graph in Figure 1 shows the rated power for various tower height of commercial turbines [2]. Therefore, capturing higher velocity winds at higher altitudes is a significant contributing factor towards improving the efficiency of wind energy.
Most of the inherently high-wind inland sites are being occupied across Europe. As a result of the limited availability of optimal sites, wind farms are also being developed in locations with less suitable wind conditions. In Europe, especially in Germany and Denmark, forest sites are becoming common, as they are currently unexploited and usually located away from urban settlements. Turbines in woodland sites require a tower height of more than three times the tree height to avoid increased turbulence, which typically results in more than 100 m tall towers [3].

Keeping the cost down is a key aspect of wind energy development. Towers account for 20-30% of the initial cost of a wind farm [4], as shown in Figure 2, with a potential of taking up an even larger proportion as they are scaling up. Therefore, improving cost efficiency of the structure has a significant contribution in the competitiveness of the wind energy sector.

1.1. Types of wind tower

Taller, cost-efficient towers are a necessity for the development of wind energy. At the moment, tubular steel is the most widely used structure for WT towers [5]. This typology shows a disproportional cost with increasing heights and onshore road transportation of the large diameter sections is becoming a major issue. Consequently, it is essential to investigate alternative solutions.

1.1.1. Tubular steel tower. Currently, the most widespread structure is the tubular steel tower, which proved to be an economically efficient solution for medium size towers [5]. Tubular towers have a tapered shape with the diameter decreasing from tip to base. They come in a number of prefabricated tubular sections of lengths up to 30 m connected together by bolted flanges. Towers up to 100m require a base diameter of no more than to 4.5 m.

However, increasing the size to more than 100 m results in a large base diameter (5 m or more) and increased wall thicknesses, which raises a number of issues. The quantity of steel required to achieve the design stiffness increases, with a significant impact on cost. Manufacturing (i.e. shaping the steel sheets) becomes energy intensive and requires performant equipment. Road transportation is also a
constrain for inland sites; the maximum allowable vehicle height in UK is 4.95 m [6], with even more restrictive limits as low as 4 m across Europe [7]. The connections between tubular sections are prone to local stresses and buckling due to fatigue.

1.1.2. Lattice tower. A possible alternative to the tubular tower is the lattice tower. Lattice towers are structures built as a three-dimensional truss from steel members welded or bolted together. These were commonly used in the past for the first experimental small sized turbines due to their simplicity of design and construction. They were the predominant onshore wind turbine structure until the 1980’s [8]. Nowadays they are still found in towers up to 30 m especially in Eastern Europe, Middle East and Asia [9]. Their presence in Western countries is very limited, especially following the commercial development of tubular steel towers. Currently there is a revived interest in the applications of lattice towers as the tubular towers show a disproportional cost with increasing heights [10]. This is due to the significantly less amount of materials utilised compared to a tubular tower of the same height and stiffness, which becomes increasingly relevant for the overall cost in the case of larger towers, as shown by the studies mentioned in the next section. Their size is not limited by transport and large base areas can be easily achieved for better stability by spacing the legs apart.

The aim of this paper is to investigate and compare the structural performance of a standard tubular steel tower to a proposed alternative lattice structure by using Finite Element Modelling and aeroelastic simulation, with the aerodynamic loads are obtained using a software based on Blade Element Momentum Theory. This is achieved by carrying out a FEM simulation and a BEM simulation, performed separately, on the same structure.

2. Tower structural analysis

Research has been conducted into the dynamic response of medium to large tubular towers [11,12], computing displacements and bending moments. A full aeroelastic analysis of a 120 m tubular tower was performed [13] by using CFD modelling of the airflow and Finite Element Modelling (FEM) to compute the stresses and displacements in the tower.

Lattice towers design and analysis was mostly performed for the purpose of transmission towers, as this was their main application in the past [14-16]. Lattice towers for WTs have also been investigated. A project from the Norwegian University of Science and Technology developed an 87. 6m lattice offshore tower, quoting steel savings of 50% compared to tubular steel [17]. Studies of lattice towers by [18,19] also show steel savings of 25-50% to their tubular counterparts. However, all the authors agree that the validity of the results are limited by unknown costs of installation and by the fact that the analysis performed on the lattice tower was only static, without accounting for turbulent wind and blade dynamics.

A report was compiled [20] that investigated the economy of several structural alternatives for 3-5 MW turbines. The study looked at conventional tubular steel tower, tubular steel towers with bolted vertical connections, pretensioned concrete towers, hybrid tower, lattice tower and wood tower of various heights (80 m - 175 m).

The proposed study aims to cover the knowledge gap of structural comparison between the two alternative tall towers by performing a full aerodynamic analysis.

The interaction between aerodynamic forces and non-rigid structures is called aeroelasticity. There are several methods to quantify and predict the aeroelastic behavior of the turbine components. Blade Element Momentum (BEM) theory analysis aerodynamic loads on an independent radial blade element of infinitesimal length, this method allows the calculation of values for torques, captured power and axial thrust on the rotor. These can then be integrated along the length of the blade to obtain the loadings transferred to the tower. The BEM method provides satisfactory results and is commonly used due to being fast and computationally cheap. The accuracy of the analysis is mainly dependent on the correct input parameters of aerofoil data, lift and drag coefficient as a function of the angle of attack [21,22]. Therefore, intensive work has been focused on the estimation of aerofoil data, both in research [23] and in the industrial development of large wind tunnel tests [24].
Computational Fluid Dynamics (CFD) can also be employed for simulating blade aerodynamics. Unlike BEM, which uses empirical and experimental data, CFD solves numerically the Navier-Stokes equations which describe the behaviour of the flow. This can be done in several ways, depending on chosen simplifications and specific computational techniques. Literature provides numerous reviews of CFD principles [25, 26] as well as of its application in wind energy [27, 28].

The main advantages and limitations of both methods have been reviewed [29, 30]. BEM method is relatively easy to compute given accurate input data, while CFD present many challenges in creating adequate mesh and turbulence models to simulate the flow around the blades. Solving non-linear equations for a 3D model is computationally expensive and it is not yet matured as an engineering tool for the wind energy industry. Due to the rapid development of computational capacity in the recent years, CFD has been used more and more in design and is approaching the cost efficiency of BEM [31]. On the other side, BEM method has been found unreliable for turbulent conditions and stall conditions [30].

A number of studies have been undertaken to check the validity and results of both methods. The results of CFD simulations, BEM analysis and experimental data from MEXICO Project were compared [31]. The results show agreement between the axial force and torque on the rotor at medium wind speeds, with deviations at high wind speeds: CFD overestimated the axial force while BEM underestimates the torque. Also, the two methods are examined in terms of turbine power coefficient at a range of wind speeds and the results show overall good agreement with measured data NREL PHASE VI experimental data wind tunnel measurements [30, 32].

Overall, there are good examples in the literature of the validity of both modelling techniques. Due to the computational requirements and complexity of 3D CFD, BEM was chosen for this study. One of the main shortcomings of this method (i.e. difficulty in obtaining reliable aerofoil data and drag/lift coefficients) will be overcome by employing well-documented and easily accessible data from the experimental 5MW NREL turbine.

2.1. Geometry
For the purpose of this study, two structural configurations were compared, tubular tower and lattice tower, in two sets of heights of 120 m and 150 m. The towers are assumed to be mounted by the baseline 5 MW 126 m diameter turbine developed by NREL [33]. This multi megawatt rotor meets the criteria of the study as it is situated at the upper end of commercial development. The rotor is developed for research purpose; thus data is well documented and accessible.

The geometry of the 120 m tubular tower is adopted from [34]. It was developed by scaling up the baseline NREL 90 m and a 103 m commercial tubular tower from Vestas. The 150 m tall tower was scaled up from the 120 m tower. The geometric parameters for both structures are presented in Table 1 and 2.

### Table 1. Dimension details of 120 m tubular tower.

| Elevation [m] | Fractional Height [-] | Thickness [mm] | Diameter [m] |
|---------------|------------------------|----------------|--------------|
| 0-30          | 0.00-0.25              | 48.00          | Base - 8.43  |
| 30-60         | 0.25-0.50              | 40.33          |              |
| 60-90         | 0.50-0.75              | 32.67          |              |
| 90-120        | 0.75-1.00              | 25.00          | Top - 3.87   |
Table 2. Dimension details of 150 m tubular tower.

| Elevation [m] | Fractional Height [-] | Thickness [mm] | Diameter [m] |
|---------------|------------------------|----------------|--------------|
| 0-30          | 0.00-0.20              | 60.00          | Base – 10    |
| 30-60         | 0.20-0.40              | 51.25          |              |
| 60-90         | 0.40-0.60              | 42.5           |              |
| 90-120        | 0.60-0.80              | 33.75          | Top -3.87    |
| 120-150       | 0.80-1.00              | 25.00          |              |

Prototypes of large-scale onshore lattice towers have not been extensively developed. Therefore, geometry principles of small-scale lattice tower and transmission towers were investigated and adapted. A recognised problem about lattice structures is the proper choice of the static scheme. This represents a research topic, and it is usually studied by means of optimisation techniques or parametric studies. Three and four-legged lattice structures were investigated [35] by varying the wall thickness and the results showed better torsional stiffness of the four-legged geometry for the same material use. A four-legged structural typology was chosen for this study. In this instance, the length of the regions was chosen in order to achieve a 10 m tip clearance, accounting for a 5m rotor overhang, 5° shaft tilt and 2.5° blade precone angles, as defined for the 5 MW NREL turbine. The second moment of inertia of the tower varies quadratically with the distance between legs [36]. The ratio of height to leg distance was scaled up from [37] and [38] as shown in Figure 3. The top width was chosen to be 4 m to accommodate for a transition piece between the rectangular top of the lattice and the 3.87 m diameter of the bottom of the 5 MW NREL turbine.

Figure 3. Tower height against leg spacing compared to literature.

2.2. Finite Element Modelling

The commercial finite element analysis package SAP2000 was used to model and size the structures. The tubular tower was modelled using two-dimensional quadrilateral (4 nodes) thin plate elements. There are two main factors that influence the accuracy of FE analysis: having a good density of the mesh and maintaining a low element aspect ratio (i.e. the ratio of the longest side to the shortest side) [39]. In this instance, 8000 and 10000 quad elements will be used for the 120 m and 150 m towers respectively. The number of elements is a compromise between computational effort and accuracy of results. The aspect ratio of the quad elements varies between 1 and 2.07.

For the tubular tower the elements were defined as thick shells with incremental thicknesses from top to bottom. Rigid diaphragms were applied every 30 m to simulate the stiffeners that are used in practice for tubular towers.

The lattice tower was modelled as a three-dimensional space frame with one-dimensional bar elements and pined connections. The members were sized to provide sufficient capacity for the applied loads based on Eurocode 3. The towers were divided into sections as shown in Figure 4 to facilitate the design of the members. Stiffeners in the form of rigid diaphragms were applied at each transition.
The appendix compiles the 3D models of the tower configurations that were drawn in AutoCAD imported into SAP2000.

Figure 4. Sizing of lattice members.

Next, the loads applied to the structure are considered:

- Self-weight as a distributed load in the elements
- Rotor load (from [33]). This was applied as a lumped mass at the top of the towers. Its components are rotor thrust (Fy) and rotor weight (Fz). The thrust acts at the root of the rotor, 2m above the top of the tower and creates a bending moment Mx
- Wind loads (from Eurocode 1), applied as diaphragm loads.

The loads were applied in a loadcase combination recommended by [40] and [41]. The applied load patterns and safety factors are summarised in Table 3. The dynamic load factor accounts for the dynamic behavior of the structure and its value is recommended in section 4.5.1 of DNV/Risø [40].

The lattice tower is sensitive to the direction of loads. Therefore, the angle of application was varied to identify the critical design situation [36]. The horizontal loads were applied concomitantly at 0, 15, 30 and 45 degrees. After 45 degrees, the structure becomes symmetrical. This is not required for the tubular tower, as it is symmetrical in all directions.

The thrust of the rotor acts at a distance of 2m from the top of the tower, creating a bending moment. This was translated in a set of four joint forces for the lattice tower and 40 joint forces for the tubular tower, with a resultant of zero. The force distribution was calculated by using an analogy adapted from bolt theory.

Table 3. Static loads.

| Load pattern       | Type      | Magnitude   | Direction | Dynamic load factor | DLC 1.1 Safety Factor |
|--------------------|-----------|-------------|-----------|--------------------|-----------------------|
| Tower Self-Weight  | Dead      | Variable    | -Fz       | -                  | 1.35                  |
| Rotor Self Weight  | Dead      | 3487.4 kN   | -Fz       | 1.165              | 1.35                  |
| Rotor Thrust       | Live      | 1000 kN     | Fy        | 1.165              | 1.35                  |
| Rotor Moment       | Live      | 2000 kNm    | Mx        | 1.165              | 1.35                  |
| Wind               | Wind (EC1)| Variable    | Fy        | -                  | 1.35                  |
2.3. Blade Element Momentum Theory Analysis

In the next stage, a time dependent aeroelastic simulation was performed on the selected models using the Blade Element Momentum (BEM) software package ASHES. The additional factors considered by the BEM analysis as opposed to just performing a static FE analysis are:

- The aeroelastic effect of the blade deformation
- The behaviour of the control system of the turbine (rotor, yaw, braking), referred to as actuation loads
- Eigenfrequency analysis of the tower-rotor system
- Instantaneous response to various wind condition and time history records

A number of 30 operating condition situations are identified in the Guideline for the Certification of Wind Turbines [41], including various combinations of production, accidental faults, fluctuation of wind. The most significant and recurrent events during the lifetime of a turbine outside of normal operation are start-up, shutdown and change in wind direction. A number of 100 simulations were run in total for all four towers and are summarised below:

- Rotor start-up for 0, 5, 10, 11.4, 15, 20, 25, 30 m/s wind speed (0-10 s)
- Normal operation for 0, 5, 10, 11.4, 15, 20, 25, 30 m/s wind speed (10-60 s)
- Yaw of rotor for a change in the direction of the wind by 45 degrees at 5, 10, 11.4, 15, 20, 25, 30 m/s wind speed (60-120 s)
- Braking system for wind speed of above 30 m/s (60-90 s). This case was simulated by increasing the wind speed from 25 m/s to 30 m/s after simulation 60 s of normal operation.
- 10 minutes normal operation at 11.4 m/s.

3. Results

3.1. Static Analysis

A number of simulations were run in SAP2000 to establish the modal and buckling parameters of the towers. The results are summarised in Table 4. The natural frequencies of the isolated tower structures were computed by SAP2000 to ensure the pairs are comparable. The results are within 15% of each other.

**Table 4. Summary of tower parameters.**

| Tower       | 120 m Tub | 120 m Latt | 150 m Tub | 150 m Latt |
|-------------|-----------|------------|-----------|------------|
| Ref.        | T1        | L1         | T2        | L2         |
| Weight [kN] | 7404      | 4384       | 12640     | 7048       |
| Nat. Freq. –Isolated tower - M I & II [Hz] | 0.705 | 0.833 | 0.631 | 0.745 |
| Nat. Freq - Isolated tower - M III & IV[Hz] | 3.034 | 2.861 | 2.276 | 2.285 |
| Nat. Freq y –Tower and rotor - M I & II [Hz] | 0.339 | 0.322 | 0.310 | 0.302 |
| Nat. Freq – Tower and rotor- M III [Hz] | 2.108 | 1.951 | 1.567 | 1.745 |
| Nat. Freq – Tower and rotor- M IV[Hz] | 2.108 | 2.231 | 1.567 | 1.751 |
| Stiffness at top [mm/kN] | 0.51 | 0.59 | 0.58 | 0.72 |
| Buckling factor- Nonlinear P-delta | 4.5 | 10.5 | 3.6 | 8.7 |
| Buckling factor – Linear SW | 165 | 177 | 132 | 103 |
| Center of Mass [m] | 46.8 | 53.68 | 54.89 | 58.25 |
In order to avoid resonance it must be ensured that the frequency of the structure is outside a safe margin of 10% the frequency of the exciting dynamic loads [1], in this case the rotational frequency of the turbine (1P), the blade passage frequency (3P) and harmonic multiples (6P, 9P, 12P). Figure 5 is the Campbell Diagram of the towers, which shows that all resonance is avoided within the operational speed of 8-14 m/s marked by the grey area.

The two comparison parameters for the towers are displacement and bending and are summarised in Table 5. The magnitude of the displacement at the top of the towers was computed for both factored and unfactored loadcases; this was done in order to obtain results that can be compared to the dynamic analysis, which provides a time response of the structure and does not account for safety factors. Similarly, the magnitude of the bending moment in the base of the towers are calculated in both situations by taking section cuts at the lowermost point of the structure.

| Tower   | T1   | T2   | L1 | L2 |
|---------|------|------|----|----|
| Max. Displacement for DLC 1.1 [m] | 0.71 | 1.06 | 1.05 | 1.25 |
| Max. Displacement – Unfactored [m] | 0.53 | 0.63 | 0.75 | 0.94 |
| Max. Base Bending Moment for DLC 1.1 [MNm] | 164.5 | 228.5 | 228.5 | 232.2 |
| Max. Base Bending Moment Unfactored [MNm] | 121.7 | 169.3 | 131.9 | 172.1 |

3.2. Dynamic Analysis
The ‘Node’ sensors placed at the top nodes of the tower captured displacements in x, y and z direction, magnitude, speed and acceleration. The displacement parameter is used to compare the alternative structures. Figure 6 illustrates the variation of hub displacement magnitude against wind speed for all the towers during normal operation and 45-degree yaw.
To capture the displacement during shutdown, brakes were applied at a wind speed of 30 m/s after 60 s of normal operation and the time history is shown in Figure 7. Transient movements are caused by the mechanical system and the inertial forces in the blades. Extreme displacements, up to 2 m, were recorded for the lattice towers under these operating conditions. The tubular towers did not display excessive motion during braking.

Next, a comparison of bending moments in the tower base was carried out. The results are shown in Figures 8 and 9, plotted together with the bending moments obtained from the FEM analysis from the unfactored loadcase.

Figure 6. Aerodynamic displacement for various wind speeds.

Figure 7. Time response of tower tip displacement under braking conditions.

Figure 8. Aerodynamic bending moment for various wind speeds 120 m tower.
4. Discussion

The results in the previous section illustrate the behaviour of the investigated structures and provide the basis for comparing the two tower options. The structures were designed to behave similarly in terms of dynamic frequency. This parameter was chosen as a baseline in order to utilise the same rotor and avoid resonance for a similar range of operating speeds. After ensuring the models were sized with sufficient capacity for the predicted loads (i.e. no failure would occur during operation), a number of parameters were compared for the alternative structures, shown in Figure 10 and 11. In terms of increase in height, it was generally observed that the behaviour of the structure varies proportionally, as expected.
4.1. Weight and size
Lattice towers were identified in the literature as more economical in terms of material usage, with savings of up to 50% [17]. Results indicate that it is indeed possible to achieve structurally sound equivalent lattice towers with 40% less weight for the 120 m set and 45% for the 150 m set. In fact, Figures 10 and 11 show that similar amount of steel is required for T1 and L2, which gains a hub height increase of 30 m. In terms of wind power, this yields a significant potential increase in the WT power output.

In addition, during the design process of the lattice members it was observed that multiple sections were oversized. This is due to the division of the towers in bulky regions for simplification. Further savings can be achieved by specialised optimisation techniques of the members, and this is a very active area of research.

An important aspect to be noted is that the considered tubular towers, adapted from the available literature, have large base diameters of 8.4 m and 10 m respectively, which in practice would pose significant issues with land transportation. This is, in fact, one of the main drivers of considering the lattice alternative, for which transportation is not an issue.

4.2. Top displacement
The structural performance the towers can be quantified by comparing the hub displacement. In the FEM analysis under static loads and with a reference wind speed of 11.4 m/s, L1 and L2 showed 20-30% more displacement than their counterparts, which was expected due to their reduced stiffness. The live aerodynamic simulation shows less displacement in the tubular towers than predicted by the FEM results, which was attributed to the safety factors used in the static analysis. Under unfactored loads, the displacement of the tubular towers agrees within 8% with the aerodynamic simulation, as illustrated in Figures 10 and 11. It is noted that the ‘Displacement BEM’ figure refers to the maximum displacement recorded during the time simulations under normal operating condition. This occurs at 11.4 m/s wind speed for all towers due to the rotor thrust peaking at the rated speed.

An interesting finding is that lattice towers are more sensitive to aerodynamic conditions. Both towers displace by approximately 35% more compared to the static analysis. This reveals that horizontal oscillation is a major factor to be accounted for when considering the alternative of lattice towers. It also
shows that a static analysis is not sufficient to accurately simulate the behaviour of the coupled tower-rotor structure.

It became obvious that the ‘abnormal’ operation of the turbine causes major fluctuations in the otherwise harmonic behaviour of the structure. The ‘Extreme Displacement’ figure refers to the response of the top of the towers under the most onerous operating condition. In all cases, this was identified to be the activation of brakes at a sudden increase of wind speed outside the operating range of the structure. L2 is the most affected by the braking torque and the inertial forces of the blades, with a 55% increase in displacement from normal operating conditions. Other reasons for stopping the turbine besides extreme wind conditions are faults, repairs, maintenance, indicating repeated occurrence and thus establishing it as a major design factor.

The implications of hub displacement extend outside just the tower performance, into the functionality of the entire wind turbine system. Several turbine failures were reported to occur due to excessive horizontal movement [42]. This might limit the application of tall lattice towers for existing, market-available turbines. In the future, the design of the electrical and mechanical components can be pushed towards higher flexibility allowance. Excessive displacement can also impact the fatigue design of the structural members.

4.3. Bending moment in the base
The reaction at the supports of the towers are a relevant parameter in assessing the capacity requirements of the foundation, which in turn has financial implications.

The static load analysis yields base banding reactions of 8% more in the case of L1 compared to T1 and only 2% more for L2 as opposed to T2. Comparable results were expected due to the similar applied loads.

In the aeroelastic analysis, a fluctuating behaviour was observed in terms of the highest bending reaction among the alternative towers for various wind speeds. The variation is more evident in the case of T1 and L1. The curves of T2 and L2 are very similar, agreeing with the results extracted in the static analysis.

For the same tower heights similar base reactions occur. Generally, for overall equilibrium, the tower foundations is checked for bearing capacity, overturning, sliding and uplift. The tubular towers transfer slightly less bending moment in the base due to higher weight, making the foundation less demanding for withstanding overturning while increasing the required bearing capacity. This indicates that the foundation requirements of both towers can be regarded as similar. One outstanding difference arises when considering the structural arrangement. The lattice tower requires four separate foundations, while tubular towers typically use one large gravity foundation. However, the financial implications cannot be easily quantified due to various unknown factors, such as size, cost of building four separate structures as opposed to one, requirements for piles.

5. Conclusions
A comparative analysis was undertaken to identify the structural performance and feasibility of tall lattice wind towers as an alternative to traditional tubular towers.

The results of this study indicate that the lattice tower is a feasible alternative in terms of structural performance for upscaling the height of the next generation wind turbines. In terms of size, significant material savings can be achieved. The increased base area required to achieve tall heights does not pose an issue for fabrication and transportation. It was also observed that the weight varies at the same rate with the increase in hub height from 120 m to 150 m for both type of towers. Foundation requirements in terms of bending capacity appeared to be equivalent for the two alternatives.

One of the main issues identified in the behaviour of lattice towers is excessive hub displacement under extreme operating conditions. Susceptibility to horizontal motion was observed to increase with
height. This poses issues with generator failure due to vibration and indicates an important design factor to be considered as part of an integrated design of the next generation wind turbine systems.

Lattice construction is a feasible alternative of the tubular tower but additional parameters should be considered in further research:

- The lattice tower installation costs appear to be higher than tubular tower. A lot of sections, connections, also more foundations, which will significantly increase the investments costs especially in presence of heavy soil conditions (rocks, etc);
- Significant top displacement should not be underestimated: In a very turbulent wind the blades could bend in the direction of the wind flow, bringing them closer to the tower, resulting in dangerous consequences.

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Appendix
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