Tubular and lattice steel wind turbine towers for onshore wind energy

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ABSTRACT

The increasing world power demand combined with the need for environment protection and sustainable energy production, has led recently to the use of alternative means of energy production minimizing CO2 emissions. Wind energy, being probably the most promising renewable energy source due to its great energy potential and applicability, concluded recently to a variety of impressive relevant structural applications. The new trend to design and construct taller wind power installations in order to increase the amount of world sustainable energy production has led to the development of multiple structural solutions both for the foundations and the upper structure of wind power generators. The most common type of wind energy converters' upper structure is the cylindrical steel tower. Research on the structural optimization of wind turbine towers is of great interest and importance due to their high manufacturing and erection costs and certain transportation limitations that prevent them from reaching greater heights. In order to increase the wind energy harvesting, the construction of taller structures and the improvement of their structural detailing is critical towards achieving greater energy production along with economy in material use and structural robustness. Since installation of on-shore wind power converters is complicated in matters of module transportation and installation, there is a need for solutions that permit the construction of lighter structures that are easy to carry on isolated mountain sites and facilitate on-site mounting. The improvement and optimization of wind production facilities is of great interest nowadays and on the civil engineering part, wind turbine towers have potential of structural detailing optimization which can result in more efficient and durable structures introducing their wider application, leading to improvements in energy production methods and costs. The present work addresses the comparison of a classic tapered steel wind turbine tower configuration with a hybrid lattice tower of the same height and energy production potential. Aiming to contribute to better understanding of the structural behaviour of both types of wind turbine towers, the research work focuses on the development of reliable numerical models along with the use of analytical equations in order to predict accurately and interpret the aforementioned structural response of the two towers by conducting a comparative study between them. The present study examines the stability performance of each tower while attempting to minimize the total material used maintaining its endurance and robustness. The numerical investigation presented is realized by performing a comparative study between a tubular steel wind turbine tower and a lattice one, of the same height and with the same loading applied

Keywords

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Wind Turbine Towers, Numerical Analysis, Structural Design, Steel Structures.

1. INTRODUCTION

The use of sustainable energy sources is considered of great importance in order to limit down the Greenhouse effect consequences due to excessive CO2 emissions deriving from the use of fossil fuels. The European Commission has established a Renewable energy directive accepted by all member States, which sets as a goal that the final energy consumption from renewables should reach or even exceed 20% of the total energy consumption by 2020 [4]. Wind energy is proved to be one of the most promising renewable energy sources due to its infinite nature and great potential. Its expansion in Europe has been remarkable the last ten years which is reflected on the total power capacity of installed wind power plants that has tripled from about 50GW in 2005 to over 150GW in 2016 according to the European annual statistics [9]. Following contemporary trends, wind turbines are constantly designed taller in order to take advantage of the increased wind energy potential when moving away from the earth's surface. When constructing taller structures, the size of the tower becomes more and more important and its contribution to the total initial construction cost becomes more and more significant. Taking into account that the upper structure of the wind turbine along with the foundation can cover almost 35% of the initial construction cost in onshore wind turbines; it is proved sensible to investigate an optimized design for the wind turbine tower in order to achieve robust structures combined with economy in material use.

Wind farms are usually large project with high economical and social impact. Since failure in such projects has great economical, structural and safety losses; the structural optimization of wind generator towers is considered of high importance. The commonest tower configuration of horizontal axis onshore wind turbines is the cylindrical steel tower. These towers consist of modules that are manufactured in the factory as cylindrical or conical subparts and then transported and mounted on-site subsequently to their final position [6]. Cylindrical steel shells in general have due to their geometry, the advantage of carrying great loads with small shell thickness. Cylindrical shells structural behavior has been proved prone to buckling, therefore many research groups have oriented their work towards that area, perfroming research both in the numerical and experimental aspect like Timoshenko and Gere [13], Bazant and Cedolin [2] and Teng and Rotter [12]. Tubular steel wind turbine towers especially are subjected to the combined loading of wind and the wind generator motion and the work of Baniotopoulos and Stathopoulos [1] has been devoted their structural behavior analysis. Lee and Bang [7] developed a numerical model to simulate a collapsed wind turbine tower by matching the actual findings on site. When designing supertall wind turbine towers, structural problems arise that have been solved with the introduction of stiffeners on the inside part of tubular towers [10] [11]. Tubular wind turbine towers, despite being thoroughly investigated, still have high manufacturing and erection costs and certain transportation limitations that prevent them from reaching greater heights where higher wind speeds provide higher energy potential for harvesting.

As stated above the construction of taller on-shore wind structures is imperative in ordert to achieve greater energy production. Following the sustainability rules that are in favour of economy in material use and structural criteria that impose certain regulations, contemporary wind turbine towers need to be designed in a way that are sustainable and robust at the same time. Since installation of onshore wind power converters is usually in isolated places tower subparts' transportation and installation difficulties impose certain limitations on maximum tower diameter and subpart length. A solution that would permit the construction of lighter structures that are easier to carry and mount on site would be much favourable compared to the classic tubular one. The lattice tower solution which has already been implemented on telecommunication masts shows great potential in substituting the tubular wind turbine supporting structure. Telecommunication towers are usually constructed with the use of standard L shaped cross-sections but the scale of the lattice towers which are able to support the rotor of a wind converter leads to cross sections that are well outside the range of standard industrial profiles. A lattice tower that is capable of accommodating the nacelle has the form of a truncated cone with a polygon or square cross-section. The implementation of lattice towers on offshore and onshore wind turbines has just been investigated in the work of some research groups [5] [8] but the tower's optimal shape and design has not yet been studied. In the present work both the tower shape is being optimized and the tower design in terms of cross-section selection too. The tower, being a statically determinate lattice structure, composes of a number of discrete structural sub-systems; the legs, the face bracing trusses (FBT), horizontal braces and secondary bracings arranged inside the plane of the face bracing trusses. These discrete structural subsystems have a particular role in the load transfer mechanism of the lattice tower and since the tower is a statically determinate structure, the axial stresses of the legs and the bracings can be determined by closed form expressions. The present work investigates the stability performance of a tubular steel wind turbine tower and compares it with the structural response of a series of lattice wind turbine towers of both hexagonal and square shape. To have comparable results, all the structures share the same height and have the same loading being applied at the hub height. All of the structural configurations can sustain the loading applied and they are compared in terms of the amount of material used.

2. NUMERICAL MODELS

The numerical models investigated in the present work are of three types; cylindrical shell towers, square shaped lattice towers and hexagonal shaped lattice towers. All of the numerical models share the same height of 76.15 meters. The loads acting on all the towers are: the vertical loading due to the nacelle weight, the horizontal loading and moment due to the rotor function and the distributed wind loading along the tower height.

2.1 Cylindrical Shell Tower

The cylindrical tower under investigation consists of 3 subparts. These subparts are manufactured in the factory and transported onsite by trucks and finally mounted to their final position with the aid of large-scale cranes. that are modelled separately. The subpart lengths are 21.8 m, 26.6 m and 27.8 m length respectively going from foundation to rotor. The tube diameter ranges from 4.3 meters at the bottom to 3 meters at the top of the tower and the shell thickness is incrementally increasing from 12mm at the top to 30mm at the bottom as shown in detail in Fig 1. The software used for the tower simulation is Abaqus software [3] and the tower shell is simulated with shell 2-dimesnional elements and

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more specifically, reduced integration shell elements S4R as described in the software manual.

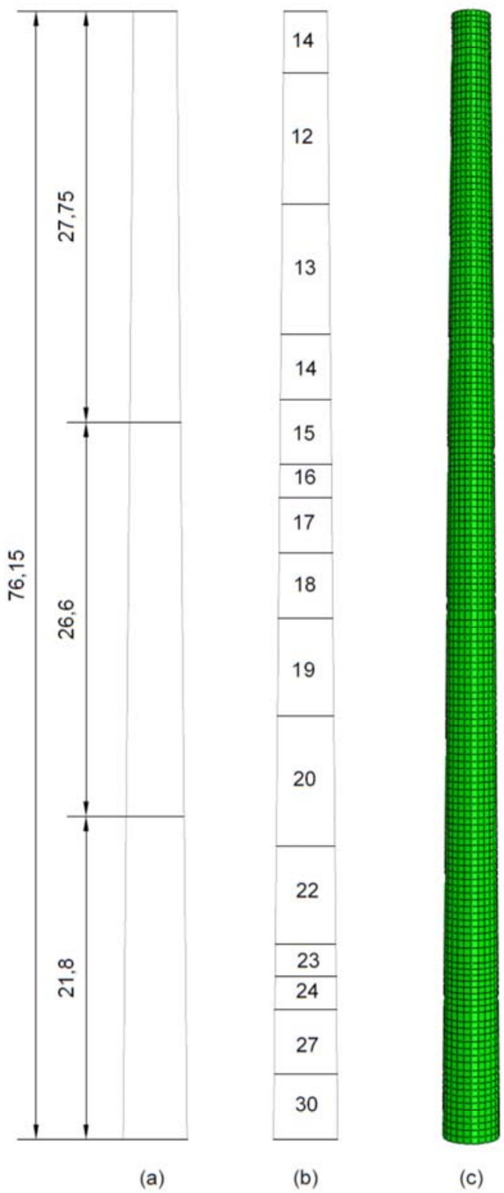

Figure 1. Tower subpart legth and shell thickness along the height

The analysis conducted in the software is material non-linear analysis for steel grade S355, where Poisson's ratio coefficient is 0.3, Young's modulus is 210 GPa, the yield stress is taken as 350 MPa and the ulti-mate strength as 510 MPa. In order to introduce plasticity data in the software the material properties have to be considered in terms of plastic true stress and true strain.

2.2 Square Lattice Tower

The square shaped lattice tower models have the same height as the tubular one and the loading conditions that they are designed for are also identical. As already stated at the introduction the structural subsystems that constitute the lattice towers have distinct roles in the load transfer mechanism of the tower. Being a statically determinate system means also the axial stresses of the tower structural elements can be determined by closed form expressions. For the purposes of the paremetric analysis a script in Mathematica software [14] is developed in order to produce tower configurations that can resist to the imposed loading that vary in weight of material used.

The tower has a square base with four face bracing trusses. The optimal face bracing truss is the V shaped and in order to minimize the total weight of the structure while maintaining its load bearing capacity, the angle of the diagonals needs to be determined. For the present investigation, the angle is set to 45 degrees and secondary braces are also used.

In the script, each sub-system; legs, horizontal V-braces, diagonal V-braces and secondary bracing are investigated and optimized separately using different subroutines. After having selected the optimal diagonal angle of the V-braces, the only parameters that need to be additionally selected for the design of the tower are the bottom and top width of the tower's face. The two factors that influence the optimal tower design at this stage are: (a) the parallel increase of the leg's axial force and the reduction of the face bracing weight when lowering the dis-tance between the tower legs and (b) the parallel reduction of the leg's axial force and the increase of the total length and slenderness of the V-braces when increas-ing the distance between the legs. These two factors are obviously antagonistic. The determination of the optimal tower weight therefore is dependent on the width of the tower at the top and the buckling checks of all the components. Since the buckling check is a highly non-linear procedure, a two-dimensional search is demanded in order to assess the variation of the two independent parameters; the width at the top and the non-dimensional parameter of the top width over the bottom width of the tower. The script used for the optimal design of the tower uses a successive iterations scheme in order to converge to a final solution when total weight is minimum.

2.3 Hexagonal Lattice Tower

As far as the hegagonal shaped lattice tower is concerned, it shares the same height as the tubular and the square shaped ones. The loading condition that they are designed is also the same. Everything that refers to the square shaped lattice tower accounts for the heganoal shaped ones too.

The hexagonal towers have a hexagonal base with six face bracing trusses. The optimal face bracing truss is again V-shaped with diagonals inclined with an angle of 45 degrees and secondary bracing is also implemnted. All four-legged and six-legged towers are designed to resist the same loads, therefore the same moment, which means that they should have equal elastic cross-sectional modulus. When considering the geometry of the tower, the legs of the towers are theoretically inscribed in a circle of identical diameter. If we would exclude any buckling considerations, the four-legged and the six-legged tower would end up using the same cross-section area for the legs in order to withstand the same design loads and exhibit the same stiffness.

The determination of the optimal tower weight as mentioned in the previous paragraph is dependent on the width of the tower at the top and the buckling checks of all the components. Having in mind the non-linear nature of buckling phenomena, again a two-dimensional search space is used also for the hexagonal towers.

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The two parameters examined independently are the width at the top and the flare angle (μ), which define the search space of towers with potential minimum material used. A similar iterative script is used for the determination of the optimal design of the hexagonal tower towards minimizing its weight.

3. RESULTS

3.1 Cylindrical Shell Tower

The cylindrical shell tower is the reference structure which was optimized in terms of material use in the initial design. The total tubular tower mass is 127.215 tn and the tower sub-modules weigh 54.54 tn, 44.817 tn and 27.858 tn respectively going from bottom to top. The tower shell thicknesses gradually increase as we approach the bottom of the structures where greater moments appear. The minimum possible tower weight is realized by minimizing the shell thicknesses while fulfilling the structural criteria as shown in Fig. 2 where the stresses are marginally below the steel yielding point.

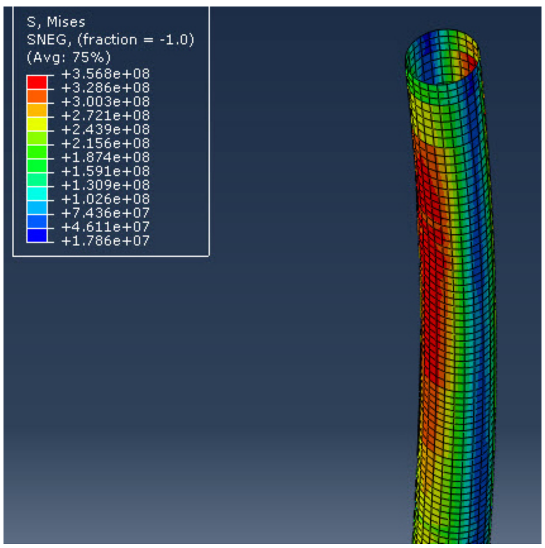

Figure 2. Tubular Tower Non-linear Analysis results.

3.2 Square Lattice Tower

The square-shaped lattice tower face consists of 5 subparts the heights of which appear in Table 1. In all the subparts circular hollow cross-sections are used and the design criteria are implemented so that the tower can sustain the imposed loads. The combinations of tower top width are [350mm to 1000mm] and flare angle μ are [0.65 to 1.3]. The total number of cases investigated in order to pick the optimal one with minimum total weight, are 126. The total tower weight for the optimal lattice tower solution is 77.47 tn and is given for top width of 800mm and flare angle of 0.6. The total weight of the tower, the legs weight and the braces weight is presented in correlation to the flare angle μ and the tower top width in Figures 3-5 respectively. Critical assumptions can be made towards wind turbine tower optimal design based on the results presented. Generally speaking, the wider the top width and the closest to 0.6 the flare angles are, the lower the values we get for the total tower weight. It is also remarkable that both legs and braces follow a smooth slope of similar shape that resembles also the total tower weight slope.

Since the wind load can come from any possible direction and the rotor turns towards the main wind flow, the tower is designed symmetrically with a wind coming towards the diagonal of the square shape since it is proved to be the least favourable direction. Each tower subpart for the above mentioned symmetry reasons is designed using the same cross-sections.

When comparing the square-shaped lattice tower to the tubular one, it is observed that the lattice solution is 40% lighter in terms of material use while maintaining the same structural response as the tubular one.

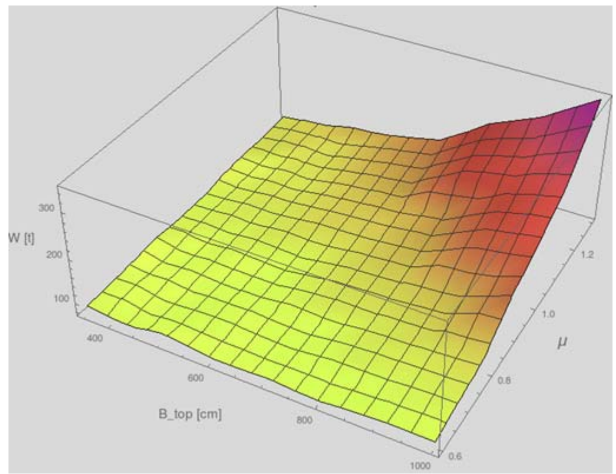

Figure 3. Total square-shaped lattice tower weight.

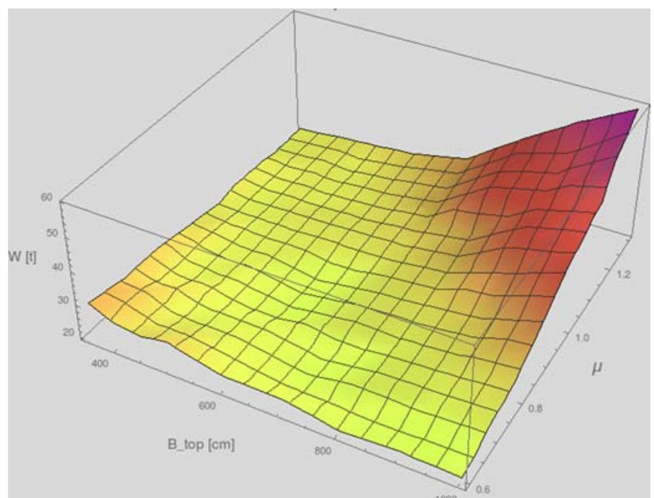

Figure 4. Square-shaped lattice tower Leg weight.

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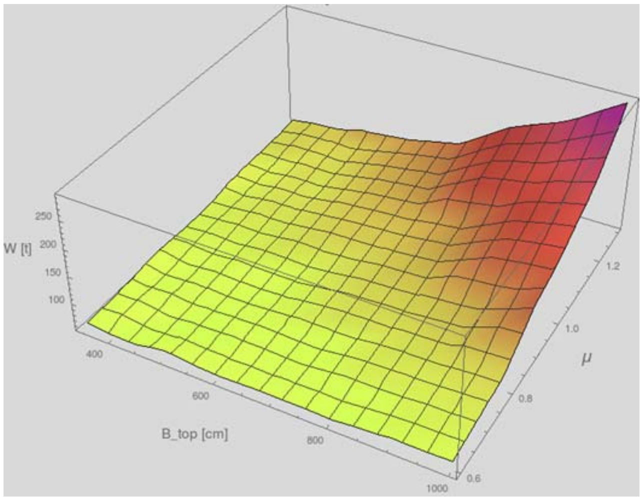

Figure 5. Square-shaped lattice tower Braces weight.

Table 1. Square Lattice tower subparts heights

	Height	**Legs**		**V-Brace Diagonals**		**V-Brace Horizontals**	
		Diameter (mm)	**Thickness (mm)**	**Diameter (mm)**	**Thicknes s(mm)**	**Diameter (mm)**	**Thickness (mm)**
Part-1	34.45	411	8	413	7	342	6
Part-2	55.53	371	8	385	7	282	5
Part-3	68.19	352	7	375	7	240	5
Part-4	75.64	340	7	363	7	216	4
Part-5	76.15	286	5	253	5	214	4

3.3 Hexagonal Lattice Tower

The hegaxonal lattice tower face consists of 6 subparts the heights of which appear in Table 2. Also for this series of towers examined circular hollow cross-sections are used and the design criteria are implemented so that the tower can sustain the imposed loads. The hexagonal towers examined belong to the search space defined by widths in the range of [300mm to 800mm] and flare angles μ in the range of [0.55 to 0.9]. The total number of cases in order to define the optimal solution with minimum total weight, are 56. The total tower weight for the hexagonal optimal lattice tower solution is 98.59 tn and is given for top width of 400mm and flare angle of 0.55. Fig 6-8 present the total weight of the tower, the legs and the braces respectively, in correlation to the flare angle μ and the tower top width. Critical assumptions can be made towards wind turbine tower optimal design based on the results presented. In principal, the narrower the top width and the closest to 0.55 the flare angles are, the lower the values we get for the total tower weight. It is worth mentioning that both legs and braces slope shape resembles he total tower weight slope.

Since the wind load can come from any possible direction and the rotor turns towards the main wind flow, the tower is designed symmetrically with a wind coming towards a diagonal of the hexagon since it is proved to be the least favourable direction. Each tower subpart for the above mentioned symmetry reasons is designed using the same cross-sections.

When comparing the hexagonal-shaped lattice tower to the tubular one, it is observed that the hex-lattice solution is 22.5% lighter in terms of material use while maintaining the same structural response as the tubular one. When compared to the square-shaped one, the hexagonal tower appears to be 22% heavier.

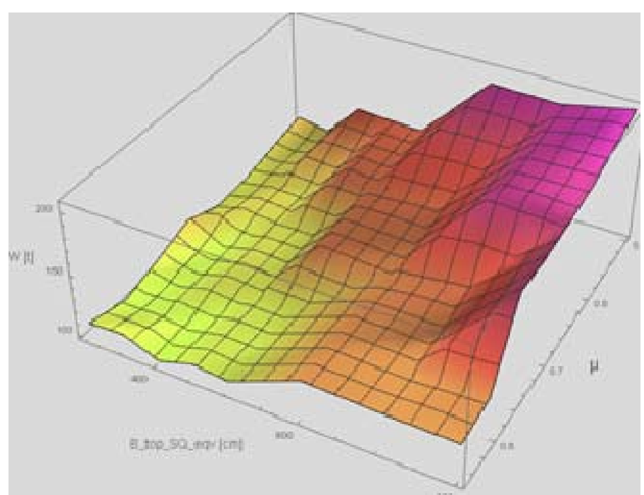

Figure 6. Total hexagonal-shaped lattice tower weight.

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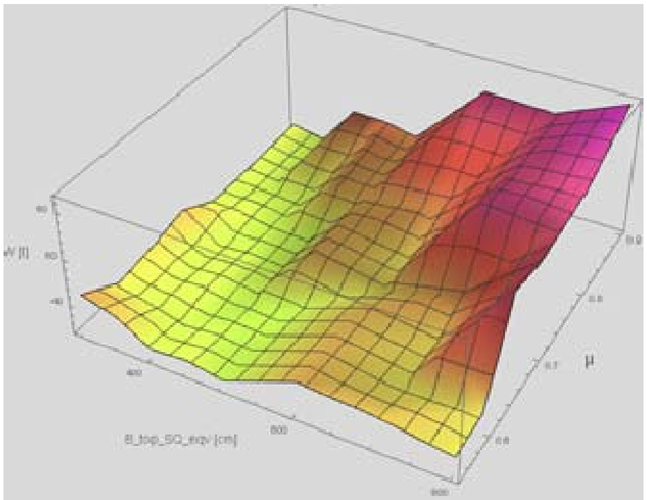

Figure 7. Hexagonal-shaped lattice tower Leg weight.

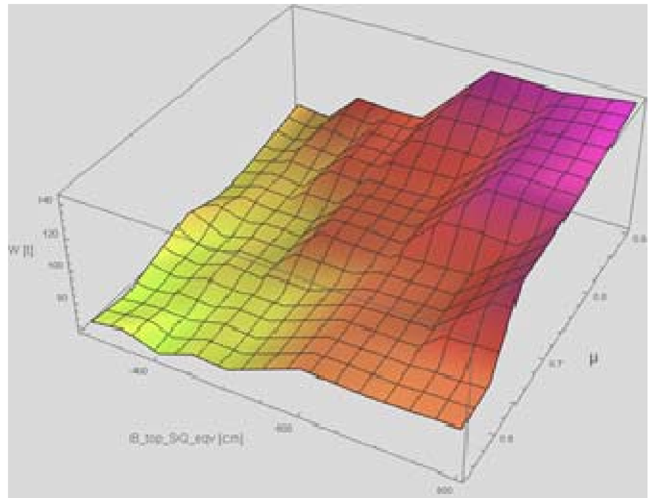

Figure 8. Hexagonal-shaped lattice tower Brace weight.

Table 2. Hexagonal Lattice tower subparts heights

	Height	Legs		V-Brace Diagonals		V-Brace Horizontals	
		Diameter (mm)	Thickness (mm)	Diameter (mm)	Thickness (mm)	Diameter (mm)	Thickness (mm)
Part-1	24.29	460	8	376	7	317	6
Part-2	42.37	425	8	347	6	281	5
Part-3	55.69	397	8	325	6	253	5
Part-4	65.38	388	8	327	6	232	4
Part-5	72.34	396	8	352	6	219	4
Part-6	76.15	339	7	270	5	212	4

4. CONCLUSIONS

The present work proposes the implementation of lattice towers as the support structure of onshore wind turbines. By substituting the traditional tubular steel tower with a lattice one there are certain gains in terms of material economy use and adequate load bearing capacity, which are irrespective to the lattice tower shape. Lattice towers have the advantage of easier mounting, easier transportation since they consist of smaller parts and mainly the fact that there is no need of large scale cranes to be used for their mounting. Since contemporary needs make the construction of taller on-shore towers imperative, the minimization of the total material use along with the transportation and mounting benefits that truss structures offer is crucial when selecting the optimal tower configuration. The tubuler steel shell tower is indeed a robust solution with high strength capacity, but the total steel used is significantly more compared to the lattice solutions. Having examined as a total 182 lattice solutions of both square and hexagonal shape, the lattice solution is proved to be robust enough also but the material used is significantly less compared to the tubular structure. The lattice towers under consideration are proved to be able to sustain great loads with minimum initial material weight. The total weight of a 76-meter tower is 22.5% less when implementing the hexagonal shaped lattice tower and 40% less when implementing the square shaped lattice tower. The additional advantages that the lattice solution may potentially offer may lead to great and advantageous changes in the configuration concept in wind turbine tower design.

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