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Life Cycle Analysis of lattice and tubular wind turbine towers. A comparative study.

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Abstract. Wind energy is the most promising sustainable energy source as one can conclude from the recent boost of wind farms installed globally. It is rather important to investigate the total environmental impacts of wind energy, not only taking into account the zero CO_2 emissions when producing electricity from wind but also assessing the total environmental burdens and resources requirement associated with the entire lifetime of all the processes related with the energy chain. In order to quantify the environmental impacts of wind energy life cycle analysis (LCA) is performed. Life cycle analysis of tall onshore wind turbine towers is not very thoroughly investigated in literature, which is a first class opportunity to perform high-end research. More specifically in this work, studies examining the life cycle performance of two types of onshore wind turbine towers are investigated; lattice and tubular. The definition of life cycle analysis and the steps applied for its implementation are also discussed. For Wind Energy LCA five phases are usually taken into consideration: manufacturing and construction, onsite erection and assembling, transportation, operation and finally dismantling. At the first steps of the present investigation, a typical system boundary is taken into account and a literature review summary describing the main conclusions from LCA studies on onshore wind turbine towers are presented. From recent LCA results on onshore wind turbines, the manufacturing stage is proved to have the greatest environmental impact, while recycling (that is used as a preferred scenario instead of reuse in the dismantling phase) is proved to act in the most favourable way. In the present study, two wind turbine towers of the same size and same energy production capacity are investigated and compared. Both structural systems, the tubular and the lattice one are proved robust enough and the total material used for their production is calculated in previous work of the research group. The two systems have different production methods, different amounts of material used and different mounting procedures which diversifies their lifecycle performance as a total and their performance in all LCA phases examined separately. Open LCA software was used to assess the lifecycle performance of the two different wind turbine tower types and very important conclusions were derived. After having performed the structural analysis of the two tower types, the LCA analysis completes the series of criteria that have to be taken into account when deciding between the two tower configurations towards more robust, more economical and more sustainable wind energy structures.

1. Introduction

The use of renewable energy sources as an alternative to fossil fuels is considered of great importance towards a free of CO2 emissions planet and the reduction of water and air contamination. The need for renewable energy production is reflected on the contemporary European Commission directive which sets the goal of at least 27% of the total energy consumption coming from renewables by 2030 [1]. Among the current renewables, wind energy is considered to be one of the most promising due to its infinite nature and great potential. The expansion of wind farms has been remarkable with the total installed capacity in Europe growing three times more in ten years and more specifically from about 66GW in 2008 to 189GW in 2018 according to the European annual statistics [2]. Wind turbines use the kinetic energy of wind which is a clean form of energy, to produce electricity without producing emissions or contaminating the atmosphere. The challenge that engineers need to face is to quantify to what extent it is a clean form of energy when taking into account not only the emissions from their operation but also the emissions and total environmental impact resulting from their manufacture, transportation, erection and future dismantling at the end of their working life.

While traditional environmental impact analyses generally focus on a restricted number of cycle steps, Life Cycle Analysis (LCA) is a holistic methodology capable of investigating and quantifying both direct and indirect environmental impacts throughout the life cycle steps of products and services. The advantage of this approach is that it can be used to compare environmental impacts for different products performing the same functions [3]. Wind farms are large-scale projects with high economical and social impact therefore the structural optimization of both wind turbine towers and wind turbine rotors is considered of high importance. For onshore wind farms, the horizontal axis wind turbines are the prevailing structural configuration, where the tower consists of cylindrical parts that are connected to each other with bolted flanges by means of pre-stressed bolts [4]. Although cylindrical shells have great advantages in terms of load bearing capacity to shell thickness ratio, when getting more slender local buckling phenomena can be catastrophic; therefore an increase of their thickness is sometimes unavoidable. As an alternative and material saving solution has been internal stiffening of tubular wind turbine towers which has been the case study of some research groups [5] [6]. Although the solution of internal stiffening has been proved advantageous in terms of material use and concurrent structural enhancement, the previous work of the current research group has focused on the elaboration of an alternative tower configuration that can permit wind turbines to reach even greater heights with less steel use and smaller scale foundations too. This new tower configuration is a self-rising lattice tower configuration, that consists of a new age of cross-sections that have been particularly optimized to minimize the material use [7].

Wind turbines installed nowadays have an increased efficiency and power generation capacity. In order to achieve those, contemporary wind turbine towers are constructed taller and taller in order to take advantage of the higher wind velocities in greater heights. Both the solution of internal stiffening and the lattice configuration have been investigated in terms of structural behaviour and have been proved robust enough to accommodate a nacelle at a greater height and sustain the greater loads deriving from its function. The environmental impact of the classic tubular steel wind turbine towers increases exponentially since both the amount of steel and the size of the tower foundation are increasing. It is therefore very interesting to compare the environmental impact of the classic wind turbine solution with the proposed lattice one since the innovative erection approach is also energy saving and can result to a solution that goes far beyond the decrease of the environmental impact deriving from the minimization of material used. LCA has been implemented for a number of cases to answer the question of the energy payback period of wind power plants where it has been found that in many cases it is less than a year [8] [9]. For onshore wind turbine towers the life cycle stages are the following: manufacture, transportation, construction/erection, operation and dismantling. When assessing the environmental impacts of the various stages, the manufacturing stage is by far the one with highest environmental impact [10] with the transportation stage following in second place with a vast difference though [11]. In the work of Martinez et al [12] it has been proved that the part of the wind turbine with the highest environmental impact is the foundation and secondarily the steel tower components. When constructing steel towers the total energy consumed for their production can be counterbalanced by reusing or recycling the steel components [13] (almost 80% of a wind turbine system can be recycled nowadays) while the environmental impact of the concrete foundation can be minimized when using cement produced in the area close to the construction site. As far as the blades are concerned, they are made of composite materials and like the foundation they cannot be recycled or reused. There are contemporary studies though that aim in investigating new age recycling technologies for composite materials and end-of-life treatment technologies.

Since the tower and foundation appear to be the wind turbine components with the highest environmental impact, the present work focuses on the investigation of the environmental performance of two alternative tower configurations; one tubular and one lattice one. To have comparable results, 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 as proved in previous work conducted by the research team and the lattice tower has 65% less steel while its foundation is 33% lighter.

2. Wind Turbine Tower Life Cycle Analysis

Along with the structural analysis of energy production systems like wind turbines, the sustainability assessment of the structure is considered nowadays equivalently important. One of the methodologies implemented in order to quantify the potential environmental impacts of systems and products over their life cycle is life cycle analysis. In this methodology, the structures' potential environmental impact is calculated from the extraction of the materials through production and use or operation of the system till its end-of-life.

Life Cycle Analysis (LCA) is a useful methodology for determining total system impacts of a given technology and is realized by associating all environmental impacts with the material acquisition, processing, manufacturing, use and disposal or recycling in the end-of-life stage. This approach is a valuable towards systems' sustainable design and is therefore used by both policy makers and industrial partners for product development and sustainable systems' management. In principal, when conducting LCA for systems or products the steps that have to be followed are: (a) the definitions of system boundaries, requirements and assumptions (b) the collection of resources for all system inputs and outputs (c) the definition of the parameters used to evaluate the environmental impacts related to the inputs and outputs (d) the assessment of the results. In order to perform a LCA, thorough research has to be performed in order to identify the factors that contribute to the environmental impact of the system. For its calculation, a series of LCA software, tools and databases can be used in accordance with the global or European standards [14] [15] that govern the sustainability assessment procedures.

As far as the wind turbine towers are concerned, the stages that are usually taken into account when performing LCA are the manufacturing stage, the transportation, the erection/construction, operation and dismantling while the duration of a turbine lifetime is assumed to be 20 years. The wind turbines' LCA results are assessed in terms of various environmental factors like Global Warming Potential, Acidification Potential, the energy payback time etc. The calculations are usually performed per lifetime stage and for all the structural components independently. The software and databases for performing LCA are various and in the present study GEMIS (Global Emission Model for Integrated Systems) open-source software [16] is selected due to its focus on construction, energy and transport fields.

3. Tower models analyzed

Unlike the various investigations related to the life cycle analyses of wind turbines, the present study focuses on the tower configuration only, taking for granted that the nacelle and blades are identical in both turbine cases. Therefore, the life cycle performance of two towers of 76.15m height has been examined; one tubular tower and one lattice one. All life stages from production of the materials to the end-of-life have been taken into account and the 20 year lifetime

The steel parts of both towers are made of steel class S355 and the foundation is assumed to be made from conventional concrete. The nacelle and blades that are supposed to be accommodated on both towers are identical and the structural analyses for both towers has already been verified. The lifetime stages taken into account were presented in the previous paragraph and for both towers the recycle/reuse scenario is selected for their dismantling. In the manufacture stage, both the production of the raw materials and the energy consumed for their fabrication is taken into account. For the transportation stage, the lattice tower subparts are produced in the factory 100km away from the construction site and transported there. On the other hand, the tubular subparts are produced in North Germany in 30m long parts and they are transported on site by ship and truck. For the erection stage, large scale cranes are used for the mounting of the tubular tower whilst for the lattice one only small scale cranes are used since the tower has this innovative self-rising system. For the dismantling stage, steel is assumed to be 85% recycled while the foundation is decommissioned the traditional way.

3.1. Tubular Tower

The tubular tower is 76.15m high and consists of three subparts of about 25m length. The subparts are fabricated in the factory by hot rolling steel plates of varying thickness and forming rings about three meters wide. The rolled plates are welded longitudinally to form these 3m rings which are connected to each other by means of circumferential welds. The final tower subparts are transported on site and are connected to each other with the aid of flanges by means of pre-stressed bolts. The use of large scale cranes is mandatory since the subparts are very long and the heavy. The tubular tower diameter is varying in height alike the shell thickness. The shell thickness distribution along the height is presented in Figure 1 and varying from 30mm at the bottom part to 12 at the top one. The tower diameter is again varying in height, beginning with 3.2 m at the bottom to 1.6m at the top.

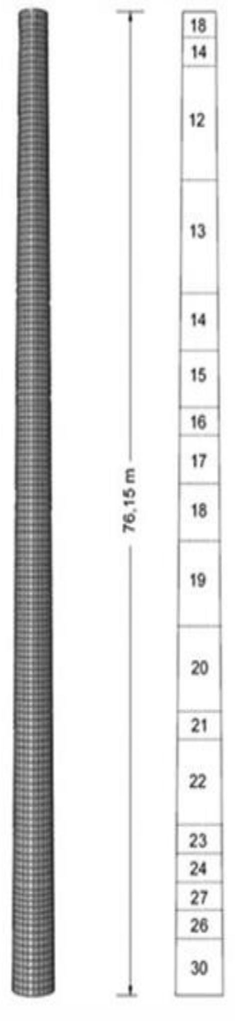
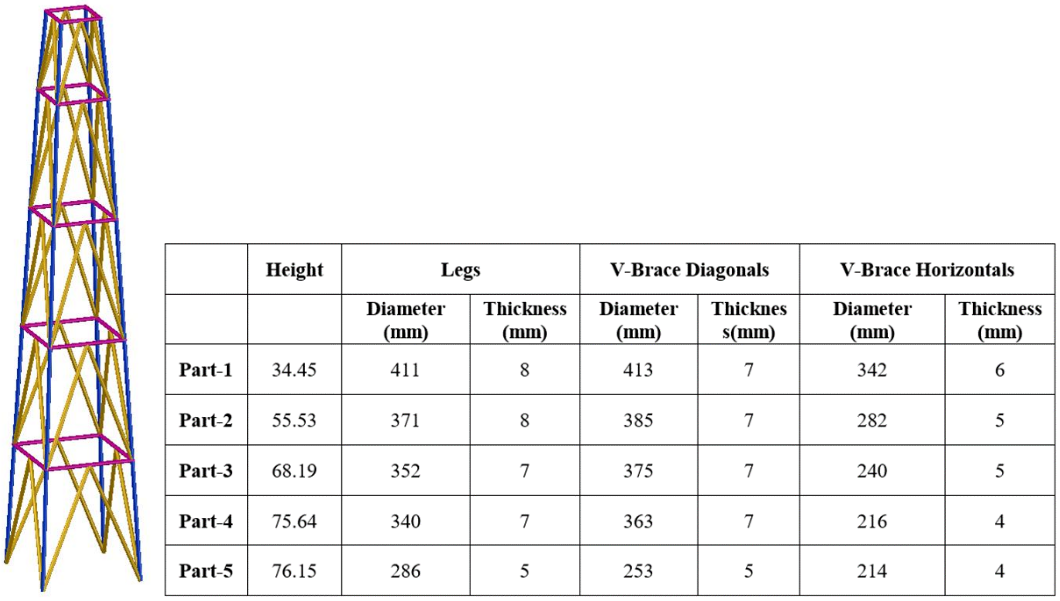


Figure 1. Figure with short caption (caption centred).

3.2. Lattice Tower

The lattice tower is of square base shape consisting of 5 subparts the heights of which appear in the embedded table of figure 2. The tower, is composed of three 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. The total tower weight for the lattice tower is 77.47 tn and circular hollow sections of varying shell thickness and diameter are used as it is presented in figure 2. The tower subparts are manufactured in conventional factories near the construction site, they are transported on site and erected to their final positions with the aid of small-scale cranes. The final tower shape and steel sections' distribution is presented in the figure below.



	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

Figure 2. Figure with short caption (caption centred).

4. Results

In the present study the LCA of two onshore wind turbine tower configurations is performed. Both towers are of 76.15m height and their structural analysis results have proved that they can both accommodate the same rotor with similar efficiency. A preliminary study is performed where all life stages from production of the materials to the end-of-life have been considered. The connection of the turbines to the grid is not examined in the present study while the lifetime of the turbines is set to be twenty years. In figure 3 below the distribution of the CO_2 emissions per lifetime stage is presented, where the steel parts construction has been proved to have the highest environmental impact.

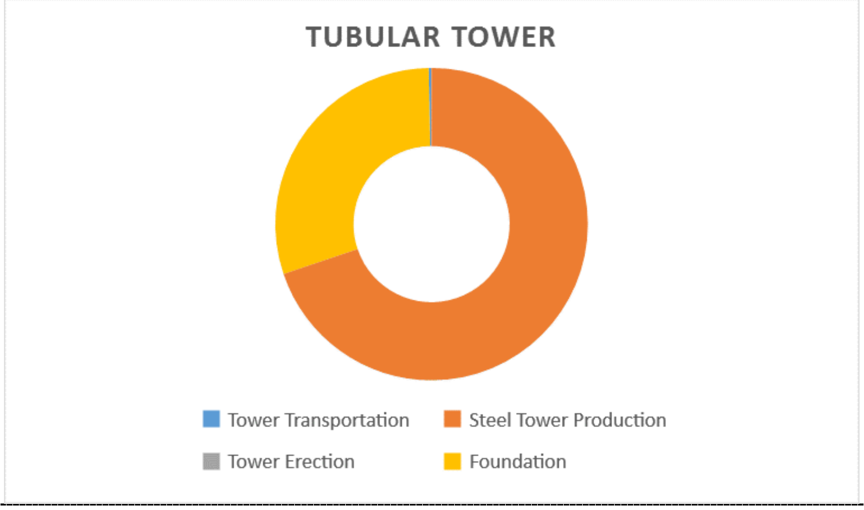


Figure 3. Distribution of CO_2 emissions per life stage for the tubular tower .

In figure 4 the distribution of the CO_2 emissions per lifetime stage for the lattice tower is presented. Again in this tower configuration the highest environmental impact appears to derive from the production of the steel sections and secondarily from the concrete foundation.

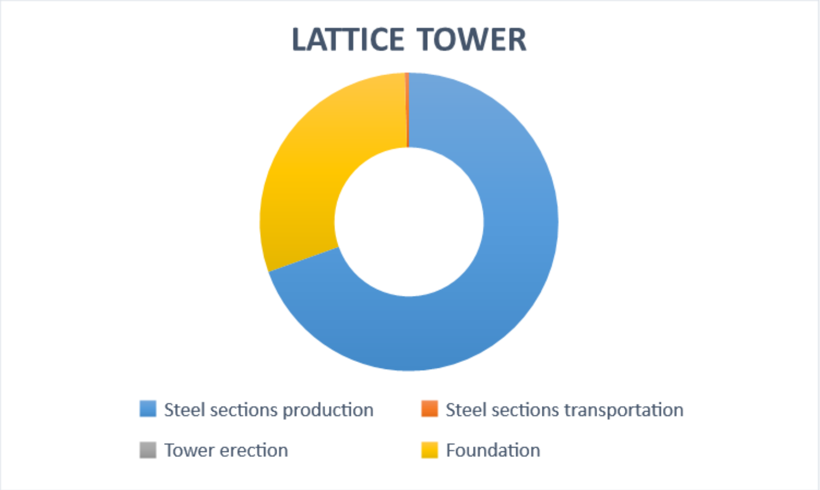


Figure 4. Distribution of CO2 emissions per life stage for the lattice tower

In order to assess the environmental impact of the two different tower configurations it is wise to compare the equivalent CO_2 emissions of the two configurations for every lifetime stage. The tower production is for both configurations approximately two times bigger than the foundation in terms of environmental impact, and the lattice tower is more environmental friendly. The gain that we can achieve when using the lattice tower configuration is 65% overall as it can be observed in figure 5.

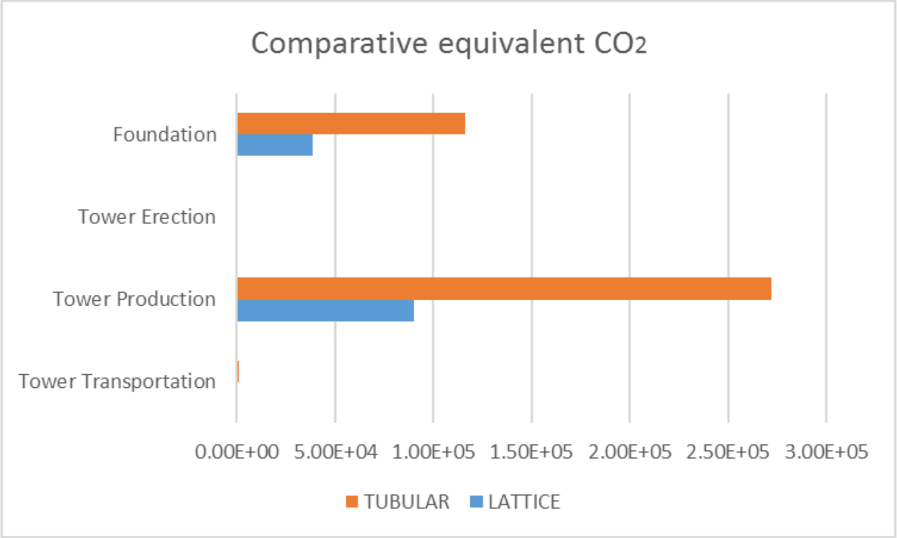


Figure 5. Comparison of CO_2 emissions for the two tower configurations

5. Conclusions

Contemporary energy needs require the development of taller wind turbines with enhanced capacities. Higher capacity means in the majority of the cases increased wind turbine sizes both in terms of blade length and tower height. Since the construction phase of the wind turbines is the phase with the highest energy consumption and environmental impact, it is worth investigating the respective increased energy required for their manufacture and erection. In the present study, after performing a comprehensive literature review it has been found that the life cycle analysis of two different wind turbine tower configurations is required in order to assess their total efficiency both structurally and environmentally. In previous studies it has been proved that the lattice tower configuration is really advantageous when reaching greater heights since 40% of material is saved in terms of the tower and 50% in terms of the foundation having identical structural behaviour. A LCA of the two different tower configurations is performed in the current study, proving that the equivalent CO_2 emissions are reduced by 65% when taking into account the life cycle of the tower and the foundation only. This research study aims at obtaining an initial approach of the environmental impact of the two different tower configurations and further more comprehensive studies on the manufacturing, construction, transportation and dismantling procedures are to follow.

6. Acknowledgements

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