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Research Article

A comparative life-cycle analysis of tall onshore steel wind-turbine towers

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Abstract

Earth has lately been suffering from unforeseen catastrophic phenomena related to the consequences of the greenhouse effect. It is therefore essential not only that sustainability criteria be incorporated into the everyday lifestyle, but also that energy-saving procedures be enhanced. According to the number of wind farms installed annually, wind energy is among the most promising sustainable-energy sources. Taking into account the last statement for energy-saving methods, it is essential to value the contribution of wind energy not only in eliminating CO_2 emissions when producing electricity from wind, but also in assessing the total environmental impact associated with the entire lifetime of all the processes related with this energy-production chain. In order to quantify such environmental impacts, life-cycle analysis (LCA) is performed. As a matter of fact, there are a very limited number of studies devoted to LCA of onshore wind-energy-converter supporting towers—a fact that constitutes a first-class opportunity to perform high-end research. In the present work, the life-cycle performance of two types of tall onshore wind-turbine towers has been investigated: a lattice tower and a tubular one. For comparison reasons, both tower configurations have been designed to sustain the same loads, although they have been manufactured by different production methods, different amounts of material were used and different mounting procedures have been applied; all the aforementioned items diversify in their overall life-cycle performance as well as their performance in all LCA phases examined separately. The life-cycle performance of the two different wind-turbine-tower systems is calculated with the use of efficient open LCA software and valuable conclusions have been drawn when combining structural and LCA results in terms of comparing alternative configurations of the supporting systems for wind-energy converters.

Keywords: energy and environment; energy system and policy; wind energy

Introduction

Some of the most catastrophic events recently have been associated with climate change due to global warming and consequences of the greenhouse effect. One of the primary reasons for global warming is the excessive emission of CO_2 combined with the parallel increase in energy demand. Due to the fact that energy reports show an increase in carbon dioxide release, primarily from fossil-fuels combustion, increasing concern on cost and security issues related to fossil-based energy has been observed [1, 2]. This has led to the exponential growth of renewable-energy sources as an alternative to fossil fuels. Renewables being free of CO_2 emissions are considered ideal for eliminating greenhouse-effect consequences and limiting water and

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air contamination. Global energy demand is continuously growing and renewable-energy production is becoming more important than ever. This need is reflected in the contemporary European Commission Directive, which sets the goal of at least 27% total energy consumption coming from renewables by 2030 [3]. Due to its nearly infinite nature and great potential, wind is considered the most promising renewable-energy source, holding second place in the power-generation capacity installed in Europe in 2018. Today, wind energy accounts for 18.8% of the EU's total installed power-generation capacity [4] and, in 2019, it is predicted to overtake natural gas, which is in first position. While conventional power sources (fossil fuel, oil, coal) are expected to decommission more capacity than they install, wind power has installed more capacity than any other form of power generation in the EU in 2018, accounting for 48% of total power-capacity installations. Its expansion in the last decade has been remarkable, tripling in power-generation capacity and, more specifically, from ~66 GW in 2008 to 189 GW in 2018 according to the European annual statistics [4]. When calculating the total environmental impact of power-generation installations, one should not only take into account the operation stage where renewables are advantageously emitting almost zero carbon dioxide, but also their manufacture, transportation, installation and dismantling stages. It is recorded that, for renewable-energy-production installations, the majority of their environmental impact results from the manufacture and installation processes [5]. Since all forms of energy generation are based on the conversion of natural-resource inputs, there are subsequent environmental impacts. When decisions for energy-system investment, planning and developing are made, it has to be ensured that all aspects are taken into account during the assessment and comparison of alternative solutions [6]. Life-cycle analysis (LCA) is a holistic methodology that can be used as a tool in detecting these potential environmental impacts associated with energy systems and in calculating their sustainability performance from their early development stages [7]. In this methodology, final products are examined and assessed in terms of their environmental impact all the way through their life cycle, from raw-material extraction until end of life [8, 9].

Wind farms as investments for energy production with high economical impact are usually assessed in terms of safety and robustness only, meaning that they are designed in order to withstand the wind loads in all phases from construction to operation and extreme wind circumstances. Even when environmental-impact analyses were conducted for wind-power generators, the methodologies deployed would take into account only a limited number of life-cycle steps. LCA, being a holistic methodology, is capable of investigating and quantifying both direct and indirect environmental impacts, taking into account all the life-cycle steps of products and services. Using LCA's advantages in comparing the environmental impact of different products, Ardente et al. [10] investigated the air and water emissions of a wind farm and compared these results with the emissions of other energy-generation systems. Several research teams have focused on the investigation of LCA for wind-generation systems. The LCA results for wind-turbine towers are commonly assessed by calculating various environmental indicators (e.g. global-warming potential (GWP), acidification potential (AP), eutrophication potential) and the energy-payback time. The energy-payback time is conceived of as the time for which a wind-energy system must operate in order to generate the amount of energy that was required for the entire life of the structure, i.e. from production to dismantling. This payback time is calculated as the ratio of the total primary energy requirements of the system throughout its life cycle over the total annual power produced by it. In the majority of wind-turbine LCA cases, a lifetime of 20 years has been taken into consideration and the analyses are in compliance with ISO 14040 [11] and ISO 14044 [12]. In almost all the cases investigated in the literature, the energy-payback indexes for wind turbines are calculated to be lower than 1 year [13, 14].

LCA results are usually presented in percentage charts and are commonly grouped either per structural component (e.g. foundation, tower, nacelle, rotor) or per life phase (e.g. manufacture, transport, erection, operation/maintenance, dismantling). The highest environmental impacts in all cases investigated are detected in the manufacturing stage of wind turbines followed by the transport phase [15]. The smallest impact is attributed to the operation stage of the turbines [16]. Thorough scientific work has been conducted on the sustainability assessment of steel construction focused on offshore wind turbines [17–19]. The assessment of energy and emissions related to the production and manufacture of materials related to an offshore wind farm using an LCA model has been performed in the work of Schleisner [20]. Tremeac and Meunier [21] drew some valuable conclusions regarding the environmental impact of wind energy by comparing payback time and CO_2 emissions of turbines with different power-generation capacities, meaning a large 4.5-MW and a small 250-W wind turbine. The size of the wind turbines, though, does not appear to be a decisive factor in optimizing their life-cycle energy performance and the embodied energy component of wind turbines over their service life [22]. In the case study presented herein, steel towers are under investigation. Although the amount of steel required for the construction of wind turbines is great, the component with the highest environmental impact is the tower foundation, because the potential recycling or reusing of steel components can lead to reduced environmental impact and, with contemporary technologies, almost 80% of a wind-power-generation system can be recycled—practically everything except the concrete foundation and the composite blades.

Not only the power-generation capacity of a wind turbine can be considered responsible for producing different results, but also the LCA methods used, even for the same structure [23]. Martinez et al. [24, 25] investigated the dependency of results on the impact-assessment methodology implemented by conducting two different studies of the same turbine using the Eco-indicator 99 and the CML methodology. Browsing through the literature, it is difficult to compare LCA results of different wind turbines where different methodologies have been implemented, because of the discrepancy of results among methodologies even when investigating the same structure.

The objective of the work presented in the current study is to perform a comparative LCA for two potential wind turbines to be deployed in a wind park located in the UK. The two potential wind-power generators carry the same wind turbine at their top: the Repower MM92 [26]. In Table 1, a number of LCAs for onshore wind-turbine towers around the globe have been grouped, where the type of tower, the hub height, the wind-turbine size and the LCA software used are presented. One can easily note that the majority of studies have focused on tubular-steel or concrete towers with a hub height up to 124 m, leaving the environmental impacts of tall steel-lattice towers almost unexplored.

For onshore wind farms, the horizontal-axis wind turbines are the prevailing structural configuration, where the tower consists of cylindrical parts interconnected with bolted flanges by means of pre-stressed bolts [29]. 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 in their thickness is in most cases unavoidable. As an alternative solution to the existing cylindrical-tower configuration, the implementation of internal stiffening of tubular wind-turbine towers has been the focus in the work of several research groups [30, 31]. 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 (in the sense of erection without external cranes) that consists of a new design of cross-sections that have been particularly optimized to minimize the material use [32]. These self-rising lattice towers efficiently combine steel parts, allowing them to fulfil the required safety, robustness and durability requirements, while keeping the solution potentially economical and environmentally sustainable.

Due to the fact that energy demands are constantly increasing, contemporary installed wind turbines need to have increased efficiency and power-generation capacity. In order to achieve this increased power-generation capacity, wind turbines are constructed using longer blades and greater tower-hub height in order to take advantage of the smoother wind flow combined with higher wind velocities at greater heights. All alternative solutions, with either the use of internal stiffening or the lattice configuration, have been studied in terms of structural performance and have been proven to be robust enough to sustain the greater loads due to higher wind velocities and the greater nacelle mass due to bigger rotors and longer blades. The environmental impact of classic tubular-steel wind-turbine towers increases exponentially, since both the amount of steel and the size of the tower foundation increase. It is therefore very interesting to compare the environmental impact of the tubular-tower solution with the proposed lattice one since the innovative erection approach leads also to energy saving and can result in a solution that goes far beyond the decrease in the environmental impact deriving from the minimization of material used. For onshore wind-turbine towers, the life-cycle stages usually taken into account 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 the highest environmental impact, with the transportation stage following in second place.

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 impact of two alternative tower configurations: one tubular and one lattice. The different tower configurations require different foundations, so valuable

Table 1 LCA overview of onshore wind-turbine towers

Publication year	Tower type	Hub height (m)	Capacity (MW)	Software
2008 [10]	Tubular steel	55	0.66	–
2008 [13]	Tubular steel	45, 46, 60	0.66, 0.60, 1.75	–
2009 [18]	Tubular concrete	124	4.50, 0.25	Sima Pro
2009 [19]	Tubular steel	60, 80	0.85, 3.0	–
2009 [21]	Tubular steel	70	2.0	Sima Pro
2012 [16]	Tubular steel	105, 65	1.8, 2.0	GEMIS
2013 [15]	Tubular steel/concrete	80	1.4	–
2014 [27]	Tubular steel/concrete	80, 100, 150	2.0, 3.6, 5.0	Gabi
2015 [28]	Tubular steel	80	2.0	Gabi
2016 [14]	Tubular steel	92.5	2.3, 3.2	Sima Pro

Table 2 Lattice-tower sections details

		Legs		V-brace diagonals		V-brace horizontals	
	Height (m)	Diameter (mm)	Thickness (mm)	Diameter (mm)	Thickness (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

conclusions of the two most important tower parts are drawn. First, the scope of the study is presented, supporting life-cycle inventory data are reported and the results of the life-cycle-impact assessment are discussed. In order for the results to be comparable, the structures share the same height and have the same loading being applied at the hub height. Both tower configurations are designed in a manner to be capable of sustaining the same loads as proved in previous works. The analysis methodologies implemented are identical while the lattice tower has 35% less steel, an almost 33% lighter foundation and many advantages in terms of transportation and erection.

1 Methodology for LCA

LCA is a useful methodology for determining the 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 at the end-of-life stage. This approach is valuable towards the sustainable design of systems and is therefore used by both policy makers and industrial partners for product development and the management of sustainable systems. In principle, when conducting LCA for systems or products, the steps that have to be followed are:

(i) the definitions of system boundaries, requirements and assumptions;
(ii) the collection of resources for all system inputs and outputs;
(iii) the definition of the parameters used to evaluate the environmental impacts related to the inputs and outputs;
(iv) the assessment of the results; in order to perform an 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 that govern the sustainability-assessment procedures [33, 34].

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's lifetime is assumed to be 20 years. The LCA results of the wind turbines are assessed in terms of various environmental factors like GWP, AP, 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 is selected due to its focus on construction, energy and transport fields [35].

2 Tower models

After having studied various cases of LCA on onshore wind-turbine towers, in the present study, the life-cycle performance of two 76.16-m-tall wind-turbine towers is carried out. The investigation of tall wind turbines is here explored, whilst the investigation of super-tall wind turbines (e.g. greater than 150 m) is currently underway. Unlike the various investigations related to the LCAs 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. To this end, the life-cycle performance of two towers—one tubular tower and one lattice—has been investigated. All life stages from production of the raw materials to the end of life have been taken into account under the assumption of a 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 have been already verified. The lifetime stages taken into account are identical for both towers: manufacturing, transportation and erection, operation and dismantling. For the dismantling stage, two different scenarios are investigated for each material: the recycle/reuse scenario and the landfill scenario. In the manufacturing stage, both the production of the raw materials and the energy consumed for their fabrication are taken into account. For the transportation stage, it was assumed that the lattice-tower subparts have been produced in the factory 100 km away from the construction site and transported there. On the other hand, for the tubular subparts, the assumption was made that they are produced in north Germany in 30-m-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 can be erected by the previously mentioned innovative self-rising approach without using tall cranes. For the dismantling stage, the materials are recycled when possible; otherwise, the landfill scenario was implemented. Further details are presented later on.

2.1 Tubular tower

The tubular tower is 76.15 m tall and consists of three subparts of 21.8, 26.6 and 27.8 m from bottom to top. The tower under investigation is an actually constructed tower [36]. The subparts are fabricated in the factory by hot rolling steel plates of varying thicknesses and forming rings about 3 m wide. The rolled plates are welded longitudinally to form 3-m rings 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. For tubular towers, the use of large-scale cranes and heavy machinery is mandatory, since the subparts are quite long and heavy. The tower is not purely cylindrical, as the lower diameter of the cross-section of the tower is 4.3 m and the top one is 3 m. The thickness of the shell wall is also not constant, starting from 12 mm at the top to 30 mm at the bottom. The tower is embedded into a reinforced-concrete foundation that is anchored to the ground and, therefore, the tower can be considered and modelled as fixed at the foundation. The shell-thickness distribution along the height of the tower is presented in Fig. 1. The total tower weight is 127 t.

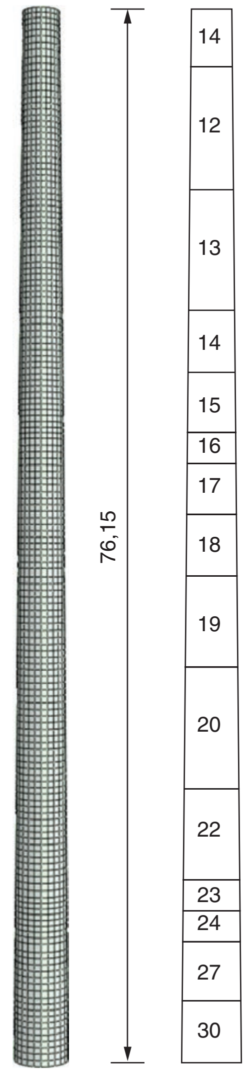


Fig. 1 Tubular-tower shell-thickness distribution

2.2 Lattice tower

The lattice tower is of square base shape consisting of five subparts along its height. The heights of the various subparts appear in Table 2. The tower is composed of three discrete structural sub-systems: the legs, the face-bracing trusses and horizontal braces and secondary bracings arranged inside the plane of the face-bracing trusses. The connections between the structural members are bolted connections with conventional steel bolts. The total tower weight for the lattice tower is 77.47 t and circular hollow sections of varying shell thicknesses and diameters are used, as presented in Fig. 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 distribution of the steel sections are presented in in Fig. 2 below.

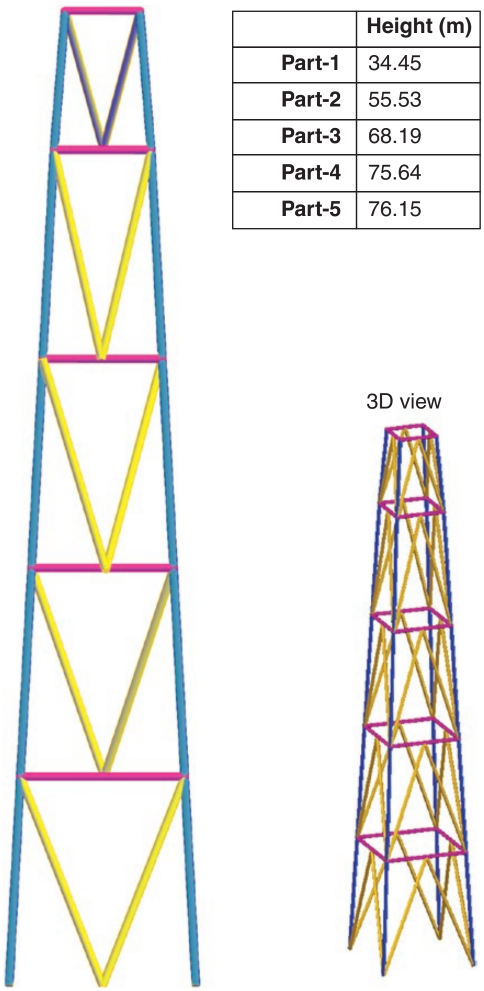
2.3 Research methodology

In order to assess the environmental impacts of the two towers under investigation, the LCA method is applied using the freely available software GEMIS [30]. As mentioned above, an LCA study is completed in four stages and, more specifically, the following in our case.

2.3.1 Analysis goal and scope definition

The goal of the present study is to compare the life-cycle environmental impacts of two wind-turbine towers. This investigation contributes to determining and quantifying the impacts of a potential wind park located in UK. Both onshore wind turbines have a power-generation capacity of 2.0 MW. They have similar function and technical specifications. However, the tower configurations differ in the manner explained in Sections 2.1 and 2.2 of the present paper.

The scope definition of an LCA includes a description of the product under investigation in terms of the system boundaries. In the case study presented here, all life stages from production of materials to the end of life of the structure are under consideration. The wind-turbine stages investigated are presented in Fig. 3 and are the component



	Height (m)
Part-1	34.45
Part-2	55.53
Part-3	68.19
Part-4	75.64
Part-5	76.15

Fig. 2 Lattice-tower configuration

manufacturing, transportation and erection, operation and then dismantling or recycling, depending on the scenario taken into account.

The connection to the grid is out of the scope of the present study and has been neglected. The lifetime of the turbines is set to be 20 years. The functional unit must be defined so that alternative solutions can be compared in a meaningful way. The energy-payback comparison takes into account the amount of energy generated over the assumed 20-year lifetime.

2.3.2 Life-cycle inventory (LCI) analysis

Wind turbines are complex structures that consist of many structural, mechanical and electrical assemblies, which comprise many sub-components. The most crucial stage in an LCA is data gathering and the maximum detail possible should be included so that the accuracy of the obtained results is not sacrificed. The LCI is the gathering of information related to primary components of a wind-turbine tower. For the manufacturing stage of the wind turbine, the two tower systems were analysed as detailed in the previous paragraphs. As far as the turbine itself is concerned, it is a 2.0-MW, three-bladed upwind horizontal-axis wind turbine with a hub height of 76.15 m. The hub and nose cone of the turbine are generally made of cast iron and fibreglass-reinforced polyester, respectively; the blades are made of a composite material consisting of 60% glass fibre and 40% epoxy; the generator is basically made of steel and copper, while the gearbox is made of cast iron and stainless steel. The energy-consumption calculation for all the manufacturing of the wind turbine has been based on data on material component weights available.

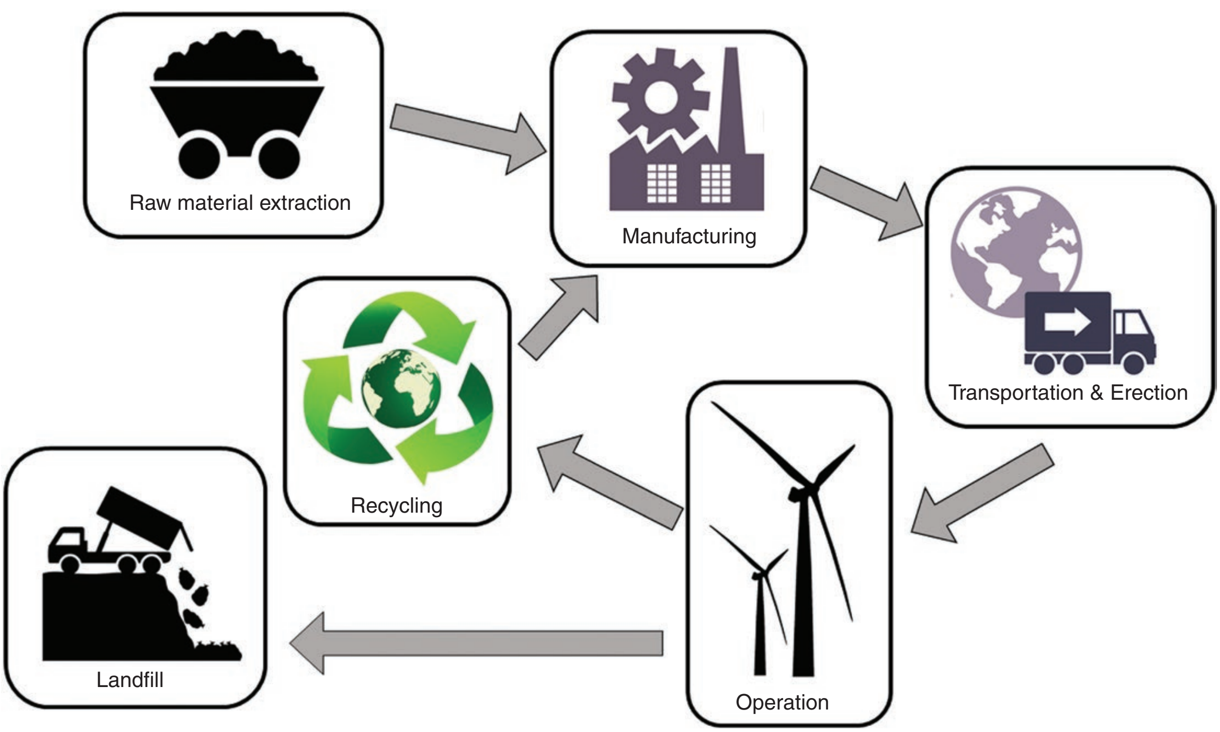


Fig. 3 LCA boundaries

For the transportation and erection stage, the turbine is assumed to be produced in Germany and transported to the UK by boat and truck. The lattice-tower components are produced in a factory near the site, whilst the tubular-tower subparts are again produced in Germany and transported to the UK by boat and truck. The distance for the components to reach the port in Germany is estimated to be 110 km, the distance at sea is estimated to be 1020 km, while the transportation of the components from the port to the site is assumed to be 130 km. The freight-transport services are imported in GEMIS software in tkm (ton-kilometre(s)) so, if the track and boat transport the tubular-tower components of 127 t over the distance of 110 km, this equals a transport service of 13 970 tkm.

As far as the operation and maintenance stages are concerned, there is a certain level of energy input required for starting the turbine, for the break-system operation, for yaw- and rotor-pitch control, etc. This energy input is normally estimated as 1% of the total electricity generated by the turbine [37]. For both turbines, maintenance of the mechanical parts is assumed to be carried out three times a year and the distance for the service team is assumed to be 100 km per trip. The life of the turbines is assumed to be 20 years. As far as the dismantling and recycling stages are concerned, again, there is an energy input taken into account that is assumed to be 2% of the total electricity generated [37]. In Table 3, the possible recycling scenarios for the main materials included in the present study are presented.

2.3.3 *Life-cycle impact assessment*

The life-cycle inventories for the two 2.0-MW wind-turbine models were used to support the life-cycle assessment in terms of the basic impact-assessment categories. GEMIS software is a freely available database used widely in Europe. It enables a detailed description of all the process steps of an energy system and has been successfully used in previous work for the calculation of the primary energy needed in the process, the emissions and the mass and energy flows of materials. The database includes >1000 products, 10 000 processes and >130 scenarios covering data from >50 countries, whilst there is freedom for the user to import additional data. Upon LCA performance, GWP, greenhouse gases, water effluents, solid waste and many more can be obtained in tabulated or graphic format. The GWP is an indicator of the impact of any process on climate change. More specifically, it is a relative scale of how much a greenhouse gas contributes to global warming and compares it to the same mass of carbon dioxide. Its measure is kgCO_2/kWh (CO_2 equivalent) and is used for the assessment of the two wind-tower systems. The basic term for assessing the energy-generation part of an LCA for the wind-energy systems studied in this work is the total cumulative energy requirement that contains the overall energy needed to construct a wind turbine. Finally, the energy-payback-time ratio is implemented in the present study in order to measure the duration of operation needed in order for the wind turbine to generate the amount of energy required for its entire life. It is calculated in the form of a ratio of total primary energy requirements of the wind turbine throughout its entire life over the total annual energy generated by the turbine. The total cumulative energy requirements for its entire life comprise the energy needed for production, transportation, maintenance, operation and decommissioning.

Table 3 Possible recycling scenarios [38]

Material	End-of-life treatment
Concrete	Landfill 100%
Cast Iron	Recycling with 10% loss
Copper	Recycling with 5% loss
Epoxy	Incinerated 100%
Fibreglass	Incinerated 100%
Plastic	Incinerated 100%
Stainless steel	Recycling with 10% loss

2.3.4 *Result interpretation*

The LCA results can be obtained from GEMIS software in tabular and graphic format. In the next section, the results of the LCA are presented. First, the material requirements per structural component are presented in a tabular format. The CO_2 equivalent per lifetime stage for the two towers is presented in a graphic form. Then, in a comparative graph, the cumulative energy requirements of the two towers are presented with specific data per stage. Finally, the component contribution to energy demand of the two towers is depicted.

3 Results

In the present study, the LCA of two onshore steel wind-turbine-tower configurations is performed. Both towers are of 76.15 m height and their structural analysis results have proved that they can both accommodate the same rotor with similar efficiency. A study is performed where all life stages from the production of the raw 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 20 years. In Table 4, the material requirements for the main components of the two towers under investigation are presented.

Table 4 Material requirements for the tower components

	Tubular tower		Lattice tower	
Component	Mass (t)	Weight fraction	Mass (t)	Weight fraction
Rotor	34	0.04	34	0.07
Nacelle	55	0.06	55	0.11
Tower	127	0.13	77.47	0.15
Foundation	750	0.78	350	0.68
Total	966		516.47	

In Fig. 4, the distribution of the CO_2 emissions per lifetime stage is presented, where the construction stage with the steel components and the concrete foundation has been proved to have the highest environmental impact. It is worth mentioning that the manufacturing phase constitutes 82% of the total equivalent CO_2 emissions of the tubular tower.

In Fig. 5, 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 manufacturing stage of the tower.

In Fig. 6, the cumulative energy requirements of the two towers are presented, where it is obvious that the lattice tower has a much lower energy requirement compared to the tubular one. For the tubular tower that can be better compared, the cumulative energy is compatible with similar 2.0-MW turbines in the work of Guezuraga et al. [16]. This can be attributed to three factors: the smaller amount of steel used for the tower construction, the

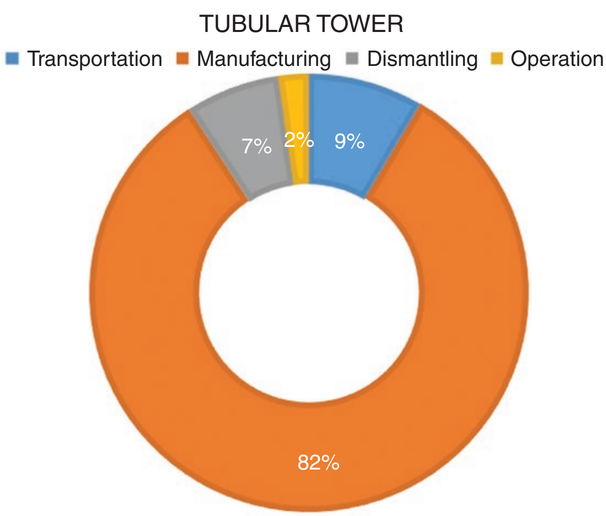


Fig. 4 Distribution of CO_2 emissions per life stage for the tubular tower

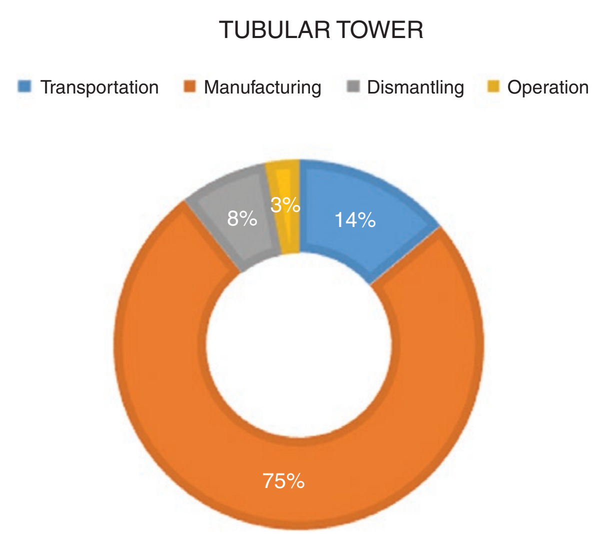


Fig. 5 Distribution of CO_2 emissions per life stage for the lattice tower

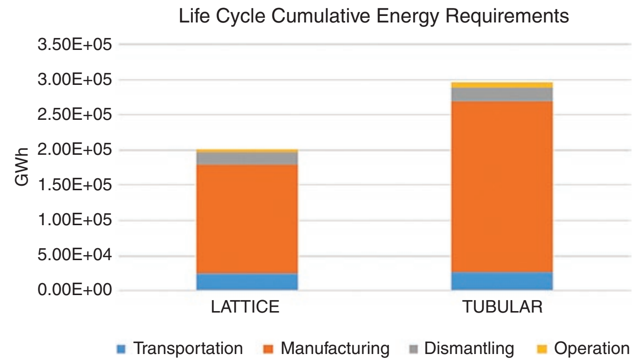


Fig. 6 Life-cycle cumulative energy requirements

reduced foundation required for a lattice structure compared to a tubular one and the transportation and erection advantages that the proposed self-rising system is offering. This can be better observed in Fig. 7, where the contribution of each wind-turbine component is presented for the two towers.

The largest cumulative energy requirements contribution comes from the manufacturing stage in both the lattice and the tubular towers, reaching values between 75% and 82% of the total life cycle of the turbines. In absolute values, though, the manufacturing/construction stage of the tubular tower is much larger compared to that of the lattice one. The average share from each tower component is shown in Fig. 7, where it is proved that the tower manufacturing and foundation construction is a larger part of the total energy requirement for the tubular tower. In both tower cases, the smallest contribution is derived from the operation phase, which accounts for only 2% of the total energy requirements.

An indicative ratio presented in the above text that can better picture the environmental impact of the two tower configurations is the energy-payback time. The energy generated by both turbines, since they are hypothetically positioned at the same spot, sharing the same hub height and same rotor, would be for a 2.0-MW turbine ~6.12 GWh assuming a 35% capacity factor as assumed in Haapala and Prempreeda [38]. The results of the payback time for both towers are presented in Table 5.

The energy-payback time for the tubular tower is 5–6 months whilst, for the lattice, it has been calculated to 4 months. These results for the tubular tower are proportional to similar 2.0-MW turbines [16] and very close to the results of the same capacity and same hub-height turbines [38]. The lattice structure has proved to be more advantageous in terms of both the material used and the transportation and erection methods applied. The steel tower fabrication along with the foundation construction are much less energy-consuming procedures compared to the tubular structure and the energy-payback period is also 15% less.

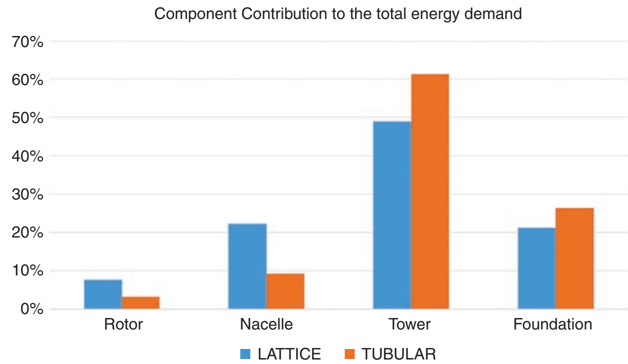


Fig. 7 Distribution of CO_2 emissions per structural component

Table 5 Energy-payback-time calculation

	Units	Tubular tower	Lattice tower
Cum. energy requirements	GWh	2.96	2.00
Annual energy generated	GWh	6.12	6.12
Energy-payback time	–	0.48	0.33
Energy-payback time	Months	5–6	4

4 Conclusions

Constantly growing global energy needs require the implementation of additional power-generation systems worldwide. Fossil-fuel shortage and consequences of the greenhouse effect have led to greener energy-production methods and wind turbines are among the most advantageous. In order to achieve greater capacity, wind turbines are nowadays constructed taller with enhanced capacities. Higher capacity means in the majority of the cases increased wind-turbine sizes in terms of both blade length and tower height. The construction of taller turbines means advanced studies in terms of structural behaviour and in most cases increased material used to achieve its robustness. Since all the construction procedures for wind-energy systems are energy-consuming procedures, it is worth investigating the total energy invested and the payback that can be achieved. In the present study, a new tower system is proposed and its enhanced contribution to energy saving is investigated. After having performed a comprehensive literature review, it has been found that the LCA of the two different wind-turbine-tower configurations is missing in order to better assess their total efficiency, both structurally and environmentally. In previous studies, it has been proved that the lattice-tower configuration is significantly more 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. An LCA is found to be crucial in terms of assessing the real contribution of these energy-production systems to environmental protection. The most important parameters calculated in the LCA conducted were the CO_2 emissions and the energy-payback time. The most impactful stage in the lifetime of a wind turbine is the manufacturing phase. The analysis conducted shows that the lattice structure is 32% less impactful on the environment in terms of equivalent CO_2 emissions. The energy-payback time for the tubular-steel tower is 5–6 months, whilst the lattice self-rising steel tower has an energy payback time of 4 months. The present study shows that only by saving material from the foundation and tower, which are the most energy-consuming components of the wind structure, could the equivalent CO_2 emissions be reduced. This research study aims at obtaining an initial approach of the environmental impact of the proposed manufacturing and erection procedure and this is the reason why a tower of 76.15-m hub height was selected, since comparable data were available. After having proved that the new tower system is robust enough and less environmentally impactful, a further more comprehensive study of taller structures is to follow.

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Conflict of Interest

None declared.

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