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Towards the sustainability in the design of wind towers

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Abstract

Wind farms are both a renewable energy production alternative and a profitable economic enterprise. At the same time these groups of wind towers can be a social-friendly solution if they solve challenging demands from the society such as integration in landscape, aesthetics, low noise nuisances...
This paper presents part of a complete research project that was carried out between 2009 and 2015. First this article presents a new wind tower proposal that has been designed to reduce these social impacts as well as satisfying environmental aspects, economic requirements and boundary conditions such as height, turbine power, soil conditions... This proposal is composed of precast concrete modules joined with high-resistance steel bars that define a post-tension structure. These components define an attractive and transparent tripod that is transversally reinforced with steel profiles. This system holds the Spanish patent “Support structure to wind turbines, number ES 2 319 709 B8” and aims to build 100-120m high towers. At this height there is better wind quality and large turbines of 3 MW can be installed.
Second, a sustainability assessment of this new hybrid wind tower has been carried out in order to evaluate its social, environmental and economic impacts compared to other solutions. Steel lattice structures, steel tubular systems, in situ concrete towers and precast concrete structures are the alternatives for wind farms that have been considered. MIVES, a MCDM methodology based on the value function concepts has been used to do this assessment, which has relied upon seminars of experts. This sustainability assessment enabled the identification of the aspects with the lowest sustainability index. These are the maintenance and deconstruction costs and for occupational hazards. Now these weak points can be corrected in the process of bringing the patented technology to market.

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1. Introduction

Among the different renewable energy production alternatives, wind farms are a profitable economic solution with a promising future ahead. In this sense, the cumulative wind power capacity until 2015 has been 435 GW [1] band its share of renewable energy production is expected to increase from 9% in 2013 to 41% in 2030 [2]. However, to achieve a bright future its social acceptance must keep growing and wind farms must be optimized in numerous aspects such their efficiency [3] and location [4] among others.

Wind farms are mainly composed of wind towers that are distributed within the onshore or the offshore limits depending on the kind off Wind Park. Wind towers have two main elements, the turbine and the tower. Numerous types of turbines can be installed on wind towers to generate important amounts of electricity up to 7.5 MW per turbine. The most common type is the three-bladed horizontal-axis turbine, which has a rotor and a nacelle among other components.

The tower elevates the turbine to the design height and transfers the loads to the foundation. Most towers are constructed using concrete and/or steel as the resistant materials. The main steel solutions are the lattice and the tubular towers. The concrete alternatives have steel reinforcements and mainly differ depending on their onsite or prefabricated building processes. The hybrid solutions combine parts built using steel and parts constructed using reinforced concrete. The turbine industry and the market itself have designed application ranges for these different solutions depending on their height. Table 1 presents the main construction alternatives for wind towers and some of their applications, strengths and weaknesses [5].

Table 1. Applications, strengths and weaknesses of wind towers main construction alternatives.

		Height (m)	Base Ø (m)	Weight/height (t/m)	Strengths	Weaknesses
Steel	Lattice	60-160	Unlimited	2-3	Easy transport & quick installation	Vulnerable joints & low fire resistance
	Tubular	60-120	3.0-4.5	2-5	Less material & optimal transport for h<80m	High transport and assembly costs for h>80m
Concrete	Onsite	60-115	3.0-8.5	8-19	Monolithic, durability & stiffness	Weather conditions vulnerability
	Precast	80-120	3.0-5.0		Quick installation	Vulnerable joints & high transport and assembly costs
Both	Hybrid	80-146	3.0-5.0	3-15	Expected to solve weaknesses of previous alternatives	In experimental stage

Lattice towers are composed of steel sections bolted and/or welded together on site. This alternative can solve different heights, from 60 m to, for example, the 160 m reached by the tower in Laasow, Germany [6]. The main advantage of lattice towers is their competitive price due to the optimization of the material used to build them, its easy transport and quick installation. Nevertheless, for heights greater than 80 m, which are the scope of this research paper, this steel solution has fewer weaknesses and is less competitive. For these more than 80 m heights the market is dominated by tapered tubular towers because of their superior optimization in transport and material [7].

Onsite concrete alternatives [8] use passive reinforcement to reduce tensile stress. In contrast, precast concrete solutions [9] use prestressing to connect the precast modules and, in addition to this active reinforcement, steel bars can be used to increase the concrete's resistance to cracking. Some towers use both technologies [10] and towers may even be precast onsite if the number of towers justifies the cost.

Finally, an example of a hybrid alternative is the tower built in Grevenbroich (Germany) that supports a 2.3 MW turbine. This tower has a bottom part built using precast concrete (82 m), which absorbs the high stresses caused at the intersection between the tower and the foundation, and a top part built using welded steel (51 m), which withstand fewer stresses and had a faster assembly.

All these alternative building technologies include a wide range of building processes and construction materials as shown in Table 1. These technologies solve economic, environmental, social and technical requirements more or less successfully having their own strengths and weaknesses. But no tool has been found in the literature to integrally assess which alternative is the most sustainable for a given set of turbine height and voltage necessities.

This research project focuses on onshore wind towers technologies for a height range from 100 to 120 m. Within this range large wind turbines of 3.0 MW or more are used, which have important environmental, economic, and technical advantages [11]. This study has also considered the tower foundation because the construction technology used to build the tower affects its size and shape and, therefore, the volumes of materials needed, the deadlines, and the installation costs. This assessment strategy enables researchers to differentiate between the various possible tower alternatives taking into account the turbine power and the tower height.

This project objectives are: a) present a new optimized building technology for wind turbine towers and b) present a sustainability assessment tool for wind towers considering their construction processes, materials, heights and turbine size among others. This tool will be developed using the multi-criteria decision making method (MCDM) called Integrated Value Model for Sustainable Assessment (or MIVES from the Spanish). This method enables to include the three main pillars of sustainability and can be used as a decision-making tool by all parties involved. This kind of MCDM for structure and infrastructure management has been satisfactorily used in other fields [12], [13].

The new construction technology developed in this research aimed to offer all the advantages of existing solutions and the latest construction and industry trends: greater height to incorporate more powerful turbines while reducing the number of towers per farm, offsite building processes, greater design freedom, etc. This technology is the result of a complete research project that was carried out between 2009 and 2015 and has been previously presented in a scientific article [14]. This new construction technology sustainability is assessed through the calculation of its MIVES sustainability index. To do so, researchers have defined specialized requirement tree, weights and value functions. Finally, conclusions and recommendations are presented referring to the proposed analysis method, its application in this project and its suitability as a tool for assessing wind tower alternatives in the future-.

2. New tower technology for large wind turbines

As previously said, this new patented technology [15] aims to support turbines equal or larger than 3.0 MW and reach the better wind quality of 100-120 heights. As shown in Figure 1, it is a tripod that has three legs build using precast concrete modules joined with high-resistant prestressed steel bars and transversely reinforced with steel profiles.

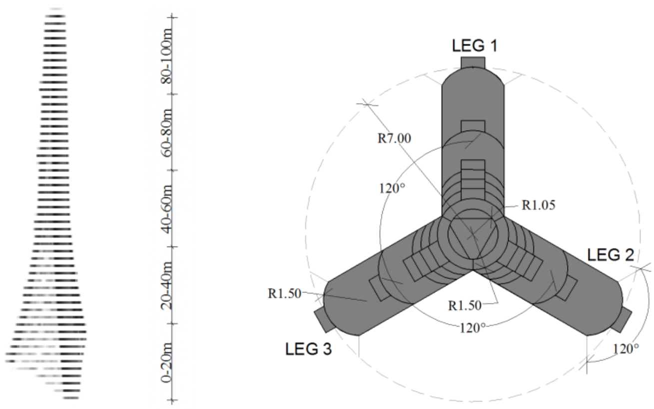

Fig. 1. From left to right, axonometric and plant view.

The design of this new tower technology satisfied the following 5 requirements. First, a circular top shape with a diameter of 3.0 m (Fig. 1), which followed the specifications of the potential manufacturer of the turbine the tower would support. Second, a modulation in constant transversal and longitudinal pieces in order to cast all these pieces using a single formwork and optimize the tower's assembly process. The cross-section of these pieces had to span a 120º circumference section because of the circular top. Third, a maximum module length of 20 m so to minimize the transport and crane costs and needs; which resulted in 15 to 18 modules for 100 to 120 m towers heights respectively. Fourth, possibility of supporting blades up to 60 ensuring a minimum separation of one meter between the blade and the tower. This is in order to avoid contact between them if the blades were bent by extreme winds. The frontal view (Fig. 1) shows that this condition determines that the top 60 m of the tower have to be entirely upright while only the bottom 40 meters can expand the diameter and, therefore, maximize structural stiffness. Fifth, an oscillation frequency for the first mode of vibration higher than 0.4 Hz, in order to ensure the stiffness of the structure as a whole and avoid coupling with the natural frequency of the electrical equipment.

Economic and technical feasibility studies, as well as studies on process optimization and foundation components, were also developed during the design of this new technology [5] [15]. This design process followed the benchmark standards for actions on structures (EC-1) and for the design of concrete structures (MC-2010) and steel structures (EC-4). For the structural and sectional calculations researchers defined models using SAP2000® (Berkeley) and AES [5]. These structural analyses proved the satisfaction of the aforementioned requirements. The resulting structure has the needed stiffness with a vibration frequency of the first period of 0.42 Hz and a peak displacement at the top of 400 mm under the worst wind conditions. Results also confirmed the capacity of the structure to support a 3.5 MW turbine at heights of up to 120 m [5]. The tower's foundation (Fig. 2) was designed with a hexagon plan in order to allow this type of tripod support structure to withstand wind loads optimally. It maximizes resistance to the overturning bending moment that might occur should it become partially detached in situations of extreme wind and it optimizes the amount of material and weight.

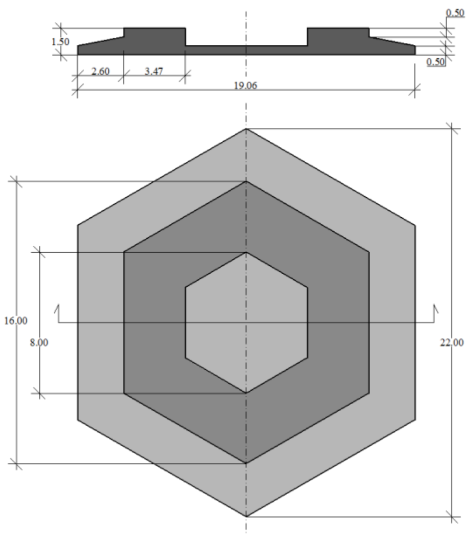

Fig. 2. Tower technology hexagon foundation.

The resulting building technology has 20 m long pieces that weigh a total of 600 kN (Fig. 2). As previously said, these pieces are joined using a continuous post-tensioned system composed of 6 Macalloy Ø 75 mm onsite bars. These pieces are also prestressed at the plant using 100 Y1860-S7 steel quality 0.6" – diameter tendons (Fig. 3) in order to prevent concrete cracking. This active reinforcement is supplemented with passive reinforcement (Fig. 3) to compensate for strong fatigue phenomena and cracking, because the legs work compressed or tensioned depending on the wind direction. All reinforcements are the same for all pieces in order to facilitate on-site steel-fixing work and prevent the serious drawbacks from incorrectly positioning a module that had a different type of reinforcement. However, these reinforcements can be optimized to minimize the use of materials and the cost of each piece.

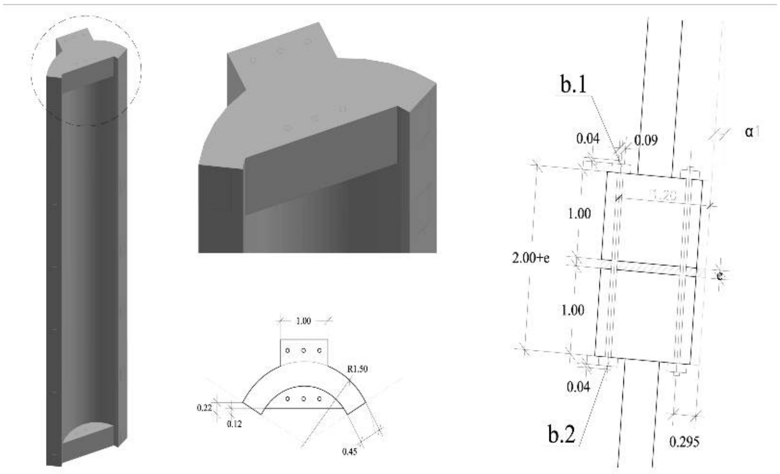

Fig. 3. Tower technology pieces.

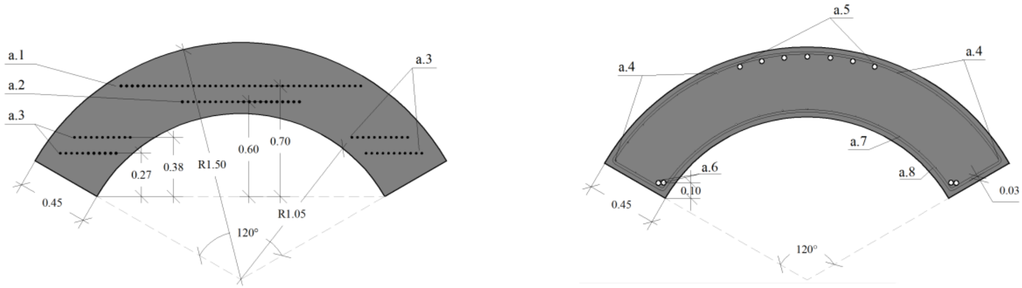

Fig. 4. Pieces active and passive reinforcement.

3. Sustainability assessment tool for wind towers construction technologies

As previously said, the sustainability assessment tool developed and applied in this research project is based on the MIVES methodology and uses value functions [17] to objectively and quantitatively assess various wind tower solutions. This strategy has been followed in previous sustainability decision-making tools and, specifically, focusing on architectural and civil engineering structures [18]. First, a requirement tree was designed and relative weights to each assessment parameter were assigned. This tree has the minimum number of indicators, which are representative and independent between them. In consequence, together with the assigned weights they offer a reliable assessment scenario that enables the objective and systematic ranking of possible wind tower solutions. This tool was developed during seminars of experts in each of the specific subjects related to the field of wind towers. The weightings of the tree's various components were defined using direct assignment and/or Analytic Hierarchy Process (AHP) [19] [20].

Table 2 presents the requirements tree of this research project, which takes into account the following constraints: a tower height of between 100 and 120 m, an on-shore tower type, a turbine with an output equal to or greater than 3.0 MW, and a maximum transportation distance of 350 km [11]. In consequence, this tree includes only those requirements, criteria and indicators most necessary and relevant to differentiating between wind towers alternatives.

Table 2. Requirements tree for wind towers alternatives.

Requirements	Criteria	Indicators	Units
R1 Economic (75%)	C1 Construction cost (40%)	I1 Direct cost (50%)	€/tower
		I2 Cost deviations (50%)	Points
	C2 Maintenance cost (40%)	I3 Cost of planned works (100%)	€/tower
	C3 Deconstruction (20%)	I4 Deconstruction (100%)	€/tower
R2 Environmental (10%)	C4 Resources (33.33%)	I5 Material consumption (100%)	Tn/MW
	C5 Energy (33.33%)	I6 Energy consumption (100%)	GWh/MW
	C6 Emissions (33.33%)	I7 CO2 emissions (100%)	$TnCO_2$-e/MW
R3 Social (15%)	C7 Occupational hazards (30%)	I8 Risk of accident (100%)	Points
	C8 Perception (60%)	I9 Proportions (50%)	
		I10 Flexibility of the solution (50%)	
	C9 Technology integration (10%)	I11 New patents (100%)	

This tree has 11 discrete indicators that belong to the three main sustainability requirements. This research project considered the decision was made by the wind farm developer, thus, the economic requirement (R1) was given the greater weight of 75%. The social branch (R3) assesses key factors for the crucial social acceptance of wind farms so it was given 15%. The environmental requirement (R2), although takes into account the important environmental impact of the building process, it was weighted only 10% because the overall environmental impact of wind farms during the whole service life is negative [21] [22]. If this assessment had been from the point of view of a local authority, or that of the tower manufacturer, the tree would be the same, but the weights might vary depending, however, the same steps would be followed to define them.

R1 studies the construction (C1), maintenance (C2) and deconstruction costs (C3). Installation time is not evaluated because it does not discriminate alternatives when the end-goal is a whole wind farm [14]. C1 and C2 have the highest weights because they assess the initial investment and amortization phases respectively. C1 has two indicators: I1 evaluates the direct cost of the materials, the transportation and the structure's assembly and I2 assesses the deviations due to unfavorable weather conditions during the building process. C2 with the indicator I3 studies the cost of maintenance planned by the tower's manufacturer. And C3 with I4 evaluates the cost of the tower end of life by disassembling it when the technology allows this process or through its demolition otherwise.

R2 has three equally-weighted criteria with their own indicator: C4 and I5 study material resources consumption during the tower building process; C8 and I6 analyze energy consumption over the tower life cycle considering the maximum feasible distances for each solution; and C9 with I7 assess the tower's emissions over its life cycle, focusing on CO_2.

R3 has three criteria: C7 occupational hazards, C8 perception and C9 technology integration. I8 from C7 evaluates the probability of workers' hazards during the tower's transport, construction, maintenance and end of life. The probability of accidents from heights is high so this criterion was given a weight of 30%. C8 studies how surrounding settlements and users of nearby roadways percept the alternative taking into account the tower's visual and landscape impact as a result of its proportions (I9) and the flexibility of the solution used (I10) in terms of its capacity to be adapted, contextualized and customized [23]. I9 assesses the tower geometric proportions, height-diameter ratio and visual permeability. For example, a lattice alternative is more permeable than a tubular solution because parts of the landscape behind the tower can be seen through it. This criterion is crucial as previous studies have shown [24], therefore it has the highest weight of 60%. I10 evaluates the design flexibility that is the technology capacity to incorporate changes. Metal lattice alternatives have the highest score while tubular metal have the lowest because of its geometric constraints due to transportation and other structural conditions. C9 studies the integration of new technology, which is crucial in order to optimize performance and improve results. Therefore I11 assesses it giving the maximum score if a technology is a patented innovation with regard to material and installation processes among others.

4. Sustainability assessment of the new wind tower technology

The sustainability assessment of the alternative presented in section 2 starts defining the parameters and shapes of the value functions for the requirements tree defined in the previous section 3. Value functions are one of the main elements of all tools based on MIVES and are defined in seminars of experts and follow this study case constraints presented in section 3. Value functions enable to measure the adimensional degree to which each solution satisfies each indicator. These functions have 5 parameters [17] that define their shape and their sensitivity to its own indicator's value variations. For example, in functions that decrease concavely the initial indicator's value variations have a lower impact on the satisfaction level than central values indicator's variations, to which they are more sensitive. After defining the value function for each indicator, the sustainability index score of each wind tower solution can be obtained applying the additive equation (1). This equation is applied to each tree level using the aforementioned indicator values (Vi) and weights (λi).

$$V = \sum \lambda_i V_i(x_i) \quad (1)$$

As it is shown in Table 3, five value functions decrease concavely (DCv), two decrease convexly (DCx), and 3 decrease linearly (DL). Indicators in which the maximum satisfaction is needed, such as economic and workers' hazards, have DCv functions. On the other hand, indicators for which the client will accept partial satisfaction, such as environmental aspects, have DCx functions.

Table 3. Value functions parameters and shapes for the sustainability assessment of wind towers within this study constraints.

Indicators	Units	x_{max}	x_{min}	C	K	P	Shape
I1. Direct cost	€/tower	2,000,000	900,000	1,100,000	1.00	2.5	DCv
I2. Cost deviations	points	90	40	50	1.00	2.5	DCv
I3. Maintenance work	€/tower·year	10,000	4,000	5,000	0.05	2.5	DCv
I4. Deconstruction	€/tower	250,000	20,000	60,000	0.05	2.5	DCv
I5. Material consumption	Tn/MW	2,000	200	500	0.01	1.0	DL
I6. Energy consumption	GWh/MW	1.5	0	0.75	1.00	1.0	DCx
I7. Emissions	ton CO_2-e/MW	1,500	0	750	1.00	1.0	DCx
I8. Occupational hazards	points	2.5	1.5	2.5	0.01	3.0	DCv
I9. Proportions	points	100	0	100	0.01	1.0	DL
I10. System's flexibility	points	100	0	100	0.01	1.0	DL
I11. New patents	points	1	0	1	0.01	1.0	DCx

Table 4 presents the sustainability satisfaction values for each indicator and requirement and the integrated sustainability index of the new tower technology presented in this research project.

Table 4. Satisfaction values Vi for requirements and indicators of this research project new tower technology.

	R1	I1	I2	I3	I4	R2	I5	I6	I7	R3	I8	I9	I10	I11	Total
Index V_i	0.57	0.83	1.00	0.33	0.38	0.86	0.80	0.86	0.98	0.64	0.31	0.90	0.60	1.00	0.61

The total sustainability index V of the wind tower technology presented in this project is 0.61 out of a maximum score of 1.00 (Table 4). It is a low index mainly due to the low economic requirement index of 0.57, which is because of the even lower maintenance and deconstruction costs indexes. The environmental and social indexes are higher with 0.86 and 0.64 values respectively and help to balance out the total sustainability index. This new technology is a patented solution that has not yet commercialized and that it has been designed to optimize mainly its technical, environmental and social features. As a result of this sustainability and taking into account these indexes, researchers have foundations to improve this patent by promoting its positive environmental and social strengths and improving its economic and social weaknesses when the tripod is brought to market. This is because this tool has been able to determine the indicators with high satisfaction – I1, I2, I5-7 and I9-11 – and which ones have to be improved – I3 and I4 and I8. Therefore, it can be concluded taking into account the overall results that the proposed alternative has future potential as wind turbine tower alternative.

Although this MIVES tool has been defined for the aforementioned specific constraints and decision maker point of view, this tool is able to simulate other decision-making scenarios involving stakeholders with other specific interests. For example, if we consider a context of economic growth and from the point of view of a public investor, then social, political and environmental factors would have more importance. Therefore, slightly different weights λi would be used for the simulation. If the satisfaction values obtained for each requirement are maintained (Table 4), and different weights are given taking into account this latter scenario such as λ(R1) = 50%, λ(R2) = 25% and λ(R3) = 25%), the total sustainability index value would be V = 0.67. This index shows a significantly better perception of the proposed technology than in the first scenario.

5. Conclusions and recommendations for the future

This research project presents two main novelties in the field of tall towers for large wind turbines: a) the design of a new technology that integrates the advantages of current solutions and b) the development and application of a robust and flexible sustainability assessment MIVES tool. In both cases no similar solutions have been found in the literature review, although there are already several alternatives available in the market with different construction processes and materials.

This new tower technology incorporates the numerous advantages of precast construction processes and modulated components as it is described in detail in section 2. It is a patented technology that has not yet been commercialized that has still room for improvement according to the sustainability assessment carried out in section 4. This assessment uses a MIVES methodology tool that has been developed in section 3. This tool can be used to evaluate the sustainability of wind turbine towers with its requirements tree, its weights and its value functions. In this research project, this three elements were defined based on expert seminars, for a scenario of economic constraints and from the viewpoint of a private wind farm owner. For the new tower technology, this tool has given a total sustainability index of 0.61 and the specific indicators with the lowest satisfaction values. These are deconstruction costs and workers' hazards, which will be corrected in the commercializing process of the patented technology.

These sustainability assessment results are based on the aforementioned constraints and viewpoint. Nevertheless, this tool can be calibrated considering other boundary conditions to obtain equally representative results as shown in section 4. Therefore, this tree can be used to evaluate the sustainability for towers in other scenarios and from other points of view by adjusting the weightings and boundary conditions accordingly. In consequence, this tool can also be suitable for analyzing wind turbine towers in general.

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