Small wind turbines: Sustainability criteria related to the local built environment

G E Malliotakis¹, Th N Nikolaidis¹,³ and C C Baniotopoulos²

¹Institute of Metal Structures, Dept. of Civil Engineering, Faculty of Engineering, Aristotle University of Thessaloniki, GR-54124, Greece,
³School of Civil Engineering, University of Birmingham, B15 2TT Birmingham, United Kingdom

²Corresponding author’s e-mail address: thnik@civil.auth.gr

Abstract. The present paper focuses on the enhancement of the development of small wind energy considering sustainable energy harvesting criteria. As known, the exploitation of wind energy as an environmental friendly energy source is carried out by wind turbine systems. In order to satisfy local energy needs, low power small scale wind turbines could be used. Their use, contributes to the reduction of carbon dioxide emissions in the local atmosphere, as well as to the consumption of electricity on site where power is produced. In the present work a comparative analysis has been performed taking into consideration two different application sites located in Crete Island, Greece. This analysis is based on actual recordings of the characteristics of the wind and followed by the selection of the optimum installation height, as well as the estimation of the construction cost. This analysis includes two different design cases using two different construction materials for the support tower, in particular steel and aluminium, taking into account the results of the respective advanced finite element analysis models. This way the proposed analysis leads to an enhanced evaluation of the sustainability of the small wind energy systems in the local built environment.

1. Introduction

Nowadays, energy stocks are being reduced rapidly. Taking into account climate change that gradually leaves its footprint, society should turn to sustainable and environmentally friendly solutions. In this crucial question answers can be given by wind energy, an inexhaustible and pure source of energy, which continues to grow at a rapid pace. Each kilowatt-hour of electricity generated by the wind replaces a corresponding one generated by fossils that heavily pollute the environment. Wind energy can be produced using several wind turbine systems. On the other hand, the inability of wind turbines to exploit a significant part of the uneven size and directional wind gusts, as well as the difficulty of storage of the generated energy, limits their exploitation.

Evolution in the field of wind power allows the construction of various types of wind turbines depending on the height, orientation and even support material, not only for large wind farms, but also for urban and suburban built environment applications, which can have a decisive contribution to enhance the concept of Smart Future Cities [3].
At the same time large wind turbines and the respective aeolian parks due to the level of noise generated and due to the aesthetic effect in areas of particular natural beauty are treated by the society with denial and skepticism. Small wind turbines are under strong competitive pressure from photovoltaics which have decreased significantly in price over the past decade [8]. A similar reduction in the manufacturing cost of small wind turbines is probably not achievable, but significant efforts can be made by the reserved of monopole towers by the cheaper and more efficiency lattice towers [1]. Technological developments allow the construction of small wind turbines in various types and sizes, with the ultimate objective being the optimum use of the available wind resource. Regardless their size and axis orientation, their use is crucial in order to meet the existing energy needs. More specifically, the most advantageous form of the system unit is related to the tower resistance to wind loading and its total weight that reflects the cost of manufacturing and installation. An effective solution to this problem may be the development of wind parks or single stations of small wind turbines which, due to their size, have a much smaller environmental impact being in the meantime able to provide power to individual units, degraded areas, waste water treatment plants and small settlements. By this way, electricity is consumed directly at the point of production with the decrease of carbon dioxide emissions into the atmosphere. The evaluation of a small wind turbine is based on two basic parameters, the height of the tower with respect to the adequacy of the location. It is obvious that the cost of building the tower of a wind turbine increases in proportion to its height. However, it is more likely that the wind turbine will be more efficient at a higher height, due to the raise of the wind speed increase. For this reason, the best proportion of installation costs is achieved compared to the value of the electricity produced.

It is worldwide known that the principal manufacturing material for wind turbine towers is the structural steel because of its high strength and connectivity.

However, aluminium alloys structures could support some types of wind turbines of average weight. Aluminium as a building material presents several advantages in comparison to steel [2], such as a) small specific weight, b) low maintenance cost due to high corrosion resistance, c) easy and low cost transportation to the point of construction, and d) possibility to extrude sections provided the possibility to design easily various types of sections. Small wind power turbines with vertical (VASWT) (see figure 1(a)) and horizontal axes (HASWT) (see Figure 2(b)) are considered those designed to respond to the specific wind potential of a site [6], having a nominal power of less than
50kW. Their main advantage is the scale of the installation with respect to the field of vision, the noise and vibration levels, the utilization of the wind potential, the generated electric power and the cost of installation. Particularly the cost of installation is beyond the rotor itself related to the support tower and the foundation on the ground.

The herein presented study explores such optimal design cases with reference to sustainability criteria of a small power wind turbine network in two respective sites in Crete Island, Greece with different wind potential characteristics. Therefore, depending on the site of application, different types of low power wind turbines could be chosen with the most important selection characteristics to be the type and the efficiency of the turbine, the total height of installation, the bearing capacity of the tower and the total construction cost. At the same time the tower design must incorporate aesthetic features for the overall shape of the structure. Particularly, the vertical axis of small wind turbines (VASWT) intended for areas where there is no smooth flow of wind. On the other hand, for open areas with laminar flow and a few obstacles, the horizontal axis type (HASWT) is preferable and for this reason it is selected in both design cases under investigation.

The first site case, (see figure 2(a)), is close to the city of Rethymnon Crete, (Islands, North-Central Crete, Greece) and the second one, (see figure 2(b)), is close to the city of Sitia Crete, (Islands, North-East Crete, Greece), both near to the area of the local waste water Treatment Plants.

2. Sustainable design selection criteria for small wind turbines

In general, sustainable development is about achieving economic growth while taking account environmental protection, so that economic and environmental benefits are available to society both now and in the future. The basic sustainable design principles in constructions concern the impact on the environment, the society and the economy. The last impact is directly related to the strength and the design lifetime of the structure.

The first design principle includes environmental indicators such as the contribution to the climate change by reducing carbon emissions, exhausting the available energy resources, disruption of the wind and the impact on the surrounding ecosystem. The second design principle includes indicators related to the society such as the visual nuisance and the aesthetic degradation, the level of noise and vibration produced and the electromagnetic interaction with the power network in the surrounding area. Finally the third design principle includes indicators related to the economy as are the operational life of the project, the total installation cost or the depreciation and profit ratio, the maintenance cost and the degree of energy autonomy in a local area.

The impact of some indicators related to the society and economy from the construction of small wind turbines parks is herein evaluated analytically and discussed. The design criteria accompanied by certified characteristics determine the type and form of a small wind turbine. The most important of those criteria are the nominal energy power, the nominal wind speed, the operating range of wind...
speeds, the total energy production per year per m\(^2\) of rotor area, the weight of the rotor, the diameter and the cover area of the rotor blades, the height of the rotor, the range of the operating temperatures, the noise lever (at 25m distance from the tower for a wind speed of 10m/s) and the operational life of the rotor.

3. Evaluation of the wind potential

The analysis of the wind potential of the site where the wind turbine is installed is a priority. Second appropriate step is the selection of the wind turbine type because is the key for an optimal power generation. In this study all that data received by local sources for the selected application sites a) close to Rethymnon (Islands, North-central Crete, Greece) [6] and b) close to Sitia, (Islands, North-East Crete, Greece) [7] respectively.

The dynamic of the wind of the mentioned selected sites is done by recording the local wind data and then by producing the respective Wind Rose diagrams (see figures 3(a) and 3(b)). These graphs correlate the distribution of the average daily wind speeds, as well as the respective directions. In addition, based on the statistical representation of the air directions, the wind turbine will have west-north-west orientation in the case a) of Sitia and north-west orientation in the case b) of Rethymnon noted that in both sites the wind flow is smooth with few obstacles.

Furthermore, from the processing of these wind data, the corresponding distribution of wind speeds in classes can be obtained for the respective sites, depending on the frequency of occurrence of each wind speed class (see figures 4(a) and 4(b)). According to all the recorded data for both site cases and taking into account five well-known types of horizontal axis small wind power turbines, a comparative evaluation (see Figure 5) can be developed. As the optimal one, the named 5HAWT type is selected, with certified nominal energy power of 8.9kW at average wind speed 5m/s and respective annual energy production of 13800kWh.
Figure 4(a). Distribution of the wind speed classes site Rethymnon, North-Central Crete.

Figure 4(b). Distribution of the wind speed classes of site Sitia, North-East Crete.

Figure 5. Comparative evaluation of sustainable design criteria of several (HASWT) suitable for the specific wind environments.

At the same time for this selected wind power turbine, the diameter of the rotor is 7.0m, the total weight of the rotor is 545kg and the level of noise at a distance of 25m measured for a wind speed 10m/s is 45DB (see Table 1).

In this case the development of a small wind net into these plant areas is taking into account. Moreover the distances between single turbine towers must be at least 35.0m (5 times the turbines rotor diameter) and the total height was taken as a) $H_T=24.0m$ for the site of Rethymnon and b) $H_T=16.0m$ for the site of Sitia. In addition to the critical wind data of each site and the construction cost, the exact height of the wind turbine is selected so that the imaginary line of the perimeter of the wind turbine surface is at a height from the ground at least twice the maximum height of the nearest obstacle of the waste (approximately 10.0m). Evaluating all these data taking into account known design requirements [3] as well as the mass and the operational actions of the rotor, a triangular lattice supporting tower formed by tubular cross-sections is selected as optimal with variable edges in height.

One significant parameter for an optimal design of small wind turbines is the range between Start-up/cut-in wind speed and the furling wind speed of the rotor blades (see Table 1). The limits of Start-up and Furling wind speed are major sustainable criteria for the selecting system in order to minimize the coordination risk for the supporting tower and to maximize the range between the two limit values and the energy production. It is noted that Furling is one method of preventing a wind turbine from
spinning too quickly simply by turning the blades away from the direction of the wind and protecting the wind turbine and the supporting tower from large oscillations and the coordination risk.

Table 1. A Sustainable design criteria of the selected Horizontal Axis Small Wind Turbine 5HAWT.

| SUSTAINABLE DESIGN CRITERIA                        | VALUE  | UNITS |
|---------------------------------------------------|--------|-------|
| Rated power(at rated speed)                        | 8.9    | kW    |
| Awea annual energy(at 5m/s average)               | 13600  | KWh/y |
| Start-up/cut-in wind speed                        | 2.2    | m/s   |
| Rated wind speed                                  | 11.6   | m/s   |
| Furling wind speed(40rpm)                         | 18.0   | m/s   |
| Rotor diameter                                    | 7      | m     |
| Weight of rotor-blade system                      | 545    | kg    |
| Total cost of rotor-blade system(approx.)          | 35000  | €      |
| Noise (for Rated wind speed)                      | 45     | DB    |
| Lifetime                                          | >25    | years |

Moreover, the wind speed of a site is low close to the ground and increases with increasing height above the ground. Really, the smooth flow of the wind over the land is interrupted by obstructions and field variations bringing wind shear due to friction of earth surface and turbulence due to the terrain features. This may be accomplished by putting the wind turbine on the highest feasible tower. Therefore, small increases in average wind speed will result in significant increases in energy output (the wind speed increases the received power eight by a factor of 8).

4. Design analysis of the supporting lattice tower of HASWT

The indicator of operational life of the wind turbine leads to the optimal design shape of the supporting tower. Thus, this shape must satisfy several sustainable design standards such as:

- The structural response at ULS and SLS design situations should be fulfilled, whistle the cost be minimum [6].
- The natural frequency (fundamental eigenfrequency) of the tower must be controlled to be far away from the rotation frequencies of the rotor system. This mean that the natural frequency of the tower should not coincide with the excitation frequencies of the rotor system at rated operating conditions (Furling wind speed). Thus, in this case the supporting lattice tower is more resilient to oscillations as a non-wind sensitive structure and classified as stiff-stiff tower [5].
- The maximum displacement at the top of the tower must be less than 5% of the height (H_T) of the tower [4] (acceptable limit to design the structure under elastic analysis mode at ULS).
- In addition the maximum displacement at the top of the tower must be less than 1÷2% of the height (H_T) of the tower (1.6%H_T for the selected rotor in respect to its weight), which is the limit of safe operation of the wind turbine at SLS [5].

In the design site of Rethymnon, a triangular cross-section of a lattice steel (S355H) tower (Model 1), with a total height of H_T=24m is chosen as optimal depending on the local site conditions (see figures 6(a) and 6(b)). The tower is composed by a Circular Hollow Section (CHS) inclined column and the web members. The top view is a triangular side cross-sectional dimension of 2.00 m at the bottom and reduced with height to 0.40 m at the top. Because of its height, the whole structure of the lattice tower could be assembled at least into 3 segments to be transported on site.

By the same way, in the design site of Sitia, a triangular shape of a lattice steel (S235H) tower (Model 2), with a total height of H_T=16m is chosen as optimal depending on the respective local site’s conditions. The tower is composed by hollow section bars taking into account different cross section shapes in comparison between a) Square Hollow Sections (SHS) and b) Circular Hollow Section
(CHS) for the inclined columns and for the web members. The top view is a triangular side cross-sectional dimension of 1.20 m at the bottom and reduced with height to 0.40 m at the top. Because of its optimal height the whole structure of the lattice tower could be assembled only into 2 segments to be transported on site.

**Figure 6(a).** Frond view of the lattice steel tower (Model 1, Hₜ=24.0m).

**Figure 6(b).** Critical mode shapes (₁ˢᵗ, ₂ⁿᵈ and ₃ʳᵈ) and axial forces distribution at ULS of the lattice steel tower (Model 1, Hₜ=24.0m).

Especially in the design case of Sitia, a lattice aluminium alloy tower (see figure 7) of the same triangular shape (Model 3) with a total height of Hₜ=16m is taken also for evaluation and comparison with the steel one.

**Figure 7.** Typical axial load distribution on the aluminium alloy lattice tower (Model 3, Hₜ=16.0m) at ULS, Section (0-8 m) and Section 2 (8-16 m).
Taking into account the advantage of the wide variety of cross-sections in respect to the series of known series of aluminium alloys [2], an optimal selection is done also here between a) Square Hollow Sections (SHS) and b) Circular Hollow Section (CHS) for the main inclined columns and the web members. In this case, a preliminary design procedure was applied, to define the optimal aluminium alloys for the bar and web elements, in respect to the width and thickness of each different section according to Eurocode 9 (see figure 8).

![Figure 8. Optimal CHS column sections of different aluminium alloys lattice tower (Model 3).](image)

All the previously described structures of lattice towers were analyzed by the respective advanced numerical models formulated by the SAP2000 computer software and their response were checked within a Eurocode 3 and 9 framework. In this analysis the numerical models were subjected to static and dynamic loads at SLS and ULS design situations under the framework of Eurocodes 0 and 1.

![Figure 9(a). Displacements arrangement at the top at SLS of the steel lattice tower (Model 2, H=16m).](image)

![Figure 9(b). Displacements arrangement at the top at SLS of the aluminium alloy lattice tower (Model 3, H=16m).](image)

The basic wind speed according Eurocode 1-4, as the main load action on the tower (the same for all the design sites under investigation) was taken as $v_b=33\text{m/s}$ (Greece, islands) and this value is higher than the respective Furling wind speed of the rotor system (18m/s). Because of the truss system of the tower for all the support structures under investigation, the axial load was the critical one for the bearing capacity of the bars at ULS.
The structural analysis of the aluminium alloy lattice tower (Model 3, $H_T=16.0m$, see figure 9(b)) with CHS bars, shows that the maximum horizontal displacements (at SLS and ULS) at the top increased in relation to the respective steel lattice tower (Model 2, $H_T=16.0m$, see figure 9(a)), both less than the design limits (see Table 2).

**Table 2.** Maximum horizontal displacements of the tower at U.L.S. and S.L.S. for the 3 lattice tower models.

| Loading Combination | Model 1 (Steel $H_T=24m$) | Model 2 (Steel $H_T=16m$) | Model 3 (Aluminium, $H_T=16m$) |
|---------------------|---------------------------|---------------------------|-----------------------------|
|                     | [Hor. displ. (top)] (cm)  | [Hor. displ. (top)] (cm)  | [Hor. displ. (top)] (m)     |
| G + W (SLS)         | 25.29<38.4 (1.6%H)        | 4.74<24 (1.6%H)           | 14.21<24 (1.6%H)            |
| 1.10G + 1.50W (ULS) | 35.29<120.0 (5%H)         | 7.87<75.0 (5%H)           | 23.6<75 (5%H)               |

Wind is essentially a dynamic action in nature. Due to this, when the natural vibration frequencies of the tower-rotor system or the most critical of the tower itself are very small to be excited by the turbulence caused by the wind in the rotor, the structure is considered to be dynamically wind sensitive. In general, the vibrations generated by the rotating machine on the top of the tower should not match the natural (fundamental) frequency ($F_1$) of the tower. In smart systems like this, the Furling process is forcing the blades of the rotor out of the direction of the wind in order to stop the blades from turning by decreasing the angle of attack, which reduces the induced drag and lift force of the rotor and its cross-section. The Revolutions Per Minute in the Furling situation is 40RPM, so the forcing frequency from one blade of the rotor is $f=0.67Hz$ (RPM/60) and the exciting frequency of the 3 blades of the rotor is $(n)f=2.0Hz$ (3·RPM/60).

On the other hand, the natural frequency of the tower-rotor vibrating system and the most dangerous case of the tower itself should not coincide with the excitation frequencies of the 1 or the 3 blades rotor system. The system of tower-rotor can be classified as Soft-Soft [$F_1<f$], Soft-Stiff [$f<F_1<(n)f$] and Stiff-Stiff [$(n)f<F_1$]. Moreover, the structural system of the tower itself must have a natural frequency that overcomes the excitation frequencies of the 3 blades rotor system.

**Table 3.** Natural frequencies ($F_1$) of the lattice tower models and classification in relation to the exciting frequencies of the rotor system ($f$).

| Structural system | Model 1 (Steel $H_T=24m$, natural frequency ($F_1$)) (Hz) | Model 2 (Steel $H_T=16m$, natural frequency ($F_1$)) (Hz) | Model 3 (Aluminium, $H_T=16m$, natural frequency ($F_1$)) (Hz) |
|-------------------|----------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| Tower             | (n)$·f=2.0<2.916$                                       | (n)$·f=2.0<4.425$                                       | (n)$·f=2.0<5.405$                                       |
| Tower-rotor       | $f=0.67<1.331<(n)f=2.0$ (Soft-Stiff tower)             | $f=2.0<2.457$ (Stiff-Stiff tower)                       | $f=2.0<2.004$ (Stiff-Stiff tower)                       |

The Soft-Soft tower classification is a case of low cost but very sensitive to oscillations and not sustainable. The Soft-Stiff tower classifications lead to a safety structure in relation to the construction cost (see Table 3, Model 1). On the other hand, by using an optimal height for the tower and moreover by selecting an aluminium alloy supporting tower, the classification become Stiff-Stiff (see Table 3, Model 2 and 3).
It is also important that in all 3 models the maximum horizontal displacements at SLS satisfies the limits of \((1.6\%)\cdot H_T\) and the horizontal displacements at ULS the limits of \((5\%)\cdot H_T\) (see Table 3).

5. Sustainability Appraisal

According to latest sustainable assessments and studies a known methodology is herein applied for appraising the sustainability of small wind turbine systems in relation to the local build environment. The sustainability indicators in the case of structures like that can be grouped under three generally accepted key themes: 1) environmental protection, 2) society and 3) resistance-economics (see Figure 11). This method introduces the main sustainability assessments for evaluating and comparing the sustainability impacts of construction models in different build environments and construction strategies. In order to obtain an overall sustainability score, each quantitative factor score have to be combined. There is a problem because each indicator is measured in different units. Therefore, this is a method of relative measure of sustainability rather than an absolute measure because is a comparative method between alternative approaches. The scores of these measures are dimensionless and can be compared with other factors. In this analysis equal weighting factors are used for all the 3 key themes, but it is easy to increase the weight of a key theme that could be evaluated as more important.

The outline of small wind turbine systems of **Model 1** for the site of Rethymnon with a Steel lattice tower of \(H_T=24m\), **Model 2** for the site of Sitia with a Steel lattice tower of \(H_T=16m\) and **Model 3** for the site of Sitia with an Aluminium lattice tower of \(H_T=16m\) have been taken into consideration in this analysis (see Table 5). Especially, the cost analysis of the tower is based on the current market value \((0,652€/per kg for steel and 1.60€/per kg for aluminum). Aluminium never corrodes in contrast with steel, which needs anticorrosion protection. Taking into account that the maintenance of steel sections are needed every five years, due to fact that the aggressive corrosive environment where the structure will take place, the cost is increased in the case of a steel structure (see figure 10).

| INDICATORS          | **Model 1** | **Model 2** | **Model 3** |
|---------------------|-------------|-------------|-------------|
|                      | Steel lattice tower, Site: Rethymnon, \(H_T=24m\) | Steel lattice tower, Site: Sitia, \(H_T=16m\) | Aluminium lattice tower, Site: Sitia, \(H_T=16m\) |
| Quantity            | Norm. score | Weight factor | Weighting score | Quantity            | Norm. score | Weight factor | Weighting score | Quantity            | Norm. score | Weight factor | Weighting score |
| Climate Change      | 24500 (kg CO2/yr) | 42.00 | 0.111 | 4.66 | 21000 (kg CO2/yr) | 29.00 | 0.111 | 3.22 | 21000 (kg CO2/yr) | 29.00 | 0.111 | 3.22 |
| Resource Energy     | 16000 (kWh/yr) | 36.70 | 0.111 | 4.07 | 13800 (kWh/yr) | 31.69 | 0.111 | 3.52 | 13800 (kWh/yr) | 31.69 | 0.111 | 3.52 |
| Waste               | 7 (kg/yr) | 40.00 | 0.111 | 4.44 | 10 (kg/yr) | 30.00 | 0.111 | 3.33 | 10 (kg/yr) | 30.00 | 0.111 | 3.33 |
|                      | **ENVIRONMENT** | **SOCIETY** | **ECONOMICS** | **ENVIRONMENT** | **SOCIETY** | **ECONOMICS** | **ENVIRONMENT** | **SOCIETY** | **ECONOMICS** |
|                      |             |             |             |             |             |             |             |             |             |
|                      |             |             |             |             |             |             |             |             |             |
| Natural Frequency   | 1.331 | 25.00 | 0.111 | 2.55 | 2.457 | 37.51 | 0.111 | 4.16 | 2.004 | 37.51 | 0.111 | 4.16 |
| Construction Cost   | 18500 (€) | 30.80 | 0.111 | 3.42 | 17000 (€) | 33.54 | 0.111 | 3.72 | 16000 (€) | 35.65 | 0.111 | 3.96 |
| Maintenance         | 1600 (kg) | 12.00 | 0.111 | 1.33 | 1000 (kg) | 20.00 | 0.111 | 2.23 | 300 (kg) | 68.00 | 0.111 | 7.55 |
|                      | **TOTAL SCORE** | **28.33** |       |       | **28.93** |       |       |       | **36.65** |       |       |

Figure 10. Sustainability scores, equal weightings.

Heritage and biodiversity, employment and businesses and aesthetics are purely qualitative factors that can not be evaluated easily. All three schemes (environment, society, economics) have the same weighting factor. Also, all indicators of each scheme are equal. In this scenario with equal weight factors, aluminium lattice tower of \(H_T=16m\) of Sitia site (Model 3) is the most sustainable solution with a total score of 36.65 whereas steel lattice tower of \(H_T=16m\) of Sitia site (Model 2) scored 34.93 and steel lattice tower of \(H_T=24m\) of Rethymnon site (Model 1) scored only 28.33. In terms of environmental theme the case of Model 1 is more sustainable because of the higher energy production. At the same time the cost of construction is increased in this case as well as the impact to the society due to the higher total height of the structure. In order to evaluate the reliability of the method, a second Scenario is presented with the following assumption. Economics theme is given twice the weighting of the environmental and society factors. This assumption can be justified by the importance of total cost of a project in decision making (see figure 11).
In this scenario with unequal weight factors, aluminium lattice tower of $H_T=16m$ of Sitia site (Model 3) is again the most sustainable solution with a higher total score of 38.88 whereas steel lattice tower of $H_T=16m$ of Sitia site (Model 2) scored 34.08 and steel lattice tower of $H_T=24m$ of Rethymnon site (Model 1) scored only 26.64.

6. Conclusions
From the comparison of supporting tower models of the small wind turbine, it seems that the lattice tower under the design load actions and especially wind action is a resilient and stiff enough structure. However it is more susceptible due to the plethora of connections susceptible to fatigue and therefore it requires a higher level of maintenance and inspection cost. The use of aluminium alloys as the construction material for the lattice tower can be a sustainable solution to these impacts.

Lattice towers are optimal structures to support small wind turbines of horizontal axis because they have the advantages of easy fabrication, less cost, easy of transportation and flexible erection. At the same time, the visual trace of a horizontal axis rotor-blades system of 7.0m diameter supported on a triangular lattice tower of total height 16-24 meters seems to be less.

The sustainability appraisal of these structures shows higher scores for towers with low heights of 16÷18m instead of higher towers of 22÷24m which at last become more wind sensitive.

The natural frequency (fundamental eigenfrequency) of the tower must be controlled to be far away from the rotation frequencies of the small wind rotor. The design in this case must be use the furling process for the control of oscillations of the tower-rotor system and the protection from the coordination hazard.

Both qualitative and quantitative factors must be combined to produce a total sustainability score where emphasis is given on one sustainability aspect or other depending on the local environment.

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