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Urban Wind: An Alternative for Sustainable Cities

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Abstract: The climate emergency has intensified the search for the generation of electricity from renewable energies in order to turn cities into sustainable cities. Small-scale wind power offers new opportunities for decentralized electricity production, avoiding dependence on the grid and transmission losses. Among viable locations within the urban environment, high-rise buildings are especially promising due to the elevated height and less turbulent wind conditions. They can also be integrated into the architecture of the building or as independent units in the urban environment. In this area, this work presents a methodology for determining the annual energy production of urban wind projects. The proposal is divided into four stages: location, wind and urban indicators, turbine selection and annual production estimation, and economic/environmental analysis. The evaluation of the solution is carried out for a Spanish case study. According to the results, more than 68,000 kWh/year can be generated with an investment recovery period of less than six years.

Keywords: renewable energies; urban wind; sustainable cities

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1. Introduction

The climate emergency has added to the current health emergency caused by COVID-19. Governments will play a fundamental role in the recovery of the energy sector. Economic aid packages are a great opportunity to link the economic recovery and the energy transition with the use of clean energies that are oriented towards a sustainable energy system [1]. However, renewable energies have proven resilient, dispelling myths about the reliability of systems with high percentages of solar and wind energy. By the year 2050, electricity would be the main energy carrier, with more than 50% participation in the total final energy use, and 90% of the total electricity needs will be supplied by renewable energy [2].

The evolution of the global wind sector is upward, both in new MW added to the total capacity and in the electrical energy generated from wind installations. Onshore wind capacity has increased by 298%, adding about 530 GW in the 2010–2020 period. A total of 32 GW has been added to the total marine capacity during the same period, increasing its global capacity by more than 1000%. The global cumulative wind capacity in 2020, including the two types of technologies (onshore and offshore), amounted to 743 GW; there was a 14% growth over the previous year. The new facilities added exceeded 92 GW, representing an increase of 14% compared to 2019 and 12.41% of the global accumulated capacity. The annual electricity generated is close to 1648 TWh. The upward trend predominates in the wind sector for projections for the next three decades. In the years 2030 and 2050, the total capacity will triple and grow by ten times, respectively, compared to 2019. An electricity generation of more than 18,000 TWh is expected [3]; see Figure 1. Despite this exponential development of the wind sector, penetration into the urban environment is invaluable. The main barriers to the implementation of urban wind energy can be characterized according to technological, social, environmental, and economic factors [4].

- Technological: Inefficient wind turbines, as they cannot capture low wind speeds in turbulent environments; therefore, electricity generation is low.
- Socio-environmental: Visual impact and noise disturbances generate little social acceptance. Safety for fauna (birds).
- Use of the wind resource: Methodologies for energy predictions based on the evaluation of the wind resource.
- Economic: Low viability of the facilities.

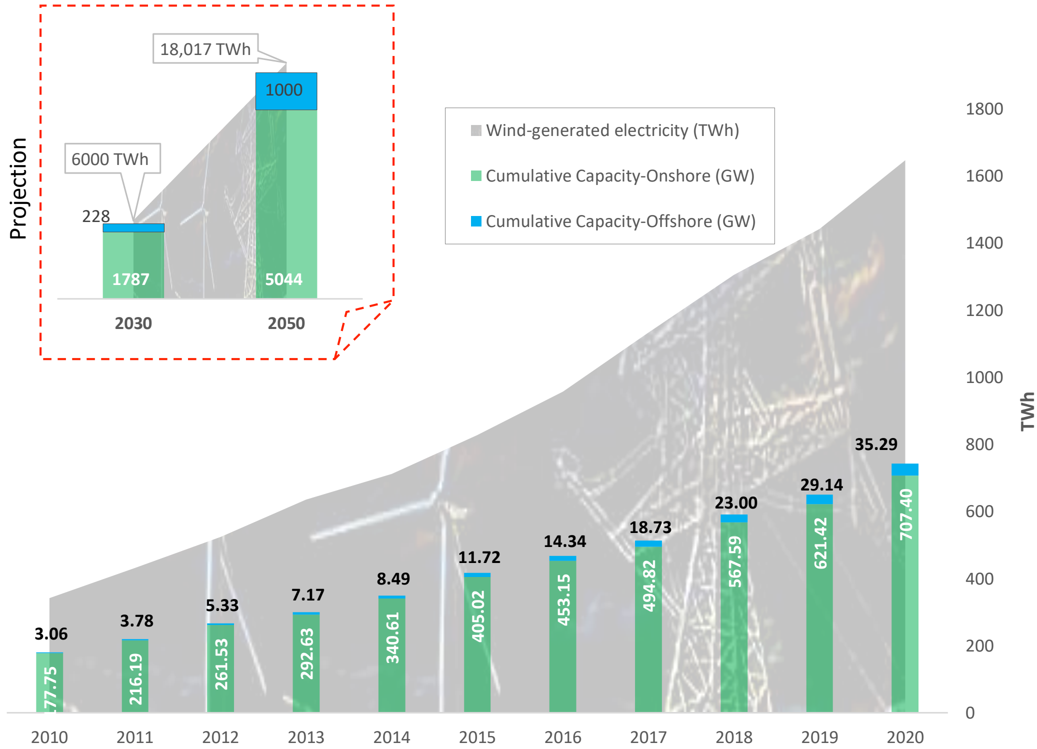


Figure 1. Evolution of electricity generation in the world. Source: [2]—authors' own elaboration.

Table 1 shows the related contributions, which are classified by the barrier of study. Many of them were based on technological barriers with the aim of optimizing technology to achieve better performance. Others studied the use of wind energy according to the positioning of the turbines made by in situ measurements, experimentation in wind tunnels, and computational fluid dynamics (CFD).

Table 1. Barriers for urban wind energy implementation. State of the art.

		Barriers			
Ref.	**Year**	**Technological**	**Socio-Environmental**	**Wind Resource Analysis**	**Economic**
[5]	2009		X	X	
[6]	2011	X	X		X
[7]	2012			X	
[8]	2013	X	X		
[9]				X	
[10]				X	

Table 1. *Cont.*

		Barriers			
Ref.	**Year**	**Technological**	**Socio-Environmental**	**Wind Resource Analysis**	**Economic**
[11]	2015			X	
[12]				X	
[13]				X	
[14]	2016			X	
[15]				X	
[16]				X	
[17]	2017	X		X	X
[18]				X	
[19]	2018	X			
[20]		X			
[21]	2019	X			
[22]		X		X	X
[23]				X	
[24]				X	
[25]	2020			X	
[26]		X		X	
[27]				X	
[28]		X		X	
[29]	2021	X		X	
[30]		X		X	
[31]				X	
[32]		X		X	

Chong et al. [6] carried out a technical–economic study of a system that integrates and optimizes various green technologies, including urban wind turbines, solar cell modules, and rainwater collectors; it is compact and can be built on high-rise buildings to provide on-site renewable energy to the buildings. The estimated annual energy savings were 195 MWh/year. The performance of urban wind systems is closely linked to the location of the turbines. Balduzzi et al. [7] investigated the proximity of buildings through the vertical profile of the wind for different building heights and roof geometries, and found that a more than 70% increase in capacity could be achieved according to previous studies of wind potential. Dilimulati et al. [19] and Toja-Silva et al. [8] demonstrated that the best-performing turbines in urban environments are vertical-axis wind turbines (VAWTs), but further optimization for urban applications is required according to the specific literature. Dilimulati et al. [19] explained that diffusers and shrouded brims around conventional wind turbines may lead to significant power output increases. Al-Quraan et al. [14] studied the potential of wind energy in two areas, with homogeneous and non-homogeneous urban deployment in terms of the heights of the buildings. The deviations between the energetic calculations of the homogeneous zone turned out to be 5%, while the non-homogeneous zone deviations were higher than 20%. Another study where the importance of the heterogeneity of the height of the buildings intervened was carried out by Millward-Hopkins et al. [10]. They compared the accuracy of three wind atlas methodologies for predicting the mean wind speed on rooftops of various UK cities, concluding that the directional effects of wind and detailed building databases were critical for predicting wind potential. Yang et al. [16] compared energy estimations based on CFD and in situ measurements in complex terrain while including wind speed, direction, and turbulence data. An improved roof design with a rounded shape to improve the density of wind energy with a relatively lower intensity of turbulence was proposed as well. Romanic et al. [11] and Hsieh et al. [9] described wind resource assessment methodologies for urban coastal environments on the roofs of buildings, including indicators of wind speed, direction, heights of buildings, and surrounding areas. Romanic et al. [11] merged

CFD at the microscale level with the atlas of wind energy at the mesoscale level with the aim of individually evaluating the wind energy of buildings with the maximum usable wind energy in the area. The selected turbines showed an important gap between the speed reached and the production of electrical energy generated. Several studies based on simple geometries, prisms, or groups of thereof evaluated the positioning on the roofs of buildings. Toja-Silva et al. [12] recommended, through their investigation of a single building with CFD and horizontal turbines, a minimum height from the roof surface of 19% and 31% of the height of the building if they are located in the upstream or downstream region, respectively. Wang et al. [13] investigated the wind energy potential on roofs of two orthogonal buildings with CFD, considering heights and distances of separation of corners. Chong et al. [22] analyzed various barriers. In this way, from a technological point of view, the two horizontal-axis wind turbines (HAWTs) showed higher capacity factors and annual energy production (AEP) than those of the vertical-axis wind turbines (VAWTs). The wind resource analysis showed that, during summer, small-scale wind turbines (SWTs) generated most of the electricity during the day, which resembled the typical South African electricity demand profile. However, during winter, electricity was mostly generated within the early hours of the morning, which did not match the typical load demand profile. Finally, the estimation of the levelized cost of electricity (LCOE) showed that the generation of SWTs was more expensive given the current conditions of the electricity market and SWT technology. The study provided a detailed, large-scale, and comprehensive assessment of urban wind energy (UWE) resources in Cape Town, South Africa. Aquino et al. [17] investigated the effect of the variables of wind direction and speed and the locations within a simulated building with a sloping roof integrated with an aero-elastic belt. The methodology covered the study of two barriers: technology and wind resource analysis. Under ideal conditions, the estimated output power generated was 200 MW, which was a bit low, but equivalent to production costs. Therefore, this technology showed relevant potential for integration into the urban environment for small-scale wind energy harvesting.

From the specific literature, these contributions give remarkable approaches to the implementation of urban wind projects. However, alternative methodologies are required by the sector to integrate all of the existing barriers of urban wind in order to demonstrate the effectiveness of urban wind projects. In this context, the objective of this paper is to propose a methodology for the implementation of viable urban wind projects from an economic point of view and with a high environmental contribution. This proposal is focused on meeting the objectives of sustainable development: 11—Sustainable cities and communities [33] and 13—Climate action [34]. The structure of the rest of the paper is as follows: Section 2 describes the urban wind energy collection systems; Section 3 details the current technology; Section 4 presents the proposed guide; the case study is given in Section 5; Section 6 discusses the results; finally, Section 7 provides the conclusions.

2. Types of Urban Wind Energy Collection Systems

Various categories of wind turbines in the design of urban structures have been identified: those that are integrated with buildings, free standing, on the roofs of buildings, and alone near buildings. Figure 2 shows a representation of this categorization.

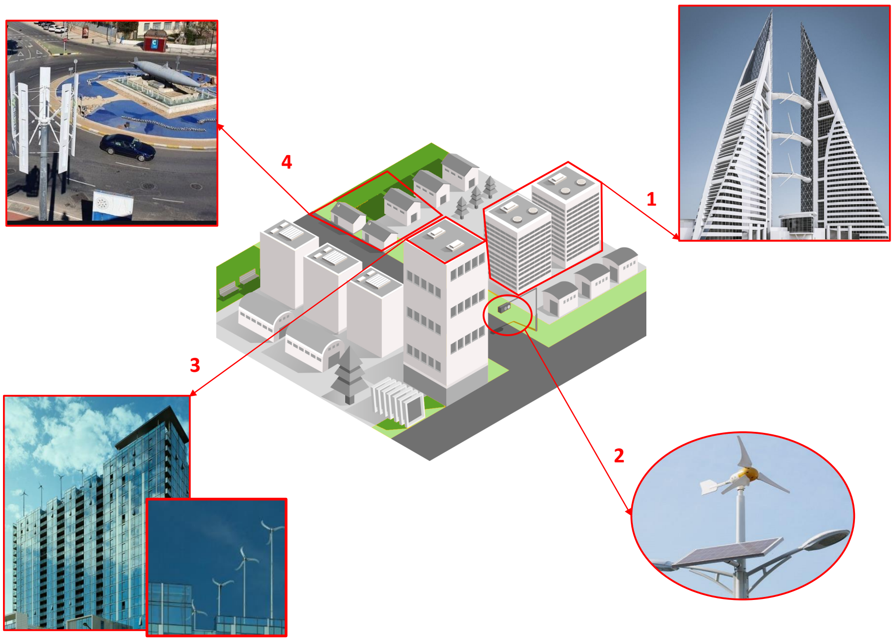


Figure 2. Types of urban wind energy collection systems. Integrated with buildings (1), free standing (2), on the roofs of buildings (3), and alone near buildings (4). Data source: [35–37]. Authors' own elaboration.

Integrated with buildings: Wind turbines integrated into the architectural design of a building are intended for skyscrapers. They can be placed in the corners of the facades of the buildings or between building blocks. The first building in which the architecture was integrated with wind turbines was the Bahrain World Trade Center (BWTC). The construction was completed in 2008; see Figure 2(1). Among its advantages, we highlight the following [38]:

- Its height reaches the layers of high wind speed without turbulence, with no need for a tower.
- The lower energy demand by covering a piece with on-site generation is a selling point.
- It is relevant for environmental awareness.
- The structure can be used to clad turbines to improve their performance, conceal them visually, and make them safer.
- The aerodynamic structure of the building can direct and concentrate the wind towards the turbine.
- The long transmission lines for energy transport, which are linked to significant losses, can be omitted.

On the roofs of buildings: In this category, the architecture of the building is not specially modified. Such constructions can be on existing or newly built buildings; see Figure 2(3). Note that not all turbines are suitable for all types of roofs. This fact is an important disadvantage in terms of safety. Depending on the roofing material, turbine vibrations can cause fatigue. However, in recent years, there has been a growing interest in the use of wind energy in buildings for distributed generation. The main advantages are [19]:

- Fewer energy losses due to decreases in transport distance.
- The energy generated is consumed directly at the installation site; the owners get a free additional source of energy.
- The typical background noise of cities covers most noise emissions from turbines.
- Shorter towers are needed.
- They are affordable for individuals and small businesses.

Free standing: Unlike the previous two categories, the turbines are not connected to the grid; they act as an autonomous system. Figure 2(2) shows a hybrid wind–solar system coupled to a streetlight. The system integrates a battery to store energy. The great advantage is that, if it is disconnected from the grid, the lighting in the area is not affected. Among the main advantages, we highlight:

- The system is independent of the grid; if it is interrupted, the lighting of the area is not affected.
- The positioning depends on the wind conditions, as it is independent of buildings.
- Potential vibrations do not affect the structure of a building.

Alone near buildings: In this type of system, the turbines are independently located near buildings. They can be connected to the grid or autonomous. Figure 2(4) shows one of the turbines installed in the surroundings of the Technical University of Cartagena (Spain). It is currently used to analyze and monitor the performance and profitability of these low-power turbines for self-consumption purposes in urban centers [37]. In general, the disadvantages of these typologies are the following:

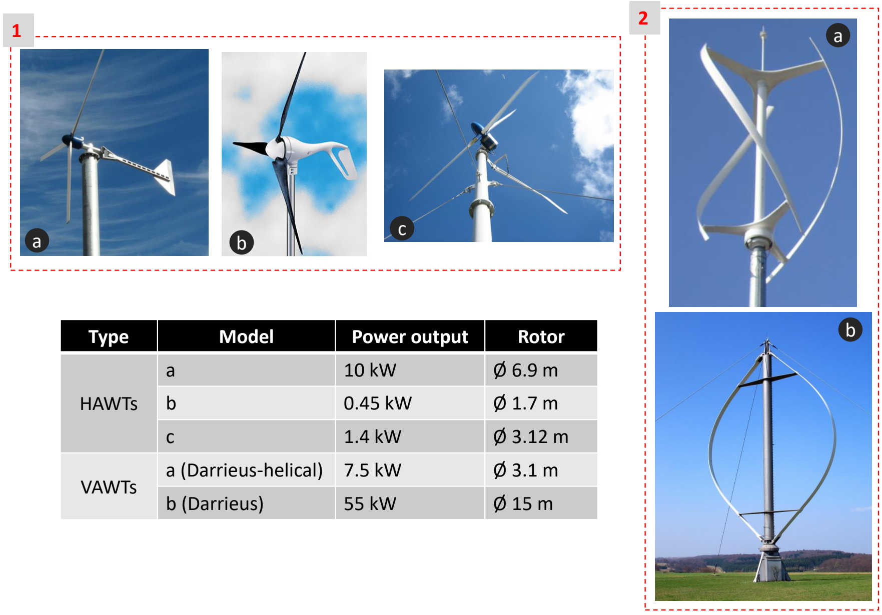
- Turbine performance depends on positioning and obstacles that can cause turbulence; therefore, future surrounding buildings have to be part of the installation project.
- Hybrid systems are recommended for systems that are not connected to the grid due to wind oscillations.
- Noise and vibrations can cause social non-acceptance.
- Wind speed in the city is lower than in rural areas, and thus, the wind turbine performance will become lower.

3. Current Technology. Horizontal- and Vertical-Axis Wind Turbines

Nowadays, there is a relevant diversity of types and designs for low-power turbines, which are mainly for urban wind applications. Generally, their technical characteristics are associated with the categories described in Section 2. The wind turbine selection—size and type—directly depends on both application and location. As with high-power wind turbines, there are several classifications according to a variety of criteria, such as the power ranges, technologies, sizes, etc. The most common classification is according to the type of axis: horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). The latter can be divided into two types: lift-based (e.g., Darrieus) and drag-based (e.g., Savonius) [4]. Figure 3 shows a classified example of turbines.

Horizontal-axis wind turbines have been standardized for high-power wind farms, either on land or at sea. However, in urban areas, they are much less effective due to the high turbulence. The higher the turbine is, the better its efficiency and the higher its power output, but the noise increases considerably. These horizontal turbines involve many components: a tower, rotor, blades, hub, control mechanisms, etc. Subsequently, challenges related to noise production, visual disturbance, and public safety were pointed out in the specific literature [20]. Nevertheless, these wind turbines can achieve very high efficiencies with a low surface roughness and a horizontal and unidirectional airflow [19].

The main characteristic of vertical-axis turbines is that they are independent of the wind direction. This is considered ideal for the turbulent and multidirectional winds of urban environments. The design is simple and requires minimal maintenance. Actually, straight blades can be used to reduce manufacturing costs. These wind turbines can be integrated into the grid or in the islanding mode [39]. Vertical-axis wind turbines produce less noise, and they have more attractive designs. The results are acceptable, despite some technical and economic drawbacks. The main disadvantages are that these wind turbines tend to stop working in gusty conditions and suffer from dynamic instabilities [4]. Table 2 summarizes the main advantages and disadvantages of both types of turbines.



Type	Model	Power output	Rotor
HAWTs	a	10 kW	Ø 6.9 m
	b	0.45 kW	Ø 1.7 m
	c	1.4 kW	Ø 3.12 m
VAWTs	a (Darrieus-helical)	7.5 kW	Ø 3.1 m
	b (Darrieus)	55 kW	Ø 15 m

Figure 3. Examples of current turbines: horizontal-axis wind turbines (HAWTs) (1) and vertical-axis wind turbines (VAWTs) (2). Data source: [40–42]. Authors' own elaboration.

Table 2. Advantages and disadvantages of urban wind turbines.

Turbine Type	Advantages	Disadvantages
HAWTs	Economic Efficient Commercial variety Proven technology in high-power wind farms	Dependent on wind direction Does not cope well with buffeting
Lift VAWTs	At a given wind speed, it is equal in efficiency to HAWT Independent of wind direction and turbulence Less vibration Shocks and little noise	More sensitive to turbulence than drag-based VAWTS
Drag VAWTs	Proven product Less acoustic emission Independent of wind direction and turbulence Less vibration Potential benefit from turbulence	Not efficient Comparatively uneconomic

4. Guide for Urban Wind Projects

The generation of electricity from wind energy in urban environments is considerably less than that in open rural areas. Consequently, the large wind turbines of wind power plants are not an alternative. Indeed, it is a complementary technology that is aligned with the objectives of sustainable cities. Given the nature of wind indicators in cities (turbulence, roughness, wind speed, directionality, and seasonality), electricity generation forecasting at the macro level can be used to address erroneous estimations with relevant economic losses. However, there are studies that focused on the macroscale of the city—or country—with satisfactory results, but they did not estimate the electrical energy produced [10,43], or they did not include an economic analysis, and thus, the feasibility of the projects is unknown [27,29,30]. To overcome this lack of contributions, the authors propose a methodological guide for urban wind projects (UWPs) with the aim of contributing to the scientific community and decision makers for matters of sustainable urban plans according to the following items:

- The methodology simultaneously integrates the different typologies of urban wind projects.

- Analysis indicators, such as wind speed, wind direction, and urban planning, are specified in each methodological stage, whether or not they are common to the different typologies.
- The results of power generation and the economic–environmental analysis are included in the proposed methodology to evaluate the implementation of such favorable alternatives.

The selection of the typology described in Section 2 is firstly carried out through the following stages: (i) location, (ii) urban and wind indicators, (iii) turbine and annual energy production, and (iv) an economic and environmental study; see Figure 4.

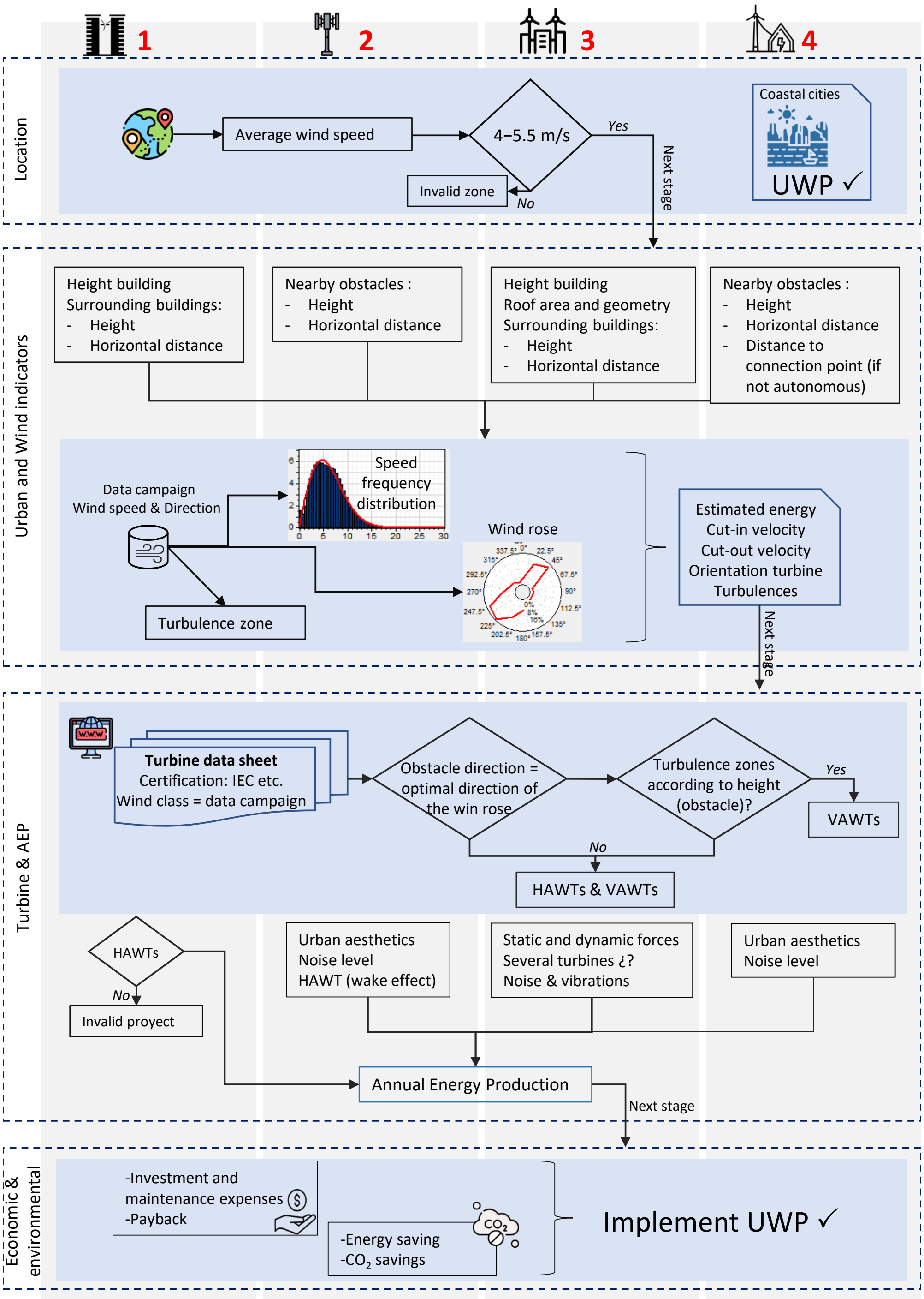


Figure 4. Proposed framework. Authors' own elaboration.

4.1. Location

Regardless of the type of project, in the location stage, we identify the study area in order to make a preliminary wind speed estimation. In general, coastal cities have greater possibilities for efficient urban wind projects [9]. Wind speed values between 4 and 5.5 m/s are recommended a priori [44]. If a location does not have at least the minimum wind speed, it is recommended to discard the urban wind project or make measurements in situ. These preliminary wind speed estimations can be obtained from the Global Wind Atlas© [45]. This database is available online with a height range from 10 to 200 m. Figure 5 shows the European wind map for a height of 50 m.

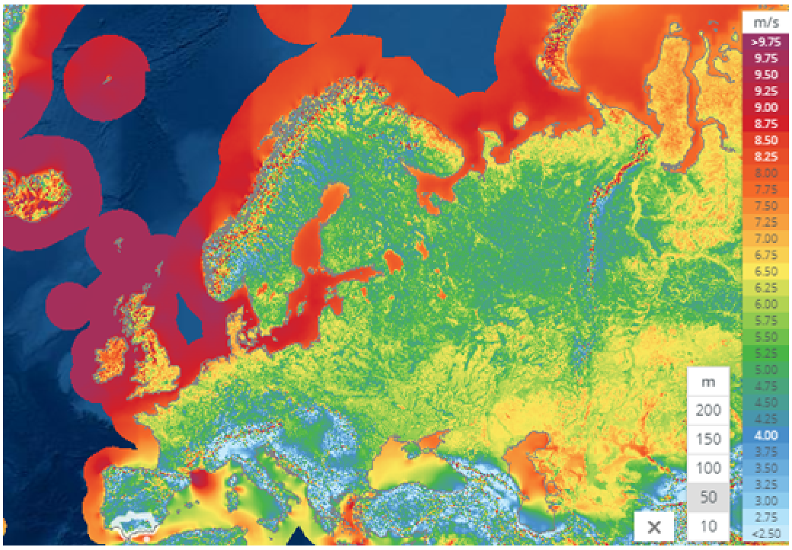


Figure 5. European wind map. Data source: [45].

4.2. Urban and Wind Indicators

In this stage, the characteristics of the site are studied from the wind and urban points of view. From the urban point of view, the heights of the buildings and the existence of obstacles are the main characteristics of the study, though, depending on the typology, one or the other intervenes.

Integrated with buildings: These projects are complex. Therefore, it is assumed that they are not built. The measures that would be necessary a priori would be the height of the building, the height of the surrounding buildings, and the horizontal distance between these buildings and the area of the site, as well as possible future building projects. Facades in the form of aerodynamic profiles or combined with a duct, tube, or passage through the building are recommended:

- Free standing: It is necessary to know the height and horizontal distance of nearby obstacles.
- On the roofs of buildings: It is assumed that the buildings are already built. The measurements that would be necessary a priori would be the height of the building, the height of the surrounding buildings, the horizontal distance between them and the area of the site, the area and geometry of the roof, and future building projects. Roofs with sloping or rounded edges are recommended to enhance the aerodynamic properties.
- Alone near buildings: It is necessary to know the height and horizontal distance of nearby obstacles. If they are wind turbines connected to the grid, the distance to the connection point should be minimized. The height of the buildings can be obtained from free-access GIS databases on websites such as Google Earth [46], Skyscraperpage [47], and WorldBuilding Map [48].

Due to wind oscillations, it is necessary to characterize wind speed at the potential site by using an extensive field data campaign of at least one year to analyze seasonality [38].

Data can be obtained from different free-access GIS database websites, such as those of the National Renewable Energy Laboratory (NREL) [49] or Vortex [50], in addition to the previously mentioned Global Wind Atlas. The main indicators to be considered are the following: frequency distribution of wind speed data, vertical wind speed profile distribution, and direction/seasonality. A wind speed frequency distribution curve represents the speed value regardless of the orientation. It provides the wind speed values to be used to obtain the estimated energy. The Weibull distribution is the most commonly used mathematical function to determine this curve [51] from the equation:

$$p_{(U)} = \frac{k}{A} \cdot (\frac{U}{A})^{k-1} \cdot e^{-(\frac{U}{A})^k}, \quad (1)$$

where $p_{(U)}$ is the probability that the wind is U, A is called the scale factor, with dimensions of speed, and k is the so-called shape factor, which is dimensionless and characterizes the asymmetry of the distribution. Wind speed varies depending on the height above the ground; the higher the height, the higher the speed. Nevertheless, this profile is affected by the orography and surrounding obstacles, which create a bubble of turbulence in which the turbines should not be located. To avoid this turbulence field, the wind turbine must be placed at twice the height of the obstacle [44]. The wind's directional characteristics are very important for the wind turbine's location, especially for horizontal axis turbines, and they are represented by a wind rose. An energy rose is a mixture of wind speed and frequency roses. It shows the average wind speed of each sector and the time during which this wind speed is collected. The orientation of the turbine must match with the greatest contribution of the energy rose.

4.3. Wind Turbine Selection and Annual Energy Production (AEP) Estimation

There are currently many low-power wind turbine manufacturers. As a general rule, in order to guarantee quality and safety under all wind conditions, regardless of the type of project, it is important to select turbines that are certified according to the International Electrotechnical Commission (IEC) [52] standards or others, such as those of IEA, AWEA [53], Renewables UK [54], or JSWTA [55]. Another important aspect is the wind class (I, II, III, IV, S); the selected turbine must have the wind class determined from the field data campaign. The choice of several study turbines is recommended in all cases. As a rule, if there are obstacles or other buildings in the same optimal direction of the wind rose, the location of an HAWT must be at twice the height of the obstacle, as long as the horizontal distance is more twenty times the height of the obstacle. If these conditions are not avoided, VAWTs should be selected. Indeed, the selection of vertical turbines should be kept in mind; if they do not have auto-starting, they require much power in turbulent environments. High specific speeds emit a lot of noise.

With regard to solutions integrated into buildings, the turbines for this type of project are usually of a high power rating; they are often of the mini-wind and, usually, HAWT type. In terms of free-standing solutions, it is necessary to consider both urban aesthetics and noise levels. If they are HAWTs, the wake effect should be avoided. For those built on the roofs buildings, it must be checked that the roof supports the static and dynamic forces produced by the turbines by conducting a study on the possibility of incorporating several turbines to increase energy efficiency and considering the necessary measurements for noise and vibrations. For turbines that are alone near buildings, the urban aesthetic and the noise levels should be taken into account. However, they should be as close as possible to a grid connection point to avoid transmission losses. The annual energy production (AEP) for each selected turbine is determined from the turbine power curve and the speed/frequency distribution according to:

$$\text{AEP} = \sum_{i=1}^{N} p_i \cdot f_i \cdot 8760, \quad (2)$$

where p_i is the turbine power output in the ith wind speed interval extracted from the "turbine power curve"; f_i is the frequency of the ith wind speed interval extracted from the "speed/frequency distribution"; N is the number of wind speed intervals; 8760 is the total number of hours per year.

4.4. Economic and Environmental Analysis

Before implementing the project, an economic and environmental analysis is carried out. For each of the turbines, we calculate:

- Investment and maintenance expenses.
- Amortization period.
- Energy saving.
- CO_2 savings.

5. Case Study

The region of Cádiz, located in the south of Spain, is selected as a study example. The residential area is a coastal zone located at 36°11′09″ N and 6°00′41″ W. The wind speed data at a height of 10 m exceed 4 m/s. The predominant direction of the wind comes from the east [45]. Once the different urban indicators for each type of urban wind system were analyzed, 19 potential alternatives were identified (see Figure 6):

- On the roofs of buildings: Ten possible alternatives, represented by polygons with a red border.
- Free standing: Five urban streets, represented by a green line and circle.
- Alone near buildings: Four alternatives, represented by blue polygons.

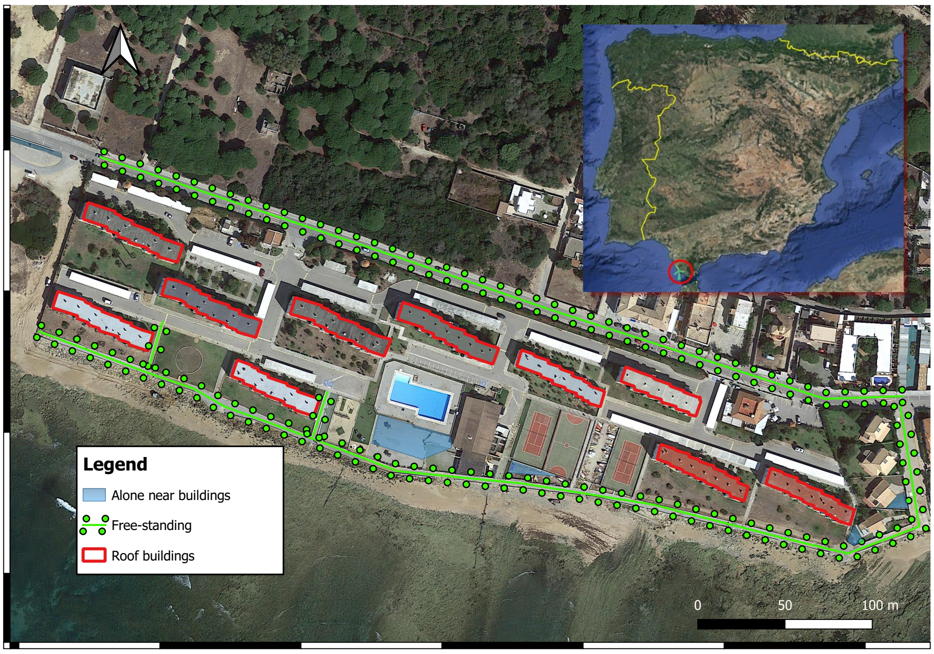


Figure 6. Overview of the study site. Authors' own elaboration.

The wind speed data measurement campaigns covered one year (data provided by the company Vortex [56])—the whole of the year 2020, with hourly measurements. The possible heights of the different typologies were analyzed (18, 9, and 5 m). The hours with the maximum wind speed oscillated between 12:00 and 18:00. For the rest of the hours, the wind speed data remained practically constant. The trend of seasonal variation of wind speeds reached its maximum values during the months of September and November and its minimum values between July and August; see Figure 7. The mean wind speeds for the heights of 5, 9, and 18 m were 5.10, 5.46, and 6.00 m/s, respectively. The most appropriate Weibull values were $k = 2.021$ and $A = 6.719$ m/s, respectively, for a height of 18 m. The orientation with the greatest power distribution was towards the east for the analyzed heights; see Figure 8. For each alternative, the specific urban indicators were considered in the prevailing wind direction; see Figure 9 and Tables 3–5.

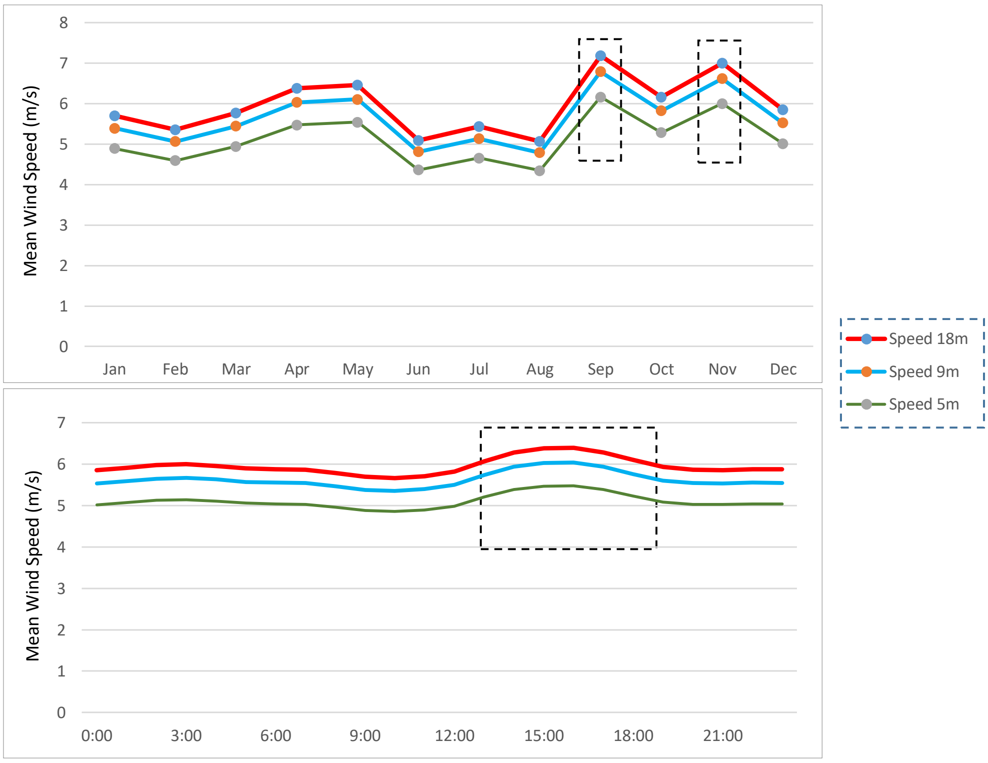


Figure 7. Seasonal and hourly analysis. Data layer: annual. Authors' own elaboration.

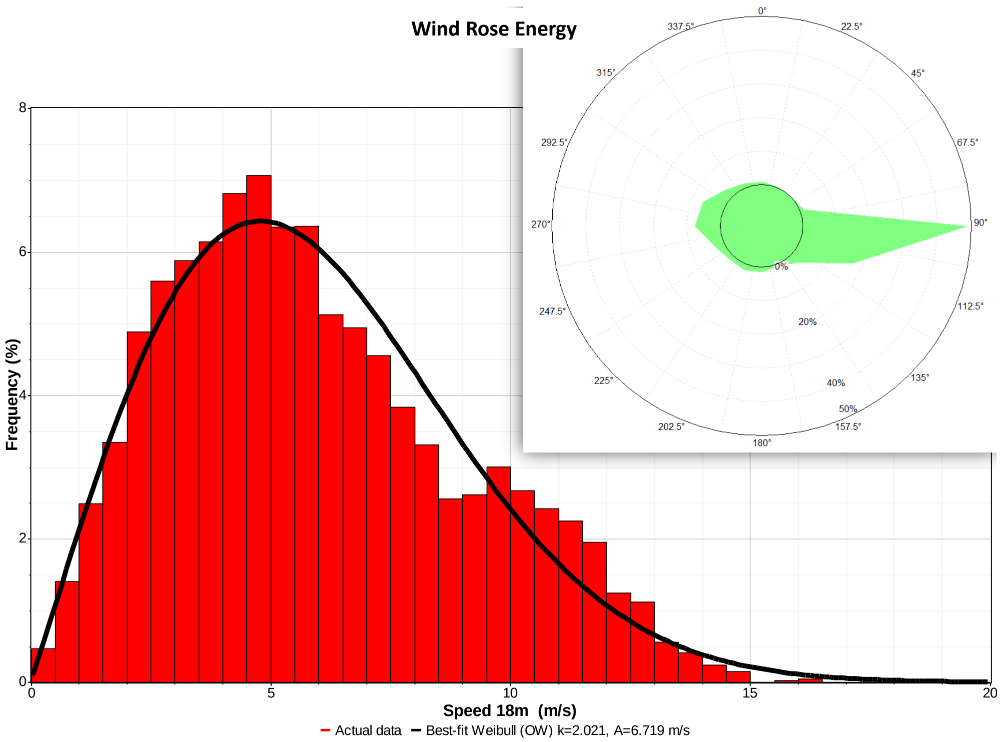


Figure 8. Frequency histogram and wind rose energy (18 m high). Data layer: annual. Green Zone: most common wind directions. Authors' own elaboration.

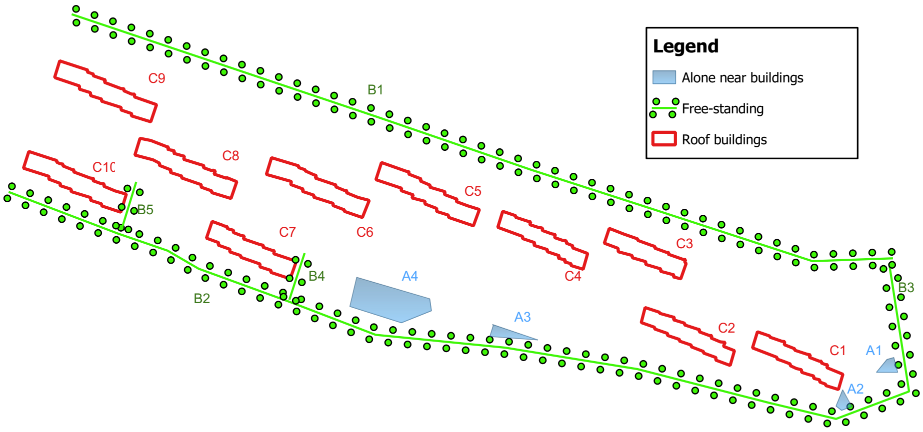


Figure 9. Alternatives identified. Authors' own elaboration.

Table 3. Alternatives of the typology of turbines alone near buildings. Urban indicators.

Alternatives	Nearby Obstacles	Height (m)	Horizontal Distance (m)	Distance to Connection (m)
A_1	Yes	3	20	<14
A_2	No			<12
A_3	Yes	15	108	<25
A_4	Yes	3	48	<52

Table 4. Alternatives of the typology of free-standing turbines. Urban indicators.

Alternatives	Nearby Obstacles	Height (m)	Horizontal Distance (m)
B_3	Yes	3–5	10–12
B_4	Yes	15	40–45
B_5	Yes	3	70–75
B_1 and B_2 are roads or paths that are close to the predominant orientation of the wind.			

Table 5. Alternatives of the typology of turbines on the roofs of buildings. Urban indicators.

Alternatives	Nearby Obstacles	Height (m)	Horizontal Distance (m)	Height Building (m)	Roof Area (m^2)
C_1	Yes	3–5	<5	15	495
C_2	Yes	15	6	15	495
C_3	Yes	3–5	14	15	495
C_4	Yes	15	<5	15	495
C_5	Yes	<3	15	15	495
C_6	Yes	15	<10	15	495
C_7	Yes	3	<60	15	495
C_8	Yes	15	<15	15	495
C_9	Yes	<3	<5	15	495
C_{10}	Yes	15	<50	15	495

HAWTs and VAWTs were analyzed for each alternative. In the typology of 'alone near buildings', alternative A_2 had no obstacles in the predominant direction of the wind. Therefore, a horizontal-axis turbine could be considered as a potential option. For the rest of the alternatives, the horizontal distances were not greater than twenty times the height of the obstacles, creating turbulence zones, and vertical-axis turbines were then selected. For the free-standing typology, the alternatives of B_3, B_4, and B_5 were discarded when encountering obstacles, as there were short-distance paths that could be illuminated with the possible turbines of alternatives B_1 and B_2. These alternatives were not found in the same direction as the prevailing wind. Subsequently, hybrid solar–wind vertical systems were then chosen. For turbines built on the roofs of buildings, the horizontal distances were not greater than twenty times the heights of the obstacles in the predominant direction of the wind. For this reason, vertical turbines were selected. However, horizontal turbines should be predominant for alternatives C_1, C_3, and C_9, but a study of potential turbulence should be included.

6. Results and Discussion

With the aim of estimating the annual energy production (AEP), wind turbines associated with the different study typologies were previously selected. The main characteristics are provided in Table 6. For the 'alone near buildings' topology, the models by both QR6 [57] and Bornay [58] for 6 kW nominal power turbines were implemented. For the wind turbines located on the roofs of buildings, the QR6 and Turby models [41] for 2.5 kW were selected. For public lighting that belonged to the free-standing topology, the DS300 off-grid model [59] was proposed. By using Equation (2), the individual AEP was calculated for the different alternatives and typologies based on the power curves of each turbine and the frequency in each group of wind speed data—see Tables 7–9 for the annual results.

Table 6. Technical details of the selected wind turbines. Data source: [41,57–59].

Feature	QR6	Bornay	Turby	DS300
Type	VAWTs	HAWTs	VAWTs	Hybrid (VAWTs+solar)
Nominal Power (kW)	6–7	6	2.5	0.3
Start Wind Speed (m/s)	1.5	3.5	3.5	3
Stop Wind Speed (m/s)	20	14	14	15.5
Number of blades	2	3	3	3
Life expectancy	30 years +	20 years +	20 years +	20 years +
Standards	MCS, ISO 9001	ISO 9001	IEC61400-2, NEN 1014	IEC61400-2

Table 7. AEP of a single turbine for individual wind speed bins ('alone near buildings' typology).

		AEP (kWh)	
Wind Speed Bins (m/s)	**Frequency (%)**	**QR6-A_1, A_3, A_4**	**Bornay-A_2**
0–1.5	4.812		
1.5–2	4.415	193.38	0
2–3	10.913	1338.37	0
3–4	13.48	3071.12	1181.20
4–5	13.61	4292.05	1788.35
5–6	13.927	5246.02	2440.01
6–7	9.635	4051.32	2447.68
7–8	7.835	3637.63	2608.12
8–9	5.174	2674.13	1994.27
9–10	6.103	3207.74	2673.11
10–11	4.643	2562.38	2236.99
11–12	3.521	2004.86	1850.64
12–13	1.257	737.76	660.68
13–14	0.532	321.57	279.62
14–16	0.136	83.39	71.48
	100	33,421.71	20,232.15

Table 8. AEP of a single turbine for individual wind speed bins (typology of a turbine on the roof of a building).

		AEP (kWh) C_1–C_{10}	
Wind Speed Bins (m/s)	**Frequency (%)**	**QR6**	**Turby**
0–1.5	4.37	0	0
1.5–2	3.35	146.77	0
1.5–3	10.48	1285.76	0
3–4	12.04	2741.32	52.72
4–5	13.88	4377.51	243.19
5–6	12.72	4789.49	278.46
6–7	10.08	4237.18	353.09
7–8	8.40	3900.42	441.56
8–9	5.88	3036.95	386.05
9–10	5.63	2957.55	492.93
10–11	5.09	2811.83	557.90
11–12	4.21	2398.31	553.46
12–13	2.37	1388.65	414.52
13–14	0.98	595.37	215.72
14–15	0.41	250.18	0
15–16	0.05	27.60	0
16–17	0.07	41.70	0
	100	34,986.59	3989.60

Table 9. AEP of a single wind turbine for individual wind speed bins (free-standing typology).

Wind Speed Bins (m/s)	Frequency (%)	AEP (kWh) B_1, B_2
0–3	24	0
3–4	15.25	20.04
4–5	15.34	33.60
5–6	12.28	42.84
6–7	9.44	41.36
7–8	6.59	43.30
8–9	6.54	57.33
9–10	5.26	69.18
10–11	3.52	61.69
11–12	1.2	26.28
12–13	0.42	12.85
13–14	0.08	2.25
14–15	0.04	1.97
	100	412.68

The ‘alone near buildings’ typology was evaluated at a height of 9 m for all alternatives. The energy production estimated for alternatives A_1, A_3, and A_4 accounted for 33,421 kWh per year when using the QR6 wind turbine, which represented a capacity factor of 54.5%. With regard to the Bornay turbine, 20,232 kWh was estimated. The initial investment associated with an individual wind turbine, including all of the necessary additional equipment, turbine installation, wiring, and technical personnel expenses amounts to almost EUR 70,000 and 15,290 for the QR6 and Bornay wind turbines, respectively. It could be concluded the QR6 wind turbine lacked feasibility, with a payback period of 69 years. However, the surplus energy amounted to 29,772 kWh/year, corresponding to the yearly demand of around nine standard residential houses in this area, assuming a consumption of 3650 kWh/year for an individual standard residential house; thus, a payback period of

6 years was determined. For the Bornay model, this period went from 13 to 2 years with five dwellings; see Figure 10.

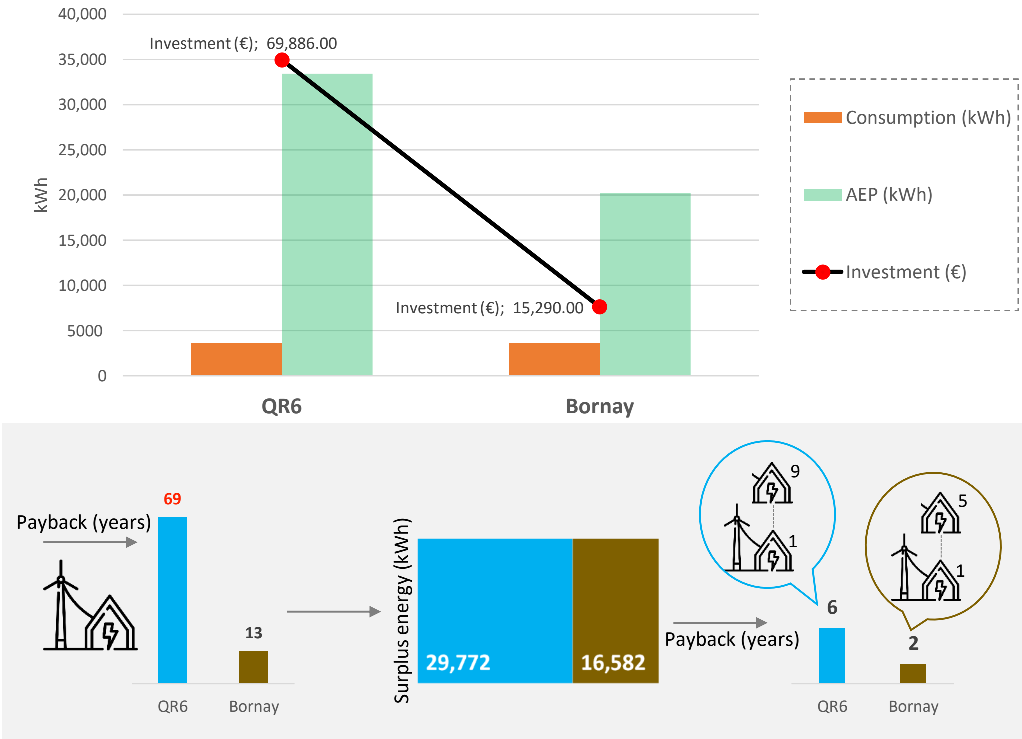


Figure 10. AEP (kWh/year), investment, payback, and surplus energy ('alone near buildings' typology for different number of houses —1 to 5, and 1 to 9). Authors' own elaboration.

The typology of turbines on the roofs of buildings was evaluated at a height of 18 m for all of the alternatives. The energy production estimation for each alternative (from C_1 to C_{10}) amounted to 34,987 kWh/year when using the QR6 wind turbine, with a capacity factor of 57%. With the Turby wind turbine model, production of 3990 kWh/year was determined. The initial investment associated with an individual turbine, including all of the necessary equipment, turbine installation, wiring, and technical personnel expenses, amounted to almost EUR 70,000 and 23,300 for the QR6 and Turby turbines, respectively. Considering a consumption per building of 547.5 kWh/year spread over 15 residential houses, the payback periods were 5 and 3 years for the QR6 and Turby wind turbines, respectively. However, in terms of the energy generated by the wind turbines, there was a surplus of more than 26,000 kWh in the case of the QR6 turbine. Therefore, the possibility of selling the energy surplus to the grid—or grouping several neighboring buildings into an energy community—should be considered according to the current international clean energy packages—for example, the initiatives promoted by the European Union. Regarding the Turby wind turbine, there is a lack of energy that leads to demand from the grid or an increase in the number of wind turbines, which, in turn, will increase the recovery period; see Figure 11. Note that these energy estimations exclude potential energy losses caused by the adjustment of the power curves, the unplanned stops of the turbines, or other additional losses, such as losses in transmission/distribution power systems, which can decrease the performance and efficiency of these solutions. Nevertheless, the QR6 wind turbine's performance can be assumed to be high. Indeed, the technical characteristics of this wind turbine have improved considerably with respect to the previous QR5 wind turbine model. The wind speed values are commissioned below 3 m/s and above 14 m/s, so the wind resources in these intervals are made use of with high frequencies in the urban environment. The blades have a 60% larger sweep area, are stiffer, and have a more precise trailing edge, reducing drag accordingly. The turbine's rotating mass is now made almost entirely of composite materials, significantly improving the power-to-weight ratio [57,60].

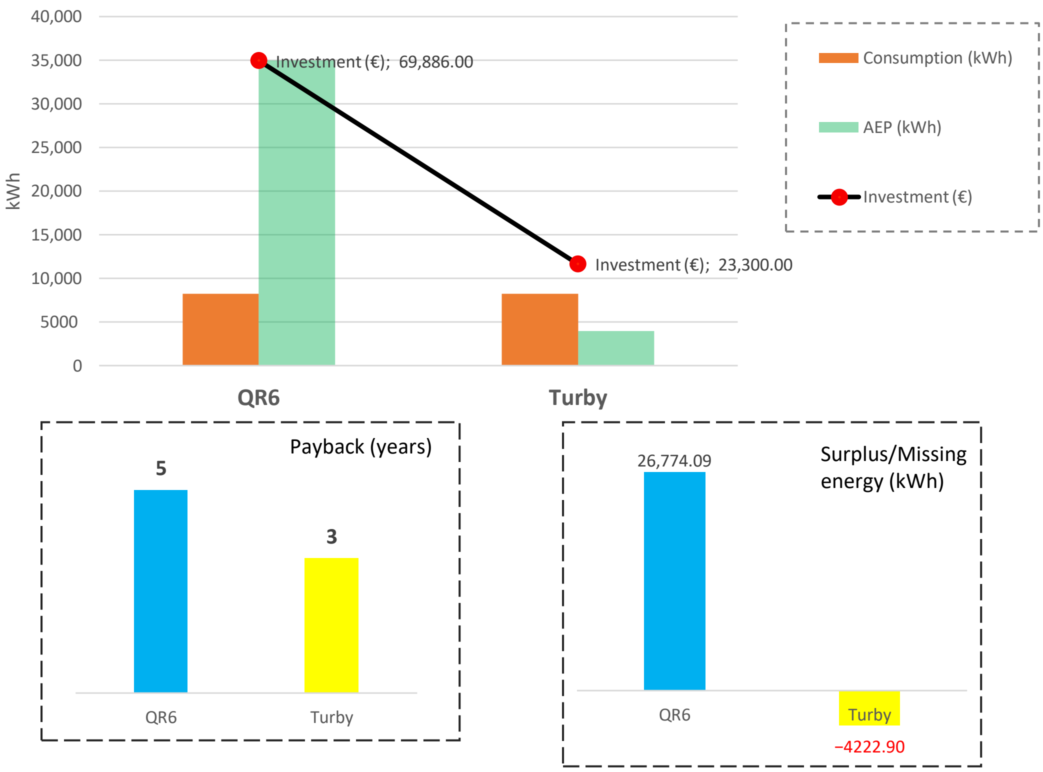


Figure 11. AEP (kWh), investment, payback and surplus/missing energy. Typology: on the roofs of buildings. Authors' own elaboration.

With regard to urban lighting, hybrid wind–solar systems are the most recommended systems for this purpose; they are autonomous and require minimal maintenance, energy with solar and wind resources is guaranteed, etc. [61–64]. The wind part of the system is capable of producing 412 kWh/year. From the economic point of view, the investment is not profitable in a short-term period. However, considering their energy savings, low maintenance, installation costs, and the reduction of the environmental impact, it can be affirmed that this solution has become essential for massive integration in current cities. Finally, the emissions avoided for the most favorable cases of the different typologies amount to 47 metric tons of CO_2 based on the factor of 6.4818×10^{-4} metric tons of CO_2/kWh [65].

In terms of the discussion of the case study, the methodology of evaluation shows that UWPs have potential to contribute significantly to power generation in urban environments. Note that it is necessary to study different alternatives according to the typology, available wind resources, and other additional constraints. The use of geographic information systems (GISs) plays a fundamental role in locating the different alternatives; likewise, the number of factors involved in their generation gives rise to the use of multi-criteria decision making (MCDM) in order to establish an optimal ranking of thereof. Governments must lay the foundations by creating pilot projects. They are crucial for demonstrating technological advances, as well as economic and environmental benefits, that can mitigate the barriers to urban wind integration.

7. Conclusions

This paper describes a methodology for determining the annual energy production of potential urban wind projects. The proposal is divided into four stages: location, wind and urban indicators, turbine selection and annual production estimation, and economic/environmental analysis. From the specific literature, various categories of wind turbines in the design of urban structures were identified and reviewed: those integrated with buildings, free-standing turbines, turbines on the roofs of buildings, and turbines that are alone near buildings. In addition, horizontal- and vertical-axis wind turbines were discussed and evaluated for urban wind applications. To characterize wind energy resources, free-access GIS databases were evaluated and, subsequently, annual energy production was determined for each solution. A Spanish case study is included in the paper, which was based on averaged wind speed data acquired over 8760 h (in 2020; 1 h sample time) provided by Vortex. A set of 19 different alternatives were identified and evaluated by considering previous urban indicators: turbines integrated with buildings, free-standing turbines, turbines on the roofs of buildings, and turbines that are alone near buildings. Horizontal- and vertical-axis wind turbines were also included in this study and, subsequently, analyzed for each alternative. From the results, relevant energy surpluses were determined, with capacity factors between 55% and 60%. Therefore, the possibility of selling energy surpluses to the grid or grouping several neighboring buildings into an energy community—in a similar way to PV installations and under current international policies—should be considered in future work and is currently a topic of interest for the authors.

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Abbreviations

The following abbreviations are used in this manuscript:

AEP	Annual energy production
BWTC	Bahrain World Trade Center
CFD	Computational fluid dynamics
HAWT	Horizontal-axis wind turbine
LCOE	Levelized cost of electricity
NREL	National Renewable Energy Laboratory
SWT	Small-scale wind turbines
UWE	Urban wind energy
VAWT	Vertical-axis wind turbine

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