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Blades design for a small wind turbine to supply a rural house. Case study

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Abstract
Nowadays the global warming has caused a growing increase of sensitivity of the population to reduce the consumption of non-renewable resources. Therefore, the use of renewable energies is currently increasing and the development of studies to install small renewable generators to supply domestic uses also does. In this line, the present research develops a methodology to design the blades of a small wind turbine with horizontal axis, applying it to a real case study. To improve the design of the wind turbine, a meteorological station was installed in the study point as well as historic registered data were used. Finally, the estimated energy produced by this generator was 1453 kWh/year and the energy could be used to supply in the rural house to complement the electrical consumption, reducing the consumption of the other non-renewable resources.
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Keywords: Renewable energy; Self-consumption; Isolated to grid; Meteorological station.

1. Introduction

The global warming is actually related with high emissions that are mainly caused by anthropic origin. Greenhouse gasses are the main source of this warming and their consequences are the variations in the biota and behavior of the species as well as variations in the climatic phenomena in specific areas [1]. These new problems cause the increase sensitivity of the people and the governments that increased the consumption of the renewable energy in last years. Spain is an example, in which the increase of renewable energy was from 17.4% to 33.7% between 2004 and 2010 [2], being currently 36.9% [3]. This increase of sensitivity as well as the development of the renewable technologies have made possible the use of renewable energy in domestic uses to reduce the non-renewable consumption or accessing to grid when the buildings are in remote areas.
The most used technologies that can be installed in domestic uses are solar and wind generator and there are different typologies and models that currently exist in the market and they are adapted to low power. However, the development of energy studies to increase the self-consumption in remote areas or to be independent to energy companies increased in last year [4], and therefore, the proposal of methodologies to improve and simplifying the carrying out of these studies makes sense. When renewable sources are considered, the wind energy is a good resource to obtain green energy, and this is justified when the high number of typologies is considered that can be classified according to position of the axis as well as their

geometry [5]. The first type of turbines is called vertical axis wind turbine (VAWT). These turbines are currently used a few occasions because they have a low efficiency and their rotational speed is lower taking advantageous of the all wind directions. Some examples are Savonius or Derrius turbine. The second type is the horizontal axis wind turbine (HAWT), in which the blade is orthogonal to flow direction. These generators are very used because they have high efficiencies and they demonstrated their better behaviour when there are variations of the wind speed. This type of generator can be classified according to the specific speed (TSR) that determines the number of blades; the position of the generator (*i.e.,* windward or leeward); and the power regulator that can be with variable or fixed rotors.
In this line, this research develops a methodology that can be used to study and design the best blade to be used in a small wind turbine. The generator is classified as HAWT and the generator is located in leeward. The design was established considering the climatic variables and using the specific software that helps to develop the calculus and the simulations. The meteorological conditions were obtained through real data values registered in a meteorological station that was specifically installed in the study point.

2. Materials and methods

The development of the proposed methodology is shown in Figure 1. This figure shows the flowchart that was defined to design the blade of the wind generator.

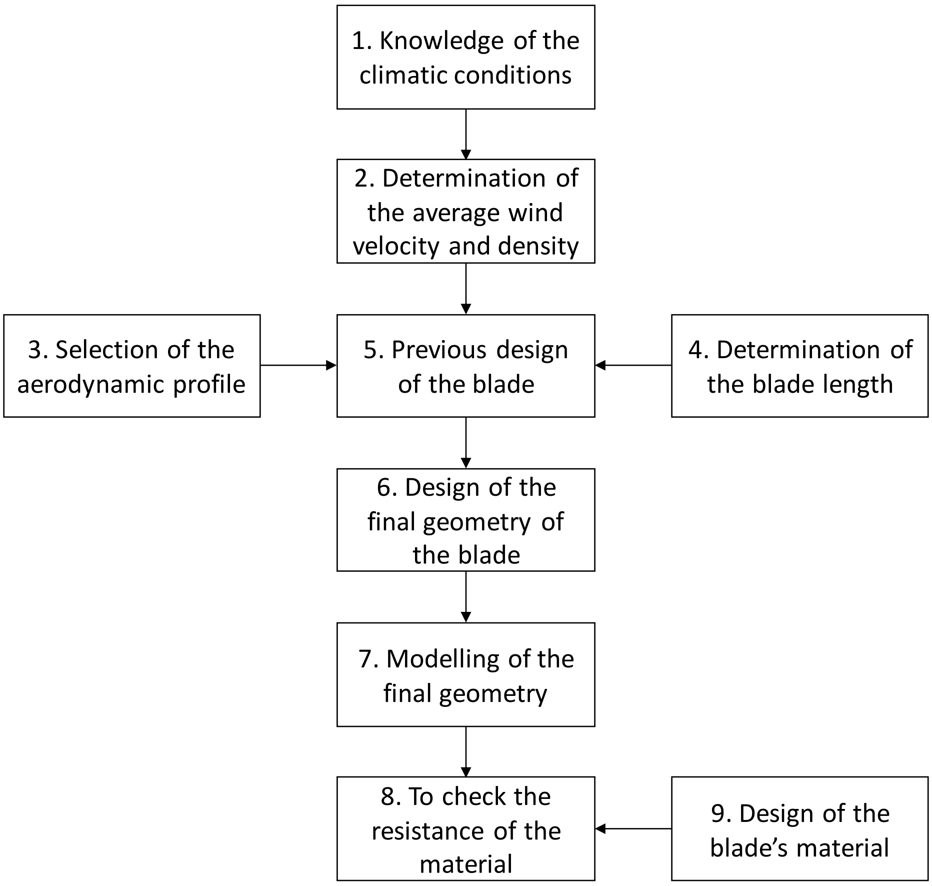

Figure 1. Methodology to design the blade of small generator.

1. Knowledge of the climatic conditions. To do so, a weather station was installed to know the velocity, direction and persistence of the wind in the case study. At the same time, the registered data that are available by Spanish meteorological agency (AEMET) were analyzed.
2. Getting of the average velocity and density of the wind. Once the data are known, the average velocity (V_{ave}) and density (ρ_{ave}) are determined by equations (1) and (2):

$$V_{ave} = C\,\boldsymbol{\Gamma}(\mathbf{1} + \tfrac{\mathbf{1}}{\boldsymbol{k}}) \tag{1}$$

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$$\rho_{ave} = \frac{P}{RT} \tag{2}$$

where C and $\boldsymbol{k}$ are the parameter of the Weibull function; $\boldsymbol{\Gamma}$ is the function gamma; P is the pressure in Pa; R is the constant of the air and it is 287 $Jkg^{-1}K^{-1}$; T is the temperature in K.

3. Selection of the aerodynamic profile. The search of the profiles is focused on NACA family (Figure 2).

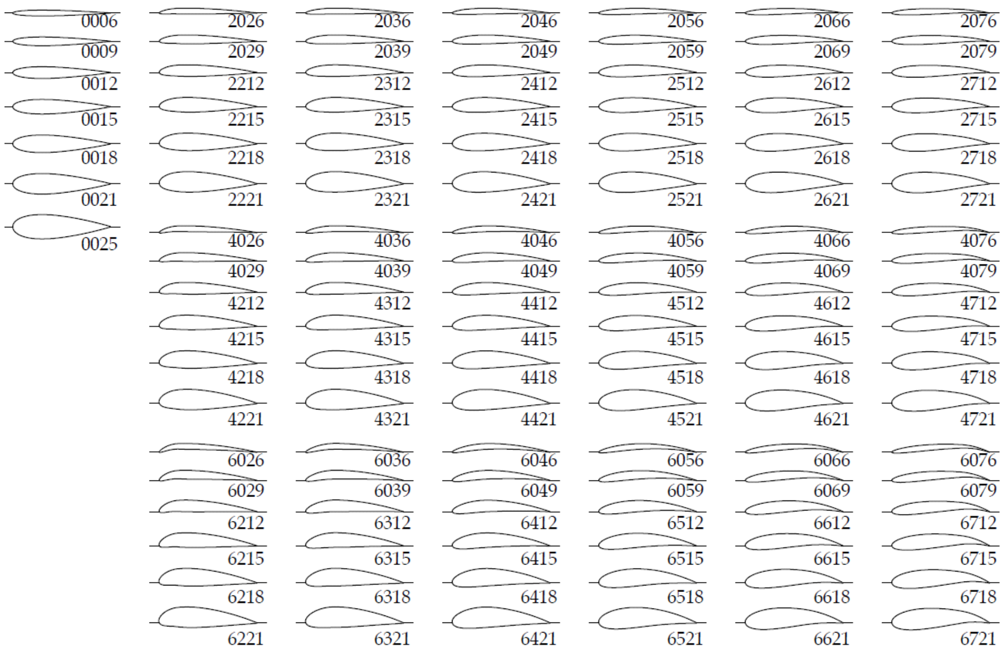

Figure 2. Example of profile included on NACA family.

4. Selection of the blade length. To consider the wind generator such as small generator, its sweeping area should be lower than 20 m2.

5. Previous design of the blade. To obtain the initial geometry, the theory of the blade element momentum (BEM) [6] is used to know the aerodynamic behavior of the blade, maximizing the aerodynamic performance. The theory divides on n elements the blade, choosing the aerodynamic profile and the tip speed ratio (λ_r) that maximizes the power coefficient. Different parameters (sustenance coefficient (Ci), aerodynamic resistance coefficient (Cd), number of blades, and wind density) have to be defined and they are applied considering the described procedural by Jaikrishna and Raghunandan, (2014) [7]. The procedural is based on determination of the following variable through equations from (3) to (9):

- Tip speed ratio;

$$\lambda_r = (4\,a - 1)\sqrt{\frac{1-a}{1-3\,a}} \tag{3}$$

where a is the axial induction factor.

- Axial induction factor (a). This ratio represents the reduction between the air velocity far away from the wind generator (Figure 3) and is defined by equation (4):

$$a = \frac{V_1 - V_2}{V_1} \tag{4}$$

where V_1 is the wind velocity far away upstream from the rotor, V_2 is the wind velocity at the rotor.

- Tangential induction factor (a');

$$a' = \frac{1-3\,a}{4\,a-1} \tag{5}$$

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- Flow angle (φ):

$$\varphi = tan^{-1}\frac{(1-a)\,V}{(1+a')\omega\,r} \tag{6}$$

where ω is the angular speed of the rotor in rad/s, r is the length of the blade in meters.
- Non-dimensional factor (B_{EP}): this coefficient is defined by the following equation:

$$B_{ep} = \frac{a}{(1+a\prime)}\,4\,sin\,\varphi \tag{7}$$

According to Figure 3, the angle defined by rotational direction and the cord is called 'twist angle' (θ) as well as the attack angle (α) that is defined between the cord and wind direction.

$$\theta = \varphi - \alpha \tag{8}$$

where ω is the angular speed of the rotor in rad/s, r is the length of the blade in meters.
Defined the ideal parameters, the optimum attack angle is defined for the maximum ratio between force coefficient (C_l) and dragging coefficient (C_d) for the chosen profile. The getting of the cord distribution (c) along the blade by the equation (9):

$$c = B_{EP}\frac{2\,\pi\,V}{z\,C_L\,\omega} \tag{9}$$

6. Design of blades geometry. The definitive shape of the blade is defined by using the open source Qblade® software [8]. This software is able to obtain the output power of the wind turbine as a function of the wind speed and the rotational speed of the generator.
7. Modelling of the final geometry. The final geometry is defined by using the open source Siemens NX® [9]. The geometry is introduced and the wind is simulated, considering a maximum wind speed of 200 km/h, obtaining the forces that are caused on the blade by the wind.
8. Design of the composed material and checking of the resistance. When the forces are known, the design of the blade's material is possible as well as the checking of its resistance. Once, the material is designed, their properties are checked by using Siemens NX®

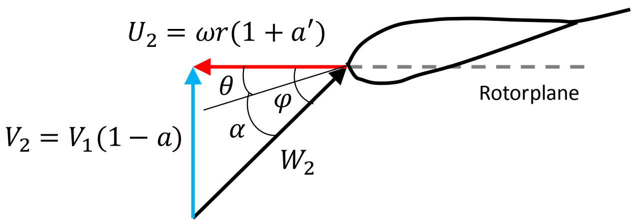

Figure 3. Scheme of velocities.

3. Results

3.1 Case study

The wind generator is designed to complement with renewable energy the consumption in a rural house that is located near Ayelo de Malferit (Valencia, Spain) (Figure 4a). According to described methodology a meteorological station (Figure 4b) was installed in the study area.
Table 1 shows the average registered values of pressure and temperature that were obtained in the experimental station. The wind was analyzed by using Mathematica ® [10], and the Weibull distribution was used to determine the average speed. The average obtained wind speed was 2.65 m/s and the Weibull parameters (k and c) were 1.34 and 2.88, respectively. Besides, the compass rose was determined by using Mathematica and registered data (Figure 4c)

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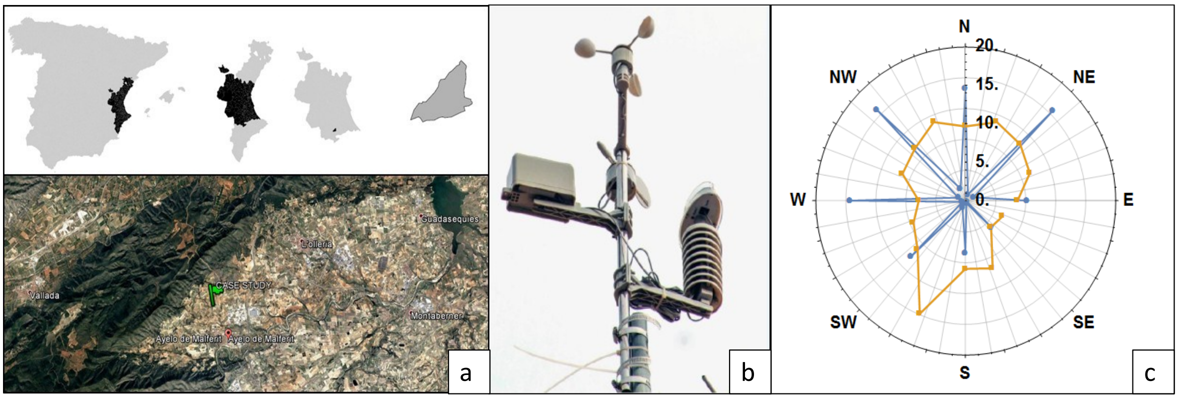

Figure 4. Case study (a), meteorological station (b), compass rose (c).

Table 1. Average registered data in the meteorological station.

Month	Temperature (ºC)	Relative Pressure (hPa)	Absolute Pressure (hPa)	Air Density (kg/m3)	Wind speed (km/h)
feb-16	12,11	1003,87	973,77	1,23	9,56
mar-16	13,23	1003,34	973,24	1,22	14,28
abr-16	15,14	1003,28	973,18	1,21	10,05
may-16	16,19	1002,17	972,07	1,21	8,13
jun-16	23,65	1007,27	977,17	1,18	8,79
jul-16	25,57	1008,31	978,21	1,18	8,88
aug-16	26,00	1009,18	979,09	1,18	8,91
sep-16	23,56	1007,27	972,07	1,18	8,37
oct-16	19,67	1008,31	977,17	1,20	8,04
nov-16	14,18	1009,18	978,21	1,22	6,55
dic-16	11,55	1007,27	979,09	1,23	8,06
jan-17	10,08	1008,31	972,07	1,24	6,59
feb-17	12,09	1009,18	977,17	1,23	9,35
Mar17	13,36	1002,40	972,31	1,22	9,68

The wind profile, *V(z)*, determines the average wind speed as a function of head over terrain. This profile can be defined by equation (10):

$$V_{hub} = V_{ave}\left(\frac{z_{hub}}{z_{med}}\right)^{\alpha} \tag{10}$$

where α is 0.2, z_{hub} is the head of the wind generator in meters, z_{med} is the head of the observation station in meter and it is 7 meters, and V_{ave} is the average wind speed that was registered by the meteorlogical station that was 2.65 m/s.

Therefore, using the last defined values and the equation (10) the wind speed (V_{hub}) was 3.09 m/s, this value was used as new average wind speed. The estimation of this speed enabled to estimate the outside theoretical power (*P*) by equations (11):

$$\mathrm{P} = \mathrm{Cp} \times \frac{\rho}{2} \times \mathrm{A} \times V_{hub}^{3} \tag{11}$$

where C_p is the power coeffient defined by Betz [11], being equal to 0.59; A is the area of the wind generator in m^2.

If the unit outside power (P_u) will be 10.49 W/m^2, considering the density equal to 1.21 kg/m^3 and the average speed 3.09 m/s.

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Once the wind speed and the density are fixed, the length was determined in 2 meters, maximum length to be considered a small generator. The aerodynamic profile NACA 4415 was chosen because this serial has a high-power coefficient, and the thickness '15' is in the majority of the small wind turbines-. Defined length and profile, the previous ideal blade was designed using Mathematica and determining the polar values of the profile (Figure 5). To obtain the polar values, the ideal geometry is necessary and therefore, the values of cords and twist angle (Table 2) were determined according to described methodology.

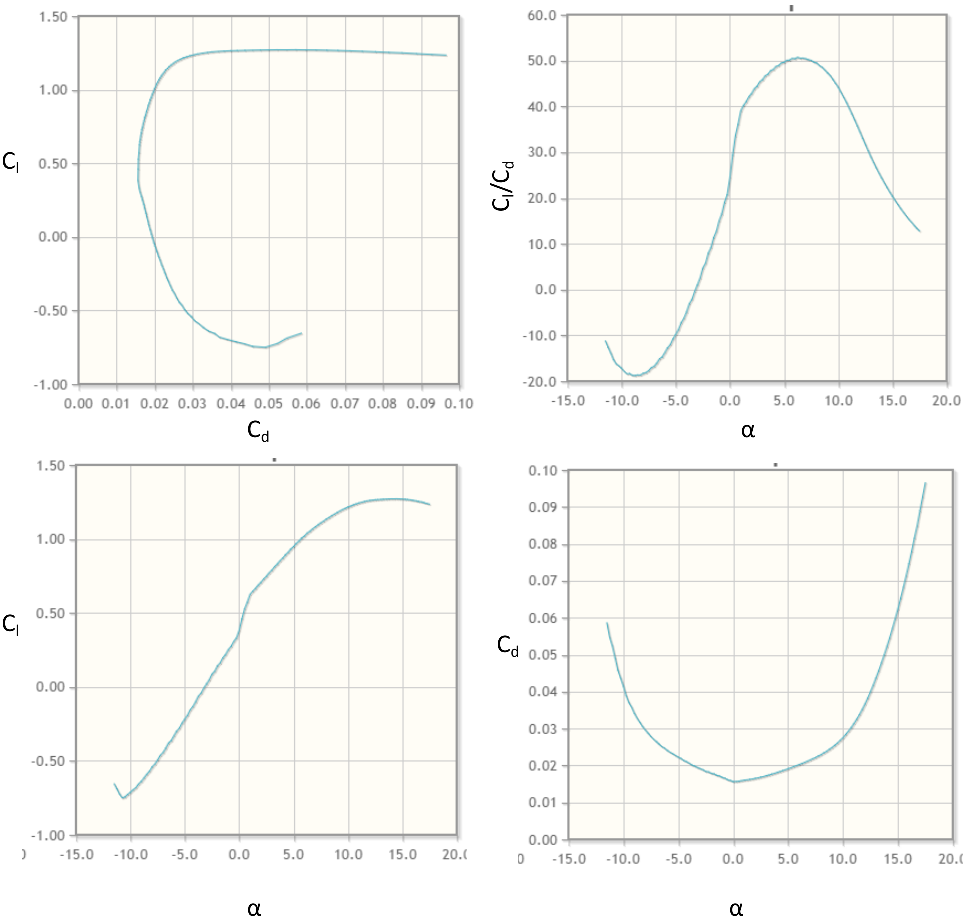

Figure 5. Polar values determined by using of Mathematica.

Table 2. Cord and twist angle of the ideal profile.

r (m)	Cord (m)	Twist angle (º)
0.2909	0.3062	23.3992
0.4727	0.2092	14.3871
0.6545	0.1980	9.3692
0.8364	0.1618	6.2974
1.0182	0.1359	4.1692
1.2000	0.1171	2.6717
1.3818	0.1027	1.5332
1.5636	0.0913	0.6495
1.7455	0.0822	-0.0531
1.9273	0.0747	-0.6295

Once the ideal geometry (Point 5. Figure 1) was developed, the final geometry was obtained using the *Qblade* software. Different profiles (Figure 6) were checked to obtain a blade operating correctly under low wind speeds, considering a minimum rotational speed equal to 200 rpm.

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At the same time, the software determined the different values of the power coefficient (C_p) and force coefficient (C_t) for different tip speed ratio (*TSR*) which are shown in Figure 7. The maximum power coefficient of the wind turbine is obtained when TSR is 7 for the optimized according to Betz and Schmitz. The rest of cases, the maximum was obtained for TSR values between 3 and 5. Finally the generated power can be estimated by *Qblade* according to Figure 8 and considering a rotational speed equal to 200 rpm.

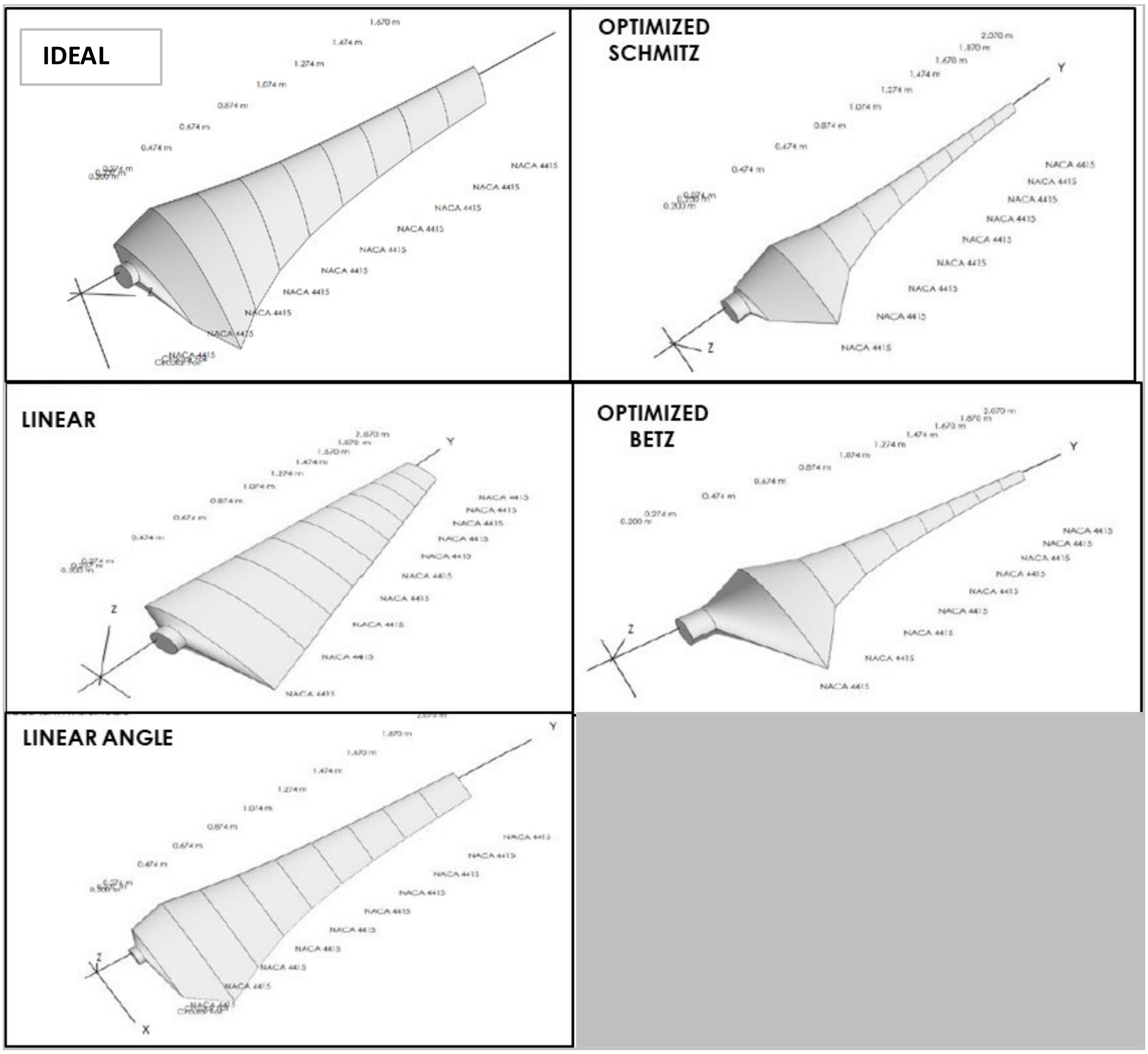

Figure 6. Different profile designed by using *Qblade*.

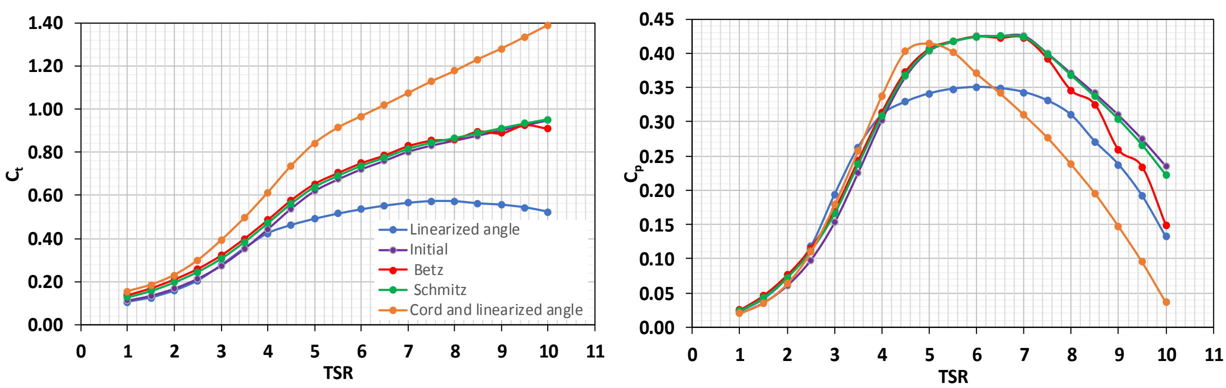

Figura 7. C_p y C_t for different *TSR*.

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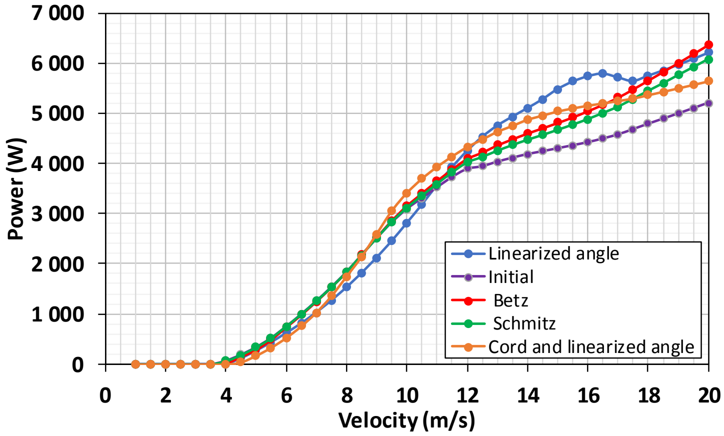
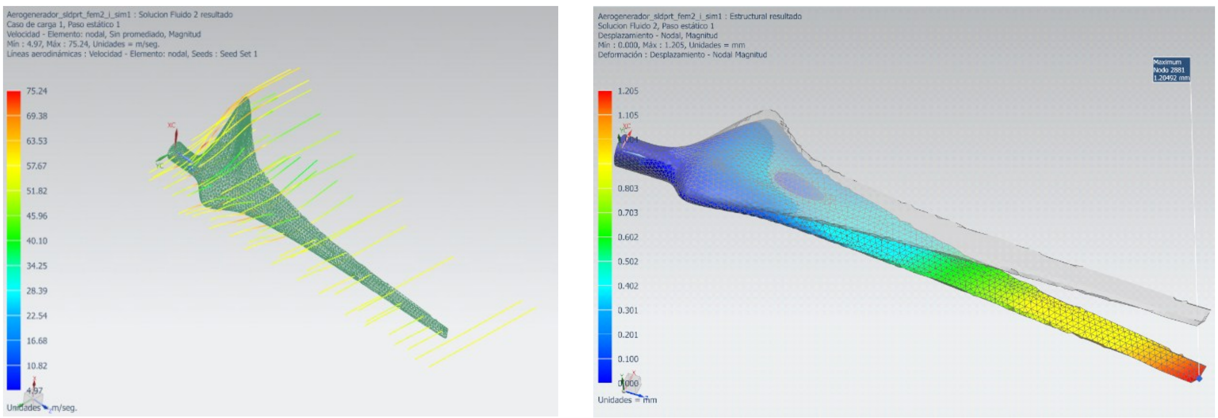


Figure 8. Generated power as a function of the velocity and simulated profile.

Once the aerodynamic profile was defined, the material of the blade had to be defined according to forces and deformations which are caused by maximum wind velocities (Figure 9a). To do so, the chosen material of the blade was fiberglass with epoxy resin. The blade was made by different layers of this fiberglass, and therefore, the mechanical properties should be determined, asits properties changes when the material is composed by different layers because fiberglass with resin is anisotropic.
The kind of selected fiberglass was “E”, this type of material is the most used in the manufacture of composites. The mechanical properties are the following: the density is 2.58 gr/cm3, the Young modulus is 72500 MPa, the breaking shear is 3400 MPa and the Poisson coefficient was 0.2. The material was made with 30% of fiber volume and the thickness of each layer had 0.5 mm and finally, six layers were defined to manufacture the blade. When the material was defined, the blade was simulated in Siemens NX®. The maximum obtained deformation (Figure 9b) was 1.20 mm when the simulated wind speed was 200 km/h. The maximum Von-Misses shear was 1.76 MPa, checking the breaking assumption.



(a) (b)

Figure 9. Analysis of stresses in the blade (a) and efforts determined (b).

Finally, once the blade was designed, the maximum developed power was obtained with the optimized Beltz profile, reaching a value of 1453 kWh/year according to speed range and the probability of the wind when the methodologic data were used. For each interval of speed, the power is shown in Table 3.
Although the power is low, the estimated power that is generated by the generator could supply the consumed power in the rural house in outside lights and low consumption such as alarms or telecontrol.

Table 3. Probability for each speed range.

Speed range (m/s)	Probability	Average Power (W)
1-2	0.243	0
2-3	0.193	0
3-4	0.136	8.312
4-5	0.088	151.00
5-6	0.053	508.02
6-7	0.032	988.17
7-10	0.033	2199.07
10-15	0.005	3982.30

4. Conclusions

The present research shows the methodology to design the blades of a small wind generator that could be used in a rural house to complement the electrical consumption with other renewable energy, such as solar. The design has been developed to be installed in the municipality of Aielo de Malferit (Valencia, Spain).

To do the design, a meteorological station was installed in the design location. These recorded data, joined to historical data consulted in two meteorological stations that are managed by Spanish Agency of Meteorology, were used to define the probabilities of different speed ranges. Currently, the climatic variable (i.e., temperature, humidity, wind speed) can be consulted in next public link. https://www.wunderground.com/cgi-bin/findweather/getForecast?query=pws:ICOMUNID358.

The methodology was implemented in Mathematica® and other public software such as Qblade®. These codes were used to design and define the blade. The programming in Mathematica was developed according to equations that defined the operation of the wind turbines. The blade was optimized to be used in low wind speeds. The optimization was developed for five different models that were based on ideal blade according to the profiles more used. Finally, the selected model was the optimized Beltz for a rotational speed of 200 rpm. The designed wind generator could generate 1453 kWh/year to be supplied in the rural house to complement the electrical consumption, reducing the consumption of the other non-renewable resources.

The development of this methodology can contribute to increase the number of energy studies related to the use of renewable energies in domestic consumption. Likewise, the methodology uses public data and resources that are available in the network (meteorological data, software) or they are the public domain. This high availability can intensify the increase of these studies, and therefore, the increase sensitivity in the use of the renewable energies.

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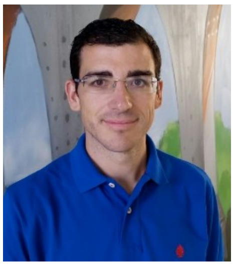

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