OPEN ACCESS

TECHNICAL NOTE

Revista Ciencias Técnicas Agropecuarias 34
January-December 2025
ISSN 1010-2760, eISSN 2071-0054
Cu-ID: https://cu-id.com/2177/v34e23

Aerodynamic Analysis of Darrieus Vertical-Axis Wind Turbines

Análisis aerodinámico de aerogeneradores de eje vertical Darrieus

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ABSTRACT: Vertical-axis wind turbines (VAWTs) have characteristics that make them ideal for rural and urban applications, especially at low heights and under low wind speed conditions. This led to the idea of developing VAWTs using indigenous technology in Cuba. However, there is currently no established local technology for the conception, design, manufacture, and installation of such systems. This research was conducted with the objective of analyzing the aerodynamics involved in the design of low-power Darrieus-type vertical-axis wind turbines. Based on a review of relevant literature, a Darrieus H-type turbine was selected for design and performance evaluation using the QBlade v0.96 software, which applies the Double Multiple Streamtube (DMS) simulation model. The results obtained from the study indicate nominal power outputs ranging from 1.1 to 1.4 kW, depending on the proposed rotor configurations.
Keywords: Vertical Wind Turbines, Double Multiple Streamtube (DMS), Wind Power.

RESUMEN: Las turbinas eólicas de eje vertical poseen características que las hacen ideales para aplicaciones rurales y urbanas; a baja altura y con bajas velocidades del viento. Surge así la idea de desarrollar turbinas eólicas verticales en Cuba. Sin embargo, no se cuenta con una tecnología autóctona estructurada para la concepción, diseño, fabricación e instalación de turbinas eólicas verticales. Por esto se plantea el problema científico: "Como contribuir a la elaboración de una tecnología autóctona para la fabricación de turbinas eólicas verticales". Este trabajo se realiza con la finalidad de "Analizar la aerodinámica en el diseño de turbinas eólicas verticales de baja potencia". Basado en el estudio de los referentes, se eligió diseñar una turbina Darrieus tipo H. Para evaluar el rendimiento de las turbinas se empleó como herramienta software Qblade v0.96 soportada en la simulación DMS. Los resultados alcanzados en la investigación determinan potencias nominales de hasta 1.1-1.4 kW conforme a los diseños de rotores propuestos.
Palabras clave: Turbinas eólicas verticales, Double Multiple Streamtube (DMS), energía eólica.

INTRODUCTION

Accelerated global warming is caused by human action and the excessive emission of greenhouse gases into the Earth's atmosphere (Meneses-Ruiz *et al.*, 2018). Greenhouse gas emissions are produced in part by the burning of fossil fuels derived from petroleum (Meneses-Ruiz *et al.*, 2018). About 86% of the world's carbon dioxide emissions come from the burning of fossil fuels for energy and material production (SE: Banco Mundial, 2023). Fossil fuels comprise 80% of the current global primary energy demand Elzinga (2023) Nearly 675 million people remain without electricity worldwide. Around 2.3 billion people rely on polluting traditional fuels and technologies to cook their food (SE: Banco Mundial, 2023).

Wind energy technology can be transformative for many developing countries, particularly vertical-axis wind turbines, which have characteristics that make them ideal for rural and urban applications, at low altitudes and with low wind speeds Damota (2022). The idea then arises that the development of vertical wind turbines using indigenous technology in Cuba can contribute to energy autonomy in different sectors of society. Following Decree Law 345 on the application of renewable energy (GOC-Cuba, 2019).

The Varona Metal-Mechanical Company is working on the development of small wind turbines, a project recently launched in 2024 (Annex 1). To achieve this goal, the company has the ongoing guidance of specialists from the Faculty of Mechanics at the José Antonio Echeverría Technological University of Havana (CUJAE).

Received: 17/01/2025
Accepted: 01/07/2025
Conflict of interest: The authors of this work declare no conflict of interests.
Author contributions: Conceptualization: A. Mulet. **Data curation:** A. Mulet, E. Navarro. **Formal Analysis:** A. Mulet, E. Navarro. **Investigation:** A. Mulet, E. Navarro. **Methodology:** A. Mulet. **Software:** A. Mulet, E. Navarro. **Supervision:** A. Mulet, E. Navarro. **Validation:** A. Mulet, E. Navarro. **Visualization:** A. Mulet, E. Navarro. **Writing - original draft:** A. Mulet, E. Navarro. **Writing - review & editing:** A. Mulet, E. Navarro.
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The main objective of this work is to evaluate the design of the Darrieus vertical wind turbines through computer-assisted simulation in order to analyze their performance during operation.

MATERIALS AND METHODS

Nomenclature

A: Swept area.
c: Chord.
d: Solidity.
e: Drag coefficient.
f: Lift coefficient.
g: Moment coefficient.
h: Power coefficient.
d: Rotor diameter.
h: Drag force.
i: Lift force.
h: Rotor height.
p: Turbine power.
pd: Available power.
v: Wind speed.
α: Angle of attack.
h: Air density.
Ω: Angular velocity.
RAR: Rotor aspect ratio.
RAA: Blade aspect ratio.
TSR: Tip speed ratio.

Materials

- Qblade v0.96
- Meteoblue
- Inventor 2023
- EPA Calculator

Methodology

The methodology established for obtaining the rotor design is shown in Figure 1 and described below.

Design requirements

To begin the design, a field investigation must be conducted to define the area and operating conditions of the wind turbine. First, the province of Havana, at the José Antonio Echeverría Technological University of Havana (CUJAE), was taken as a reference location. Its location is approximately 57 meters above sea level Bader *et al.* (2025), which provides a working fluid density of 1.173 (Méndez, 2023). In addition to this, other characteristics that demonstrate the climatic parameters

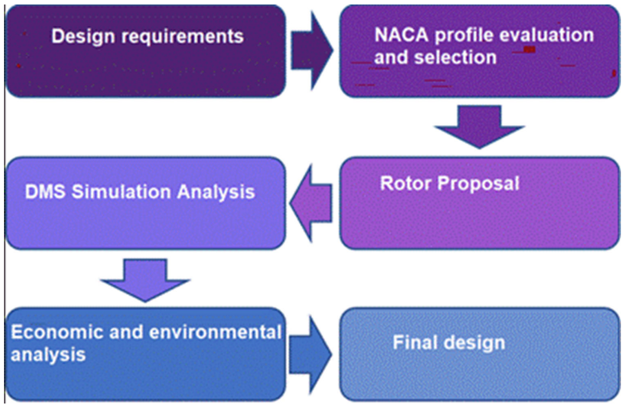

Figure 1. Rotor design methodology.

in the city of Havana to which the prototypes will be subjected during operation must be taken into account. These are presented in Table 1. These measurements are from January to December of the last 30 years, based on data from the Meteoblue meteorological station in Basel (Bader *et al.*, 2025).

Table 1. Average climatic parameters in Havana.

Annual Data	Average
Average Daily Maximum Temperature °C	29,67
Average Daily Minimum Temperature °C	20,33
Average Hot Day Temperature °C	32,50
Average Cold Night Temperature °C	16,58
Total Precipitation (mm)	38,33

NACA Airfoil Evaluation and Selection

NACA airfoils are a series of profiles created by the National Advisory Committee for Aeronautics (NACA), a United States federal agency founded on March 3, 1915 (Jankovsky *et al.*, 2025). Figure 2 summarizes the main components of an airfoil.

Figure 2. Parts of an airfoil.

When selecting a suitable profile, it was decided to use pre-built and highly tested airfoils to easily obtain information and avoid the testing required when creating a proprietary profile.

There are hundreds of profiles in the NACA line, but only three were considered. These are NACA 0018, NACA 4412, and NACA 61300. See Figure 3 below.

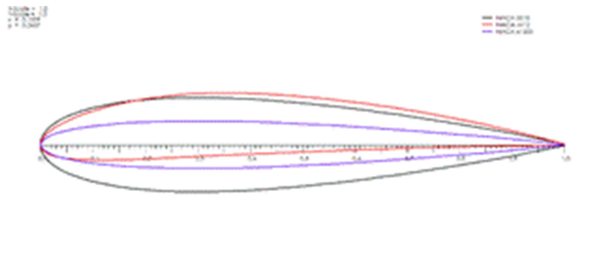

Figure 3. NACA profiles subjected to studies.

Qblade, by Qblade Team (2019), is an open-source software that uses XFoil/Xfrl5 to help users quickly design and calculate an airfoil performance. It can then be directly integrated into a wind turbine rotor design and simulated.

The first step is to perform a simulation to obtain the coefficients, and, of the airfoils over a sweep of angles of attack between α=−10° and α=+20°. The results are shown in Figure 4.

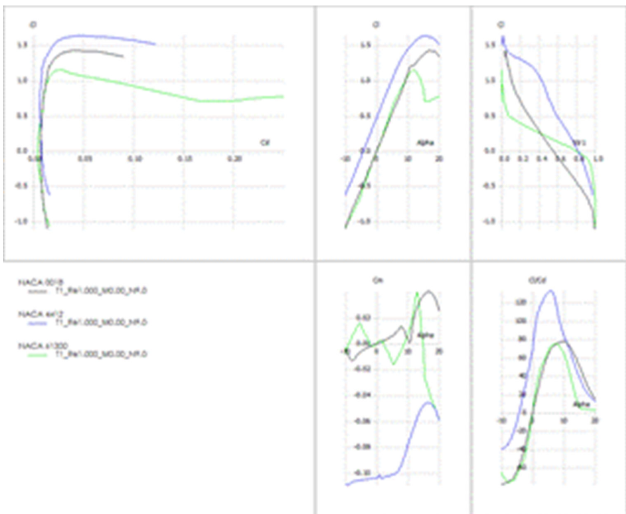

Figure 4. NACA polar simulation, Re=100000.

According to the results obtained, shown in Figure 4, the NACA 4412 airfoils offer the best aerodynamic efficiencies (/) compared to the other airfoils studied.

Now it is necessary to transform the coordinates from polar coordinates to 360° coordinates.

The dynamic pitch control system with its actuators was not implemented in this project (the pitch will be fixed at 0°), so it is advisable to have a NACA that offers high aerodynamic efficiency over a wider angle of attack range.

Rotor proposal

Rotor solidity can be interpreted as the ratio of the blade's geometric area to the area swept by the rotor:

solidity,

blade area,

rotor area

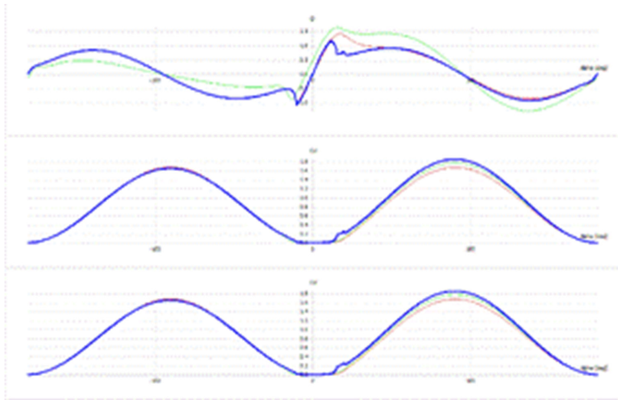

Figure 5. Aerodynamic coefficients at 360º.

$$\text{Solidity} = \sigma = \frac{Blade\ \ area}{rotor\ \ area} = \frac{n \cdot c}{\pi \cdot D} \tag{1}$$

The specific rotor speed and power coefficient directly depend on the value of the rotor's solidity. High-solidity turbines produce high torque at low speeds (solidity up to 0.8), while low-solidity turbines produce lower torque but higher speed, which is desirable for power generation rotors (Quintero, 2016). This parameter should be selected between value between 0.1 and 0.25 (Bernardo, 2018).

The turbine: a greater number of blades results in more constant torque on the shaft, reducing fatigue. Furthermore, it allows the turbine to start without being limited to specific high-torque positions. However, it is important to keep in mind that the number of blades significantly affects rotor solidity (Quintero, 2016).

The rotor aspect ratio relates the height of the blades to the rotor diameter. Increasing this value increases the shaft's angular velocity, thus making power generation more efficient (Quintero, 2016).

$$RAR = \frac{H}{2R} \tag{2}$$

The blade aspect ratio relates the height of the blades to their chord. The longer the rotor blades, the more the losses generated by the vortices at the wing tips are attenuated; consequently, increasing the blade aspect ratio increases the turbine's efficiency (Quintero, 2016). Reducing the aspect ratio worsens the performance of the wind turbine blade. In the case of VAWTs with straight blades, the use of long, thin blades with a high blade aspect ratio is recommended (Bernardo, 2018).

$$RAA = \frac{H}{c} \tag{3}$$

Below are the proposed design specifications for the rotor to be used during testing for this project:

Table 2. Rotor design specifications.

Rotor Parameter	
D (m)	2
H (m)	2
A (m^2)	4
n (-)	4
c (m)	0.2
σ (-)	0.51
RAR (-)	1
RAA (-)	10

The preliminary design of the rotor is presented in the following image, figure 6.

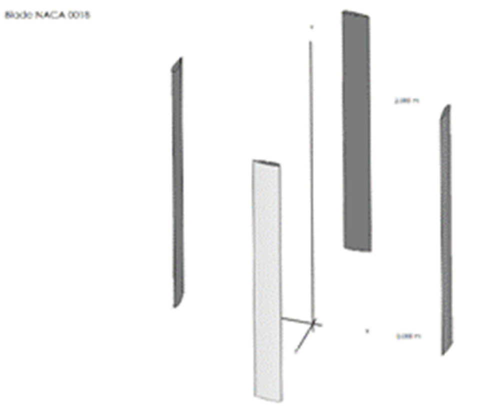

Figure 6. Preliminary rotor design.

DMS simulation analysis

The simulations are based on the Double Multiple Streamtube (DMS) model. This model was developed by Ion Paraschivoiu for the analysis of Darrieus rotors. It is an advanced derivation of the actuator disk theory combined with Blade Element Momentum (BEM) theory (Jankovsky *et al.*, 2025).

DMS Rotor Simulation

For each rotor type, there is a Cp range; this can also be defined as the power obtained relative to the available wind power (Fraire, 2020).

$$Cp = \frac{P}{Pd} \quad (4)$$

A more useful way to determine wind turbine efficiency is to use the tangential velocity ratio (TSR) (Fraire, 2020).

$$TSR = \lambda = \frac{R \cdot \Omega}{v} \quad (5)$$

When calculating an estimate of our project's Cp, we see that it is directly related to TSR (λ).

To determine Cp, the simulation parameters are:

v = 5.69 m/s

ρ=1,173 kg/m3

RESULTS AND DISCUSSION

The results of the rotor simulations using the DMS method are shown in Figure 7 below.

Analyzing the results obtained in the Rotor DMS Simulation, for a constant wind speed of 5.69 m/s, the wide operating range can be appreciated, which is of great benefit because, for a given wind speed, it has a wide variety of rotational speeds; or vice versa, for a given rotational speed, it will have a wider range of wind speeds, where the turbine is able to fully harness the wind's energy.

The turbine with the NACA 4412 profile shows the highest power coefficient due to its high lift coefficient compared to the other profiles, but it also has the lowest

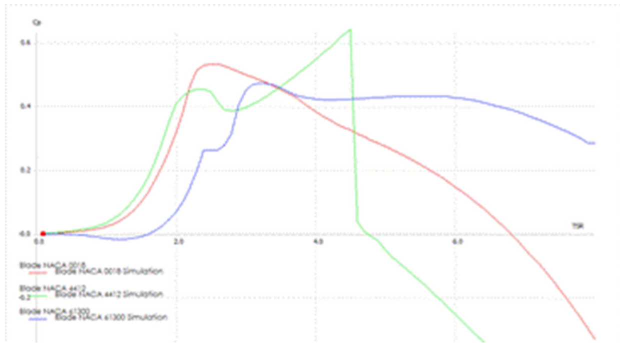

Figure 7. Cp vs TSR.

TSR amplitude. The NACA 0018 turbine presents balanced Cp results and a wide TSR range, its line is clean due to its symmetrical profile. The turbine with the NACA 61300 profile has the lowest Cp in the TSR range 1-2, but at the same time it has the widest TSR amplitude profile and compared to the others it is the one that maintains a Cp above 0.4 for most of its line.

If the torque coefficient is plotted against the TSR, the characteristic curve in Figure 8 is obtained.

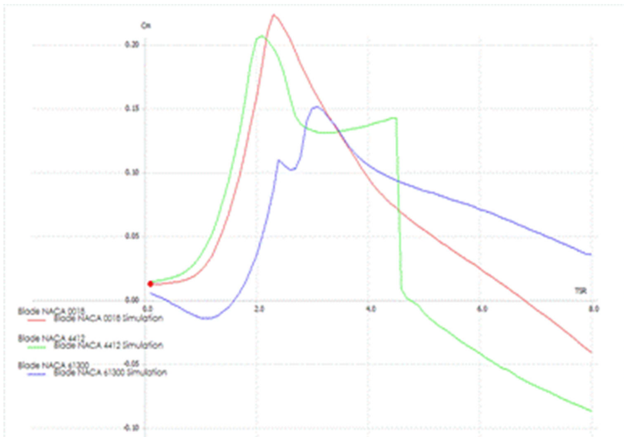

Figure 8. Characteristic curve of Cm vs TSR.

Figure 8 shows the variation in the torque produced by the wind turbine as a function of its rotational speed.

One of the disadvantages of H-Darrieus wind turbines is that they sometimes require a high starting torque due to their negative torque coefficient values for TSR close to zero. However, based on the results obtained in the simulation of these profiles configured for the rotor dimensions in the aforementioned section, this characteristic is not met, which is why they offer good results when breaking inertia and initiating rotational motion.

Multi-Parameter DMS Simulation

In this simulation, the rotor simulation range can be selected, i.e., maximum, minimum, and increment values for wind speed, rotation speed, and pitch angle. Power values can be obtained versus wind speed or versus rotation speed, which are very useful for characterizing turbines for energy production (Barragán, 2015). Figure 9 shows the configured wind speeds of 1-10 m/s.

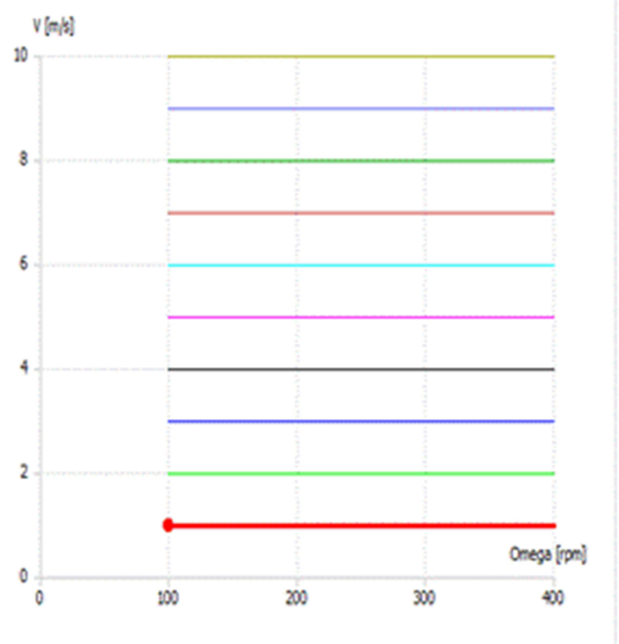

Figure 9. Wind speed and rpm (min-1).

Below, the DMS Multi Parameter simulation of power in relation to the min-1 of the NACA 0018, 4412 and 61300 respectively is shown in Figures 10, 11 and 12.

Analyzing the results obtained in the Multi Parameter DMS Simulation, for a variety of wind speeds ranging from 1-10 m/s and a range of 100-400 min-1.

Tables 3, 4, and 5 show the simulation results for the NACA 0018, NACA 4412, and NACA 61300, in that order, respectively.

Table 3. Blade NACA 0018 Simulation Results.

Blade NACA 0018 Simulation					
v(m/s)	min-1	P [W]	v(m/s)	min-1	P [W]
1	100	-0,63646	2	100	4,64799
	200	-5,09827		200	-5,09166
	300	-17,2447		300	-17,0402
	400	-40,8948		400	-40,7862
3	100	28,7128	4	100	79,5447
	200	-2,70256		200	37,1839
	300	-17,1844		300	-42,1842
	400	-39,9081		400	-40,7333
5	100	111,217	6	100	94,0231
	200	105,044		200	229,702
	300	29,372		300	125,496
	400	-135,319		400	-21,6205
7	100	79,7104	8	100	69,8496
	200	401,254		200	636,358
	300	263,349		300	473,65
	400	120,955		400	297,472
9	100	63,0677	10	100	61,2419
	200	887,046		200	889,737
	300	775,246		300	1142,59
	400	525,78		400	840,353

The graphs show how the turbine with the NACA 4412 profile produces greater maximum power compared to the NACA 0018 and NACA 61300 turbines, with the latter producing the lowest output. The NACA 61300 could be ruled out if only the aforementioned point were considered, but if a turbine that operates at a specific wind speed is desired, the turbine that produces the maximum power at that speed should be cho.

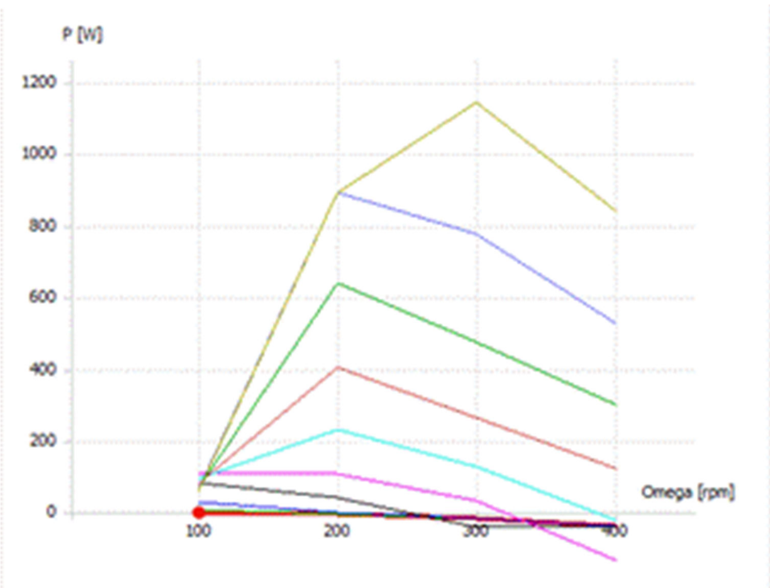

Figure 10. Power generated by the NACA 0018 profile turbine.

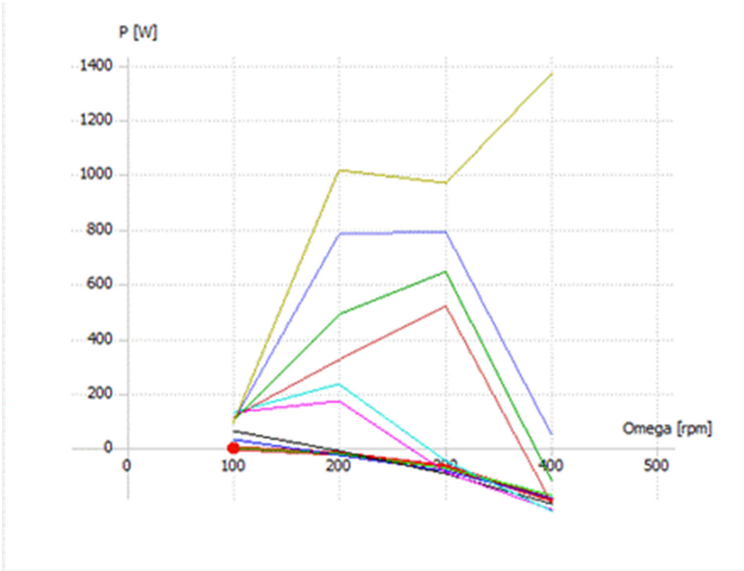

Figure 11. Power generated by the NACA 4412 profile turbine.

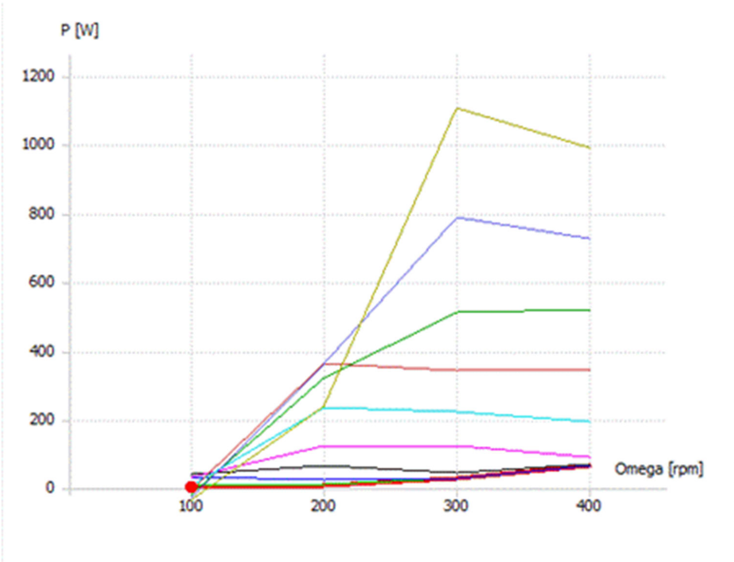

Figure 12. Power generated by the NACA 61300 profile turbine.

The amount of energy a wind turbine can generate depends greatly on the characteristics of the wind. Therefore, before installing a wind turbine, it is important to know the wind potential at the site. This parameter is essential when deciding which wind turbine to select.

In Havana, for example, the average minimum wind speed is around 3.33 m/s with a standard deviation of 0.53 m/s (16%), the average wind speed is 4.84 m/s, and the maximum wind speed is approximately 6.37 m/s with a standard deviation of 0.59 m/s (9%) (Méndez, 2023).

With this in mind, it can be observed in Tables 3, 4, and 5 that turbines with NACA 0018 and NACA 4412 profiles, at wind speeds between 1 and 3 m/s, produce almost no power. It is from 4 m/s and above at low speeds of 100 and 200 RPM that they produce significant power. Above 4 m/s, the turbines begin to produce significant power, and 1.36 kW. However, the NACA 61300 rotor is capable of generating power at low wind speeds, as shown in Table 5.

Finally, in view of the results shown above, it can be stated that the best option of the turbines shown in this work corresponds to the NACA 61300 rotor, considering its power with respect to the others, for speeds below the design point, which can be useful in a region where wind conditions are variable.

Economic valuation and social contribution.

Economic valuation

For calculation purposes, this technical and economic evaluation model for small-scale wind energy projects is used. The turbine's electrical generation capacity is shown in Tables 6, 7, and 8 below, based on wind speeds of 1-10 m/s.

Table 4. Blade NACA 4412 Simulation Results.

Blade NACA 4412 Simulation					
v (m/s)	**min-1**	**P [W]**	**v (m/s)**	**min-1**	**P [W]**
1	100	-3,18588	2	100	-1,8432
	200	-21,6937		200	-25,487
	300	-70,2326		300	-76,044
	400	-189,615		400	-173,55
3	100	29,1418	4	100	61,1209
	200	-29,2681		200	-14,746
	300	-86,0186		300	-98,933
	400	-185,46		400	-203,9
5	100	126,776	6	100	126,19
	200	170,616		200	233,134
	300	-91,5401		300	-49,767
	400	-227,688		400	-234,15
7	100	110,646	8	100	100,369
	200	318,869		200	488,967
	300	516,228		300	640,671
	400	-199,036		400	-117,97
9	100	95,3748	10	100	93,364
	200	776,099		200	1014,21
	300	786,828		300	966,108
	400	49,1511		400	1364,92

Table 5. Blade NACA 61300 Simulation Results.

Blade NACA 6Blade NACA 61300 Simulation					
v (m/s)	**min-1**	**P [W]**	**v (m/s)**	**min-1**	**P [W]**
1	100	1,04084	2	100	8,10093
	200	7,91343		200	8,32672
	300	26,6527		300	26,8777
	400	63,1607		400	63,3074
3	100	29,0583	4	100	39,9098
	200	23,7601		200	64,8074
	300	28,1027		300	42,6056
	400	63,9384		400	66,6138
5	100	29,5547	6	100	8,24862
	200	123,491		200	232,467
	300	122,485		300	218,725
	400	87,1254		400	190,081
7	100	-7,07141	8	100	-19,022
	200	359,973		200	319,278
	300	339,362		300	509,953
	400	344,77		400	518,459
9	100	-27,888	10	100	-34,049
	200	362,926		200	236,437
	300	784,575		300	1104,13
	400	724,76		400	987,928

Table 6. Energy power delivered from 1-3 m/s

Wind speed (m/s)	**1**	**2**	**3**
Useful power (W)	63,16	63,31	63,94
Power (W/day)	1515,86	1519,38	1534,52
Power in (kW/day)	1,52	1,52	1,53
Power (kW/month)	45,48	45,58	46,04
Power (kW/year)	545,71	546,98	552,43
Unit price kWh = $	15,02	15,05	15,18
Annual unit price kWh = $	180,18	180,58	182,16

Table 7. Energy power delivered from 4-6 m/s

Wind speed (m/s)	**4**	**5**	**6**
Useful power (W)	66,61	123,49	232,47
Power (W/day)	1598,73	2963,78	5579,21
Power (kW/day)	1,60	2,96	5,58
Power (kW/month)	47,96	88,91	167,38
Power (kWh/year)	575,54	1066,96	2008,51
Unit price kWh = $	15,84	29,34	111,38
Annual unit price kWh = $	190,08	352,04	1336,58

Table 8. Energy power delivered from 7-10 m/s

Wind speed (m/s)	**7**	**8**	**9**	**10**
Useful power (W)	359,97	518,46	784,58	1104,13
Power (W/day)	8639,35	12443,02	18829,80	26499,12
Power in (kW/day)	8,64	12,44	18,83	26,50
Power (kW/month)	259,18	373,29	564,89	794,97
Power (kW/year)	3110,17	4479,49	6778,73	9539,68
Unit price kWh = $	308,60	747,50	2128,08	4331,75
Annual unit price kWh = $	3703,20	8970,00	25536,96	51981,00

Environmental Analysis

It has been proven that wind technology is highly necessary today; however, according to studies, social empowerment has not been taken into account in many countries, as actions aimed at educating people have been lacking. In the case of Cuba, we are not exempt from this problem, we are not exempt from this problem, and it is necessary to demonstrate the importance of harnessing wind energy based on vertical turbines. Nominal power data were entered into the EPA (Meneses-Ruiz et al., 2018).

Greenhouse gas equivalency calculator (kWh avoided)

This perspective focuses on the amount of energy that does not need to be generated from polluting sources, such as fossil fuels, thanks to the energy produced by the wind turbine.

Table 9. Kilowatt hours in CO2 equivalent (Source EPA)

Kilowatt-hours avoided (kWh)	1,1
CO2 equivalent (t)	0,0008

Table 10. This CO2 emissions equivalent (Source EPA)

Gallons of gasoline consumed	0.086
Gallons of diesel consumed	0.075
Pounds of coal burned	0.861
Home energy use for one year	0.0001
Household electricity use for one year	0.0001
Barrels of oil consumed	0.002
Propane cylinders used for home barbecues	0.035
Number of smartphones charged	93.5

Table 11. This equivalent of avoided greenhouse gas emissions (Source EPA)

Tons of waste recycled instead of being disposed of in landfills (t)	0.0003
Trash bags of waste recycled instead of being disposed of in landfills	0.033

Table 12. This carbon equivalent sequestered (Source EPA)

Urban tree seedlings grown for 10 years	0.013

CONCLUSIONS

This paper presents the analysis of three turbines with NACA 0018, NACA 4412, and NACA 61300 profiles, for wind speeds of (1-10) m/s and a rotor diameter of 2 m. These parameters were chosen to study the utilization of wind energy in areas with low wind speeds.

Only 4-blade turbines were analyzed, and simulations were performed using the QBlade program. It was found that the turbines studied have similar maximum power; however, observing their characteristic curves, it was determined that the turbine with the NACA 61300 profile represented the best option.

Analyzing the results in Tables 6, 7, and 8, it can be assumed that the product meets the energy needs of a residential home.

The NACA 61300 profile turbine offers a viable option for optimal wind energy utilization in urban and rural areas with low wind parameters.

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Annex 1. General Assembly of the Darrieus type VAWT vertical wind turbine 1.2 kW power.