RGSA – Revista de Gestão Social e Ambiental
ISSN: 1981-982X
Submission date: 03/18/2024
Acceptance date: 05/20/2024
DOI: https://doi.org/10.24857/rgsa.v18n2-200
Organization: Interinstitutional Scientific Committee
Chief Editor: Éverton Hillig
Assessment: Double Blind Review pelo SEER/OJS

COMPARATIVE ANALYSIS OF AERODYNAMIC EFFICIENCY IN SMALL-DIAMETER WIND TURBINE BLADES: NACA 4412 VS. CLARK Y

Valdir Tesche Signoretti [1]
Alexandre Augusto Simões Filho[2]
Ricardo Luiz Perez Teixeira [3]
Rogério Fernandes Brito [4]
Paulo Mohallem Guimarães[5]

ABSTRACT

Objective: This study aims to compare the efficiency of the Naca 4412 and Clark Y airfoil profiles for small-diameter wind turbines using Solidworks® modeling, 3D printing, wind tunnel testing, and computational simulation. The hypothesis posits that the Naca 4412 will be more efficient.

Theoretical Framework: Wind turbines convert the kinetic energy of wind into electrical energy, with the rotor being responsible for converting kinetic energy into mechanical energy, which is subsequently converted into electrical energy by the generator. Studies highlight the importance of optimizing the aerodynamics of the blades to maximize efficiency.

Method: The Naca 4412 and Clark Y profiles were modeled in Solidworks® and 3D printed using high-quality ABS. The blades were tested in Armfield C15-10 and Edibon EEEC wind tunnels, measuring lift and drag forces at different angles of attack (30º to 70º) and varying wind speeds to achieve different Reynolds numbers.

Results and Discussion: The Naca 4412 profile exhibited higher lift and drag compared to the Clark Y. At angles of 50º and 60º, both profiles showed greater efficiency, with the Naca 4412 achieving higher maximum angular velocity (357.93 RPM at 50º, 510.91 RPM at 60º). The performance difference can be attributed to the twist of the Naca 4412 and turbulence effects at low speeds.

Research Implications: The results provide insights for the development of more efficient wind turbines, particularly in urban contexts where small wind turbines are used.

Originality/Value: This study contributes by experimentally comparing two widely used airfoil profiles, offering valuable data for the optimization of small wind turbine blades.

Keywords: Airfoil profiles, Clark Y, Efficiency, Naca 4412, Wind tunnel, Wind turbines.

[1] Universidade Federal de Itajubá (UNIFEI), Itabira, Minas Gerais, Brazil.
E-mail: valdirsignoretti@unifei.edu.br Orcid: https://orcid.org/0009-0000-3675-9068
[2] Universidade Federal de Itajubá (UNIFEI), Itabira, Minas Gerais, Brazil.
E-mail: alexandresimoesf@unifei.edu.br Orcid: https://orcid.org/0009-0000-0752-1237
[3] Universidade Federal de Itajubá (UNIFEI), Itabira, Minas Gerais, Brazil. E-mail: ricardo.luiz@unifei.edu.br
Orcid: https://orcid.org/0000-0003-2641-4036
[4] Universidade Federal de Itajubá (UNIFEI), Itabira, Minas Gerais, Brazil. E-mail: rogbrito@unifei.edu.br
Orcid: https://orcid.org/0000-0002-6833-7801
[5] Universidade Federal de Itajubá (UNIFEI), Itabira, Minas Gerais, Brazil.
E-mail: pauloguimaraes@unifei.edu.br Orcid: https://orcid.org/0000-0002-2919-7666

ANÁLISE COMPARATIVA DA EFICIÊNCIA AERODINÂMICA EM PÁS DE AEROGERADO-RES DE PEQUENO DIÂMETRO: NACA 4412 VS. CLARK Y

RESUMO

Objetivo: O objetivo deste estudo é comparar a eficiência dos perfis aerodinâmicos Naca 4412 e Clark Y para aerogeradores de pequeno diâmetro, utilizando modelagem em Solidworks®, impressão 3D, testes em túneis de vento e simulação computacional, com a hipótese de que o Naca 4412 seja mais eficiente.

Referencial Teórico: As turbinas eólicas convertem a energia cinética do vento em energia elétrica, sendo o rotor responsável pela conversão da energia cinética em energia mecânica, posteriormente convertida em energia elétrica pelo gerador. Estudos destacam a importância da otimização aerodinâmica das pás para maximizar a eficiência.

Método: Foram modelados perfis Naca 4412 e Clark Y no Solidworks® e impressos em 3D com ABS de alta qualidade. As pás foram testadas em túneis de vento Armfield C15-10 e Edibon EEEC, medindo forças de sustentação e arrasto em diferentes ângulos de ataque (30º a 70º), variando a velocidade do vento para obter números de Reynolds distintos.

Resultados e Discussão: O perfil Naca 4412 apresentou maior sustentação e arrasto em comparação ao Clark Y. Em ângulos de 50º e 60º, ambos os perfis mostraram maior eficiência, com o Naca 4412 destacando-se em velocidade angular máxima (357,93 RPM a 50º, 510,91 RPM a 60º). A diferença de desempenho pode ser explicada pela torção do Naca 4412 e efeitos de turbulência em baixas velocidades.

Implicações da Pesquisa: Os resultados fornecem insights para o desenvolvimento de aerogeradores mais eficientes, especialmente em contextos urbanos onde pequenos aerogeradores são utilizados.

Originalidade/Valor: estudo contribui ao comparar experimentalmente dois perfis aerodinâmicos amplamente utilizados, oferecendo dados valiosos para a otimização de pás de aerogeradores de pequeno porte.

Palavras-chave: Aerogeradores, Clark Y, Eficiência, Naca 4412, Perfis aerodinâmicos, Túnel de vento.

ANÁLISIS COMPARATIVO DE LA EFICIENCIA AERODINÁMICA EN PALAS DE AEROGENERADORES DE PEQUEÑO DIÁMETRO: NACA 4412 VS. CLARK Y

RESUMEN

Objetivo: Objetivo: Este estudio tiene como objetivo comparar la eficiencia de los perfiles aerodinámicos Naca 4412 y Clark Y para aerogeneradores de pequeño diámetro, utilizando modelado en Solidworks®, impresión 3D, pruebas en túneles de viento y simulación computacional. Se plantea la hipótesis de que el Naca 4412 será más eficiente.

Marco Teórico: Los aerogeneradores convierten la energía cinética del viento en energía eléctrica, siendo el rotor responsable de convertir la energía cinética en energía mecánica, que posteriormente se convierte en energía eléctrica mediante el generador. Estudios destacan la importancia de optimizar la aerodinámica de las palas para maximizar la eficiencia.

Método: Se modelaron los perfiles Naca 4412 y Clark Y en Solidworks® y se imprimieron en 3D utilizando ABS de alta calidad. Las palas fueron probadas en túneles de viento Armfield C15-10 y Edibon EEEC, midiendo fuerzas de sustentación y arrastre en diferentes ángulos de ataque (30º a 70º) y variando la velocidad del viento para obtener diferentes números de Reynolds.

Resultados y Discusión: El perfil Naca 4412 presentó mayor sustentación y arrastre en comparación con el Clark Y. En ángulos de 50º y 60º, ambos perfiles mostraron mayor eficiencia, destacando el Naca 4412 en velocidad angular máxima (357,93 RPM a 50º, 510,91 RPM a 60º). La diferencia de rendimiento puede explicarse por la torsión del Naca 4412 y los efectos de turbulencia a bajas velocidades.

Implicaciones de la investigación: Los resultados proporcionan información para el desarrollo de aerogeneradores más eficientes, especialmente en contextos urbanos donde se utilizan pequeños aerogeneradores.

Originalidad/Valor: Este estudio contribuye al comparar experimentalmente dos perfiles aerodinámicos ampliamente utilizados, ofreciendo datos valiosos para la optimización de palas de aerogeneradores de pequeño tamaño.

Palabras clave: Aerogeneradores, Clark Y, Eficiencia, Naca 4412, Perfiles aerodinámicos, Túnel de viento.

RGSA adota a Licença de Atribuição CC BY do Creative Commons (https://creativecommons.org/licenses/by/4.0/).

1 INTRODUCTION

A wind farm is an installation that houses several wind turbines interconnected in a network to produce electrical energy (Akanto et al., 2023). The energy generated is transported to electrical substations through transmission lines and then distributed to homes and businesses (Braunbehrens , Vad , & Bottasso , 2023). Economic studies evaluate the financial viability of the project, including investment, operation and maintenance costs, as well as energy production forecasts (Hadi , Oudah , & Al- Baldawi , 2020). Wind farms are an important source of renewable energy and can contribute to reducing the environmental impacts caused by fossil fuels (Bald , 2022; Hamed & Alshare , 2022).

One of the main negative environmental impacts of wind energy is the visual impact of wind turbines (Nazir et al., 2020; Hamed & Alshare , 2022). Another negative environmental impact of wind energy is noise (Msigwa , Ighalo , & Yap , 2022; Nazir et al., 2020). Currently, wind energy is one of the fastest growing sources of renewable energy in the world, around 30% per year, accounting for approximately 5% of global electrical energy production (Dehghani-Sanij et al., 2022; Singh et al ., 2022). The installed capacity of wind energy worldwide reached 743 GW at the end of 2020, according to data from the Global Wind Energy Council (Liu & Zeng , 2022; Liu, Sun, & Wang, 2023).

The potential for wind energy production in Brazil is estimated at around 500 GW, more than double the total capacity currently installed in the country (De Jong et al., 2019). Despite the great potential for wind energy production in Brazil, there are still challenges to be overcome for the full development of this energy source (Shafiullah et al., 2013; Da Ponte, Calili , & Souza, 2021). One of the main challenges is the need to invest in energy transmission infrastructure to allow the integration of wind farms into the national electricity system (Góes et al., 2021; Dranka & Ferreira, 2020).

This research compared the efficiency of the Naca 4412 and Clark Y aerodynamic profiles for small diameter wind turbines, using Solidworks ® modeling, 3D printing, tests in wind tunnels and computer simulation. The hypothesis is that the Naca 4412 is more efficient.

2 THEORETICAL FRAMEWORK

Wind turbines are equipment that convert the kinetic energy of the wind into electrical energy (Gantha , Barik , & Nayak , 2021). The rotor consists of wind-driven blades, converting the wind's kinetic energy into mechanical energy (Chaudhuri et al., 2022). The generator converts mechanical energy into electrical energy, while the control system ensures the optimized operation of the wind turbine in different wind conditions (Peng , Liu, & Jiang, 2021). Rotor blades are designed to capture maximum kinetic energy from the wind (Moghadassian & Sharma , 2020; Chaudhuri et al., 2022).

Before reaching the generator, the movement generated by the blades is transmitted to a gear transmission system (Roga et al., 2022; Peng , Liu, & Jiang, 2021). This transmission system, together with the control system, works to obtain maximum energy generation efficiency from the system. The low rotor speed would not generate much energy, as the generator cannot capture the energy when the blades rotate at low speed (Cai et al., 2024; Desalegn , Gebeyehu , & Tamrat , 2022). Therefore, the reduction box, combined with the control system, increases the speed of the generator shaft and the efficiency of mechanical energy capture in the generator, allowing the mechanical energy from the movement of the blades to be captured with greater efficiency, depending on the variability of factors that influence the movement of the blades.

Wind turbines can be divided into classes according to their reference speed and average speed (Pinto, 2012). As shown in Table 1, wind speed categories are defined based on parameters such as VREF, the annual mean speed; VM, the maximum expected speed in a 10-minute period; VRAJ50, the maximum speed over a period of 50 years; and I, the turbulence intensity for winds of 15 m/s. Categories A and B are assigned to different turbulence conditions, with A being for higher values and B for lower values, characterizing the project regardless of the wind speed of the mentioned classes. The representation of A as standard deviation of the longitudinal wind speed indicates the associated turbulence.

Table 1

The four classes of wind turbines, according to IEC (International Electrotechnical Commission).

WIND TURBINE CLASS	I	II	II	IV	S
VREF (M/S)	50	42.5	37.5	30	VALUES SPECIFIED BY THE DESIGNER
VM (M/S)	10	8.5	7.5	6.0	
VRAJ50= WREF	70	59.5	52.5	42	
VRAJ1 = 1.05VRAJ50	52.5	44.6	39.4	31.50	
A I15(%)	18	18	18	18	
The	TWO	TWO	TWO	TWO	
B I15 (%)	16	16	16	16	
The	3	3	3	3	

Source: Adapted from Pinto, MO (2012). Fundamentals of Wind Energy (1st ed.). Rio de Janeiro: LTC.

The choice of control system equations and parameters depends on the characteristics of the wind turbine and local wind conditions (Yang et al., 2021; Deng et al., 2021). To implement these control methods, electronic control systems and actuators are used to adjust wind turbine blades. Electronic control systems use sensors to measure wind speed, rotor speed and other relevant variables. Based on these measurements, the control system adjusts the blades to maintain the desired rotor speed and maximize wind turbine efficiency. Speed control, pitch control and tilt control are the main control methods used in wind turbines to maximize their efficiency and ensure the stability of the electrical grid (Nash, Nouri , & Vasel -Be- Hagh , 2021; Raouf et al ., 2023).

With increasing demand for clean energy, new technologies are being developed to improve the efficiency and power generation capacity of wind turbines (Roga et al., 2022; Bošnjaković et al., 2022). One of these technologies is the floating wind turbine, capable of producing energy in deep waters where fixed wind turbines cannot be installed. These wind turbines are attached to floating platforms anchored to the ocean floor. Additionally, researchers have been working on more aerodynamic blade designs to improve the efficiency of wind turbines (Krishnan , Al- Obaidi , & Hao , 2023).

3 METHODOLOGY

When selecting the aerodynamic profile for a small diameter wind turbine with a horizontal axis, it is essential to consider the peculiarities of each profile. The most suitable profiles for this application are Naca 4412 and ClarkY , due to their distinct aerodynamic properties (Tokul & Kurt, 2023; Mohamed, Ravindran , & Rajendran , 2021).

The Naca 4412 profile stands out for its stability at different angles of attack, increasing the efficiency of the wind turbine in varied wind conditions (Kapdi , Dahiya , & Naranje , 2016). On the other hand, the ClarkY profile , although less common in small diameter wind turbines, stands out due to the accentuated curvature at the bottom, which provides greater support at lower wind speeds (Çetin et al., 2005). However, the softness of the curvature at the top of the ClarkY profile can result in loss of lift at high wind speeds, making it more suitable for low power wind turbines in larger diameters.

Solidworks ® engineering software , as shown in Figures 1 to 4. The representations highlight the modeling of the blades with details from the top and side views, both for the Naca 4412 profile and the ClarkY profile . In Figure 1, the modeling of the Naca 4412 profile blade is presented from above, detailing its aerodynamic geometry. In Figure 2, the same modeling is shown, now with the inclusion of axes for better visualization and reference. In Figure 3, we can see the representation of the lateral modeling of the blade using the Naca 4412 profile, highlighting specific aspects of the blade's aerodynamics. In Figure 4, the modeling of the blade with the ClarkY profile is depicted , highlighting its distinct aerodynamic particularities.

Figure 1

Blade modeling in the Naca 4412 profile software, top view.

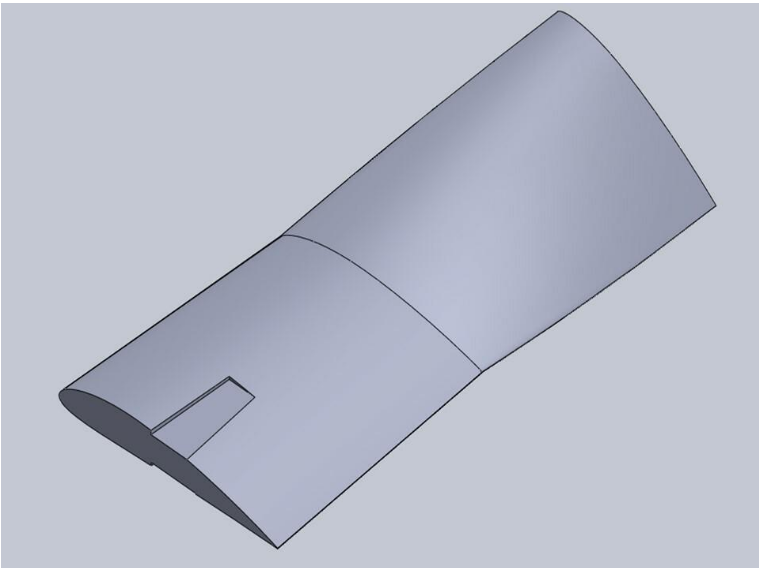


Figure 2

Modeling of the blade in the Naca 4412 profile software, top view with axes.

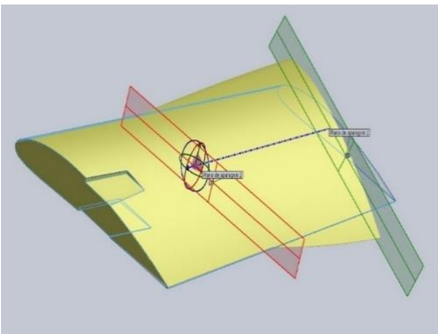


Figure 3

Modeling of the blade in the Naca 4412 profile software, side view.

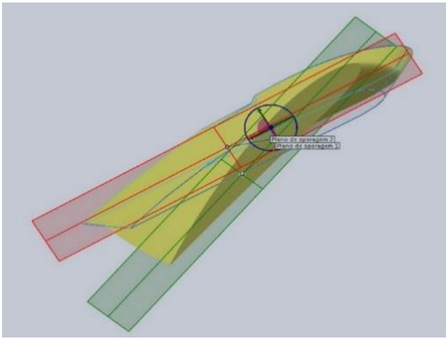
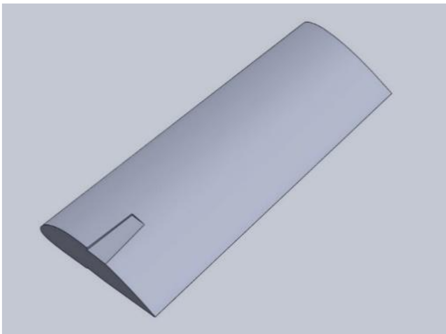


Figure 4

Blade modeling in ClarkY profile software .



3D printing of different aerodynamic blade profiles, Naca 4412 and ClarkY , was carried out for wind tunnel testing with lengths of 152 mm and 167 mm. For 3D printing, materials such as high-quality and high-resolution ABS were used to ensure the precision of the blade profiles. The result for one of the blades is shown in Figure 5.

Figure 5

Shovels designed and printed on a 3D printer

Figure 6

Blades manufactured by 3D printer being used in the wind tunnel. General view of the tunnel

Figure 7

Blades manufactured by 3D printer being used in the wind tunnel. View of the blades

Initially, three-dimensional models of aerodynamic blade profiles were created using 3D modeling software. These models were adjusted to meet desired specifications, such as dimensions, angles, and curvatures, and then exported to a file format suitable for 3D printing. After printing (Figure 6 and Figure 7), the blade profiles were carefully inspected to ensure the quality and integrity of the models. Then, the blades were mounted on a support and taken to the wind tunnel.

To collect drag force data, the Armfield C15-10 model wind tunnel was used (Figure 8), while to collect angular velocity data, the Edibon EEEC model wind tunnel was used, both located in the laboratory ventilation and refrigeration system from UNIFEI/Itabira.

The test results were used to evaluate the aerodynamic efficiency of the different profiles. The data obtained was compared and analyzed to determine which blade profile performed best in each of the conditions tested. These results can be used to develop new, more efficient and sustainable aerodynamic blade designs. The measurement of lift and drag forces was carried out in an Armfield C15-10 model wind tunnel, as shown in Figure 8, for the Naca 4412 and ClarkY aerodynamic profiles , with the aim of evaluating the performance of these profiles.

Figure 8

Armfield model C15-10 wind tunnel

The methodology adopted consisted of fixing each blade on the wind tunnel test bench and varying the wind speed to obtain different values of Reynolds number, a dimensionless parameter of fluid speed in relation to the dimensions of the blade. Then, measurements of the lift and drag forces were carried out for each aerodynamic profile.

To measure the lift force, a load sensor was used to measure the vertical force exerted on the blade by the wind. The measurement of the drag force was carried out with a dynamometer, which measures the horizontal force exerted on the blade by the wind. These measurements were made for each wind speed and Reynolds number.

With the data obtained from the measurements, graphs were constructed in the Origin ® software to evaluate the relationship between lift and drag forces as a function of wind speed and Reynolds number. The results showed that the Naca 4412 aerodynamic profile presented greater lift compared to the ClarkY profile , but also greater drag resistance. Finally, the measurement of lift and drag forces in the Armfield C15-10 wind tunnel for the Naca 4412 and ClarkY aerodynamic profiles proved to be efficient in evaluating the performance of these profiles. Data collection in an Edibon EEEC model wind tunnel , presented in Figures 9 and 10, is a methodology used to evaluate the aerodynamic behavior of different blade models under controlled conditions. To carry out this collection efficiently, it is necessary to follow a set of steps.

Figure 9

Edibon EEEC model wind tunnel . Side view

Figure 10

Edibon EEEC model wind tunnel . Front view

First, the blade models that will be evaluated are selected. In the case in question, the Naca 4412 and ClarkY profiles were chosen , widely used in the wind turbine industry and representative of the aerodynamic characteristics of industrial blades. Next, the range of angles of attack that will be tested is defined. Angles from 30 degrees to 70 degrees were evaluated, in increments of 10 degrees. The angle of attack is the measurement of the angle between the blade and the wind direction, and its variation allows evaluating the aerodynamic performance of the blade in different operating conditions.

To collect data, specific equipment is used, such as a wind tunnel and a rotation measurement system. The wind tunnel creates a controlled, consistent airflow over the blade, while the measurement system records blade speeds at different angles of attack.

To ensure the accuracy of the results, each angle of attack was tested four times for each blade profile. This allows you to calculate the mean and standard deviation of measurements, reducing the uncertainty of the results. At the end of data collection, the results are analyzed and the aerodynamic performance of the different blade profiles at different angles of attack is compared. This analysis can be used to optimize the design of wind turbine blades, improving their efficiency and reducing production and maintenance costs.

4 RESULTS AND DISCUSSIONS

After selecting the profiles, 3D printing and the methodology followed to obtain the results, the following data on the aerodynamic parameters of the ClarkY and Naca 4412 profiles were obtained. Table 2 presents the maximum time in which the profiles reached the maximum angular velocity , while Table 3 presents the maximum speed that the profiles reached at 100% wind tunnel power.

Table 2

Response time until reaching the maximum angular velocity for each angle at 100% wind tunnel power for the Naca 4412 profile

Angle (Degrees)	ClarkY	Naca 4412
40º	162 seconds	134 seconds
50th	162 seconds	135 seconds
60º	162 seconds	136 seconds

Table 3

Response time until reaching the maximum angular velocity for each angle at 100% wind tunnel power for the ClarkY profile

ANGLE (DEGREES)	CLARKY	NACA 4412
40º	211.26 RPM	251.04 RPM
50TH	301.70 RPM	357.93 RPM
60º	425.59 RPM	510.91 RPM

The analysis of Table 2 and Table 3 allows us to experimentally conclude that the most efficient aerodynamic profiles are between angles of 50º and 60º. Under these conditions, the blades, with the same wind tunnel speed, reach a higher RPM (revolutions per minute), increasing energy production efficiency without additional manufacturing or process costs. The experiment largely achieved the objective of identifying a more efficient aerodynamic profile for small wind turbines. It was found that the Naca 4412 profile is the most suitable for this type of application, such as power generation in urban centers, as it presented better responses to wind tunnel speeds compared to the ClarkY profile .

The difference between the speed times of the Naca and ClarkY profiles , presented in Table 2, can be explained by physical effects, such as the boundary layer in the blade flow. The Naca 4412 profile has a twist that, at each angle of attack, advances the tip of the profile by 20º. This, added to the effect of turbulence at low speeds for very high angles of attack , results in a small increase in speed. With each angle measured, the angle of the profile tip becomes more advanced, causing a detachment that reduces the profile's efficiency at low speeds.

In Table 4, the lift force values of the Naca 4412 and ClarkY profiles at different angles of attack are presented, with 40% of the wind tunnel power.

Table 4

Lift force for speeds of 8.0 m/s corresponding to 40% wind tunnel power

Angle (Degrees)	ClarkY (Newton)	Naca 4412 (Newton)
15th	0.35	0.38
30th	0.40	0.43

The support force values of the Naca 4412 and ClarkY profiles showed an average difference of 0.3 N for the measured angles, guaranteeing a gain in efficiency between the profiles. The Naca 4412 profile, as it has a torsion angle, generates an area in the direction of flow that helps increase the support force, as described in the work of Choi et al. (2023).

In Table 5, the drag force values of the Naca 4412 and ClarkY profiles at different attack angles are presented, with 40% of the wind tunnel power.

Table 5

Drag force for speeds of 8.0 m/s at 40% wind tunnel power

Angle (Degrees)	ClarkY (Newton)	Naca 4412 (Newton)
15th	0.07	0.14
30th	0.23	0.31

The drag force values of the Naca 4412 and ClarkY profiles showed an average difference of 0.7 N for the measured angles, this difference being more significant than that of the lift force. This is due to the twist of the Naca 4412 profile, which occupies a larger area than the ClarkY profile . Furthermore, the geometry of the Naca 4412 profile, with a bulge on the lower surface, also helps to increase the support force, as described by Abbott and von Doenhoff (1959).

In Table 6, the values of the lift coefficient (Cl) of the Naca 4412 and ClarkY profiles at different angles of attack are presented, with 40% of the wind tunnel power.

Table 6

Lift coefficient (Cl) of the profiles at angles of attack of 15º and 30º

ANGLE (DEGREES)	CLARKY (CD)	NACA 4412 (CD)
15TH	0.09	0.12
30TH	0.24	0.27

The difference observed in Table 6 between the values of the blades' lift coefficients (Cl) confirms that, in addition to the twist of the Naca 4412 profile, its aerodynamic characteristics contributed to the blade's efficiency gain. At an angle of attack of 15º, there was a percentage increase of 30% in Cl in relation to the Naca 4412 profile, and at an angle of attack of 30º, an increase of 11% also in relation to the Naca 4412 profile. The decrease observed in the percentage between the profiles is probably due to the displacement of the flow pressure center during the measurement, which can interfere with the torque generated in the profile.

In Table 7, the drag coefficient (Cd) values of the Naca 4412 and ClarkY profiles are presented at different angles of attack, with 40% of the wind tunnel power. The values presented in Table 7 for the drag coefficient (Cd) of the Naca 4412 profile were higher than those of the ClarkY profile . These values are important for analyzing the results, as they show that, as the angle of attack changes, the Cd decreases, enabling a gain in efficiency in the resulting force. Analyzing the difference between the increase in drag coefficients between the Naca 4412 and ClarkY profiles at attack angles of 15º and 30º, it is observed that the Naca 4412 profile had an increase of 225%, while the ClarkY profile had an increase of 266%. %.

Table 7

Drag coefficient (Cd) of the profiles at angles of attack of 15º and 30º

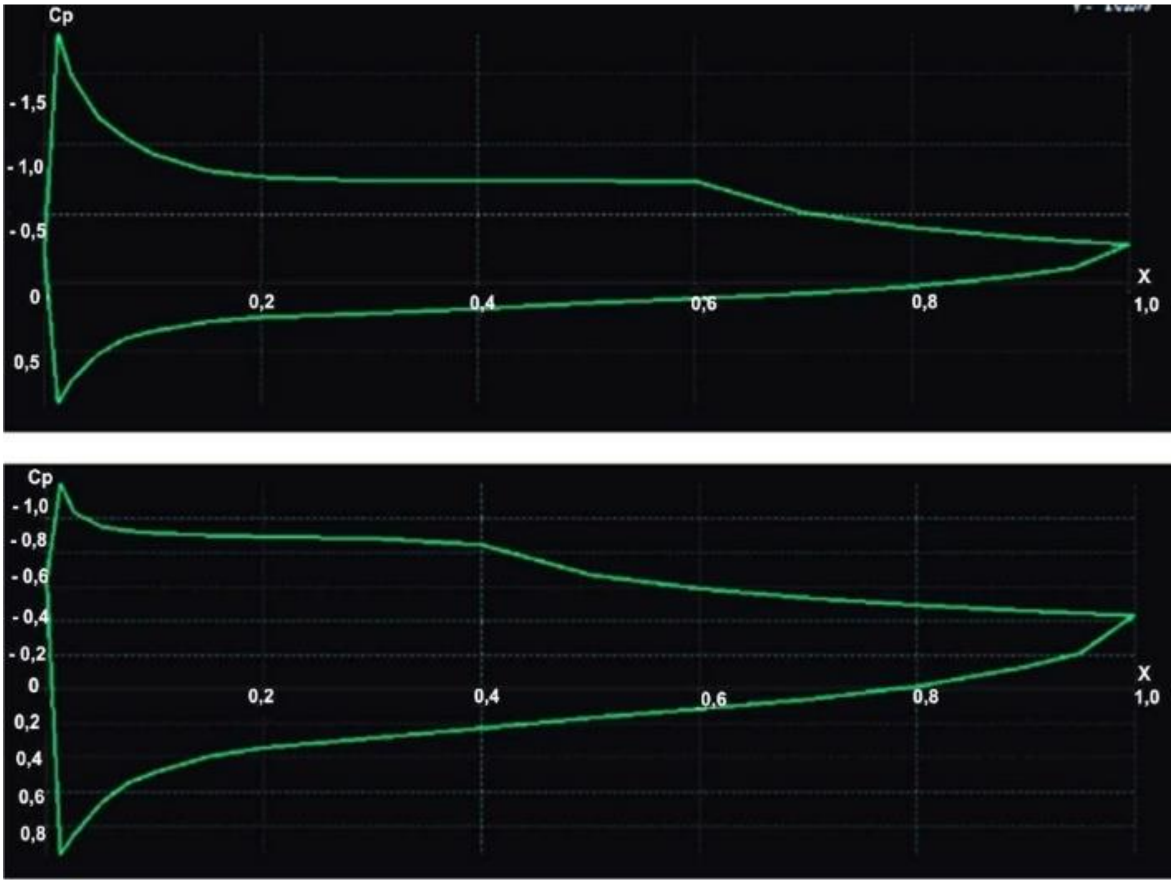
Angle (Degrees)	ClarkY (CD)	Naca 4412 (Cd)
15th	0.09	0.12
30th	0.24	0.27

This difference is probably related to the area of the boundary layer that forms at different angles of attack. In the Naca 4412 profile, the increase in the boundary layer was smaller due to a more intense flow, while in the ClarkY profile a possible increase in the boundary layer was formed due to the flow reduction, generating a more significant increase in the area of the boundary layer, as the streamlines are strictly correlated with the pressure distribution around the object under analysis.

A simulation was carried out using the Xflr5 software to obtain a parameter on the behavior of the boundary layer of the Naca 4412 and ClarkY profiles . Figure 11 presents a comparison of the pressure coefficient (Cp) in the Naca 4412 profile vs the angle of attack in a standard-sized blade.

Figure 11

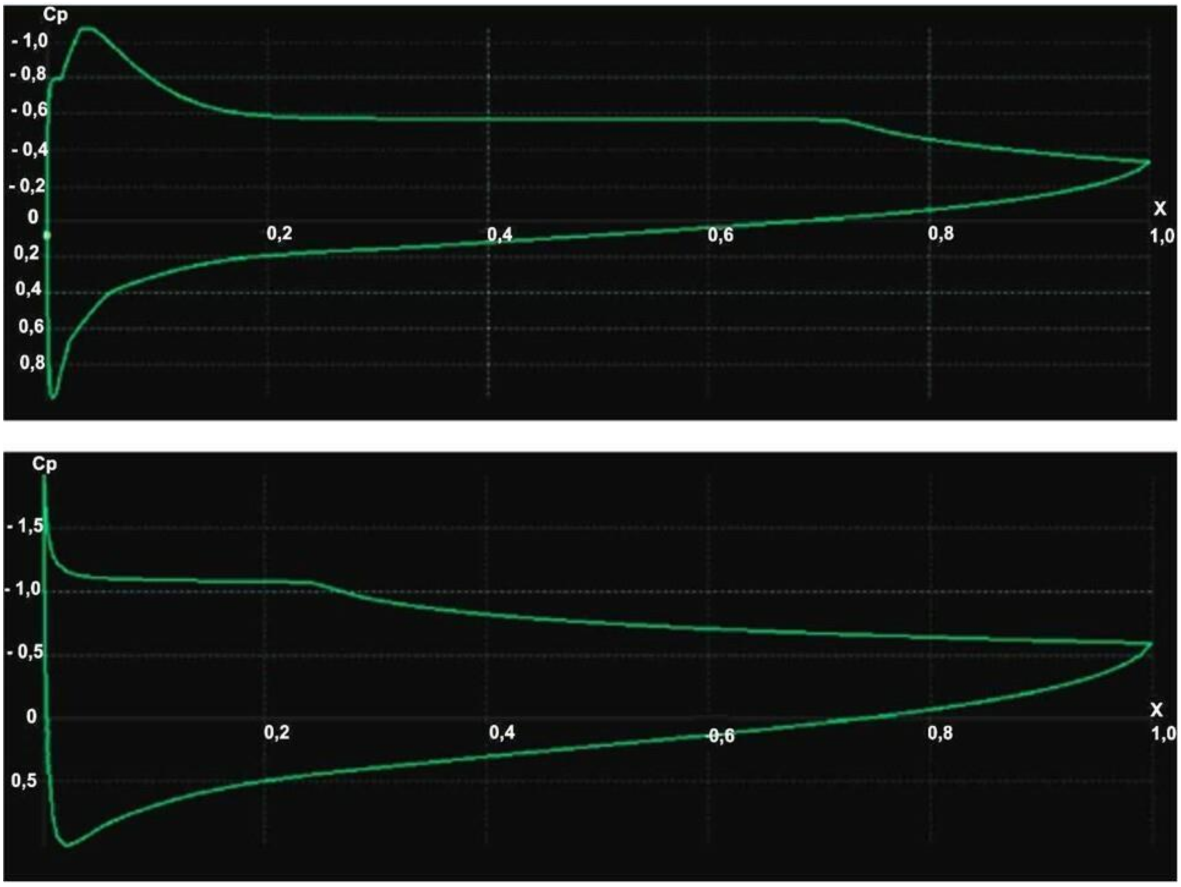
Pressure coefficient (Cp) in the Naca 4412 profile as a function of the angle of attack on a standard size blade . The angle of attack in the upper figure is 15º and, in the lower one, 30º



In Figure 12, a comparison of the pressure coefficient by angle of attack is shown also in a normalized blade with the ClarkY profile . In this figure, it is possible to observe that the boundary layer in the ClarkY profile is more predominant when the angle of attack is changed, observing the pressure distribution around the blade. Therefore, it can be seen that, with the best flow based on the Naca 4412 profile, chosen for the job, this profile stands out in terms of efficiency compared to the ClarkY profile .

Figure 12

Pressure coefficient (Cp) in the ClarkY profile as a function of the angle of attack on a blade of normalized size . The angle of attack in the upper figure is 15º and, in the lower one, 30º

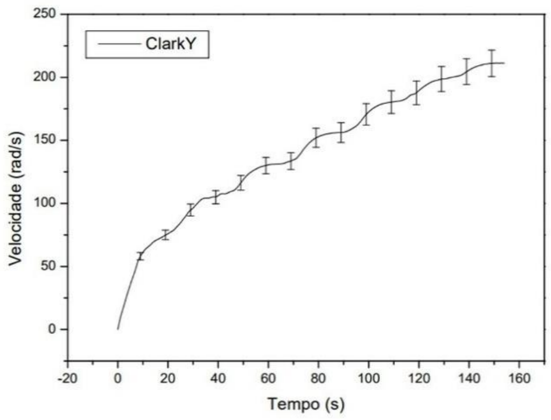


The data were obtained under the following conditions: the Reynolds number was found to be 30,000. As the Reynolds number is above 2,400, the regime is turbulent. The measurements were carried out at a temperature of 27ºC, with an air density equal to 1.17 kg/m³.

In Figure 13, the angular velocity values as a function of time for the ClarkY profile are presented . It is observed that, with the increase in speed, the measured dispersions indicate an instability of the fluid as it passes through the blades due to the increase in speed. This is in line with Ludwig Prandtl 's theory , according to Altenbach and Bruhns (2020), which states that increasing speed can result in a loss of efficiency at certain points of the blade, especially at the tip, which suffers from the difference in tangential speed. in relation to the fluid velocity, causing a loss of efficiency.

Figure 13

Angular velocity values as a function of time for the ClarkY profile



In Figure 14, the values of angular velocity in relation to time are presented for the Naca 4412 profile. This profile presents less dispersion, as indicated by the standard deviation, which is in agreement with the results of maximum velocity as a function of time. . The likely explanation for these data is that the Naca 4412 profile has greater aerodynamic stability compared to the ClarkY profile , allowing better energy absorption for the transformation of the rotational movement due to the greater lift coefficient (Cl) and torsion of the shovel.

Figure 14

Angular velocity values in relation to time for the Naca 4412 profile

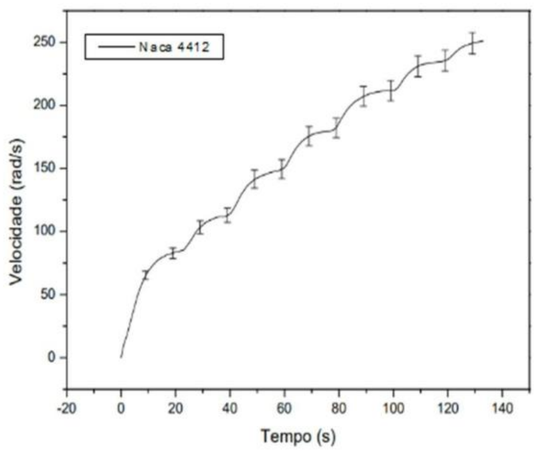
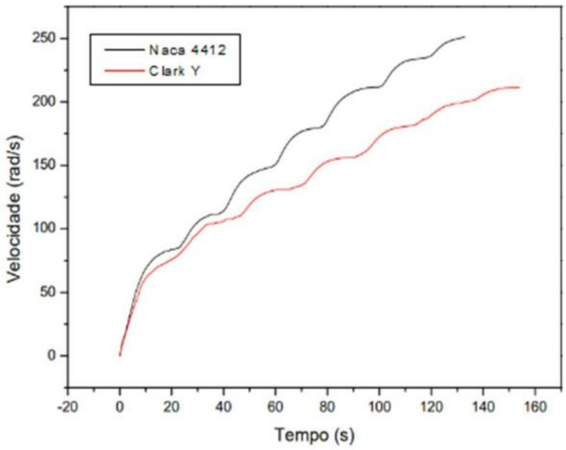


Figure 15 presents the difference in the total angular velocity measurement between the Naca 4412 and ClarkY profiles . The Naca 4412 profile showed a shorter accommodation time to reach its maximum speed , a higher maximum angular velocity and an average efficiency 23% higher compared to the ClarkY profile .

Figure 15

Difference in total angular velocity measurement between Naca 4412 and ClarkY profiles



In short, the simulation carried out in the Xflr5 software allowed a comparative analysis between the Naca 4412 and ClarkY profiles in relation to the behavior of the boundary layer. The Naca 4412 profile demonstrated greater efficiency, as evidenced by the pressure coefficient (Cp) in relation to the angle of attack , as shown in Figure 11. In contrast, Figure 12 illustrated that the boundary layer in the ClarkY profile is more prominent with the variation of the angle of attack, reflecting a lower efficiency. The data were obtained under turbulent regime conditions, with Reynolds number above 2,400, temperature of 27ºC and air density of 1.17 kg/m³. Figures 13 and 14 show the angular velocity values in relation to time for the ClarkY and Naca 4412 profiles, respectively, highlighting the superior aerodynamic stability of the Naca 4412 profile, which presented an average efficiency 23% higher than the ClarkY profile , suggesting its suitability for applications in small diameter wind turbines.

The results obtained from the aerodynamic parameters of the ClarkY and Naca 4412 profiles indicate superior efficiency for angles of attack between 50º and 60º. The blades, operating at the same speed as the wind tunnel under these conditions, achieve higher revolutions per minute (RPM), which increases efficiency in energy production without additional manufacturing costs. The Naca 4412 profile proved to be more suitable for applications in small wind turbines, such as urban energy generation, due to its better responses to wind tunnel speeds compared to the ClarkY profile .

The difference in velocity times of the Naca and ClarkY profiles can be explained by physical effects, such as the boundary layer in the blade flow. The Naca 4412 profile, with its characteristic twist, generates an area in the direction of flow that helps increase the support force. This results in a 23% higher average efficiency compared to the ClarkY profile .

The lift and drag force values of the Naca 4412 and ClarkY profiles showed significant differences , with the Naca 4412 profile presenting higher values in both cases. These results are aligned with the aerodynamic characteristics of these profiles and contribute to the understanding of their efficiency in different operating conditions.

The analysis of the lift and drag coefficients also reinforces the superiority of the Naca 4412 profile in terms of aerodynamic efficiency. The difference observed between the profiles confirms that, in addition to the twist of the Naca 4412 profile, its aerodynamic characteristics contribute significantly to the gain in blade efficiency .

Figure 11 to Figure 15 provide a clear visualization of the profile behaviors in relation to the aerodynamic parameters studied, confirming the analytical and experimental results obtained. In summary, the Naca 4412 profile stands out as the most efficient choice for applications in small wind turbines, especially in urban environments.

5 CONCLUSION

Based on the tests carried out in the wind tunnel and the analysis of the Naca 4412 and ClarkY aerodynamic profiles for application in small diameter horizontal axis wind turbines, it is concluded that both profiles are suitable for this specific application. The computer simulation also corroborated these results , highlighting the Naca 4412 profile as more efficient due to its bulging at the bottom of the blade, as expected from the literature.

The Naca 4412 profile has demonstrated stable performance over a wide range of angles of attack and is recommended for wind turbines operating at moderate wind speeds. On the other hand, the ClarkY profile , with its more accentuated curvature at the bottom, presents greater efficiency at low wind speeds , being more suitable for low power wind turbines.

Experimental data indicated that the most efficient profiles are between angles of attack of 30° and 60°, due to the response time to reach maximum speeds. The Naca 4412 profile also stood out in terms of maximum speed compared to the ClarkY profile , especially for small applications , such as urban residences.

The analysis of lift and drag forces reinforced the importance of the torsion of the Naca 4412 profile for gaining efficiency. The lift and drag coefficient showed a drop as the angle of attack increased, contributing to a gain in efficiency in the resulting force.

The aerodynamic stability of the Naca 4412 profile was evidenced by the results, showing lower dispersion measured by standard deviation compared to the ClarkY profile . These results are valuable for the development of more efficient and sustainable wind turbines.

The results obtained in the research are relevant for the future development of new aerodynamic blade designs for small diameter wind turbines, including residential applications. Suggestions for future work include the analysis of corrosive processes in wind turbines, the use of Xfoil software to analyze aerodynamic parameters, the machining of profiles in different materials and a more detailed analysis of the drag and lift coefficients in different wind and speed conditions.

ACKNOWLEDGEMENTS

Thanks to the research groups at the Federal University of Itajubá LEFTER100, GPESE and Metals Group for supporting the development of the research, as well as the Federal University of Itajubá for all the support provided.

REFERENCES

Akanto, J. M., et al. (2023). Dynamic analysis of grid-connected hybrid wind farm. *International Journal of Power Electronics and Drive System (IJPEDS)*, 14(2), 1230-1237.

Altenbach, H., & Bruhns, O. T. (2020). Prandtl, Ludwig. In H. Altenbach & A. Öchsner (Eds.), *Encyclopedia of Continuum Mechanics* (pp. 289). Springer. DOI: 10.1007/978-3-662-55771-6_289

Bald, J. (2022). Reviewing the ecological impacts of offshore wind farms. *npj Ocean Sustainability*, 1.

Barooni, M., et al. (2022). Floating offshore wind turbines: Current status and future prospects. *Energies*, 16(1), 2.

Bošnjaković, M., et al. (2022). Wind turbine technology trends. *Applied Sciences*, 12(17), 8653.

Braunbehrens, R., Vad, A., & Bottasso, C. L. (2023). The wind farm as a sensor: learning and explaining orographic and plant-induced flow heterogeneities from operational data. *Wind Energy Science*, 8(5), 691-723.

Cai, W., et al. (2024). Cross-coupling control design of a flexible dual rotor wind turbine with enhanced wind energy capture capacity. *Renewable Energy*, 220, 119629.

Çetin, N. S., et al. (2005). Assessment of optimum tip speed ratio of wind turbines. *Mathematical and Computational Applications*, 10 (1), 147-154.

Chaudhuri, A., et al. (2022). Energy conversion strategies for wind energy system: Electrical, mechanical and material aspects. *Materials*, 15(3), 1232.

Da Ponte, G. P., Calili, R. F., & Souza, R. C. (2021). Energy generation in Brazilian isolated systems: Challenges and proposals for increasing the share of renewables based on a multicriteria analysis. *Energy for Sustainable Development*, 61, 74-88.

De Jong, P., et al. (2019). Estimating the impact of climate change on wind and solar energy in Brazil using a South American regional climate model. *Renewable Energy*, 141, 390-401.

Dehghani-Sanij, A. R., et al. (2022). Assessment of current developments and future prospects of wind energy in Canada. *Sustainable Energy Technologies and Assessments*, 50, 101819.

Deng, X., et al. (2021). Review of energy storage systems for wind power integration. *Applied Energy*, 291, 116862.

Desalegn, B., Gebeyehu, D., & Tamrat, B. (2022). Wind energy conversion technologies and engineering approaches to enhancing wind power generation: A review. *Heliyon*, 8(11).

Dranka, G. G., & Ferreira, P. (2020). Towards a smart grid power system in Brazil: Challenges and opportunities. *Energy Policy*, 136, 111033.

Farr, H., et al. (2021). Potential environmental effects of deepwater floating offshore wind energy facilities. *Ocean & Coastal Management*, 207, 105611.

Gantha, B. P., Barik, S. K., & Nayak, B. (2021). Wind turbines in energy conversion system: Types & techniques. In *Renewable Energy and Future Power Systems* (pp. 199-217).

Góes, M. F. B., et al. (2021). Wind power projects in Brazil: challenges and opportunities increasing co-benefits and implications for climate and energy policies. *Environment, Development and Sustainability*, 23(10), 15341-15367.

Hadi, F. A., Oudah, S. S., & Al-Baldawi, R. A. (2020). An economic study of a wind energy project using different sources of wind data. *Iraqi Journal of Science*, 322-332.

Hamed, T. A., & Alshare, A. (2022). Environmental impact of solar and wind energy-a review. *Journal of Sustainable Development of Energy, Water and Environment Systems*, 10(2), 1-23.

Kapdi, R., Dahiya, R., & Naranje, V. (2016). Analysis and optimization of horizontal axis wind turbine blade profile. *International Journal of Research in Engineering and Technology*, 5, 19-24.

Krishnan, A., Al-Obaidi, A. S. M., & Hao, L. C. (2023). A comprehensive review of innovative wind turbine airfoil and blade designs: Toward enhanced efficiency and sustainability. *Sustainable Energy Technologies and Assessments*, 60, 103511.

Liu, F., Sun, F., & Wang, X. (2023). Impact of turbine technology on wind energy potential and CO_2 emission reduction under different wind resource conditions in China. *Applied Energy*, 348, 121540.

Liu, Y., & Zeng, Z. (2022). Wind Energy. In *The Palgrave Handbook of Global Sustainability* (pp. 1-17). Cham: Springer International Publishing.

Moghadassian, B., & Sharma, A. (2020). Designing wind turbine rotor blades to enhance energy capture in turbine arrays. *Renewable Energy*, 148, 651-664.

Mohamed, W. M. W., Ravindran, N. P., & Rajendran, P. (2021). A CFD simulation on the performance of slotted propeller design for various airfoil configurations. *CFD Letters*, 13

(3), 43-57.

Msigwa, G., Ighalo, J. O., & Yap, P. S. (2022). Considerations on environmental, economic, and energy impacts of wind energy generation: Projections towards sustainability initiatives. *Science of The Total Environment*, 849, 157755.

Nash, R., Nouri, R., & Vasel-Be-Hagh, A. (2021). Wind turbine wake control strategies: A review and concept proposal. *Energy Conversion and Management*, 245, 114581.

Nazir, M. S., et al. (2020). Potential environmental impacts of wind energy development: A global perspective. *Current Opinion in Environmental Science & Health*, 13, 85-90.

Peng, X., Liu, Z., & Jiang, D. (2021). A review of multiphase energy conversion in wind power generation. *Renewable and Sustainable Energy Reviews*, 147, 111172.

Pinto, M. O. (2012). *Fundamentos de Energia Eólica* (1st ed.). Rio de Janeiro: LTC.

Raouf, A., et al. (2023). Wind energy conversion systems based on a synchronous generator: Comparative review of control methods and performance. *Energies*, 16(5), 2147.

Roga, S., et al. (2022). Recent technology and challenges of wind energy generation: A review. Roga, S., et al. (2022). Recent technology and challenges of wind energy generation: A review. *Sustainable Energy Technologies and Assessments*, 52, 102239.

Roga, S., et al. (2022). Recent technology and challenges of wind energy generation: A review. *Sustainable Energy Technologies and Assessments*, 52, 102239.

Shafiullah, G. M., et al. (2013). Potential challenges of integrating large-scale wind energy into the power grid–A review. *Renewable and Sustainable Energy Reviews*, 20, 306-321.

Singh, U., et al. (2022). Wind energy scenario, success and initiatives towards renewable energy in India—A review. *Energies*, 15(6), 2291.

Tokul, A., & Kurt, U. (2023). Comparative performance analysis of NACA 2414 and NACA 6409 airfoils for horizontal axis small wind turbine. *International Journal of Energy Studies*, 8 (4), 879-898.

Yang, K., et al. (2021). A review of ducted wind turbines: A promising technology for wind energy harvesting. *Renewable and Sustainable Energy Reviews*, 137, 110653.