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Original Research

Optimal Airfoil Selection for Small Horizontal Axis Wind Turbine Blades: A Multi-Criteria Approach

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Abstract

Over the last century, the growing demand for clean energy has emphasized wind energy as a promising solution to address contemporary energy challenges. Within the realm of wind energy, the wind turbine plays a pivotal role in harnessing the kinetic energy of the wind and converting it into electrical power. Among the various components of the wind turbine system, turbine blades assume a critical role in capturing the wind's kinetic energy and converting it into rotational motion. Consequently, the design of wind turbine blades holds the utmost importance in determining the overall performance and efficiency of the entire wind turbine system. One essential aspect of blade design involves selecting an appropriate airfoil. Throughout history, numerous airfoil profiles have been developed for various applications. Notably, National Advisory Committee for Aeronautics (NACA) and National Renewable Energy Laboratory (NREL) airfoils have been tailored for aircraft and large-scale wind turbine blades, respectively. However, the quest for suitable airfoil types for small-scale wind turbine blades has been ongoing. This study delves into an examination of over 62 distinct NACA and NREL aerofoil types tailored for small horizontal-axis wind turbine blades. Employing specialized software, namely QBlade, specifically designed for modeling and simulating wind turbine blades, the study calculates key parameters such as power output, stress, deformation, and weight for each airfoil. Subsequently, based on the simulated data, the optimal airfoil is identified using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) multi-criteria selection approach. This selection process takes into account simulation results pertaining to power output, stress, deformation, and weight. The decision-making process involving multiple criteria is facilitated using Excel and Python. The findings of this study reveal that among the 62 airfoil types under consideration, the NACA 0024, NACA 2424, and NACA 4424 airfoils emerge as the most suitable choices for small horizontal-axis wind turbine blades.

Keywords: wind energy, airfoil selection, horizontal axis wind turbine blades, multi-criteria approach

1. Introduction

The demand for Energy has been increasing significantly over the past years. Energy in the form of electricity has become a central commodity for the survival of human beings (Gopinath & Meher, 2018). Urbanization and rapid economic growth are the major factors for the rise in the demand of electricity over the past decades. By 2030, global electricity consumption is expected to reach 31657 TWh (Shahbaz et al., 2015). Previously the demand for electricity was met by the burning of fossil fuels which caused the environment to suffer as a consequence. This has resulted on a shift in the focus of the production and utilization of energy on clean and renewable energy sources. The use of renewable energy has fascinated the world's interest, as it can be used to meet current and future energy needs. Of all the available options for renewable energies, wind energy has become one of the inevitably promising energy source options, owing to its cost-effectiveness, sustainability, and low environmental impact (Hsu et al., 2014; Liu, 2016).

An efficient generation of electricity from wind requires a well organised equipment and set of tools. The mass, shape and size of each part plays an important role on the process. One of the critical parts of a wind turbine is its blades. The shape of wind turbine blades has direct impact on both performance and cost of power production. This is because the efficiency of the wind turbine blades decide the con-version of kinetic energy associated with wind to mechanical energy (Torque) then power generation (Beig & Muyeen, 2016). The efficiency of the rotor in extracting power from the wind is a function of the aerodynamic characteristics of the airfoil sections used in the design of the rotor blades. The blade is made up of a number of different airfoil cross sectional aerodynamic shapes (Corke et al., 2015; Islam et al., 2019).

An airfoil is the foundation of wind turbine blade design, and accordingly, optimizing its design plays a key role in improving aerodynamic performance, noise control, and structural robustness of a rotor blade (Sudarsono et al., 2013). Figure 1 indicates how the airfoil distributed along the blade. For the last three decades, different airfoil was developed by different companies such as National Advisory Committee for Aeronautics (NACA), National Renewable Energy Laboratory (NREL) were used for wind turbine blades. But NACA series airfoil were designed for developing airplane wings. Also NREL has developed air-foils specifically designed for large scale wind turbine blade applications (Islam et al., 2019).

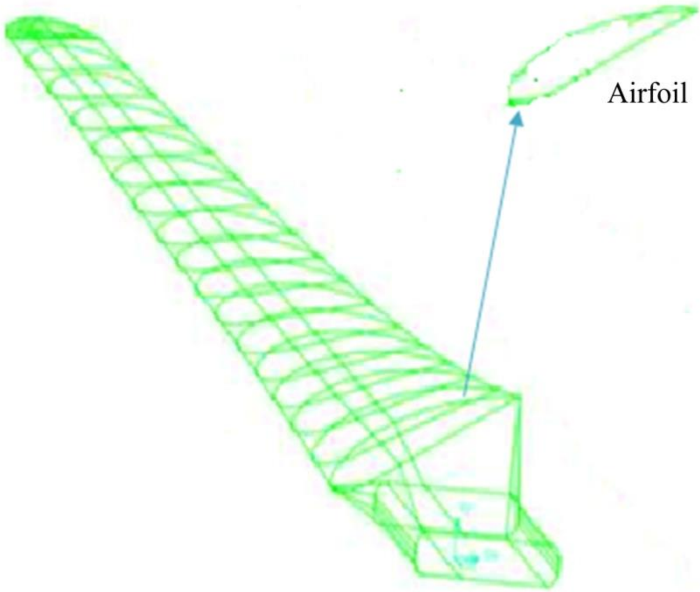

Fig. 1. Blade of wind turbine and its airfoil distribution (customized from Sudarsono et al., (2013)).

Both NACA and NREL have not developed initially for small scale wind turbines. While NACA airfoils have been widely used in various applications, including wind turbine blades, they also possess certain limitations and challenges. The NREL airfoils, such as the NREL S-series airfoils, are primarily designed and optimized for large-scale wind turbines (Islam et al., 2019). While these airfoils have been extensively tested and proven effective for utility-scale wind turbines, they may not be suitable for small-scale wind turbine blades due to several reasons (Osei et al., 2020) such as Reynold number, scale effects and structural considerations. Small-scale wind turbines typically operate at lower wind speeds, resulting in lower Reynolds numbers. But the NREL airfoils are optimized for higher Reynolds numbers typically encountered by large-scale turbines.

For small scale wind turbine, researchers have primarily focused on developing new airfoil (Noronha & Krishna, 2021; Osei et al., 2020; Wang & Li, 2021), selecting an appropriate airfoil from the developed airfoil such as NACA and NREL series (Islam et al., 2019) to enhance the efficiency of wind turbines. For instance, Islam et al. (Islam et al., 2019) presented a comparison study of different airfoils from the NACA and NREL airfoil families, aiming on suitability for small horizontal wind turbines, and finally showed that NACA airfoils have better average performance criteria whereas NREL airfoils have better stability criteria. For The comparisons, the criteria are: maximum glide ratio at lower and higher Reynolds number, difference between angle of attack between lower and higher Reynolds number and percentage deviation of maximum glide ratio from stall point. Noronha and Krishna (2021) conducted comparison of different airfoils based on the selected airfoils. Result were analyzed by using QBlade software with different Reynolds number (Re_c) and considering different angles of attack (AOA) using Computational Fluid Dynamics and QBlade, and the result showed that SG6043 is the suitable airfoil for small horizontal axis wind turbine with low wind speed.

Selection of airfoils needs criteria for selecting an optimum one for wind turbine blades. Others have concentrated on selecting airfoils based on their properties. However, these selection methods fail to address the aforementioned challenges adequately. They merely prioritize the properties possessed by the airfoils without assessing their suitability and effectiveness for wind turbine blades. Unfortunately, this approach proves to be ineffective as certain airfoils were originally designed for diverse applications, such as aircraft, and operate under significantly different conditions. To overcome this limitation, the most effective strategy for airfoil selection is to empirically evaluate the performance of each airfoil in the context of wind turbine blades.

In the past, the selection of airfoils for small-scale wind turbines has often been limited to single-criterion decision-making, lacking in-depth assessments. However, in contemporary times, there is a growing trend towards employing multi-criteria decision-making (MCDM) techniques. These methods are increasingly utilized for determining preferences, such as selecting the most suitable wind turbine types, thereby addressing the limitations of previous approaches techniques (Rehman et al., 2020). MCDMs are also employed for material selection in wind turbine blade construction blades (Okokpujie et al., 2020), as well as across various other sectors. In the context of small-scale wind turbine blade design, the adoption of multi-criteria selection methods is becoming imperative. When it comes to airfoil selection criteria, MCDMs offer the advantage of simultaneously evaluating numerous parameters. These parameters may encompass aspects like lift-to-drag ratio, stall behavior, structural integrity, and manufacturing feasibility. These MCDM approaches involve the analysis and ranking of various airfoil designs through the application of mathematical models and decision matrices. This holistic approach enables a comprehensive evaluation of airfoil options, leading to more informed and effective decision-making processes.

Indeed, for small-scale wind turbines, the utilization of multi-criteria decision-making is essential when it comes to selecting an airfoil. With this in mind, our study focuses on evaluating various NACA and NREL airfoils to determine their compatibility with small horizontal-axis wind turbines. To conduct these assessments, we turned to QBlade software, which has been purposefully crafted for the analysis of wind turbines based on the blade element momentum theory. As a novelty, an extensive research of over 62 NACA and NREL aerofoil types tailored for small horizontal-axis wind turbine blades was carried out. Key parameters such as power output, stress, deformation, and weight for each airfoil were numerically assessed using QBlade program. Subsequent to the simulation phase, we rigorously scrutinized the results obtained from the software. To make an informed decision regarding the most suitable airfoils, we applied a multi-criteria decision-making approach known as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This approach has been tailored specifically to cater to the unique requirements and constraints associated with small-scale wind turbines, ensuring a methodical selection process for the most appropriate airfoils in this context.

2. Methodology

To achieve the overarching goals of this research paper, a logical flow diagram (Fig. 2) was developed to provide a structured framework. This diagram serves as a visual representation of the sequential steps and connections that will guide the research process and ensure the attainment of the desired objectives. Figure 2 illustrates the sequential process of our study. The initial step involves the modeling and simulation of all the chosen airfoils, during which we calculate essential parameters such as power out-put, weight, stress, and blade deflection for each airfoil. Following this, the second step encompasses the selection of the optimal airfoil from the pool of candidates. This selection is based on a comprehensive evaluation that takes into account the calculated power output, weight, stress, and deflection, employing a multi-criteria decision-making methodology known as TOPSIS.

2.1. NACA and NREL airfoil types

In this study, we incorporated a total of 50 NACA series airfoil types, along with 10 NREL variants, and an additional 2 distinct airfoil types. To obtain the essential *x* and *y* coordinate data for each of these airfoil profiles, we sourced this information from an open-source airfoil data repository available at http://airfoiltools.com/ as referenced in (AirfoilTools, 2013). This comprehensive dataset served as the foundation for our simulations and evaluations, enabling us to assess the suitability of these diverse airfoil profiles for our research on small horizontal-axis wind turbines.

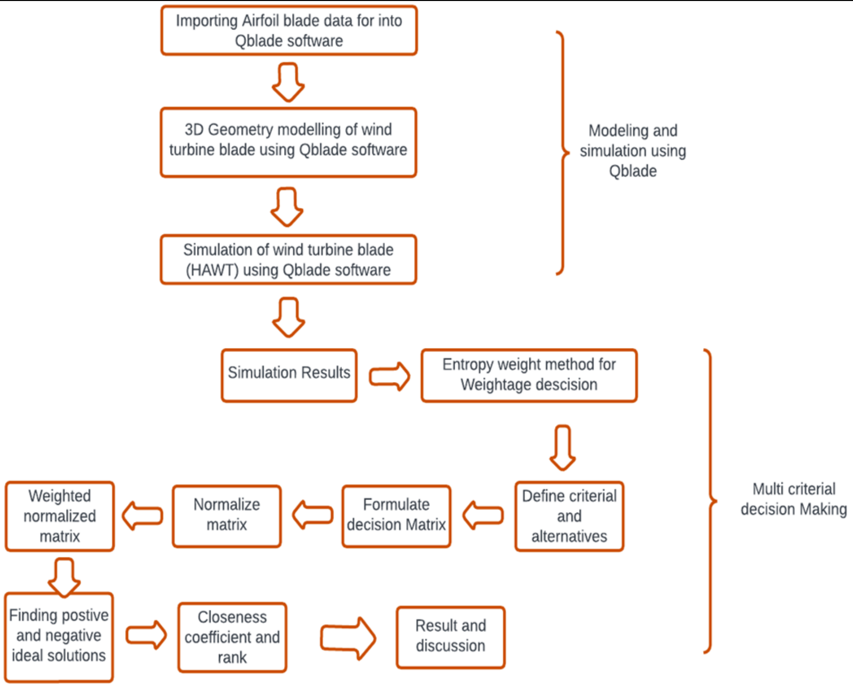

Fig. 2. Schematic flow diagram for methodology of the study.

Those airfoils have varying geometries, including differences in thickness, curvature, and camber distribution, leading to distinct aerodynamic performances. NREL's S807, S808, S809, S812, S816, S819, S823, S827, and S835, for instance, are designed by the NREL and are tailored for specific wind turbine applications, with variations in lift and drag characteristics. Similarly, AS5048 (18%) and NLR-7301 are airfoils optimized for particular aerodynamic efficiency and structural considerations. On the other hand, airfoils like NACA 63A010, 63-015A, 63-210, and 63-212 feature unique combinations of camber and thickness distributions, affecting their lift and drag performance across different angles of attack. Additionally, NACA airfoils such as 63-215, 63(2)-215 MOD B, 63-412, and 63-415 offer variations in thickness and camber to suit diverse aerodynamic requirements. Furthermore, NACA series airfoils like 64-008A, 64-012A, and 642-015 exhibit differences in thickness and camber for specific lift and drag characteristics at varying Reynolds numbers. Lastly, NACA airfoils such as 22112, 23012, and 23015 possess unique geometries optimized for specific applications, while others like NACA 0006, 0008, 0009, and 0010 feature variations in thickness and camber suitable for different aerodynamic conditions. These variations in airfoil geometries ultimately influence the aerodynamic performance, structural integrity, and overall efficiency of wind turbine blades.

2.2. Parameters for blade design for each airfoil

In this study, we employed existing parameters from small-scale wind turbine blades. The specific blade chosen for our airfoil analysis is part of a small horizontal-axis wind turbine (HAWT) utilized by the Department of Aerospace and Mechanical Engineering at the University of Notre Dame, Indiana, as detailed in (Corke et al., 2015). We utilized the wind turbine data to create a model of the blade geometry, which includes characteristics such as the chord length and twist angle.

The pertinent specifications of this turbine and its rotor geometry are comprehensively outlined in Table 1. The notations include the Reynolds number, which characterizes the flow regime of the air over the blade, as well as coefficients such as $c_d(\alpha)$ and $c_l(\alpha)$ representing the drag and lift forces as functions of the angle of attack (α) respectively. Additionally, parameters like the tip-speed ratio (λ), number of blades (B), and radius (R) of the blade are crucial in determining the efficiency and behavior of the turbine. Other important notations include $V_{\text{cut-in}}$, $V_{\text{cut-rated}}$, and $V_{\text{cut-out}}$, denoting the wind speeds at which the turbine starts generating electricity, reaches its rated power output, and shuts down to prevent damage, respectively. Hub heights indicate the elevations at which the turbines are installed, while the composition of the blade material is often described using terms like Glass/epoxy *E*. Furthermore, density (ρ) represents the mass per unit volume of air, influencing various aerodynamic and structural aspects of the turbine design.

Table 1. Characteristics of the University of Notre Dame wind turbines rotor, prepared on the basis of (Corke et al., 2015).

Parameter	Value
Re_c	0.5×10^6
$c_d(\alpha)$	$0.327 + 0.1059\alpha - 0.0013\alpha^2$
$c_l(\alpha)$	$0.006458 - 0.000272\alpha + 0.000219\alpha^2 - 0.0000003\alpha^3$
λ	$-2° \leq \alpha \leq 12°$
B	3
R	4.953 m
$V_{\text{cut-in}}$	3.0 m/s
$V_{\text{cut-rated}}$	11.6 m/s
$V_{\text{cut-out}}$	37 m/s
Hub heights	20 m
Glass/epoxy E	25 GPa
Density (ρ)	1915 kg/m^3

2.3. QBlade software for wind turbine blade modelling and simulation

2.3.1. QBlade

QBlade is an open-source tool developed at the Berlin Institute of Technology (TU Berlin) to assist in wind turbine blade design and simulation (Marten & Wendler, 2013). It is designed to be an all-in-one solution for aerodynamic wind turbine design and simulation. Unlike some other tools, it does not require data import from external sources or format conversions. QBlade offers various functionalities accessible through its graphical user interface (Marten & Wendler, 2013). Essentially, it's a collection of methods and tools for creating early-stage wind turbine blade designs.

For finite element simulations, it's crucial to consider the aerodynamic loads. The primary types of wind loads that significantly impact blade structural strength and stiffness are aerodynamic loads. These loads can be divided into tangential (F_T) and axial (F_N) force components, which can be calculated using the following equations:

$$F_N = L(\alpha)\cos\phi + D(\alpha)\sin\phi \tag{1}$$

$$F_T = L(\alpha)\sin\phi - D(\alpha)\cos\phi \tag{2}$$

Here, ϕ represents the flow angle, α is the angle of attack, $L(\alpha)$ and $D(\alpha)$ are the coefficients of lift force and trust force, respectively, and F_N and F_T are the normal and tangential forces, respectively.

2.3.2. Modeling and simulation process

The modeling and simulation were conducted in accordance with the following steps.

1) The turbine geometry data, as provided in the Table 1, was used to import the airfoil into QBlade for blade modeling.
2) Subsequently, the blade model was employed in nonlinear lifting line simulations within the software, using airfoil data obtained from an airfoils tool website.
3) The same input parameters, including radius, wind speeds, number of blades, tip speed ratio, and material properties, were applied to each analysis, except for the airfoil coordinates, which were imported.
4) The blade model was then imported into QFEM (QBlade's Finite Element Method module) to define the mechanical properties, utilizing glass fiber reinforced material properties outlined in Table 2.
5) The aerodynamic load, consisting of both tangential and normal forces, was specifically computed for an average wind speed of 11.6 m/s, representing the University of Notre Dame Wind Turbines rotor.
6) This aerodynamic load was then applied to the blade model to calculate stresses, total deformation, and the weight of the blade. For each airfoil the calculated results i.e. power, weight, stress and deformation was listed in Table A1 (Appendix A).

3. TOPSIS for multi-criteria selection

TOPSIS stands for "Technique of Order Preference Similarity to the Ideal Solution". It is a multi-criteria decision analysis (MCDA) method that was first introduced by Hwang and Yoon (1981). The method is based on finding an ideal and an anti-ideal solution and comparing the distance of each one of the alternatives to those. It has been successfully applied in various instances and can be considered as one of the classical MCDA methods that has received a lot of attention from scholars and researchers (Papathanasiou & Ploskas, 2018).

One of the methods used for multi-criteria selection is TOPSIS. Of the numerous criteria decision-making (CDM) methods, TOPSIS is a useful technique for ranking and selecting a number of possible alternatives by measuring Euclidean distances. In this technique, a set of alternatives is compared based on the weights specified for each criterion. The results are then normalised and the geometric distance between each alternative and the ideal alternative are calculated. This method is used in different sectors for selecting things which have many conflicting criteria (Balioti et al., 2018).The method is simple and computationally efficient. The procedure of TOPSIS consists of a series of steps listed below (Fu, 2008).

Step 1: define/identify the decision criteria and alternatives.

The TOPSIS approach to the multi-criteria selection of airfoil geometry requires meeting additional decisions criteria and identification of alternatives. In this work, 62 airfoil geometries were considered based on the five decision criteria. The decision criteria are: i.e. power, weight, stress, deflection, and torsional frequency of turbine blades, and the alternatives are the airfoils listed in Table A1 (Appendix A).

Step 2: formulation and normalization of the decision matrix. The matrix listed in Table A1 (Appendix A), is normalized using Eq. (3).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m}(x_{ij})^2}},\ i = 1, \ldots, m \text{ and } j = 1, \ldots, n \tag{3}$$

where: r_{ij} and x_{ij} are normalized value of the decision matrix element and original value of the decision matrix element, respectively; m is the number of alternatives or airfoil types and n is the number of decision criteria or attributes.

Step 3: weightage calculations for the attributes.

The third requirement is to assign weights to each of the five criteria to calculate the weighted normalized decision matrix. One of the appropriate methods used for weight calculation is an entropy method, which is used for the evaluation of weights for CDM. The entropy method uses the decision table to compute the weights regardless of the operator's choice. Entropy methods have gained much importance in recent years, as these methods reduce the decision makers' experiments as much as possible by implementing mathematical computation for determining the weights. In the entropy method, the higher the difference in performance values, the more weightage is considered, and the airfoils with similar performance are given lower weightage. The following is a common procedure for objective weight through entropy, which was listed as shown in steps 1–2. A detailed procedure of the entropy method is given with examples by Lotfi & Fallahnejad (2010).

Step 1: normalization of performance indices in decision matrix to obtain the project outcomes p_{ij}:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{4}$$

Step 2: computation of the entropy measure of project outcomes using the following equation:

$$E_j = -k \sum_{i=1}^{m} p_{ij} Lnp_{IJ},\ \text{in which } k = 1/ln\ (\text{m}) \tag{5}$$

where L *is* natural logarithm base, p_{IJ} is normalized project outcome.

Step 3: using the entropy concept to determine the objective weight w_j:

$$w_j = \frac{1 - E_j}{\sum_{i=1}^{n} 1 - E_j} \tag{6}$$

where w_j is objective weight.

Using the stepwise formulas listed, the entropy weights for the attributes and criteria would be computed.

Step 4: construction of the weighted normalized decision matrix.

A weighted normalized decision matrix is constructed using the weightage calculations obtained in step 3 for each criterion's attributes:

$$v_{ij}=w_j r_{ij},\ j = 1, 2, \dots m,\ \ i = 1, 2, \dots n \tag{7}$$

where v_{ij} is weighted normalized decision matrix.

Step 5: calculation of the ideal best and ideal worst.

In this article the criteria (attributes) for power, the minimum value is the ideal worst, and the maximum value is the ideal best value. For stress, weight, and deflection, the maximum value is the ideal worst value, and the minimum value is the ideal best value.

Step 6: calculation of the Euclidean separation distance for each airfoil type.

Eq. (8) was used to calculate the Euclidean distance from the ideal best:

$$S_i^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^*\right)^2} \tag{8}$$

where S_i^+ is Euclidean distance from the ideal best and and v_j^* is ideal best value for criterion j.

Calculate the Euclidean distance from the ideal best using Eq. (9):

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2} \tag{9}$$

where S_i^- is Euclidean distance from the ideal worst

Step 7: calculation of the relative closeness to the ideal solution or closeness coefficient C_i:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{10}$$

Step 8: Rank of preference alternatives order. The solution with the highest value of R_i is the best solution. We developed Python code based on the TOPSIS steps for selecting an optimum airfoil. Additionally, we used Excel to verify the results and select the best alternative from the available options.

4. Results and discussion

The results and discussion are divided into two sets of analysis. In the first set, data for each airfoil was discussed comparatively to identify the best in terms of power output, stress and deflection created on the blade because of air-foil data variation, weight of the turbine blade due to airfoil data, and modal behavior of the blade. This procedure is repeated for all criteria, and the best solution is found for all airfoils. In the second analysis, the results of the TOPSIS analysis are briefly discussed. Details of these analyses are provided in the following sections.

4.1. Power output comparison

The 4.953 m wind turbine blade was modelled using the open-source tool QBlade software for each airfoil. The unsteady simulation was performed for HAWT in the time domain by using a QBlade for all airfoils. The power output and power coefficient were obtained from each airfoil with the same input parameters, such as wind speed V_{hub} = 11.6 m/s and a hub height of 20 m for 5 seconds. The power output obtained from simulation for the first five tops (maximum) and two minimums is listed in Table 2. After a detailed aerodynamic comparison based on power and power coefficient, it was concluded that NACA 6409, NACA 6412, and NACA 4412 are the most suitable airfoils for small horizontal axis wind turbines operating at low wind speeds.

Table 2. Results of selected output power.

Name of airfoil	**NACA 6409**	**NACA 6412**	**NACA 4412**	**NACA 0012**	**NACA 4415**
Power output (kW)	37.18	36.9732	36.4	36.3671	36.2179
Efficiency	0.47	0.4688	0.465	0.4649	0.4613

4.2. Comparison of weight of the blade

The QBlade software not only calculates critical parameters such as power output but also takes into account the weight of each blade when assessing different airfoil designs for wind turbines. It is worth noting that variations in airfoil data can lead to changes in blade size (Plaisier & Smeets, 2016). These size variations are directly related to the weight of the blades, which, in turn, have a significant impact on the aerodynamic power generated (Batu & Lemu, 2020). Table 3 provides a breakdown of the blade weights for the top-selected airfoils based on weight considerations. It is a well-known fact that optimizing wind turbine blade design to reduce the cut-in wind speed can lead to substantial performance enhancements (Batu et al., 2020; Eker et al., 2006). One effective approach to achieve this reduction is by minimizing the weight of the turbine blades. A lower blade weight, characterized by lower density, enables the wind blade to overcome friction and initiate rotation at lower cut-in wind speeds.

As depicted in Table 3, the weights of the wind turbine blades for the top five airfoils, ranging from minimum to maximum weight, are presented. For the sake of comparison, the last two airfoils with the maximum weight are also included. Based on these weight considerations, and after careful examination of the results, it would be advisable to consider NACA 0006, NACA 64-008A, and NACA 0008 as strong contenders for wind turbine blade applications. Furthermore, it's evident from the data that NACA airfoils outperform NREL airfoils in terms of weight considerations, further underlining their potential suitability for wind turbine blade design (Plaisier & Smeets, 2016).

Table 3. Results of selected weight of blade for best airfoils considering only weight

Name of airfoils	NACA 0006	NACA 64-008A	NACA 0008	NACA 1408	NACA 2408
Weight (kg)	44.9898	46.6282	47.2789	47.2844	47.29

4.3. Comparison of stress and deformation of the blade

Each air foil has a different shape and size. The shape and size of any structure may affect the stress-stain properties of that structure. When all the studied airfoils were applied to wind turbine blades, different stresses and deformations were obtained. The von Misses stress and deformation results for all the different airfoils listed in Table 4 were studied by targeting minimum stress to improve the life span of the blade. At a design stage of turbine blades, they are required to be low in weight. Moreover, safe stress and strain levels should satisfy the requirements of the specific application.

Table 4. Equivalent von mises stress and total deformation results of selected airfoils.

Name of airfoils	NACA 0024	NACA 2424	NACA 4424	NACA 23024	NACA23021
Von Mises stress (MPa)	499.04	502.62	505.59	505.63	689.78
Name of airfoils	**NACA 4421**	**NACA 4424**	**NACA 2424**	**NACA 0024**	**NACA 23024**
Deflection (mm)	0.4897	0.979	0.98527	0.98824	0.99

4.4. Selection of best air-foils using TOPSIS

4.4.1. Weightage calculations for the attributes

Using these listed stepwise formulas, the entropy weights for the attributes and criteria are computed and the results are shown in Table 5. This weight of the criteria is used to calculate the value and is used in step 4 of the TOPSIS methods for constructing weighted normalized decision matrixes.

Table 5. Weightage for all criteria

Power (kW)	Stress (MPa)	Weight (kg)	Deflection (mm)
0.251	0.251	0.248	0.249

4.4.2. Rank of preference

In our quest to identify the optimal airfoil for wind turbine blade applications, we took into account several crucial criteria, including power output, turbine blade weight, stress, and deflection. The outcomes of our TOPSIS analysis have been summarized in Table 6, ordered from the best-performing airfoil to the least. Our focus in this discussion is on the top fifty airfoils, as they represent the best candidates based on our evaluation.

Significantly, NACA 0024 emerges as the optimal selection, attaining the highest ranking in closeness coefficient (C_i) values among the airfoils considered. Following closely as the second-best

option across all criteria is NACA 2424. Additionally, NACA 4424 and NACA 23024 share the third position, indicating their equally strong suitability for small-scale wind turbine blade applications.
It's worth highlighting that our results diverge from single-objective selection methods used in prior research, such as SG6043 and SG6042 (Noronha & Krishna, 2021; Salgado et al., 2016), as well as from the most commonly employed airfoils for small-scale wind turbines, including NACA 0012, NACA 0015, NREL S825, and NREL S833 (Hazmoune et al., 2021).

Since the wind turbine works under complex operational conditions, we highly recommend the airfoil selected using multi-criteria decision-making methods. Our top recommendations, based on this approach, include NACA 0024, NACA 2424, NACA 4424, and others as listed in Table 6. These airfoils have demonstrated their strong suitability across a range of critical criteria, making them well-suited choices for small-scale wind turbine blade applications. The shapes of the top two airfoils, NACA 0024 and NACA 2424, are presented in Figure 3.

Table 6. Result of selected best aifoils using multi-criteria decisions.

Name of airfoil	Power output (kW)	Weight (kg)	Stress (MPa)	Deflection (mm)	C_i	Rank
NACA 0024	26.919	58.1058	499.04	0.9882	0.999996	1
NACA 2424	26.83	58.07	502.62	0.9853	0.999989	2
NACA 4424	29.393	57.95	505.59	0.979	0.999981	3
NACA 23024	23.825	58.03	505.63	0.99	0.999981	4
NACA 23021	27.624	56.2974	689.78	1.314	0.999371	5
NACA 0021	27.929	56.277	696.62	1.3156	0.999344	6
NACA 2421	33.389	56.298	697.47	1.3	0.999341	7
NACA 4421	35.597	56.3527	720.05	0.4897	0.999252	8
NREL's S835	33.359	55.4758	758.27	1.371	0.999095	9
NREL's S823	35.041	55.3279	815	1.438	0.998847	10
NREL's S827	31.943	53.0972	865	1.6016	0.998614	11
NREL's S808	34.769	55.0478	869.55	1.5285	0.998592	12
NREL's S819	33.023	54.8617	873.11	1.5583	0.998575	13
NREL's S812	34.06	53.7635	893	1.6194	0.998478	14
NREL's S809	32.19	53.7612	900.1	1.629	0.998442	15

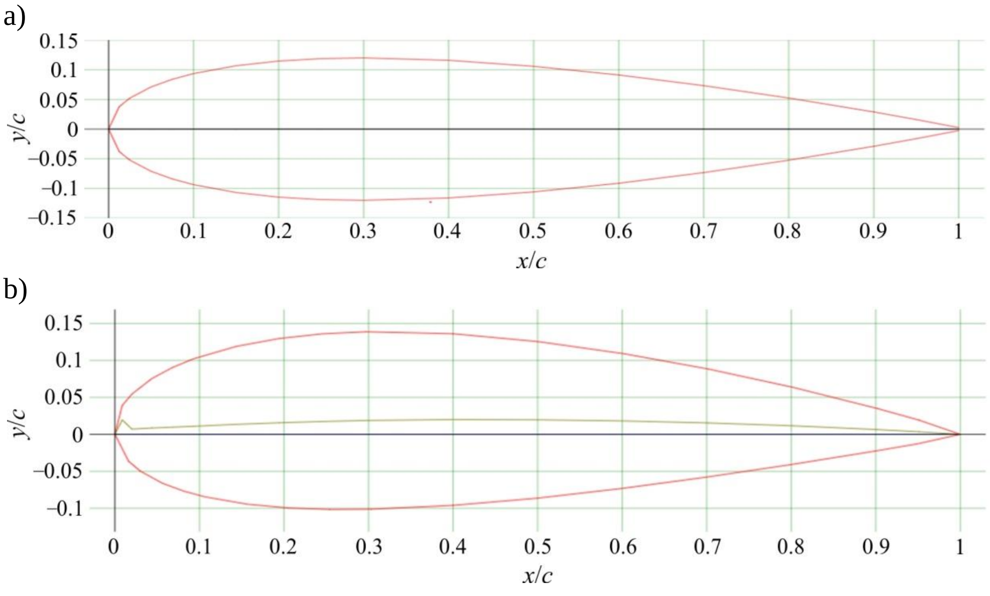

Fig. 3. Shape of the top selected airfoils by multicriteria decision-making methods: a) NACA 0024, b) NACA 2424.

5. Conclusions

One essential part of efficient wind turbine blade design is the selection of the best airfoil type. In this paper, NACA and NREL air-foils were studied for wind turbine blade application with the objective of minimum weight, stress, and maximum power. The airfoil data was taken from the airfoil tools site and the same input parameters like radius, wind speeds, number of blades, tip speed ratio, and material were used for each analysis, and except airfoil coordinates were imported. Performance of turbine blades was simulated using BEM-based finite element QBlade program. Multiple-criteria decision-making is needed to select the optimum airfoil based on the simulated results. The TOPSIS method is adapted in this paper to effectively address the requirements of a multi-criteria airfoil selection problem, where four different yet important selection criteria were considered. These criteria are power output, stress, deflection of the blade, and weight of the turbine blade. The TOPSIS method, based on information entropy, is proposed as a multi-criteria decision for airfoil selection for 62 airfoil types. The simulation analyzes are the source of the conclusions listed below:

- Based on weight, NACA 0006 is recommended since it gives low weight.
- Based on power output and efficiency, NACA 6409 was recommended.
- With the objective of low stress and low deformation, maximum power output, and low weight of turbine blades, with a MCDM method (TOPSIS), the NACA 0024, NACA 2424, and NACA 4424 would be recommended.

For future research, we recommend expanding the study to include more airfoil types and refining our selection criteria. Additionally, integrating advanced simulation techniques and considering environmental factors could enhance our understanding. We also propose validating our findings by conducting experiments on the top 10 selected airfoils. By pursuing these avenues, we aim to develop more efficient wind turbine blades for sustainable energy production.

Appendix A

Table A1. Simulation results from QBlade software.

No.	Name of airfoil	Power output (Cp)	Weight of the turbine blades (kg)	Stress (MPa)	Deflection (mm)
1	NREL's S807	33.79	53.1091	1254.55	2.154
2	NREL's S808	34.7685	55.0478	869.55	1.52845
3	NREL's S809	32.19	53.7612	900.1	1.629
4	NREL's S812	34.06	53.7635	893	1.61974
5	NREL's S816	34.0063	53.5192	921.09	1.66795
6	NREL's S819	33.0243	54.8617	873.11	1.55833
7	NREL's S823	35.0407	55.3279	815	1.43798
8	NREL's S827	31.943	53.0972	865	1.60157
9	NREL's S835	33.359	55.4758	758.27	1.37096
10	AS5048 (18%)	33.8477	53.666	1080.63	1.9599
11	NLR-7301	31.3295	52.4296	1305.82	2.24668
12	NACA 63A010	25.68	48.3348	4843.6	8.13
13	NACA 63012A	27.55	49.7144	3080.28	5.196
14	NACA 63-015A	27.7907	51.7244	1732.6	3.027
15	NACA 63-210	30.294	47.4928	5249.39	8.49
16	NACA 63-212	30.09	48.8956	3282.38	5.389
17	NACA 63-215	32.1669	50.84	1875.93	3.16502
18	NACA 63(2)-215 MOD B	32.21939	51.2481	1718.21	2.908
19	NACA 63-412	33.1729	48.9256	3265.03	5.32476
20	NACA 63-415	35.15	50.8559	1874.88	3.14
21	NACA 64-008A	21.5667	46.6282	8809.18	14.6596
22	NACA 64-012A	27.5557	49.7144	3040.28	5.19693
23	NACA 642-015	26.5361	50.799	1867.09	3.19
24	NACA 22112	31.812	50.533	2804.48	4.83103
25	NACA 23012	32.7564	50.5177	2811.07	4.82641
26	NACA 23015	33.1298	52.5278	1606.14	2.82731
27	NACA 23018	31.9138	54.4149	1021.7	1.85241
28	NACA 23021	27.6235	56.2974	689.78	1.314
29	NACA 23024	23.8248	58.03	505.63	0.99
30	NACA 23112	32.6462	50.5469	2811.12	4.804
31	NACA 24112	33.36	50.55	2805.3	4.75497
32	NACA 25112	33.96	50.5626	2780.19	4.69773
33	NACA 0006	21.96	44.9898	18986.61	30.92
34	NACA 0008	23.1354	47.2789	8206.36	13.25
35	NACA 0009	29.39	48.2185	5979.9	10
36	NACA 0010	27.6	49.0013	4561.141	7.7193
37	NACA 0012	36.3671	50.5193	2817.38	4.831
38	NACA 0015	29.93	52.49	1611.25	2.83
39	NACA 0018	28.86	54.426	1021.45	1.85541
40	NACA 0021	27.929	56.277	696.62	1.31559
41	NACA 0024	26.919	58.1058	499.04	0.98824
42	NACA 1408	29.5393	47.2844	8294.58	13.729

Table A1. *Cont.*

43	NACA 1410	30.952371	48.9982	4532.52	7.62657
44	NACA 1412	30.59	50.4761	2836.54	4.846
45	NACA 2408	31.29	47.29	8041.49	13.249
46	NACA 2410	31.95	49.006	4475.1	7.49882
47	NACA 2411	34.66	49.65	3489.81	5.844
48	NACA 2412	32.5557	50.4949	2808.49	4.78
49	NACA 2414	34.393	51.8863	1897.09	3.28281
50	NACA 2415	34.25	51.5503	1596.98	2.78483
51	NACA 2418	34.49	54.4161	1021.65	1.8423
52	NACA 2421	33.389	56.298	697.47	1.3
53	NACA 2424	26.83	58.07	502.62	0.98527
54	NACA 4412	36.4	50.575	2667.36	4.5125
55	NACA 4415	36.2179	52.5847	1553.2	2.69
56	NACA 4418	36.1381	54.5096	901.44	1.4685
57	NACA 4421	35.5968	56.3527	720.05	0.4897
58	NACA 4424	29.3927	57.95	505.59	0.979
59	NACA 6409	37.18	48.2545	4682.89	7.5859
60	NACA 6412	36.9732	50.7167	2474.15	4.1
61	NACA747A315	31.73	51.1269	1744.01	2.994
62	NACA747A415	33.3	51.1516	1740.66	2.97278

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Optymalny Dobór Profilu Łopatek Małych Turbin Wiatrowych o Osi Poziomej: Podejście Wielokryterialne

Streszczenie

W ciągu ostatniego stulecia rosnące zapotrzebowanie na czystą energię uwydatniło energię wiatrową jako obiecujące rozwiązanie umożliwiające sprostanie współczesnym wyzwaniom energetycznym. W dziedzinie energii wiatrowej turbina wiatrowa odgrywa kluczową rolę w wykorzystywaniu energii kinetycznej wiatru i przekształcaniu jej w energię elektryczną. Spośród różnych elementów systemu turbin wiatrowych, łopaty turbin odgrywają kluczową rolę w konwersji energii kinetycznej wiatru w ruch obrotowy. W związku z tym konstrukcja łopat turbin wiatrowych ma ogromne znaczenie przy określaniu ogólnej wydajności i efektywności systemu turbin wiatrowych. Jednym z istotnych aspektów konstrukcji łopaty jest dobór odpowiedniego profilu. Na przestrzeni ostatnich dekad opracowano wiele profili płatów do różnych zastosowań. Warto zauważyć, że profile NACA (National Advisory Committee for Aeronautics) i NREL (National Renewable Energy Laboratory) zostały dostosowane odpowiednio do łopat samolotów i wielkogabarytowych turbin wiatrowych. Trwają jednak poszukiwania odpowiednich typów profili do łopat małych turbin wiatrowych. W badaniu tym szczegółowo zbadano 62 różne typy profili NACA i NREL dostosowanych do łopat małych turbin wiatrowych o osi poziomej. Wykorzystując specjalistyczne oprogramowanie QBlade, opracowane specjalnie do modelowania i symulacji zachowania łopat turbin wiatrowych, w badaniach obliczono kluczowe parametry turbiny, takie jak moc wyjściowa, naprężenia, odkształcenia i masę każdego płata. Następnie, na podstawie symulowanych danych, zidentyfikowano optymalną geometrię płata przy użyciu wielokryterialnego podejścia TOPSIS (technika wyboru preferencji według podobieństwa do idealnego rozwiązania). W procesie wyboru odpowiedniej geometrii łopaty uwzględniono wyniki symulacji dotyczące mocy wyjściowej, naprężeń, odkształceń i masy. Proces podejmowania decyzji uwzględniający wiele kryteriów przeprowadzono za pomocą procedury Python w programie Excel. Wyniki badań wskazały, że spośród 62 rozważanych typów płatów, profile NACA 0024, NACA 2424 i NACA 4424 wydają się być najbardziej odpowiednim wyborem na łopaty małych turbin wiatrowych o osi poziomej.

Słowa kluczowe: energia wiatrowa, dobór profilu łopaty, łopaty turbin wiatrowych o osi poziomej, podejście wielokryterialne