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Hydrokinetic turbines, an alternative for the transformation of the Agro-Industrial sector

Carlos A. Cuenca[1, 2*], *Anthony S.* Barzola[1], *Bristol E.* Carriel[1], and *Ruben J.* Paredes[1]

[1]Escuela Superior Politécnica del Litoral, ESPOL, Facultad de Ingeniería Mecánica y Ciencias de la Producción, Guayaquil 09015863, Ecuador
[2]Facultad del Mar y Medio Ambiente, Universidad Del Pacifico, Ecuador

Abstract. This study focuses on the design optimization of hydrokinetic turbines for the agro-industrial sector, employing the Blade Element Momentum Theory (BEMT) methodology. Through detailed comparison, the NACA 4412 profile was identified as optimal, considering environmental conditions. The project developed a 5-kW turbine suitable for irrigation canals, capable of adapting to water velocities between 1.5 and 3.5 m/s, which ensures a reliable energy supply with an estimated annual production of 11 MWh. Mechanical integrity assessments using aluminum 319 alloy demonstrated safety factors above 1.3 under both static and dynamic conditions, ensuring the turbine's structural integrity. The design of the turbine, accommodating a flow speed of 2.5 m/s, reflects a commitment to maximize performance in irrigation environments. Furthermore, the study highlights the turbine's flexibility to seasonal flow variations, ensuring consistent energy generation. The implementation of hydrokinetic turbines represents a significant advancement towards sustainable energy solutions in agriculture, offering a potential reduction in operational costs and optimization of water resource management. Finally, this research underscores the transformative potential of renewable technologies in enhancing the resilience and sustainability of agricultural practices.

1 Introduction

In the dynamic landscape of the industry, the search for sustainable and efficient energy sources has become an unavoidable priority. In this context, hydrokinetic turbines emerge as an innovative solution with revolutionary potential, especially in providing energy for agricultural irrigation systems.

Rivers, as natural sources of energy, have historically been underestimated in their capacity to power irrigation systems. However, the advent of hydrokinetic turbine technology is changing this perception by offering a renewable and environmentally friendly alternative. By harnessing the kinetic force of water flow without the need for large retention structures, these turbines present an adaptable solution with a low environmental impact to meet the energy demands of agricultural areas.

* Corresponding author: cacuenca@alumni.usp.br

A critical element in the design of these turbines is the configuration of the blades. Through an evaluation process, aerodynamic profiles are selected to optimize turbine performance and efficiency. Previous studies have found that asymmetric airfoil profiles exhibit superior performance compared to symmetric profiles for this type of application, [1]. This supports the selection of an asymmetric airfoil profile for the current design to maximize the turbine's performance and efficiency. Among various options, the NACA 4412 profile from the National Advisory Committee for Aeronautics (NACA) stands out, as shown in Fig. 1, which illustrates the relationship of lift-to-drag ratios (C_L/C_D) for each analyzed NACA profile across different angles of attack, [2]. This asymmetric profile has demonstrated superior performance in terms of the lift-to-drag coefficient ratio, making it an ideal choice to maximize turbine efficiency. The optimal performance point has been identified at an angle of attack of 5°, providing the perfect balance between lift and drag.

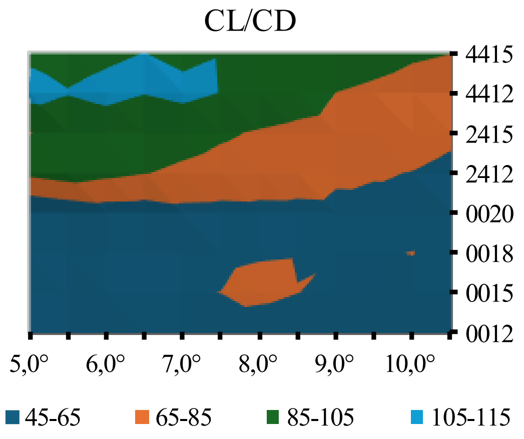


Fig. 1. Comparisons of NACA profiles based on their C_L/C_D ratio.

In this context, the Blade Element Momentum Theory (BEMT) method emerges as a fundamental tool for the design and optimization of hydrokinetic turbines [3], [4], [5]. This methodology enables accurate analysis of the normal and tangential forces acting on each blade segment, unravelling the complex hydrodynamic phenomena present in the interaction between the turbine and the water flow.

By leveraging the BEMT approach to understand and model these forces, engineers can mechanically evaluate the strength of the blades and optimize their design to maximize the energy efficiency and durability of hydrokinetic turbines. This integration of mathematical theory with hydrokinetic engineering represents a significant milestone in the pursuit of sustainable energy solutions for agriculture, promoting self-sufficiency and resilience in agricultural communities.

This study examines the potential of hydrokinetic turbines to transform the agricultural industry. The research focuses on the application of the BEMT mathematical model and the NACA 4412 aerodynamic profile in the development of these innovative technologies. By leveraging the consistent water flow in agricultural settings, this work aims to contribute to a more prosperous and sustainable future for the sector.

2 Methodology

In this study, the aerodynamic performance of eight profiles, including both symmetrical and asymmetrical NACA designs, was evaluated using the QBlade software (Academic Public License), [6], as detailed in Table 1. The objective was to identify the most suitable aerodynamic profile for the blades of hydrokinetic turbines intended for agricultural irrigation systems. Analysis within a range of angles of attack from 5.0° to 10.5° revealed that the NACA 4412 profile, highlighted in a darker grey colour, consistently outperformed the others in terms of the lift coefficient (C_L), making it the preferred choice.

Table 1. Profile selection analysis

NACA	Angle of attack											
	5,0°	5,5°	6,0°	6,5°	7,0°	7,5°	8,0°	8,5°	9,0°	9,5°	10,0°	10,5°
0012	62,6	61,8	60,2	63,6	61,8	60,4	58,9	57,8	56,5	55,8	55,0	48,7
0015	55,2	56,7	63,3	64,0	64,5	65,1	67,6	65,1	63,0	60,9	62,8	60,7
0018	52,3	52,3	57,3	57,3	58,5	63,5	64,3	64,6	64,9	64,3	65,2	61,1
0020	46,8	51,4	55,8	55,3	59,4	58,9	59,8	60,1	60,8	61,1	61,4	61,7
2412	89,1	94,4	89,7	85,6	82,2	79,1	76,4	74,1	67,8	66,1	64,6	59,6
2415	84,6	88,7	92,8	88,0	91,5	87,3	83,5	80,3	77,4	74,5	71,9	69,5
4412	112,3	106,1	111,2	105,7	110,1	104,6	99,7	95,1	84,9	81,0	73,5	67,4
4415	101,0	96,3	100,8	105,1	100,3	104,2	103,0	102,2	97,5	93,3	89,2	85,6

2.1 BEMT Methodology

The BEMT is an essential methodology in the design of hydrokinetic turbines, enabling a detailed and precise mechanical analysis [7], [8]. This approach segments the turbine blade into numerous small elements, analysing the interactions between these elements and the incident water flow, as shown in Fig. 4a. BEMT integrates the lift and drag forces acting on each element to calculate the distribution of forces along the blade's span and, consequently, the power output of the turbine.

Fig. 2 shows a flowchart based on the BEMT methodology, developed to estimate the determination of the turbine's power coefficient, which is a critical factor in assessing turbine performance [9].

Where P: Power [W]; C_{pw}: Betz's Power Coefficient; ρ : Density [kg/m3]; h: Depth [m]; v: Velocity [m/s]; Δr: Radius Differencial [m]; C_L: Lift Coefficient; C_D: Drag Coefficient; φ: Relative Angle; β: Torsión Angle; C_N: Normal Force Coefficient; C_T: Tangential Force Coefficient; a: Axial Induction; a': Angle Induction; $a_i - a_{i-1}$: Axial Induction Analysis; $a'_i - a'_{i-1}$: Angle Induction Analysis; F: Loss Factor; C_P: Power Real Coefficient.

In the BEMT methodology, design parameters such as velocity, depth, and power generation are integrated with the characteristics of the selected aerodynamic profile. Subsequently, the relative angle and torsion angle are calculated, enabling the assessment, as specified in [10], to determine the normal and tangential force coefficients.

Furthermore, for a comprehensive analysis, axial and angular induction factors are included, relating to fluid behaviour. By utilizing these factors, the relative angle is recalibrated, initiating an iterative process to determine the normal and tangential force coefficients. This iterative procedure continues until the residual error of the flow factors decreases below 1×10^{-3}.

Ultimately, the loss factor at various points along the blade is computed, aiding in the calculation of the power coefficient, as detailed in the Fig. 2. This metric serves as a crucial indicator of the potential exploitable energy.

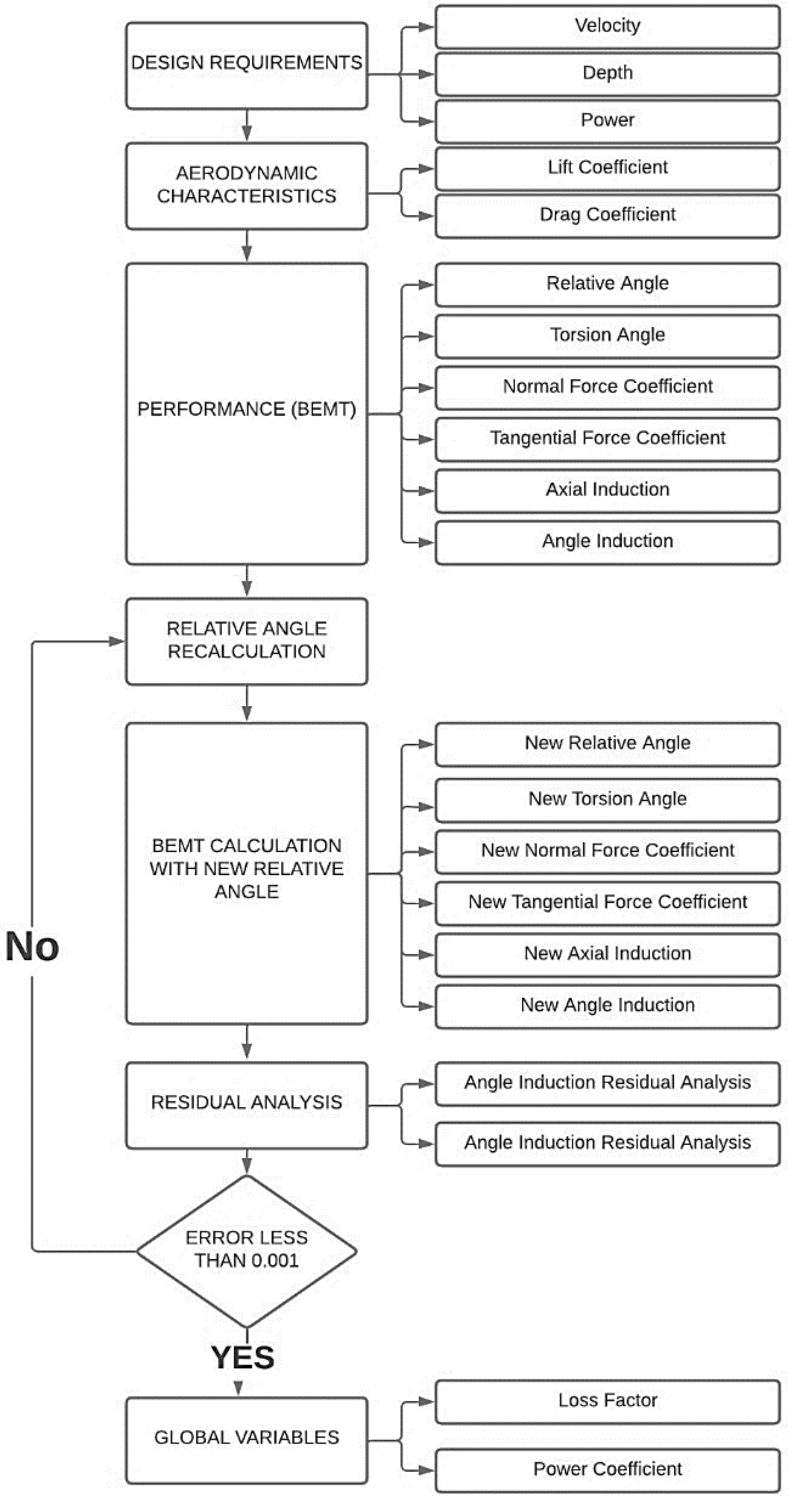


Fig. 2. Flowchart of the BEMT Methodology for Hydrokinetic Turbine Design

2.2 Rotor sizing

The sizing process is done using equation (1), [11]. In this study, the conditions and parameters shown in Fig. 5b was employed:

$$R_{ext} = \sqrt{\frac{2P_{turbina}}{C_{pw}\pi\rho v^3\eta}} \tag{1}$$

Where $P_{turbina}$: Power; ρ: Fluid density [kg/m^3]; C_{pw}: Power Coefficient; v:velocity; η: efficiency

Target power output guides rotor sizing and involves careful planning of rotor size and configuration of transmission stages, including the gearbox and generator. This integration of mechanical and electrical factors ensures optimal system performance under variable load conditions.

2.3 Axial and tangential forces

The determination of axial and tangential forces is crucial for analysing the mechanical behaviour of hydrokinetic turbine blades. Equations (2) and (3) are central to this study, as they enable the calculation of these forces, which are essential in selecting materials that provide structural stability and resilience against deformations due to varying pressure profiles.

$$F_N = \left(\frac{\rho}{2}\right)\sum_{i=1}^{10}[C_L\cos(\varphi_i) + C_d\sin(\varphi_i)]\left[\frac{V(1-a_i)}{\sin(\varphi i)}\right]^2 C_i F_i \varDelta_r \tag{2}$$

$$F_T = \left(\frac{\rho}{2}\right)\sum_{i=1}^{10}[C_L\,\mathrm{sen}(\varphi_i) - C_d\cos(\varphi_i)]\left[\frac{V(1-a_i)}{\sin(\varphi i)}\right]^2 C_i F_i \varDelta_r \tag{3}$$

Where ρ: Fluid density [kg/m3]; C_L: Lift coefficient of the hydrodynamic profile; C_d: Drag coefficient of the hydrodynamic profile; φ_i: Optimal angle of incidence [º]; α: Axial flow factor; V: Fluid flow velocity [m/s]; C_i: Chord length of the blade element [m]; F: Total loss factor; $\varDelta_r$: Length of radius of each element.

Having determined the magnitude of forces along each section of the blade, the load distribution was graphically represented and modelled using a polynomial curve. Subsequently, applying the theory of double integration, the equations for shear and bending moments were derived [12].

2.4 Mechanical-Structural Analysis

During the mechanical analysis, the stress calculation process utilized fundamental Equations (4), (5), and (6) to determine the forces acting on the blade's plane. This facilitated a comprehensive mechanical analysis of the total stress distribution along the blade, employing Equation (7).

$$\sigma_x = \sum_{i=1}^{n} \frac{M_z y}{I_z} + \frac{M_y z}{I_y} \tag{4}$$

$$\sigma_y = 0 \tag{5}$$

$$\tau_{xy} = \sum_{i=1}^{n} \sqrt{\left(\frac{V_y Q}{I_z t}\right)^2 + \left(\frac{V_z Q}{I_y t}\right)^2} \tag{6}$$

$$\sigma" = \sqrt{\sigma_x^2 - \sigma_x \sigma_y + \sigma_y^2 + 3\tau_{xy}^2} \tag{7}$$

Where: M_z, M_y: Moment about the z axis and y axis respectively [Nm]; I_z, I_y, : Inertia with respect to the z axis and y axis respectively $[m^4]$; Q: First moment of area with respect to the neutral axis $[m^3]$; t: Profile width $[m^4]$; V_z, V_y: Shear force with respect to the z axis and x axis respectively [N]; σ_x, σ_y: Normal stress with respect to the x axis and the y axis respectively $[N/m^2]$; y: Distance in y to the neutral axis $[m]$; z: Distance in z to the neutral axis $[m]$; $\sigma"$: Von Mises Stress $[N/m^2]$.

These equations are essential for comprehending the impact of external forces on the structural integrity of the component. They are also indispensable in the design and optimization of mechanical systems, ensuring their safe and efficient operation across a range of industrial applications.

2.5 Failure Theories

The methodology for analysing static failures is critical to ensure the safety and efficiency of systems. To address this, theories such as the maximum normal stress, maximum shear stress, and distortion energy are employed. These theories enable precise evaluation of material and component resistance under repeated loading conditions, allowing for the identification of potential weak points in the design. Consequently, corrective measures can be implemented to maintain the structural and operational integrity of turbines and other devices involved in renewable energy generation, where Equations (8), (9), and (10) are fundamental in this analysis:

$$n_1 = \frac{s_y}{\sigma"} \tag{8}$$

$$n_2 = \frac{s_y}{\sigma_1 - \sigma_2} \tag{9}$$

$$n_3 = \frac{s_{ut}}{\sigma_1} \tag{10}$$

Where: n_1: Safety factor of the distortion energy criterion; n_2: Safety factor of the maximum shear stress criterion; n_3: Safety factor of the maximum normal stress criterion; s_y: Yield Stress $[N/m^2]$; s_{ut}: Ultimate tensile stress $[N/m^2]$

Regarding safety considerations, assessment was conducted using the distortion energy method. By applying the von Mises stress criterion, the stress distribution within the blade was elucidated, considering the diverse loads acting upon it. Furthermore, to enhance clarity, the principal stresses were delineated on the Mohr circle, facilitating the determination of safety margins based on both the maximum shear stress and maximum normal stress criteria.

To ensure adequate resistance in fluctuating environments, criteria are selected that account for more than just static loads, considering a range of factors affecting component resistance and durability. These include vibrations from turbine operation and load fluctuations due to changes in wind speed or power demand. Additionally, component size and geometry significantly influence fatigue resistance by determining stress distribution and heat dissipation capabilities as described by the Equation (11).

$$s_e = k_a k_b k_c k_d k_e k_f s_e'' \tag{11}$$

Where: k_a: Surface condition modification factor; k_b: Resizing factor; k_c: Load modification factor; k_d: Temperature modification factor; k_e: Reliability factor; k_f: Various effects modification factor; s_e'': Fatigue resistance limit in rotating beam

The importance of these considerations stems from the fact that fluctuating loads can induce cyclic stresses in materials, potentially leading to crack formation and eventual component failure. The size and shape of turbine blades also affect stress distribution during operation, influencing fatigue resistance and the lifespan of components.

3 Result

The design of the turbine blade, utilizing the NACA 4412 profile (seen in Fig. 3), has demonstrated promising performance outcomes. The selection of this profile was predicated on its superior lift-to-drag coefficient ratio, which has facilitated more efficient airflow dynamics and enhanced the blade's ability to harness the kinetic energy of the flow. The figure depicts the geometry in non-dimensional units, with a maximum value of 1 that can be adjusted with scaling factors as needed, allowing for flexibility in representation.

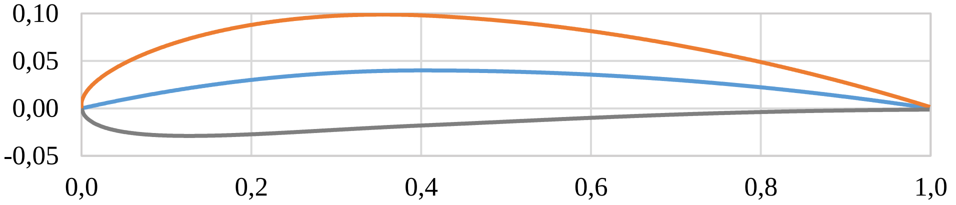
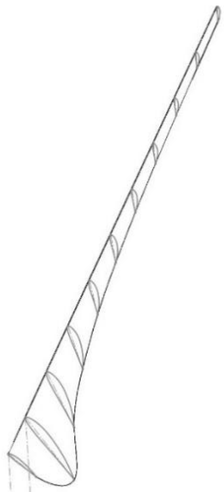


Fig. 3. NACA Profile 4412

The dimensioning of the hydrokinetic turbine for river applications, utilizing the BEMT methodology, has led to significant advancements by accounting for the specific characteristics of river flow, [13], [14]. The Fig. 4 illustrates the adjustments made to the blade profiles and the overall geometry of the turbine to optimize its efficiency in harnessing the kinetic energy of the water flow.

The specific speed is defined as the ratio between the tangential speed at the blade tip and the free flow reference speed. Conversely, the power coefficient signifies the extractable energy from the flow movement, [10]. In this scenario, the attributes of the Napo River near agricultural and livestock regions are used as a benchmark for comparison.



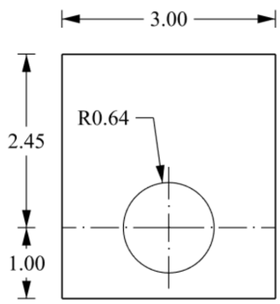
(a)

Item, Units	Value
Power, [kW]	5,0
Velocity, [m/s]	2,5
Specific speed	6,0
Power Coefficient	0,49
Gearbox efficiency	0,96
Transmission System Efficiency	0,98
Generator efficiency	0,9
General Efficiency	0,85
Temperature, [°C]	27,00
Liquid Density, [kg/m^3]	996,5
External radio, [m]	0,70
Internal Radio, [m]	0,14

(b)

Fig. 4. Turbine blade: a) 3D CAD model, b) Main characteristics of the blade

Furthermore, it is crucial to define the site-specific requirements for deploying hydrokinetic turbines in rivers to accommodate seasonal variability, water depth, and site topography, which is shown in Fig. 5, [15].



(a)

Item, Units	Value
Depth, [m]	2.45
Velocity, [m/s]	1.5-3.5
Length, [m]	4.00
Width, [m]	3.00

(b)

Fig. 5. a) Main dimensions of the water flow canal, b) Main characteristics of the turbine

The analysis of the load function, reflecting the normal and tangential forces acting on the turbine blades due to fluid interaction, has revealed consistent patterns, as shown in Fig. 6. The results outlined in Fig. 7 detail the material selection process, which is grounded in a mechanical analysis that incorporates safety factors from both static and dynamic failure theories.

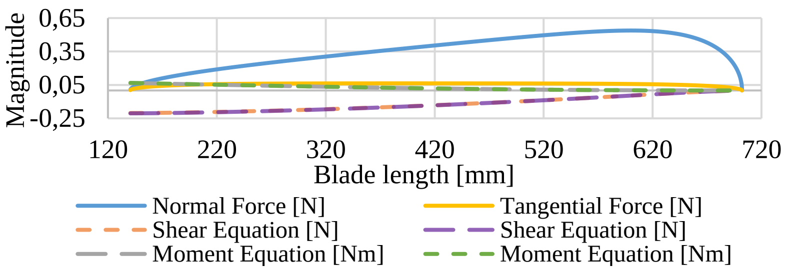
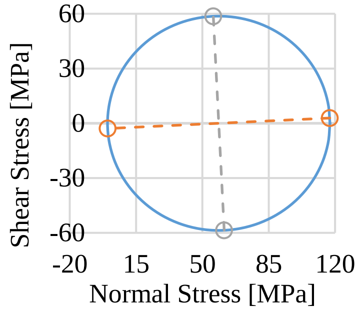


Fig. 6. Behavior of normal and tangential force along the profile.

This selection process aims to ensure the turbine's structural integrity against the significant fluid pressures encountered during operation.

MATERIAL SELECTION		
Normal Stress 1	117.24	MPa
Normal Stress 2	0	MPa
Shear Stress	2.87	MPa
Von Misses	117.35	MPa
Creep Resistance	165.00	MPa
Material	Aluminum Alloy 319	

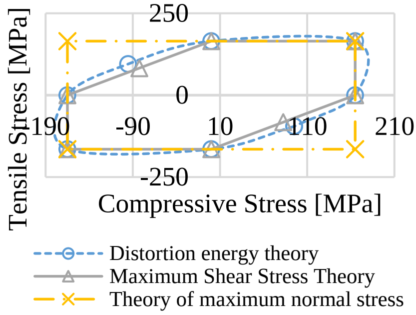
(a)



(b)

STATIC FAILURE THEORY	
Maximum Shear Stress Theory	1.406
Theory of maximum normal stress	1.407
Distortion energy theory	1.406
DYNAMIC FAILURE THEORY	
ASME Elliptic Fatigue Failure	1.22

(c)



(d)

Fig. 7. a) Material, b) Mohr's circle, c) Failure theory results, d) Static failure theory

4 Analysis

The integration of renewable technologies within the agro-industrial sector is crucial for ensuring a sustainable energy supply. Nowadays, scientists and businesses worldwide are exploring ways to harness clean and reliable energy from the environment. However, each of these renewable options has its own drawbacks.

Solar and wind power are dependent on weather conditions, while large-scale hydropower dams can potentially damage the environment. Geothermal energy requires specific geological conditions and can be costly to set up. Biofuels, on the other hand, necessitate complex technology and may not be truly carbon neutral.

Despite these challenges, the adoption of renewable energy solutions in the agro-industrial sector remains essential for achieving long-term sustainability and reducing the reliance on fossil fuels. Continued research and innovation are crucial to overcome the limitations of existing renewable technologies and develop more efficient, cost-effective, and environmentally friendly energy alternatives.

This is where a new technology called hydrokinetic systems comes in. These systems capture the energy from moving water in rivers, currents, and tides. Unlike traditional dams, they don't require blocking the water flow, minimizing environmental impact. They're also relatively easy to install and move, making them suitable for remote areas without access to power grids.

While each hydrokinetic system might not generate a lot of power on its own, by connecting them together, we can significantly increase their output. There's still a lot of research to be done to improve this technology, especially in converting water energy into electricity more efficiently. Scientists are also focusing on better turbine designs and understanding the environmental impact of these systems.

Enhancing energy efficiency and improving the competitiveness of agricultural operations are vital goals. The agro-industrial sector must reduce operational costs to better develop its production systems and achieve long-term environmental sustainability. This project involves designing a 5-kW hydrokinetic turbine, utilizing NACA 4412 profiles, to supply irrigation canals, marking a significant advancement in creating energy solutions tailored to the specific needs of these communities.

Analysis of the blade forces revealed a gradual increase in normal force along the blade length, an expected outcome due to the higher water pressure at the blade tips. Conversely, the tangential force remained relatively constant, likely due to friction and resistance to blade movement. These findings affirm the hydrodynamic design's efficacy and the turbine's ability to efficiently harness the kinetic energy of the water flow within the irrigation canal.

The blade stresses were assessed using three static failure theories: distortion energy, maximum shear, and normal stress. Findings indicate that with aluminum 319 alloy, safety factors above 1.3 are attainable under both static and dynamic conditions, ensuring the turbine's structural integrity and preventing premature failures [16].

Designed for an optimal speed of 2.5 m/s, the hydrokinetic turbine can operate across a range of water velocities from 1.5 to 3.5 m/s, accommodating the river's annual variability. This versatility allows for consistent energy generation despite seasonal flow rate changes in the irrigation canal, with a realistic annual production estimate of 11 MWh, as shown in Fig. 8.

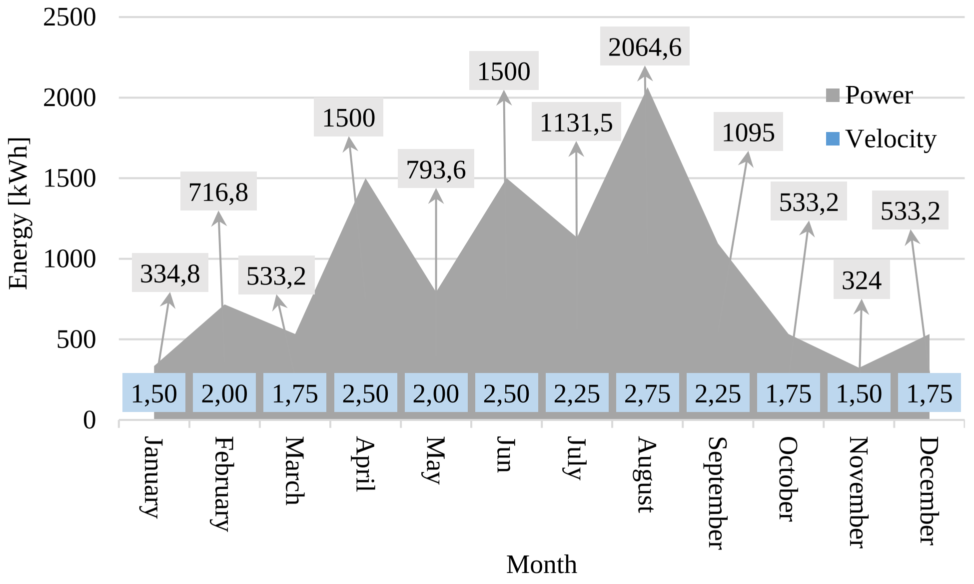


Fig. 8. Analysis of energy production in different seasons of the year.

Hydrokinetic turbines offer a promising alternative for the agro-industrial sector, leveraging the proximity of rivers and irrigation canals to generate energy. However, the flow rates vary throughout the month, necessitating a more nuanced analysis. To this end, the different speeds of the Napo River were considered to justify the energy production, [15].

Unlike conventional hydropower, these systems do not require dams, thereby minimizing environmental impact. Their ease of installation and operation makes them suitable for diverse aquatic environments. The adoption of hydrokinetic systems can bring numerous benefits, including reduced reliance on fossil fuels, improved energy security, enhanced productivity and efficiency, and decentralized energy generation.

Embracing hydrokinetic systems can power farms and food processing facilities, empower rural communities, enhance food security, and contribute to a healthier planet, ensuring a sustainable future for both the agro-industrial sector and the environment.

The project's adaptability to various industrial applications is notable, as it leverages river speeds and geographic conditions without requiring extensive infrastructure. It can conform to diverse hydrological conditions and irrigation canal requirements, offering a flexible solution for different agricultural settings [17], [18].

The deployment of hydrokinetic turbine technology holds the potential to revolutionize energy management in agricultural communities. By providing a dependable and sustainable energy source, it aids in reducing operational costs and enhancing water resource management. For instance, farmers with a 5.6-hectare area under tomato and bean cultivation, currently dependent on diesel-powered irrigation, could satisfy their monthly electricity needs, which range from 506.7 to 3571.4 kWh based on the crops' phenological stages [19], [20].

Also, the deployment of hydrokinetic turbines in the agro-industrial sector not only advances renewable energy technologies but also significantly contributes to several Sustainable Development Goals (SDGs). Specifically, this technology supports SDG 7 (Affordable and Clean Energy) by providing a reliable and sustainable energy source that enhances energy security and reduces dependence on non-renewable energy sources. Furthermore, the use of hydrokinetic turbines aligns with SDG 6 (Clean Water and Sanitation) by promoting efficient water management in agricultural practices without the need for large dams, which can adversely affect aquatic ecosystems. Additionally, the implementation of this technology contributes to SDG 13 (Climate Action) by reducing greenhouse gas emissions associated with conventional energy production methods. By integrating these sustainable practices, the project not only addresses the immediate energy needs of the agricultural sector but also promotes long-term environmental sustainability and resilience against climate variability, [21].

Developing a hydrokinetic turbine for the agro-industrial energy supply is a significant stride towards innovative and sustainable energy solutions. Its adaptability, operational efficiency, and potential positive impact on agricultural communities make it a pivotal component in the pursuit of more sustainable and resilient agricultural practices.

5 Conclusion

The choice of the NACA 4412 airfoil profile for the hydrokinetic turbine, based on comparative analyses with both symmetric and asymmetric profiles in prior research, exemplifies a pragmatic strategy aimed at enhancing turbine performance and hydrodynamic efficiency.

The application of the BEMT methodology is crucial for achieving the best outcomes in hydrokinetic turbine design at conceptual level. The turbine 1.4 m diameter turbine was optimized to function at a flow speed of 2.5 m/s and to attain a power requirement of 5 kW, showcasing a commitment to maximizing performance in irrigation canal environments. This optimization is underpinned by a detailed analysis of installation requirements, such as operational depth and a water velocity range of 1.5 to 3.5 m/s, to ensure successful deployment in agricultural settings.

The estimation of annual energy generation considers seasonal water flow variations and their effect on energy availability, coupled with an operational timeframe of 10 hours per day, offering a thorough perspective on the performance and sustainability of hydrokinetic turbines in the agro-industrial sector.

The choice of aluminum alloy 319 as the optimal material, following comprehensive mechanical analysis, guarantees the stability of the fluid-structure interaction. This selection is key to the turbine's durability and consistent performance under varying operational conditions.

6 Recommendations

Based on the findings, the following recommendations are proposed for future analyses:

Evaluating the project's feasibility with respect to the flow velocities and watercourse depths where the hydrokinetic turbine will be deployed is essential for optimizing its performance.

It is crucial to analyse the economic factors associated with manufacturing and installation across different regions to ensure the project's viability.

A simulation study to observe the structural behaviour under the forces exerted by water flow is recommended to validate the results obtained.

For successful implementation, the development of a control system is advised. This system should enable operation across variable speed ranges and safeguard the structure from potential damage.

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