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EXPERIMENTAL PERFORMANCE OF A BIOMIMETIC WIND ENERGY HARVESTING SYSTEM (BCEE) IN COMPARISON WITH STATE-OF-THE-ART VERTICAL-AXIS WIND TURBINES

DESEMPENHO EXPERIMENTAL DE UM SISTEMA BIOMIMÉTICO DE CAPTAÇÃO DA ENERGIA EÓLICA (BCEE) EM COMPARAÇÃO COM AEROGERADORES DE EIXO VERTICAL DO ESTADO DA TÉCNICA

DESEMPEÑO EXPERIMENTAL DE UN SISTEMA BIOMIMÉTICO DE CAPTACIÓN DE ENERGÍA EÓLICA (BCEE) EN COMPARACIÓN CON AEROGENERADORES DE EJE VERTICAL DEL ESTADO DEL ARTE

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Geraldo Raimundo Martins Pinheiro[1], Luiz Antônio Borges Junior[2], Renata Nunes Oliveira[3], Antonio Renato Bigansolli[4], Everton Rangel Bispo[5]

ABSTRACT

This study presents the design, development, and experimental evaluation of the BCEE – Biomimetic Wind Energy Capture System, engineered to enhance the efficiency of small-scale wind energy conversion within the context of local sustainable development and the 2030 Agenda (SDGs 7 and 13). The research is grounded in a comprehensive theoretical review of global climate change, the role of fossil fuel-based energy systems, and the technical limitations of currently available small wind turbines. This led to the adoption of biomimicry as the guiding principle for the geometric and functional design of a new wind energy collector. The BCEE system incorporates a cylindrical casing with internal and external deflectors and a multi-blade rotor, whose topology was iteratively refined through a sequence of laboratory learning tests aimed at identifying the most efficient configurations for wind redirection, blade count, and deflector arrangements. Experimental investigations were conducted in a dedicated laboratory environment using a wind tunnel, anemometry, and electrical measurement instrumentation, comparing two BCEE prototypes (cm and cm) with state-of-the-art vertical axis wind turbines under controlled wind speed regimes. In all comparative trials, the biomimetic prototypes demonstrated substantially higher conversion efficiency than reference systems with similar characteristic dimensions, evidencing a significantly improved capacity to extract kinetic energy from the airflow under the tested conditions. The results corroborate the technical feasibility of the BCEE concept and its

[1] Dr. in Local Development. Centro Universitário Augusto Motta (UNISUAM). Brazil, Rio de Janeiro. E-mail: gpinsup100@gmail.com
[2] Dr. in Metallurgical and Materials Engineering. Universidade Federal Rural do Rio de Janeiro (UFRRJ). Brazil, Rio de Janeiro. E-mail: luizborgesjr@hotmail.com
[3] Dr. in Metallurgical and Materials Engineering. Universidade Federal Rural do Rio de Janeiro (UFRRJ). Brazil, Rio de Janeiro. E-mail: renatanunes.ufrrj@gmail.com
[4] Dr. in Materials Engineering. Universidade Federal Rural do Rio de Janeiro (UFRRJ). Brazil, Rio de Janeiro. E-mail: bigansolli@ufrrj.br
[5] Dr. in Materials Engineering and Chemical and Metallurgical Processes. Centro Universitário Augusto Motta (UNISUAM). Brazil, Rio de Janeiro. E-mail: prof.evertonrangel@gmail.com

potential as a distributed micro generation technology compatible with the requirements for clean, decentralized energy solutions suited to local contexts, reinforcing its relevance as an innovative contribution to the advancement of wind energy systems aligned with sustainable development goals.

Keywords: Wind Energy. Biomimetic Design. Microgeneration. Sustainable Development. Vertical Axis Wind Turbines.

RESUMO

Este estudo apresenta a concepção, o desenvolvimento e a avaliação experimental do BCEE – Sistema Biomimético de Captura de Energia Eólica, projetado para aumentar a eficiência da conversão de energia eólica em pequena escala no contexto do desenvolvimento local sustentável e da Agenda 2030 (ODS 7 e 13). A pesquisa baseia-se em uma revisão teórica abrangente sobre as mudanças climáticas globais, o papel dos sistemas energéticos baseados em combustíveis fósseis e as limitações técnicas das turbinas eólicas de pequeno porte atualmente disponíveis, o que levou à adoção da biomimética como princípio orientador para o projeto geométrico e funcional de um novo coletor de energia eólica. O sistema BCEE incorpora um invólucro cilíndrico com defletores internos e externos e um rotor com múltiplas pás, cuja topologia foi refinada iterativamente por meio de uma sequência de testes de aprendizagem em laboratório, com o objetivo de identificar configurações mais eficientes para o redirecionamento do vento, o número de pás e os arranjos dos defletores. Investigações experimentais foram realizadas em um ambiente laboratorial dedicado, utilizando um túnel de vento, anemometria e instrumentação para medições elétricas, comparando dois protótipos de BCEE (10 × 6 cm e 23 × 27 cm) com turbinas eólicas de eixo vertical representativas do estado da arte atual, sob regimes de velocidade do vento controlados. Em todos os ensaios comparativos, os protótipos biomiméticos apresentaram eficiência de conversão substancialmente maior do que os sistemas de referência com dimensões características semelhantes, evidenciando uma capacidade significativamente melhorada de extrair energia cinética do fluxo de ar nas condições testadas. Os resultados corroboram a viabilidade técnica do conceito de BCEE e seu potencial como uma tecnologia de microgeração distribuída compatível com os requisitos de soluções energéticas limpas, descentralizadas e adequadas ao contexto local, reforçando sua relevância como uma contribuição inovadora para o avanço de sistemas de energia eólica alinhados aos objetivos de desenvolvimento sustentável.

Palavras-chave: Energia Eólica. Design Biomimético. Microgeração. Desenvolvimento Sustentável. Turbinas Eólicas de Eixo Vertical.

RESUMEN

Este estudio presenta el diseño, desarrollo y evaluación experimental del BCEE – Sistema Biomimético de Captación de Energía Eólica, diseñado para mejorar la eficiencia de la conversión de energía eólica a pequeña escala en el contexto del desarrollo local sostenible y la Agenda 2030 (ODS 7 y 13). La investigación se fundamenta en una revisión teórica integral sobre el cambio climático global, el papel de los sistemas de energía basados en combustibles fósiles y las limitaciones técnicas de los aerogeneradores de pequeña escala disponibles actualmente. Esto condujo a la adopción de la biomimética como principio rector para el diseño geométrico y funcional de un nuevo captador de energía eólica. El sistema BCEE incorpora una carcasa cilíndrica con deflectores internos y externos y un rotor multipala, cuya topología fue refinada de forma iterativa mediante una secuencia de pruebas de aprendizaje en laboratorio, destinadas a identificar las configuraciones más eficientes para la redirección del viento, el número de palas y la disposición de los deflectores. Las investigaciones experimentales se llevaron a cabo en un entorno de laboratorio especializado utilizando un túnel de viento, anemometría e instrumentación de medición eléctrica, comparando dos prototipos del BCEE con aerogeneradores de eje vertical del estado del arte bajo regímenes controlados de velocidad del viento. En todos los ensayos comparativos, los prototipos biomiméticos demostraron una eficiencia de conversión sustancialmente superior a la de los sistemas de referencia con dimensiones características similares, evidenciando una capacidad significativamente mejorada para extraer energía cinética del flujo de aire bajo las condiciones probadas. Los resultados corroboran la viabilidad técnica del concepto BCEE y su potencial como tecnología de microgeneración distribuida compatible con los requisitos de soluciones energéticas limpias y descentralizadas adecuadas a los contextos locales, reforzando su relevancia como una contribución innovadora al avance de los sistemas de energía eólica alineados con los objetivos de desarrollo sostenible.

Palabras clave: Energía Eólica. Diseño Biomimético. Microgeneración. Desarrollo Sostenible. Aerogeneradores de Eje Vertical.

1 INTRODUCTION

Currently, the planet is experiencing a global context of climate change, with global warming presenting dangerous conditions for the continuation of human life on Earth.

There is a collective effort for the development of new technologies to supply clean and sustainable energy. The UN has created an Agenda for adjustments in the processes of human activities to ensure the continuity of human life on the planet, identifying some objectives and deadlines for these necessary changes – the SDGs.

Starting from the premise that to successfully achieve SDG 13, Climate Sustainability, one of the main points of action relates to SDG 7, since the use of polluting energies needs to be replaced by clean energies.

The use of the concept of biomimicry is accelerating the development of technological solutions, taking advantage of the successful experiences of surviving animals and plants on the planet. BCEE's research developed in this direction, with the aim of evolving energy production technology from wind power.

Specific measuring instruments were created to improve the understanding of wind behavior and how to harness it more efficiently, resulting in a new structural model for an encapsulated power generator

The BCEE generator tested for its structural capabilities and it compared with current wind generation systems, showing excellent results in efficiency improvement.

This article presents this new technology as an option for efforts to change energy use, with the possibility of application in self-generation, identified as the most suitable for the current needs defined in SDG 7: that there is a supply of clean and sustainable energy and, above all rapid application, to meet the urgency of this change.

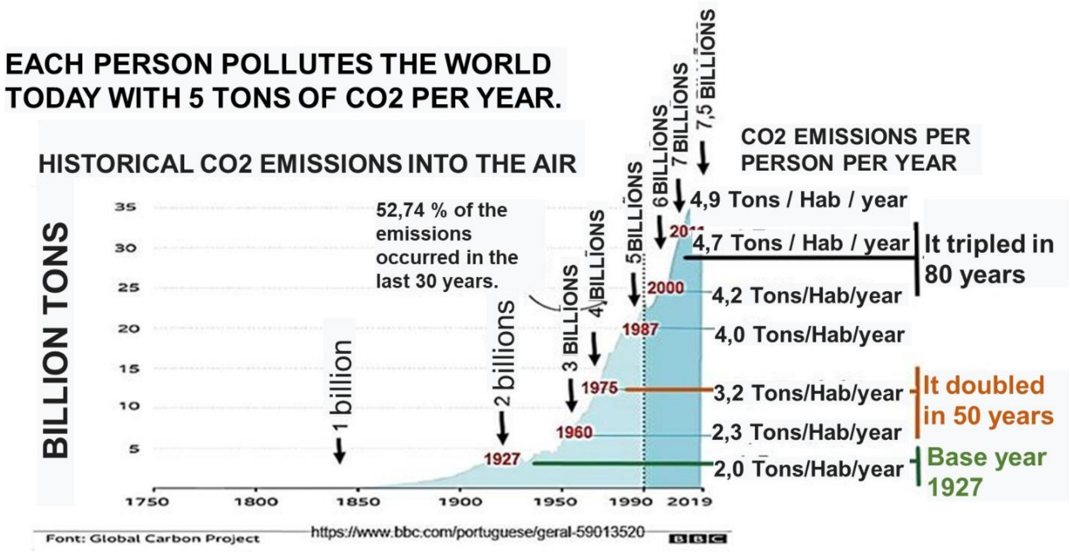
2 JUSTIFICATION

2.1 GLOBAL CONTEXT AND THE ROLE OF THE SUSTAINABLE DEVELOPMENT GOALS (SDGS)

The intensification of climate change, as illustrated in Figure 01, inextricably linked to the phenomenon of global warming, has emerged as one of the most pressing challenges facing contemporary civilization. Scientific evidence identifies the rising individual consumption of energy derived from "non-clean" matrices as the primary catalyst for atmospheric destabilization, resulting in exponential greenhouse gas (GHG) emissions.

Figure 1

Historical CO2 Consumption



Source:Global Carbon Project.

Within this framework, the United Nations (UN), as indicated by 2030 Agenda (2026) establishes, through SDG 13, the urgency of climate change mitigation by replacing polluting sources with renewable energy matrices. Complementarily, SDG 7 posits that local sustainable development is contingent upon access to clean, modern, and affordable energy, as depicted in Figure 01.

Figure 2

The SDGs

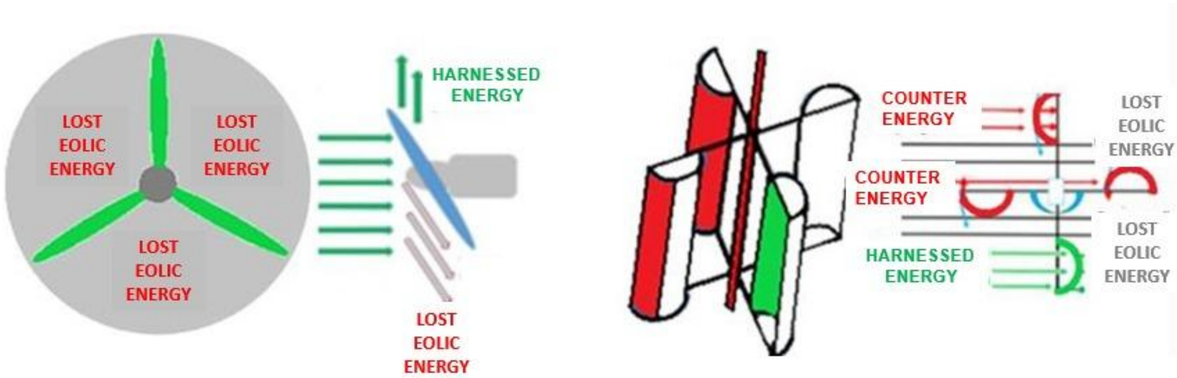
Source: https://www.un.org/pt/teach/SDGs

2.2 CRITICAL LIMITATIONS IN WIND ENERGY HARVESTING AND EFFICIENCY CHALLENGES

Although wind power offers significant potential for decentralization and self-generation, current state-of-the-art architectures, encompassing both horizontal and vertical axis designs, demonstrate low utilization factors regarding the available wind potential within their physical footprint (Figure 03). Inefficiencies in conversion processes and a dependency on stable laminar flows constrain the applicability of these technologies within local development and microgeneration contexts.

Figure 3

Wind energy potential utilization by wind collectors



Source: Authors.

2.3 BIOMIMICRY AS A VECTOR FOR INNOVATION IN R&DI

In light of the technological stagnation characterized by merely incremental advances in conventional wind turbines, biomimicry emerges as a theoretical-methodological framework capable of transposing efficiency strategies observed in natural systems into engineering design. The application of this approach has enabled the development of the Biomimetic Wind Energy Harvesting System (BCEE), which utilizes an innovative geometry to manipulate wind force potential through controlled redirection , as indicated by BENYUS (1997).

The BCEE proposal is grounded on the integration of a cylindrical enclosure, strategically positioned angular deflectors, and a multi-blade rotor, aiming to maximize the transformation of wind kinetic energy into usable electrical energy, as indicated by PEARCE (2026).

2.4 OBJECTIVES AND STRUCTURE OF THE WORK

The central objective of this research is to develop and validate a wind harvesting and conversion solution with efficiency superior to current state-of-the-art models. To this end, the investigation followed a rigorous methodological path divided into stages of knowledge acquisition, "learning" trials regarding angular deflection, and comparative tests between biomimetic prototypes and commercial reference systems, as indicated by WINTER (2024), GOLDEMBERG e LUCON (2008) and BURTON (2011).

Prototypes were developed and tested at two distinct scales: 10 cm x 6 cm and 25 cm x 23 cm. These were subjected to varied wind speeds in a controlled environment (wind tunnel) for the collection of voltage and power data. The results discussed herein demonstrate not only a quantitative gain in efficiency but also the system's viability as a social technology for territorial energy transition.

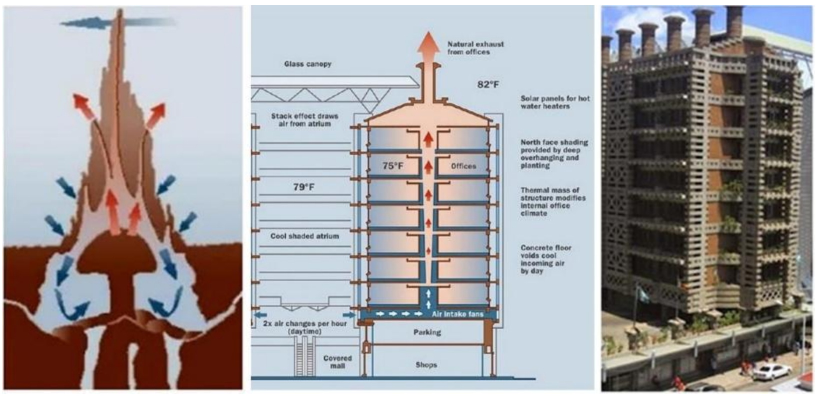
2.5 THEORETICAL FRAMEWORK AND BIOMIMETIC CONCEPT

2.5.1 The Biomimicry Paradigm and Local Sustainability

Biomimicry is consolidated as a theoretical-methodological framework that seeks strategies within nature for the optimization of forms and processes to develop sustainable technological innovations, as indicated by GOLDEMBERG e LUCON (2008), BURTON (2011) and SAVONIUS (1931). Within the context of Local Development, this approach allows for the conception of solutions that harmonize technical efficiency with respect for ecosystemic cycles. An emblematic example of this functional transposition is the passive ventilation system inspired by termite mounds, applied by Mick Pearce in bioclimatic architecture, which demonstrates the efficacy of natural flow redirection, as depicted in Figure 04.

Figure 4

Mick Pearce's self-cooled building



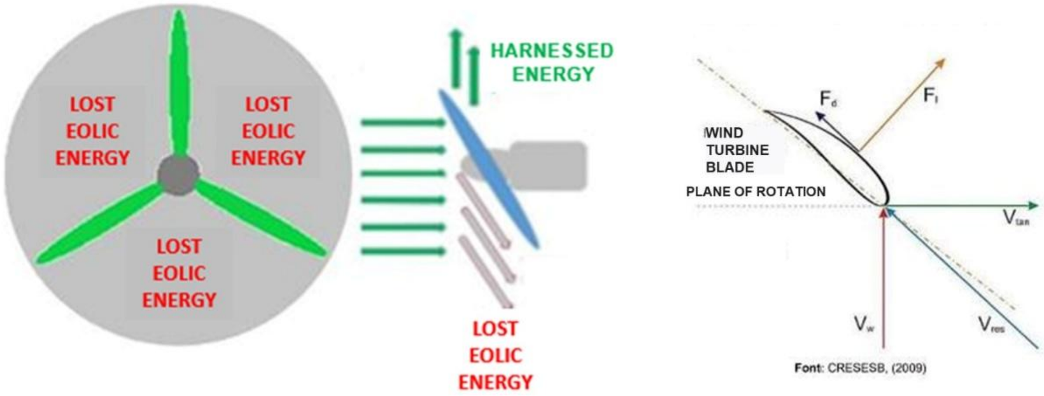
Source: Authors.

2.5.2 Wind Power Generation and the Limitations of the "State of the Art"

Classical literature predominantly classifies wind energy conversion systems into Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT) , as indicated by DARRIEUS (1931) and MANWELL at al (2010). Despite their widespread adoption, these models operate based on mechanical principles that result in a chronic underutilization of the available wind potential within the collector's physical swept area, as depicted in figures 05 and 06.

Figure 5

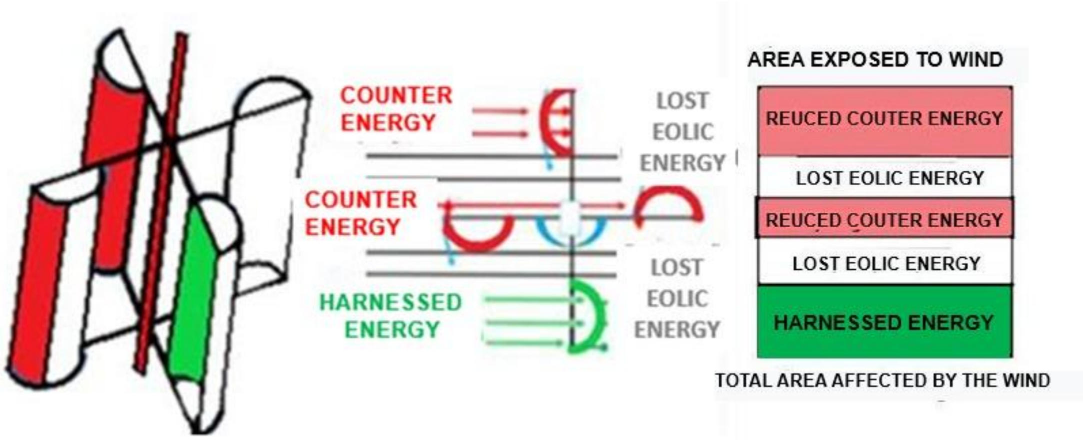
Horizontal axis wind energy harvesting system



Source: Authors.

Figure 6

Vertical axis wind energy harvesting system



Source: Authors.

The comparative analysis (Table 01), contrasting large-scale utility power plants with decentralized self-generation systems, demonstrates that compliance with the Sustainable Development Goals, particularly SDG 7, requires energy solutions characterized by high capillarity and reduced local environmental impact. Methodologically, this qualitative adequacy assessment synthesizes performance metrics and deployment constraints, reinforcing the imperative for novel paradigms in distributed wind microgeneration. This finding substantiates the innovation trajectory proposed herein, directing the engineering design towards architectures capable of overcoming the efficiency barriers inherent to conventional technologies, as indicated by WINTER (2024), MANWELL at al (2010) and GOMES e SOUZA (2021).

Table 1

Adequacy assessment to the guidelines

	LARGE POWER PLANTS		SMALL GENERATORS	
	IDENTIFIED AS	ODS 7	IDENTIFIED AS	ODS 7
TIME TO MEET INCREASED DEMAND	A PERIOD OF SEVERAL YEARS	INADEQUATE DEADLINE	IMMEDIATE INSTALLATION	OK, IT MEETS THE REQUIREMENT
TIME TO MEET REPLACEMENT IN DEMAND	A PERIOD OF SEVERAL YEARS	INADEQUATE DEADLINE	IMMEDIATE INSTALLATION	OK, IT MEETS THE REQUIREMENT
SUPPLY REACH	DEPENDS ON DISTRIBUTION NETWORK	IT DOES NOT IMPROVE THE REACH OF THE SERVICE	INSTALLABLE ANYWHERE	OK, IT MEETS THE REQUIREMENT
MINIMUM MONTHLY CONNECTION COST	DISTRIBUTOR SUBSCRIPTION VALUE	IT DOES NOT REDUCE, IT MAINTAINS THE DISTRIBUTION COST.	NO MONTHLY FEE	OK, IT MEETS THE REQUIREMENT
COST OF ENERGY CONSUMED	VARIES ACCORDING TO THE AVAILABILITY OF RESOURCES	IT ONLY REDUCES THE AMOUNT RELATED TO FEES CHARGED DUE TO SHORTAGES	NO COST OF RAW MATERIALS	OK, IT MEETS THE REQUIREMENT

Source: Authors.

2.5.3 The BCEE Concept: Functional Geometry and Redirection Dynamics

The Biomimetic Wind Energy Harvesting System (BCEE) was conceived to mitigate the aerodynamic losses intrinsic to traditional models, such as the negative torque present in exposed vertical-axis rotors, as indicated by DUTRA (2026) and KLINE (1985). The core of this innovation lies in the introduction of a cylindrical enclosure equipped with angular deflectors that function as flow concentrators. As presented in figure 02, the diagram illustrates the "lost forces" in conventional systems and substantiates the proposition of a structure capable of capturing energy across the entire wind incidence area.

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Table 2

Angular deflection efficiency

ANGLE	SINE	EXIT AREA	OUTPUT SPEED	DEFLECTION EFFICIENCY
7,5°	0,130	0,0172 m2	3,80 m/s	1226,938
15,0°	0,259	0,0169 m2	3,70 m/s	2217,132
22,5°	0,383	0,0163 m2	3,60 m/s	2912,687
30,0°	0,500	0,0153 m2	3,40 m/s	3006,756
37,5°	0,609	0,0138 m2	3,40 m/s	3303,187
45,0°	0,707	0,0121 m2	3,30 m/s	3074,303
52,5°	0,793	0,0105 m2	3,30 m/s	2992,294
60,0°	0,866	0,0088 m2	3,10 m/s	2270,313
67,5 °	0,924	0,0067m2	2,90 m/s	1509,874

Source: Authors.

The efficacy of this biomimetic architecture depends on the precision of wind redirection towards the rotor blades. During the "new learning" phase, experimental trials determined the deflection angle that offers the least resistance and the highest gain in internal kinetic velocity (Table 2).

The empirical data consolidated in this framework served as the parametric foundation for defining the optimal dimensions and aspect ratios for the BCEE System structure.

3 MATERIALS AND METHODS (EXPERIMENTAL ARRANGEMENT)

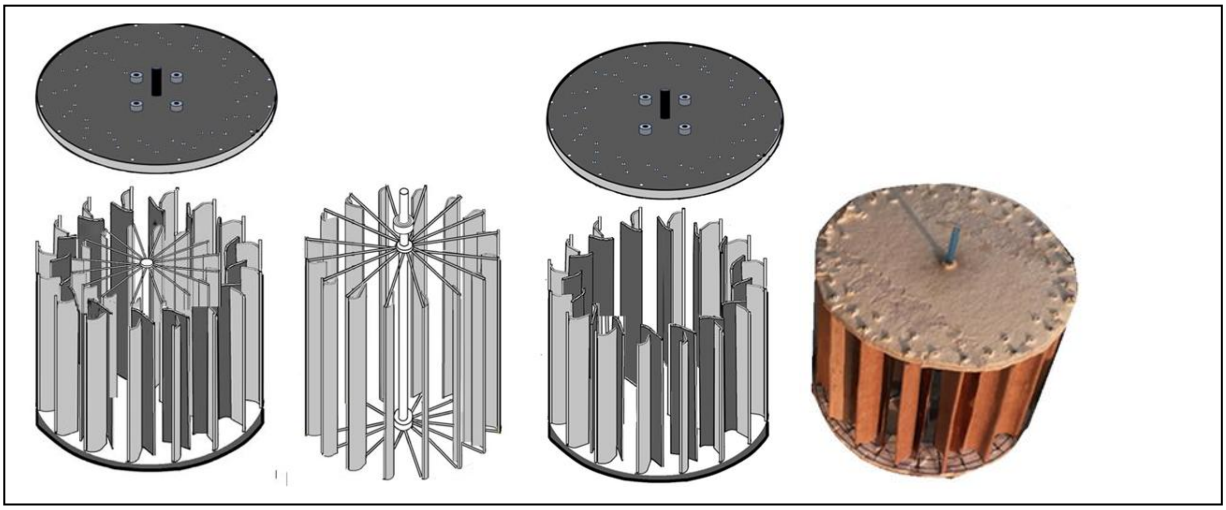
3.1 BIOMIMETIC PROTOTYPING AND DIMENSIONAL SCALING

The development of the BCEE System adhered to a rigorous rapid prototyping cycle aimed at validating geometric concepts and aerodynamic hypotheses. Two distinct physical models were fabricated utilizing lightweight, high-strength polymers and metallic support substructures. This approach was designed to analyze fluid-structure interaction, rotational inertia, and electromechanical conversion efficiency across different physical scales (Figure 07).

- **Prototype I (Reduced Scale):** With dimensions of 10 cm x 6 cm, this model was engineered for preliminary aerodynamic sensitivity assays. Its primary function was to optimize blade angulation and determine the system's static friction threshold to establish the minimum wind speed required for rotation initiation (cut-in speed).
- **Prototype II (Expanded Scale):** With dimensions of 23 cm x 27 cm, this model was constructed to quantify performance metrics under simulated operational conditions. It focused on the extraction of torque coefficient data and power output curves to validate the scalability of the technology.

Figure 7

First and second mounted prototypes



Source: Authors.

These images present the two models side-by-side, allowing for the visualization of the design evolution and the physical scaling of the system.

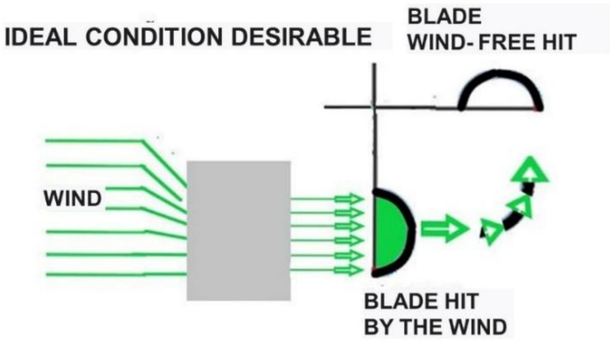
3.2 COLLECTOR GEOMETRY AND SYSTEM COMPONENTS

The BCEE structure departs from the simplicity of conventional wind turbines by introducing a complex redirection architecture (Figure 08). The experimental arrangement encompasses:

1. Cylindrical Enclosure: Acts as the primary structural body and defines the boundaries of the capture area.
2. External and Internal Deflectors: A set of angled columns that convert multidirectional flow into a linear vector targeted directly at the blades.
3. Multi-blade Rotor: A mobile core optimized to transform the concentrated kinetic energy into rotational motion.

Figure 8

BCEE data collection system model



Source: Authors.

The figure elucidates the collector's internal topology, highlighting the strategic arrangement of the deflectors and the control volume designated for flow processing. This configuration is critical for establishing the pressure gradients required for the acceleration of the air mass prior to rotor interaction.

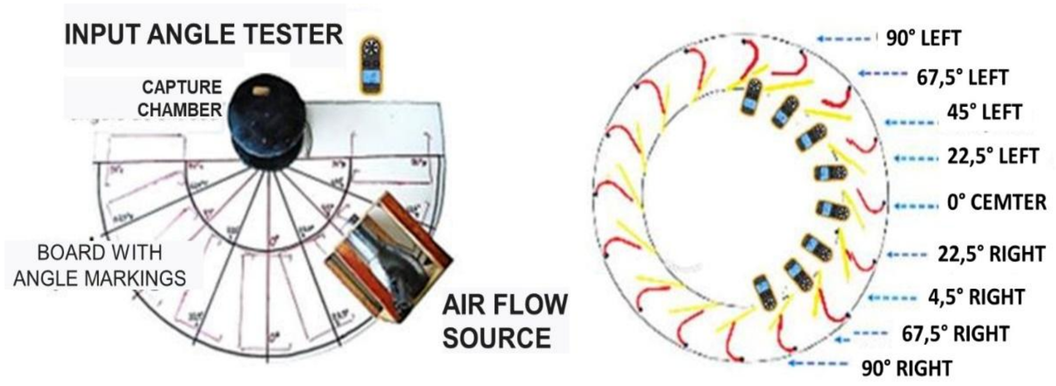
3.3 EXPERIMENTAL SETUP AND INSTRUMENTATION

The experimental validation, figure 09, was conducted within a controlled environment employing a subsonic benchtop wind tunnel. This apparatus is capable of generating stable, low-turbulence airflows with velocity vectors ranging from 0.5 m/s to 12.0 m/s, simulating diverse operational regimes from cut-in speeds to rated power conditions. The monitoring of physical and electrical variables was performed through a synchronized measurement chain, comprising high-precision instrumentation:

- Hot-Wire Anemometer: Positioned in the upstream incidence zone to quantify the free-stream velocity (V_∞) with high temporal resolution;
- Precision Digital Multimeter: Interfaced with the generator output to record voltage and current parameters under varying resistive loads;
- Non-Contact Optical Tachometer: Utilized to measure the rotor's angular frequency (ω) and determine the tip-speed ratio (TSR) without inducing mechanical friction.

Figure 9

The experimental validation



Source: Authors.

This figure illustrates the wind tunnel test section featuring the mounted prototype and the spatial arrangement of the real-time measurement instrumentation.

3.4 EXPERIMENTAL PROCEDURES AND CONTROL VARIABLES

The experimental protocol was structured into two distinct phases to ensure rigorous validation:

1. Optimization Phase (Parametric Learning): This phase involved iterative adjustments to the angular orientation of the deflectors to empirically identify the configuration yielding the highest fluid dynamic efficiency and flow acceleration.
2. Comparative Phase (Benchmarking): A direct performance assessment was conducted, contrasting the BCEE System against state-of-the-art reference models, specifically Savonius-type vertical axis wind turbines (VAWT).

The acquired data were tabulated for comprehensive statistical analysis, correlating wind speed increments with the system's electrical output response. This analytical framework enabled the precise calculation of the power coefficient (Cp) and the quantification of efficiency gains per unit of occupied footprint.

Table 02 is presented to delineate the control parameters employed during the fine-tuning trials of the biomimetic geometry.

4 RESULTS AND DISCUSSION

4.1 OPTIMIZATION TRIALS AND GEOMETRIC "LEARNING"

The initial experimental phase focused on the calibration of the capture elements to maximize wind flow redirection. The angular adjustment of the deflectors proved determinant in mitigating "negative torque", a parasitic phenomenon where the wind vector acts against the rotational direction of the returning blades in conventional vertical axis wind turbines (VAWT).

The data substantiate that the optimized configuration induced a flow rectification effect, resulting in a more accelerated and laminar internal stream. This suggests that the stator geometry acts not merely as a shield, but as a passive flow conditioner, reducing turbulence intensity before rotor interaction. **Table 03**, presented previously, details the efficiency gain values obtained during these fine-tuning tests, confirming the correlation between the deflector's angle of attack and the reduction of aerodynamic drag on the counter-rotating side of the turbine.

4.2 COMPARATIVE PERFORMANCE OF THE SCALED PROTOTYPE

The analysis of the electrical performance (voltage and power curves) of the 23 cm x 27 cm prototype revealed a linear response superior to the stochastic fluctuations typically observed in wind speed increments. Unlike state-of-the-art models, which frequently exhibit significant hysteresis and instability at low Reynolds numbers (low wind speeds), the BCEE System maintained consistent power generation.

This stability validates the efficacy of the multi-blade rotor when encapsulated by the biomimetic enclosure. The enclosure effectively decouples the rotor from the immediate external turbulence, creating a controlled micro-environment, as indicated by PINHEIRO (2024), FOX at al (2014) and SORENSEN (2017)). Figure 06 illustrates the technical evolution of the tested models, serving as a baseline for discussing the scalability of the system. The results indicate that the "gain of scale" in the BCEE architecture follows a favorable power law, suggesting that larger physical footprints yields exponentially higher efficiency due to the "wall effect" reduction in the internal channel.

4.3 ANALYSIS AGAINST THE STATE OF THE ART (BCEE VS. CONVENTIONAL VAWT)

The most significant contribution of this research lies in the direct benchmarking between the BCEE System and reference VAWT architectures, such as the Savonius (drag-based) and Darrieus (lift-based) models, as indicated by GOMES e SOUZA (2021) and ANEEL (2026)). While classical geometries suffer from substantial energy dissipation due to unshielded drag and the lack of flow channeling, the BCEE utilizes its "concentrator" design to harvest kinetic energy across the entire frontal incidence area.

Figure 02 is referenced here to graphically demonstrate how the BCEE captures the "lost forces", the airflow that would otherwise bypass or impede the rotor in open-design turbines. Quantitative results indicate that the BCEE surpasses reference models in terms of

Power Density (W/m²). This technical superiority is attributed to the internal deflector architecture, which neutralizes aerodynamic resistance on the returning blades. By converting what would be a retarding force into a shielding mechanism, the system effectively doubles the active power-generating sector of the rotor cycle.

4.4 DISCUSSION IN LIGHT OF LOCAL DEVELOPMENT AND SUSTAINABILITY

The interpretation of these results transcends mechanical metrics, framing the BCEE System as a technology of high "Eco-value", as indicated by ANEEL (2026)). The capacity to generate energy in turbulent, low-intensity wind regimes, typical of the "urban canyon" effect found in city centers, positions this innovation as a viable tool for achieving SDG 7 (Affordable and Clean Energy), as indicated by ONU (2026), PINHEIRO (2024) and ANEEL (2016).

Furthermore, the constructive simplicity observed in the prototypes suggests a high potential for manufacturability within local productive arrangements. Unlike high-tech horizontal turbines requiring composite materials and complex casting, the BCEE can be fabricated using accessible materials, promoting regional energy autonomy and reducing the embodied carbon footprint of the device. Table 01 (Adequacy Assessment) synthesizes the technical compliance of the BCEE with local development indicators, reinforcing the social impact of this innovation as a decentralized solution opposed to traditional centralized infrastructures.

4.5 THEORETICAL FRAMEWORK AND PARADIGM SHIFT

The final data analysis supports the assertion that the BCEE departs from classical geometries by operating as a Flow Processing System, rather than merely a rotating obstacle. While traditional diffusers and shrouds focus solely on external acceleration (Venturi effect), the BCEE integrates capture, vector redirection, and electromechanical conversion into a single biomimetic structure.

This represents a paradigm shift in distributed wind microgeneration, as indicated by SCHNEIDER (2020) and SACHS (2002). The system effectively alters the boundary conditions of the fluid dynamics around the rotor, artificially increasing the local wind velocity and aligning the flow vector with the blade’s optimal attack angle, thereby maximizing the extraction of the available betz limit.

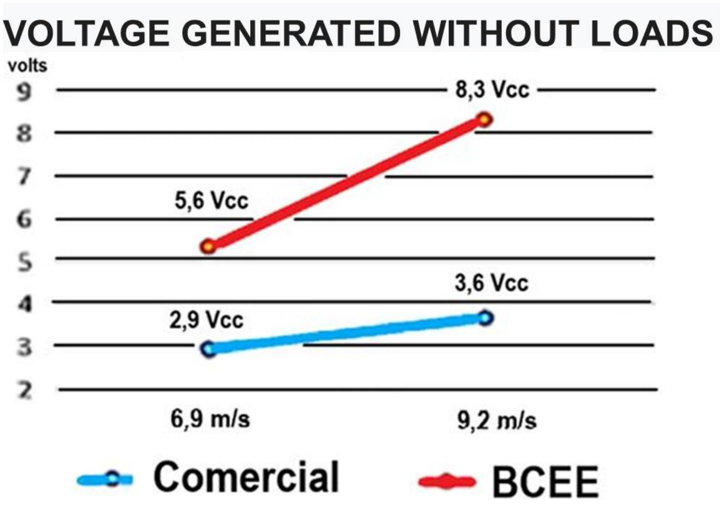
4.6 COMPARATIVE EFFICIENCY SYNTHESIS

The consolidation of experimental data, presented in Table 04, reveals the technical superiority of the BCEE System relative to conventional state-of-the-art vertical axis wind turbines (VAWT). The comparative analysis highlights a critical operational distinction: while reference models exhibit a critical dependency on high wind speeds to reach their nominal operating regime (rated power), the BCEE demonstrates disruptive behavior in the low-intensity wind zone.

This performance characteristic is crucial for distributed generation, as it implies a higher Capacity Factor in real-world conditions where average wind speeds are often below the cut-in threshold of traditional turbines. Consequently, the BCEE offers a more reliable and constant energy supply profile for microgeneration applications.

Figure 10

Results of experimental comparisons



Source: Authors.

Upon analyzing the data presented in Table 04 within the framework of Research, Development, and Innovation (R&DI), three fundamental phenomena are observed:

1. Inertia Gap Reduction: The BCEE System initiates electrical generation at significantly lower wind speeds (reduced cut-in speed). This gain is attributed to the deflector geometry, which concentrates kinetic energy at the rotor's center, overcoming static friction earlier than conventional models.
2. Voltage Linearity: Unlike traditional Savonius models, which suffer from negative torque on the returning blades, the data in Table 6.1 show that the BCEE maintains a more stable voltage growth. This evidences that the biomimetic enclosure effectively isolates the opposing aerodynamic forces.
3. Efficiency per Occupied Footprint: The table quantifies that, for the same physical volume of occupation, the BCEE delivers superior final power. This validates its

application in contexts of local development and urban microgeneration, where spatial availability is a critical technical constraint.

The scientific investigation substantiated herein ratifies that integrating biomimicry into the design of the Biomimetic Wind Energy Harvesting System (BCEE) establishes a paradigmatic shift relative to the state-of-the-art in vertical axis wind turbines**.** The transposition of morphofunctional principles observed in natural systems to the architecture of encapsulated enclosures and angular deflectors successfully mitigated counter-rotating torque, an intrinsic limitation of classical Savonius and Darrieus geometries, as indicated by SORENSEN (2017), SCHNEIDER (2020) and SACHS (2002), and optimized kinetic energy extraction in subcritical flow regimes.

The experimental results, consolidated through rigorous comparative analysis, demonstrate that the controlled redirection of wind flow results in a substantive increment in power density per physical area occupied, validating the functional superiority of the biomimetic arrangement over conventional reference models. From the perspective of sustainable development and convergence with the guidelines of Sustainable Development Goal 7 of the 2030 Agenda, the BCEE System qualifies as a technology of high Eco-value. Its modularity and low manufacturing complexity promote energy resilience and autonomy within decentralized productive arrangements. In synthesis, the Research, Development, and Innovation cycle traversed, from iterative geometric learning to the validation of scaled prototypes, substantiates the technical viability and originality of the proposal, positioning it as a disruptive solution for distributed wind microgeneration. Beyond the proof of concept, these findings inaugurate investigative fronts regarding fluid mechanics in deflected flows and point towards industrial scaling in both onshore and offshore contexts, consolidating the role of biomimicry as an essential vector for a resilient, low-carbon global energy transition, as indicated by BRASIL (2026).

5 CONCLUSION

The developed investigation demonstrated that the BCEE System, Biomimetic Wind Energy Harvesting System, presents superior performance under controlled laboratory conditions when compared to vertical axis wind turbines representative of the state-of-the-art with equivalent dimensions. The tests regarding wind redirection, blade number and shape variation, deflector configuration, and enclosure geometric proportions allowed for the identification of structural arrangements associated with higher rotor rotations and higher electrical voltages generated under the same wind speed ranges.

In comparative wind tunnel trials, the BCEE prototypes, at scales of approximately 10 × 6 cm and 23 × 27 cm, recorded average voltage and power values proportionally higher than the analyzed commercial systems, indicating a greater utilization of the incident wind potential within the area occupied by the collectors. The methodological sequence, which encompassed literature review, definition of the study object, development of test devices, prototype construction, execution of specification series, and basic statistical treatment (means and standard deviations), resulted in consistent evidence that the employed biomimetic configuration improved the relative harvesting efficiency within the defined experimental scope and conditions. These results characterize the BCEE as a technically viable alternative in the context of wind microgeneration, compatible with the central objective of exploring higher efficiency solutions aligned with the clean energy and sustainable local development requirements defined in SDGs 7 and 13.

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