Received 21 March 2025; revised 24 June 2025; accepted 7 August 2025.
Date of publication 11 August 2025; date of current version 29 August 2025.

Digital Object Identifier 10.1109/OAJPE.2025.3597533

Development of a Low-Speed Wind Turbine for Brazilian Onshore Areas: A Preliminary and Conceptual Design

JAMES ROJAS WATERHOUSE[1], CRISTHIAN R. MORANTE VILLARREAL[2], GUILHERME BEPPU DE SOUZA[2], FERNANDO VILAS BOAS RIBEIRO[2], CARLOS HENRIQUE GASPARETTI[2], KAUAN PIRES QUEVEDO[2,3], JOSIEL GONÇALVES DOS SANTOS[4], GEORGE CAMARGO DOS SANTOS[4], AND MARLOS JOSÉ RIBEIRO GUIMARÃES[4]

[1]Department of Aeronautical Engineering, University of São Paulo, São Carlos 13566-590, Brazil
[2]NewCo Blades Technology, São Carlos 13565-261, Brazil
[3]Department of Mechanical Engineering, University of São Paulo, São Carlos 13566-590, Brazil
[4]Eletrobras Furnas, Rio de Janeiro 20030-000, Brazil

CORRESPONDING AUTHOR: J. R. WATERHOUSE (james@sc.usp.br)

This work was supported by Eletrobras Furnas and Agência Nacional de Energia Elétrica (ANEEL) under Grant PD-00394—19004/2019.

ABSTRACT This article presents a comprehensive design study of a low-speed wind turbine optimized for regions with weak wind resources, with a particular focus on Brazil's extensive territories. The research challenges conventional turbine designs by incorporating innovative strategies to enhance aerodynamic performance, structural integrity, and cost efficiency. Consolidated computational tools were integrated with optimization algorithms, creating an innovative multidisciplinary optimization framework. Multiple configurations were assessed based on energy output, load mitigation, and economic viability, leading to the identification of promising designs that effectively balance performance targets with practical constraints. The study highlights how a structured multidisciplinary design optimization (MDO) approach, applied during the preliminary and conceptual design phases, enables the development of configurations well-adapted to low-wind-speed environments. These findings result into the output configuration achieving a rated wind speed of 6.45 m/s, and moreover they offer a scalable framework for future research and field validation in low-wind-speed applications. Therefore, the objective of developing a viable wind turbine prototype using custom multidisciplinary optimization models was successfully achieved.

INDEX TERMS Low-speed wind turbine, wind turbine design, multidisciplinary optimization.

I. INTRODUCTION

ALONGSIDE the increasing global energy demand and environmental imperatives, sustainable energy production is becoming an essential focus in the global economy [1]. With electricity demand expected to rise by 50% by 2060 [2], the efficient use of energy resources has never been more crucial. Renewable sources of energy, particularly wind power, are leading the charge in addressing these challenges, offering a sustainable and inexhaustible alternative to traditional fossil fuels [1], with rapid technological innovations driving the sector forward [3].

Wind energy has emerged as a key pillar in renewable energy generation, aiding in the reduction of greenhouse gas emissions and the diversification of the global energy matrix. Brazil, with its vast and diverse wind resources, is a prominent player in wind energy production [4]. The northeastern and southern regions of Brazil are generally characterized by the highest wind speeds, with the northeast exhibiting the greatest potential for wind energy exploration. Specifically, the states of Rio Grande do Norte, Bahia, and Ceará benefit from consistently strong winds, averaging above 8 m/s at an altitude of 80 m. These conditions facilitate exceptionally high-capacity factors for wind farms, frequently surpassing 50% [4]. However, a significant portion of Brazil's wind potential lies in low-wind-speed regions, where traditional turbines often under perform. In this areas, the mean wind speed typically ranges from around 5 m/s to 8 m/s at an altitude of 100 meters, which is insufficient for conventional turbines to operate at optimal capacity [5]. This disparity results in a substantial untapped resource, highlighting the need for technologies specifically designed to efficiently harness energy from these lower-wind environments. Further complicating this issue, the Northeast region, while the largest wind energy producer, is geographically remote from the Southeast, which is the largest energy consumer market, accounting for 42% of Brazil's population and 53% of its GDP [6], [7]. This situation highlights the need to explore energy solutions closer to these demand centers, which could reduce transmission losses and improve energy security.

Over the years, Brazil has made impressive strides in developing its wind energy supply chain through substantial investments from both the public and private sectors [8]. As a result, the country has successfully built a robust supply chain for turbine manufacturing, installation, operation, and maintenance [9]. However, Brazil still faces a critical gap in domestic technological solutions; most technologies in use are based on foreign designs [10]. These designs are typically optimized for wind conditions commonly found in regions like Europe, the United States, and parts of Asia, which dominate global wind energy research and development [11], [12]. This reliance on imported technologies underscores the necessity for strong national research and development to create solutions specifically suited to Brazil's unique wind conditions. Therefore, national R&D efforts are crucial for bridging this technological gap, reducing dependency on foreign technologies, and ensuring Brazil's continued leadership in the global renewable energy market [10].

The challenge posed by low-wind-speed regions is significant, as conventional turbines, engineered for higher wind speeds, are not viable in areas where sustained winds fall below 7 m/s [13]. To address this, Low-Speed Wind Turbines (LWTs) have emerged as a promising solution, designed to operate efficiently in these challenging conditions. Recent advancements in LWT aerodynamics, structural design, and control systems have made it possible to harness energy effectively from low-intensity winds [14], [15].

This study focuses on the conceptual and preliminary design phases of the "Aerogerador de Baixa Velocidade" (ABV), a novel horizontal-axis small wind turbine optimized for Brazil's low-wind regions. The primary objective is to maximize energy capture while addressing the unique wind characteristics of these areas. The baseline project involves a 250 kW onshore wind turbine aiming for certification under IEC Class IIIB [16], but optimized for wind conditions lower than typical Class III sites [16], providing a robust proof-of-concept that balances technical feasibility, cost, and risk. To achieve these objectives, a comprehensive multidisciplinary framework was employed, integrating aerodynamics, strcutures, and economic modeling. State-of-the-art computational tools – prioritizing open-source tools – were used for simulating and optimizing energy production, ensuring the design's robustness, performance, and cost-effectiveness.

The engineering methodology adhered to the established design process, focusing on two key phases:

- Conceptual phase: Establishing the system's architecture and defining performance targets tailored to Brazil's specific wind conditions.
- Preliminary phase: Advancing the design through with higher-fidelity modeling and simulations, including aeroelastic analysis and structural optimization to ensure the turbine's efficiency in low-wind conditions.

Through this structured approach, the ABV turbine aims to integrate innovative features, materials, and configurations to meet the project's rigorous performance criteria. This innovative design represents a significant step toward cost-effective, sustainable wind energy solutions for Brazil's low-wind-speed regions, positioning the country for continued growth in the renewable energy sector.

II. WIND TURBINES AND ABV

According to the International Electrotechnical Commission standard IEC 61400-2, small wind turbines are defined as having a rotor swept area below 200 m^2, typically generating up to 50 kW at voltages under 1000 V AC or 1500 V DC [17]. Building on this classification, [18] established distinct operational categories with associated power outputs and rotational limits: micro (1 kW; 700 rpm), mid-range (5 kW; 400 rpm), and mini (20+ kW; 200 rpm).

On the other side, IEC 61400-1 defines a conventional wind turbine primarily in terms of its power characteristics and design philosophy. It applies to turbines with rotor diameters exceeding 5 meters and typical power ratings above 100 kW. The standard also classifies turbines according to average wind speeds – ranging from $V_{\text{avg}} = 7.5$ m/s to 10 m/s – and turbulence intensity categories (A, B, and C) that reflect different operating conditions.

According to [19] and [20], approximately 99.7 % of wind turbine installed globally are conventional wind turbines and the rest are small wind turbines. Furthermore, most of the conventional wind turbines falls into 1.5 MW - 8 MW power capacity range, and as noted by [21], most of them exhibit cut-in wind speeds no lower than 3.0 m/s, being primarily engineered for regions with high wind energy potential.

Conversely, but so interesting, is that most of the worldwide area is covered by regions with low-wind-speed. Studies [22], [23], [24] highlight the predominance of low wind speed within regions around the world and the high wind energy unexplored potential they detains because of the poor performance conventional turbines typically exhibit. These conditions (low wind speed) precipitate critical aerodynamic and structural challenges unleashing undesired consequences for the industries: elevated cost associated with R&D projects. Simultaneously, growing energy demands drive the industry toward increased energy capture predominantly through rotor upscaling, exacerbating structural design constraints that increasingly necessitate advanced composite materials.

This is where low-speed wind turbines, such as ABV, become relevant. They are designed to operate in low wind speed environments at relatively reduced rotor heights. Despite component-level similarities between conventional and small wind turbines, a prevalent misconception holds that large-scale turbine technology is directly scalable downward. This assumption is erroneous, as significant technological distinctions primarily stem from limited consumer awareness regarding wind resources and structural loading characteristics [14]. Furthermore, these turbines often simplify or even omit control systems due to economic constraints – a practice that demonstrably compromises operational efficiency [25].

ABV is a disruptive concept targeting small-scale operational regimes where conventional turbine designs underperform. Though architecturally rooted in traditional turbines, it addresses low-wind-speed sites, exemplified by the Brazil case study but readily applicable globally. The project maximizes aerodynamic energy extraction through standardized and robust models, which are extended via a holistic design process employing a rigorous Multidisciplinary Design Optimization (MDO) framework [26], [27], aligning cost-effectiveness with technical performance. By serving low-wind-speed regions, ABV challenges conventional paradigms that overlook vast global wind potential, hence bridging this gap necessitates unconventional configurations that merge small-turbine simplicity with large-turbine engineering sophistication, as detailed in the subsequent section.

The ABV project was initiated in 2019 with the aim of developing a wind turbine specifically optimized for low-wind-speed regions. After several design iterations, the project has concluded the design stage, and the first prototype is currently in manufacturing stage, with installation planed in the near term. This article presents the innovative design methodology employed during these early stages, highlighting the use of a multidisciplinary design framework to integrate aerodynamic, structural, and economic aspects. Rather than detailing the complete product, the focus is to disseminate the methodology which may serve as a replicable approach for similar applications worldwide.

III. MATERIALS AND METHODS

As a complex engineering endeavor, the development of a wind turbine necessitates structured methodologies to address its inherently multivariable and multi-objective challenges. These approaches, rooted in proven practices from the aerospace industry [28], are systematically applied across three distinct phases: conceptual design, preliminary design, and detailed design. This paper focuses exclusively on the first two phases, as they establish the foundational framework for turbine optimization while remaining within the scope of this study.

The conceptual phase aims to develop comprehensive insights into the performance of the proposed low-speed wind turbine, thereby defining critical parameters that serve as the foundation for subsequent critical reviews. For the purposes of this work, the main objectives include wind resource analysis and site characterization, defining key operational features of the turbine to meet site-specific needs, and conducting feasibility assessments of the turbine's principal characteristics.

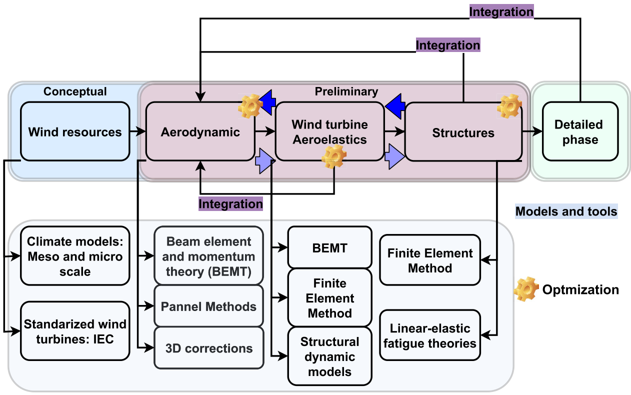


FIGURE 1. **ABV design process.**

The preliminary phase follows the conceptual design and is responsible for refining it through robust and sophisticated analyses, where trade-offs typically occur. This stage encompasses blade aerodynamic and structural design, typology and structural analysis of miscellaneous components, control system definition, and the estimation of loads acting on the principal components.

The wind turbine design process. depicted in Figure 1, inherently operates non-sequentially, with parallel and iterative execution across tightly coupled disciplines – particularly aerodynamics, structural dynamics, and aeroelastics – due to four interdependent load sources: fluid-structure interactions (governing aerodynamic forces), gravitational effects (from component mass), inertial effects (including centrifugal/gyroscopic loads), and operational transients (e.g., emergency braking). Crucially, inertial loads directly correlate with blade mass properties, while resultant deformations bidirectionally couple with aerodynamic performance through altered flow attachment and stall characteristics, creating complex feedback loops. To manage these interdependencies during conceptual and preliminary design, the framework depicted in 1 employs multidisciplinary optimization (MDO) to systematically coordinate power maximization and structural integrity objectives. This computational strategy is computed through a Python-Matlab-Bash workflow that automates inter-module data exchange with each module contributing a distinct function within the integrated optimization framework.

Wind resources module employs downscaling methodologies [29] to refine synoptic-scale models [30] from mesoscale to microscale resolutions [31], [32], enabling precision micrositing. Moreover, this module generates IEC 61400-1-compliant wind profiles [16] using open-source tools (InflowWind [33], TurbSim [34], and IECWind [35]) covering all Design Load Cases–including power production, fault scenarios, and parked conditions–through synthesized gusts, shear profiles, and turbulence spectra.

Aerodynamic module utilizes Blade Element Momentum Theory (BEMT) with two-dimensional coefficients derived from XFLR5 [36], enhanced by three-dimensional corrections via Selig's extrapolation [37] and Viterna's method [38] for full polar characterization (-180° to +180°). These aerodynamics feed into the aeroelastic analysis module, where OpenFAST [39] simulates turbine-wide dynamic responses in front of standardized wind profiles trying to cover all the spectra of operation. This validated platform [40], [41] incorporates nonlinear aerodynamics, tower shadow effects, Weibull-distributed winds, component flexibility (blades, tower, shaft), and control system interactions.

Finally, the structural module employs finite element methods (FEM) integrating BECAS [42] for blade cross-sectional analysis with in-house tools for static and fatigue failure criteria. Fatigue life estimation is performed via MLife [43], processing FEM-derived stress and strain spectra to ensure component integrity across operational lifetimes.

A. MULTIDISCIPLINARY OPTIMIZATION ALGORITHMS

Given the complexity and the multitude of variables involved in the design process, the framework incorporates three layers of design optimization, independent yet interconnected through aeroelastic models, that operate sequentially with distinct focuses.

1) AERODYNAMIC OPTIMIZATION (MDO_1)

This layer integrates aerodynamic and aeroelastic modules to maximize the power coefficient C_P while constraining rated power output to 250 kW within site-specific wind velocity bounds$V_1 \leq V_{rated} \leq V_2$, where V_1 and V_2 depends on wind site characteristics.

$$MDO_1 = \{max(C_P)\} \quad \text{subject to} \quad \begin{cases} P(V_{\text{rated}}) = 250\text{ kW} \\ V_1 \leq V_{\text{rated}} \leq V_2 \end{cases} \tag{1}$$

Maximizing the power coefficient requires maintaining blade operation near the optimal tip speed ratio (λ_{OPT}), which is achieved through carefully defined spanwise distributions of chord ($\bar{c}$) and twist ($\bar{\gamma}$) – the first two decision variables. Additionally, blade span (b), which determines the rotor radius and thus the swept area, plays a critical role in energy capture and is treated as the third decision variable. Practically, the objective of MDO_1 is extract the highest quantity of power from air given a site condition, and the decision process is represented in the workflow showed in the Figure 2. The iterations were mediated by an evolutionary algorithm [44], prioritizing the individuals that best met the criteria presented in section IV. Moreover, this model serves as the foundational input for the MDO_2 and MDO_3, providing the optimized blade outer surface geometry.

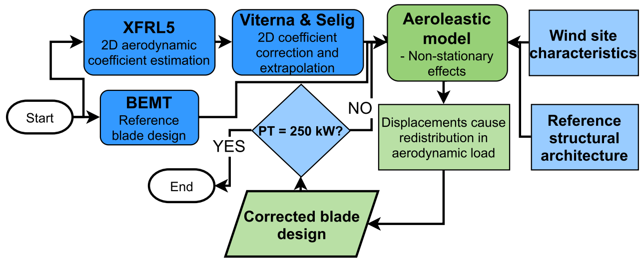


FIGURE 2. Schematic design of MDO_1 process.

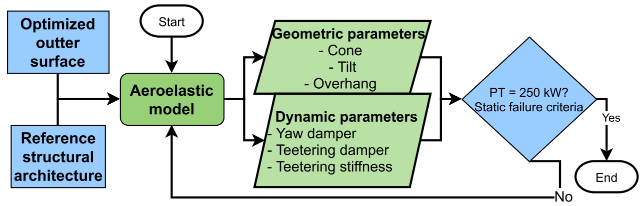


FIGURE 3. Schematic design of MDO_2 process.

2) DYNAMIC OPTIMIZATION (MDO_2)

The dynamic optimization phase, which is illustrated in Figure 3, operates under strict geometric invariance constraints, preserving both the blade outer aerodynamic surface (resulting from MDO_1) and a reference structural architecture. Its objective function minimizes dynamic loads on critical components through genetic algorithm manipulating system-level parameters while maintaining the output power and static failure requirements:

$$MDO_2 = \min_{x_d} \left\{ |\mathbf{u}_{\text{tower}}|, |\mathbf{M}_{\text{bearings}}|, |\mathbf{u}_{\text{blade tip}}| \right\} \tag{2}$$

where the decision vector $\mathbf{x}_d = [c_{\text{yaw}}, c_{\text{teeter}}, k_{\text{teeter}}, \theta_{\text{tilt}}, \phi_{\text{cone}}, d_{\text{overhang}}]$ encompasses yaw damping coefficients (c_{yaw}), teetering stiffness and damping (k_{teeter}, c_{teeter}), shaft tilt angle (θ_{tilt}), blade cone angle (ϕ_{cone}), and overhang distance (d_{overhang}). This phase exploits load-path redirection mechanisms–such as increasing cone angle to mitigate flapwise moments or tuning teeter stiffness to damp edgewise vibrations–while maintaining fixed aerodynamic contours.

3) STRUCTURAL OPTIMIZATION (MDO_3)

The Figure 4 represents the structural optimization process, which initiates with the reference structural architecture used in the previous MDO, but freely reconfigures, using a genetic algorithm, the internal topology to minimize the blade mass while withstanding the failure criteria $\mathcal{L}^*$. Preservation of the outer blade surface geometry is critical, as modifications would necessitate restarting the optimization process and potentially increase development time. Consequently, alterations to aerodynamic surfaces are reserved as a last resort exclusively for achieving structural compliance when all other design variables have been exhausted.

$$\text{MDO}_3 : \min_{\mathbf{t}, prop} \{W_{\text{blade}}\} \quad \text{s.t.} \quad \begin{cases} g_1(t, prop) = \mathcal{L}^*_{\text{ult}} \\ g_2(t, prop) = \mathcal{L}^*_{\text{fat}} \end{cases} \tag{3}$$

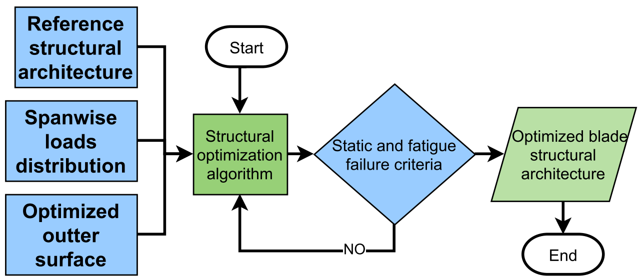


FIGURE 4. **Workflow of blade structural optimization process.**

Decision variables encompass spanwise composite thickness distributions $\mathbf{t} = [t_{\text{spar-cap}}, t_{\text{shear-web}}, t_{\text{shell}}]$ and material selection parameters *prop* that alternate between carbon/glass fibers and core materials (XPS foam, PVC foam, or balsa wood). Achieving structural adequacy requires material properties, cross-sectional area, and inertia properties that collectively withstand ultimate and fatigue loading conditions.

B. ECONOMIC MODELING

Cost, while emerging as a consequence of the design process, critically determines the technical and economic viability of the turbine. During blade structural design, decision variables are evaluated not only for aerodynamic performance but also for their impact on manufacturing expenses. These costs extend beyond blades to encompass manufacturing of other sub-systems, as well as installation and transportation of the wind turbine.

The cost model adapts the National Renewable Energy Laboratory (NREL) wind turbine cost framework [45], extending it to incorporate truss towers and teetering systems cost estimation, which are absent in the original formulation. The total turbine cost (CT_{total}) aggregates component-level expenses from: the blade manufacturing costs (CT_{Blade}); T-bolt expenses ($CT_{\text{T-Bolts}}$), which scale linearly with fastener count; lightning protection costs ($CT_{\text{Lightning}}$) correlate with blade span; Bearing systems (CT_{Bearings}) aggregate yaw, main, secondary, and pitch-bearing costs (multiplied by blade count); transportation costs ($CT_{\text{Transport}}$) are proportional to the number of blades; pitch systems (CT_{Pitch}) incur fixed costs per blade since it covers actuators and gearboxes; yaw system expenses (CT_{Yaw}) vary with operational strategy: free, damped, or actively controlled, where the first means no cost and the others depending on the components that make this; teetering cost has a similar approach ($CT_{\text{Teetering}}$); foundation costs ($CT_{\text{Foundation}}$) follow a power-law relationship with hub height and rotor area; and tower costs (CT_{Tower}) differentiate between configurations:

$$CT_{\text{tower}} = \begin{cases} \$3.5 \times \mathit{TowerMass}, & \text{if lattice tower,} \\ 0.4649 \times (\mathit{SweptArea} \times z_{hub}) + 324.33, & \text{if tubular tower.} \end{cases} \tag{4}$$

This adaptation specifically addresses the original model's omission of truss towers by introducing a mass-based cost formulation for lattice towers, while retaining the empirical tubular tower cost correlation.

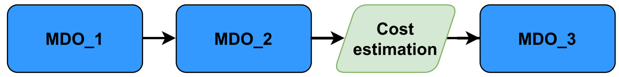


FIGURE 5. **Decision process for optimizing wind turbine configurations.**

Finally, the design methodology commences with an efficient aerodynamic foundation (MDO_1), progressing to the comprehensive definition of wind turbine configurations through integrated dynamic and geometric parameters, including cost estimation (MDO_2 + Cost estimation model). This framework culminates in blades and components structural design to withstand operational loads throughout the projected 20-year service life. Incorporating these cost factors into the optimization process (Figure 5) ensures a holistic evaluation of economic viability, yielding an integrated approach that simultaneously optimizes technical performance while adhering to practical economic constraints. The resultant outcome is a cost-effective, high-performance turbine solution.

IV. RESULTS

The study systematically passes through the conceptual and preliminary design phases to develop a technically and economically viable solution for low-wind-speed regions named "Aerogeradores de Baixa Velocidade" (ABV).

As part of the conceptual design phase the wind turbine design necessitates the identification of key governing features, which are not merely typological characteristics but are fundamentally driven by site-specific constraints and international standards. Their integration ensures design decisions aligning with operational viability, regulatory compliance, and commercial feasibility.

One-year anemometry measurements at 60 m, 80 m, 100 m, and 102 m validate a mean wind speed range of $V_{avg} = 4.5\ m/s$ to $6.5\ m/s$ at 50 m to 70 m, consistent with CEMIG operational data [46] and Global Wind Atlas benchmarks [30].

Furthermore, this study enables definitive classification within the IEC 61400-1, where the measured reference wind speed $V_{ref} = V_{avg}/0.2 = 27.84\,m/s$ positions the turbine well below the Class III upper limit of $37.5\,m/s$. Consequently, the structural design adheres to Class III with Turbulence Intensity Category B, corresponding to a standardized reference velocity of $V_{avg} = 7.5\,m/s$. Crucially, wind velocities serve dual roles:

- Operational Optimization: The site-specific $V_{avg} = 4.5\,m/s$ to $6.5\,m/s$ guides power curve calibration and energy yield maximization.
- Structural Design: The standardized $V_{avg} = 7.5\,m/s$ governs structural certification via extreme operating gust models and ultimate load validation.

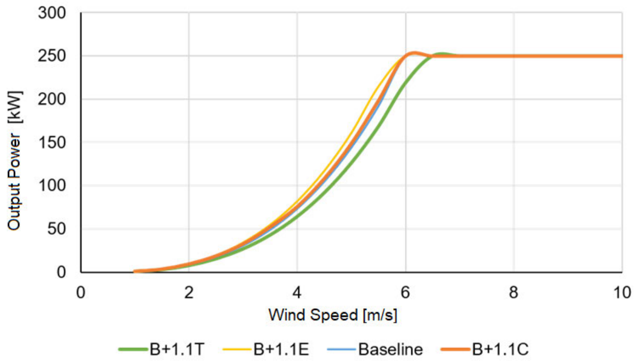


FIGURE 6. Output power curve for the ABV wind turbine. A value of 1.1 indicates a 10% increase relative to the baseline model for the specified parameters.

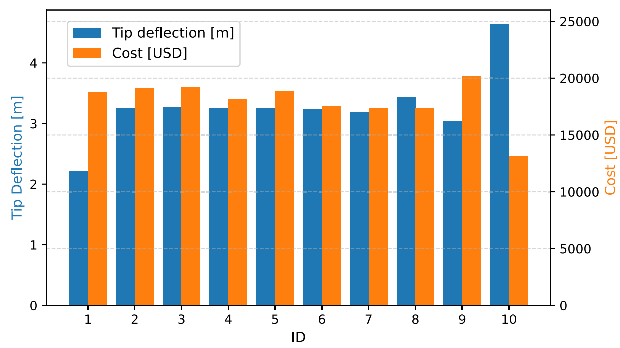


FIGURE 7. Impact of structural architecture on performance and cost.

TABLE 1. Structural Configurations.

ID	Configuration
1	Reference blade (comparison baseline)
2	Sandwich cores: Balsa wood
3	Sandwich cores: PVC foam
4	Sandwich cores: XPS foam
5	Two shear webs
6	Fiberglass leading edge
7	Fiberglass trailing edge
8	Fiberglass around spar caps
9	Carbon fiber spar caps
10	Fiberglass spar caps

The design process targets a wind turbine with a rated power of 250 W, operating at a rotor angular speed of 21 rpm and designed for rated wind speeds between 6.3 and 6.5 m/s. These fixed specifications – along with the classification under IEC Class IIIB and hub heights ranging from 60 to 70 meters – are treated as initial design constraints. Beyond these, additional limitations emerge dynamically throughout the design process, validated through feasibility analyses of key system characteristics. All constraints are progressively refined and exposed as iterative design decisions narrow the solution space.

A. BLADE AERODYNAMIC AND STRUCTURAL SENSITIVITY ANALYSES

Building on the aerodynamic design methodology established in Section III – which prioritizes optimization of chord distribution, blade span, and twist angles to maximize power coefficient – this paper quantitatively evaluates the relative influence of these parameters on rated output power. Figure 6 reveals the performance impact of isolated modifications to the baseline BEMT-derived blade geometry: Variant E (span extension) demonstrates marginal enhancement in power extraction, while Variant T (twist augmentation) exhibits a more pronounced opposing effect. Variant C (chord adjustment) shows negligible impact on the operational envelope curve. This parametric analysis establishes twist distribution and blade span as the primary drivers of energy yield, with both parameters demonstrating significant capacity to modify the rated wind speed.

Despite the favorable results associated with increasing the blade span to enhance wind turbine operational performance, it is essential to consider the structural implications of such a modification. One of the most significant challenges is the increase in blade tip deflection, which heightens the requirements for tower clearance as dictated by international standards.

To mitigate this issue, a straightforward approach involves enhancing the blade's stiffness. This can be achieved through various means, with modifications to structural parameters being among the most accessible and effective strategies. Accordingly, several variations of the baseline structural architecture were assessed, as summarized in Table 1, and the corresponding results are illustrated in Figure 7.

The structural variations presented in Table 1 were selected based on their potential impact on structural performance and manufacturability. Additional considerations included the recyclability of materials at the end of the blade's service life, as well as cost and market availability. The reference blade configuration was defined based on structural architectures of similar blades. All of them were submitted to a finite element method (FEM) structural model, developed under a conservative design philosophy. The model incorporated high-performance engineering materials to ensure the blade could adequately withstand a representative reference load, defined by extreme load conditions in accordance with IEC standards.

As illustrated in Figure 7, the use of advanced materials such as carbon fiber in the spar caps offers a direct and effective solution for reducing deflection. However, this approach significantly increases costs, potentially undermining the economic feasibility of the project. The figure also highlights the effects of other structural modifications, all aimed at enhancing the blade's cross-sectional properties.

A particularly promising and cost-effective alternative is the use of fiberglass spar caps. This configuration yields an approximate 30% reduction in cost, although it results in higher blade tip deflection. Nevertheless, this drawback can be mitigated through complementary strategies involving the dynamic behavior or typological characteristics of the wind turbine, or a combination thereof.

Furthermore, the use of core materials such as XPS foam, balsa wood, and PVC foam is noteworthy. These materials offer a balance between structural performance, cost, and sustainability, making them attractive options for further investigation.

B. MULTIDISCIPLINARY OPTIMIZATION AND ECONOMIC ANALYSIS

The conceptual design phase employs Multidisciplinary Design Optimization (MDO) as the primary framework for system integration, building upon prior sensitivity analyses. This phase coordinates parallel development workflows for all major wind turbine components while simultaneously evaluating fundamental typology configurations, including dynamic and geometric parameters established in Section III. Through this integrated approach, 18 distinct configurations were systematically generated, each representing a unique combination of six design variables: blade count (2 or 3), rotor orientation (downwind/upwind), hub connection type (rigid/teetered), power control strategy (pitch-regulated), yaw system architecture (damped-free/active), and tower topology (lattice/tubular).

To enable precise configuration tracking, an alphanumeric nomenclature was implemented, comprising six sequential designators: B2/B3 (blade count), OU/OD (upwind/downwind orientation), HR/HT (rigid/teetered hub), PP (pitch control), YDF/YAC (yaw damping/active control), and TT/TL (tubular/lattice tower), all showed in Table 2.

All 18 configurations were evaluated through the integrated design workflow (Figure 5), resulting in two optimized blade designs from MDO_1: one with a 37.5 m span for bi-bladed configurations and another with a 32 m span for tri-bladed setups. Both designs achieved the target power output. The bi-blade version featured a root chord of 2.79 m and a tip chord of 0.52 m, while the tri-blade had a root chord of 2.44 m and the same 0.52 m tip chord; both designs shared a blade root circle diameter of 1.32 m.

The optimized outer surfaces of both blade advanced through the integrated workflow into the MDO_2, where all 18 configurations underwent evaluation to identify optimal dynamic and geometric parameters aligned with the wind turbine's primary objectives. Throughout this process, the blade outer geometry remained invariant while the reference structural architecture (ID 1 from sub-section IV.IV-A) was optimized at a first stage via MDO_3 using simplified ultimate failure criteria.

MDO_2 analysis yielded critical insights into component loads and displacements, with configurations 6, 7, 13, and 16 demonstrating notably low blade tip deflection (4.70 m).

TABLE 2. Critical aeroelastic outputs used as decision criteria.

ID	Configuration	u_{tip}	u_{tower}	M_{yaw}	M_{root}
1	B2-OD-HT-PP-YDF-TT	4.90	1.30	1905.70	1495.00
2	B2-OD-HT-PP-YDF-LT	4.70	0.20	662.20	964.50
3	B2-OD-HR-PP-YDF-TT	4.80	0.50	1769.60	1559.00
4	B2-OD-HR-PP-YDF-LT	4.80	0.50	2008.00	1719.00
5	B2-OD-HT-PP-YC-TT	5.00	0.40	509.00	918.60
6	B2-OD-HT-PP-YC-LT	4.50	0.20	484.30	856.00
7	B2-OD-HR-PP-YC-TT	4.50	0.40	901.50	934.30
8	B2-OD-HR-PP-YC-LT	4.90	0.20	879.20	1003.00
9	B2-OU-HT-PP-YC-TT	4.70	0.40	807.50	772.20
10	B2-OU-HT-PP-YC-LT	4.70	0.20	663.70	855.50
11	B2-OU-HR-PP-YC-TT	4.70	0.50	805.60	1053.00
12	B2-OU-HR-PP-YC-LT	5.50	0.20	827.00	1043.00
13	B3-OD-HR-PP-YDF-TT	4.50	0.10	773.40	658.20
14	B3-OD-HR-PP-YDF-LT	4.60	0.20	753.60	655.70
15	B3-OD-HR-PP-YC-TT	4.70	0.20	640.60	554.20
16	B3-OD-HR-PP-YC-LT	4.50	0.10	683.80	558.10
17	B3-OU-HR-PP-YC-TT	5.80	0.30	702.40	550.10
18	B3-OU-HR-PP-YC-LT	5.70	0.10	720.80	561.10

Performance evaluations revealed distinct advantages across configurations: each exhibited unique optimization trade-offs, with specific IDs excelling in key operational domains such as blade root bending moments and tower-top displacements.

Ultimately, 15 configurations achieved feasible material solutions using carbon/glass fiber composites for the blade structural design, while configurations 1, 4, and 15 were not. These results were obtained under strict outer surface invariance constraints, maintained to manage computational expense within practical limits.

C. FINAL CONFIGURATION SELECTION AND RECOMMENDATIONS

Throughout the optimization process, constraints guided convergence toward three primary objectives: blade mass minimization, load severity reduction, and energy production maximization. The final configuration selection constitutes a multi-faceted decision prioritizing cost-effective solutions that maintain power production efficiency and structural integrity, with economic viability serving as the decisive criterion. Implementation of the simplified cost model–though excluding decommissioning, labor, and other lifecycle factors–provides essential decision-making insights by quantifying trade-offs between performance gains and economic outlays.

The Figure 8 confirmed that blades, tower, and foundation collectively dominate capital expenditures. Paralel to this, within the blade field, carbon fiber blades incur 40-60% higher material costs than fiberglass equivalents, establishing fiberglass as the economically preferred solution.

Comparative analysis between configurations with tubular towers (odd IDs) and truss towers (even IDs) demonstrates

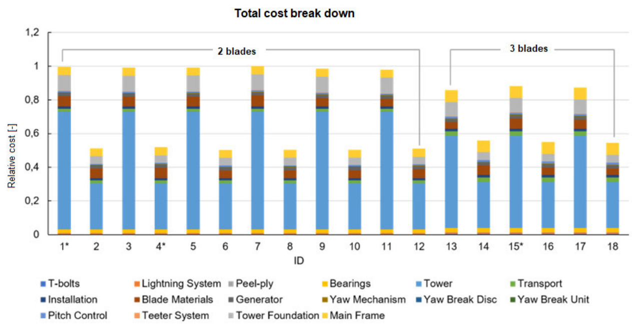


FIGURE 8. Overall breakdown of wind turbine costs. In the configurations marked with "*" it was not possible to obtain structural architectures that resisted the applied efforts.

that tubular towers exhibit significantly higher costs, primarily due to reduced rigidity and compromised natural frequencies that necessitate additional material to achieve required structural stability. In contrast, lattice towers display superior rigidity and dynamic performance, achieving comparable load resistance with approximately 50% cost reduction. Among tubular tower configurations, 3-bladed designs (IDs 13, 15, and 17) yield lower relative costs attributable to smaller rotor diameters, which reduce both aerodynamic loads and material requirements. Conversely, for lattice towers, 2-bladed configurations prove more cost-effective than 3-bladed alternatives, as the latter introduce disproportionate increases in manufacturing complexity and structural demands.

The technical and economic assessments identified configurations 2, 6, 8, 10, and 12 as highly competitive, with a technical tie in cost-effectiveness. However, fatigue loads spectra particularly favor teetered hub designs for load mitigation. Additionally, while upwind configurations necessitate active yaw control, downwind designs can eliminate these actuators, reducing both acquisition and maintenance costs.

Configurations IDs 2 and 6, featuring 2-bladed downwind rotors paired with lattice towers, emerged as the most promising candidates. These designs strike an optimal balance among cost efficiency, structural simplicity, and operational reliability. It was chosen, however, to retain yaw actuators (ID 6) in early prototypes to ensure dynamic stability until advanced modeling confirms that such systems can be safely eliminated under real-world conditions.

The blade structural architectures of the two final configurations advanced to the Multidisciplinary Design Optimization phase (MDO_3), targeting definitive blade design with integrated fatigue criteria. This final optimization incorporated qualitative outcomes from prior analyses – particularly cost considerations – leading to the exclusion of carbon fiber and balsa wood materials from the design space to enhance economic viability.

Ultimately, the optimized blade architecture features a single shear web with dual spar caps, reinforced leading/trailing edges, and complementary sandwich cores. Constructed from unidirectional, biaxial, and triaxial glass fiber laminates with PVC foam cores – all epoxy-resin infused – the final design achieves a mass of 3791.50 kg. While heavier than carbon-fiber benchmarks, this configuration delivers substantial cost savings while maintaining fatigue resistance. Integrated with the ID6 wind turbine configuration, the blade's key features are summarized in Table 3.

TABLE 3. Final ABV configuration.

Parameter	Configuration/Value
Power regulation	Pitch-regulated
Rotor orientation	Downwind
Nº of rotor blades	2
Cone angle	+8°
Rated power	250 kW
Rated wind speed	6.45 m/s
Rotor diameter	74.91 m
Hub height	61.32 m
Cut in wind speed	2.3 m/s
Cut out wind speed	12.3 m/s
Design life time	20 years

V. CONCLUSION

This study demonstrates the transformative potential of innovative design approaches for advancing wind energy technologies in regions with untapped resources, particularly Brazil's vast low-wind-speed territories. By challenging conventional paradigms, the ABV concept (detailed in Table 3) – featuring lattice towers, downwind rotor configurations, and teetered hub systems – proves that tailored solutions can unlock significant energy generation in areas traditionally deemed unsuitable for wind power.

The multidisciplinary optimization process produced designs that improve aerodynamic efficiency, structural integrity, and cost-effectiveness. Notable outcomes include: (i) reduced structural loads due to teetering and aeroelastic-based optimization, mitigating blade root moments and yaw bearing stresses; (ii) balanced trade-offs between performance and material costs, fulfilling aerodynamic and structural requirements; and (iii) aerodynamic refinement through iterative chord, twist, and span adjustments accounting for unsteady flow, resulting in blade geometries tuned for low-wind regimes.

Nevertheless, opportunities remain for enhancing workflow efficiency. Accelerated communication between design phases through multidisciplinary optimization (MDO) could reduce development timelines. This would require improved decision protocols for cohesive data interchange and enhanced cost modeling, particularly the inclusion of decommissioning expenditures involving substantial labor and logistical resources.

Finally, the project's success stems from synergistic collaboration among academia, industry, and policymakers. Robust institutional support from ANEEL and Eletrobras Furnas further underscores the critical role of public-private financing in de-risking early-stage renewable projects, cultivating local expertise, and strengthening supply chains.

REFERENCES

[1] O. Nematollahi, H. Hoghooghi, M. Rasti, and A. Sedaghat, "Energy demands and renewable energy resources in the middle east," *Renew. Sustain. Energy Rev.*, vol. 54, pp. 1172–1181, Feb. 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032115011375

[2] F. Abulfotuh, "Energy efficiency and renewable technologies: The way to sustainable energy future," *Desalination*, vol. 209, nos. 1–3, pp. 275–282, Apr. 2007. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0011916407001312

[3] M. K. G. Deshmukh, M. Sameeroddin, D. Abdul, and M. A. Sattar, "Renewable energy in the 21st century: A review," *Mater. Today, Proc.*, vol. 80, pp. 1756–1759, May 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214785321041031

[4] C. Cacciuttolo, M. Navarrete, and D. Cano, "Advances, progress, and future directions of renewable wind energy in Brazil (2000–2025–2050)," *Appl. Sci.*, vol. 15, no. 10, p. 5646, May 2025.

[5] A. K. de Souza Mendonçça and A. C. Bornia, "Análise da velocidade do vento com base no modelo logar ítmico de cisalhamento do vento: Um estudo de caso para algumas cidades Brasileiras," *Res., Soc. Develop.*, vol. 9, no. 7, 2020, Art. no. e298973984, doi: 10.33448/rsd-v9i7.3984.

[6] Empresa de Pesquisa Energética. (2024). *Consumo Mensal De Energia Elétrica Por Classe (regiões E Subsistemas)*. [Online]. Available: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/consumo-de-energia-eletrica

[7] Instituto brasileiro de Geografia e Estatística. (2022). *Sistema De Contas Regionais*. [Online]. Available: https://www.ibge.gov.br/estatisticas/economicas/contas-nacionais/9054-contas-regionais-do-brasil.html?edicao=41862&t=resultados

[8] M. M. Herrera, I. Dyner, and F. Cosenz, *Alternative Energy Policy for Mitigating the Asynchrony of the Wind-Power Industry's Supply Chain in Brazil*. Cham, Switzerland: Springer, 2018, pp. 199–221.

[9] A. Gerybadze and M. Klein, "Frugal innovation strategies and global competition in wind power," *Int. J. Technol. Manage.*, vol. 83, no. 1/2/3, p. 114, 2020.

[10] C. Gandenberger and M. Strauch, "Wind energy technology as opportunity for catching-up? A comparison of the TIS in Brazil and China," *Innov. Develop.*, vol. 8, no. 2, pp. 287–308, Jul. 2018, doi: 10.1080/2157930x.2018.1428050.

[11] G. R. D. Brown, R. J. Barthelmie, and H.-G. Kim, "The suitability of European designed wind turbines for the east Asian market," *J. Environ. Sci. Int.*, vol. 18, no. 8, pp. 825–831, Aug. 2009.

[12] M. S. Mayeed and A. Khalid, "Optimization of the wind turbine designs for areas with low wind speeds," in *Proc. ASME 9th Int. Conf. Energy Sustainability*, 2015, Paper V002T19A002.

[13] T. Burton, N. Jenkins, D. Sharpe, and E. Bossanyi, *Wind Energy Handbook*. Hoboken, NJ, USA: Wiley, 2011. [Online]. Available: https://books.google.com.br/books?id=dip2LwCRCscC

[14] S. R. Venkatramakrishnan, J. K. Pandey, A. K. Mondal, and A. Karn, "Low speed wind turbines for power generation: A review," *J. Adv. Res. Fluid Mech. Thermal Sci.*, vol. 67, no. 1, pp. 146–169, Mar. 2024.

[15] A. Suresh and S. Rajakumar, "Design of small horizontal axis wind turbine for low wind speed rural applications," *Mater. Today, Proc.*, vol. 23, pp. 16–22, Jan. 2020.

[16] *Wind Energy Generation Systems-Part 1: Design Requirements*, document IEC 61400, International Electrotechnical Commission, 2019.

[17] *Wind Energy Generation Systems—Part 2: Design Requirements for Small Wind Turbines*, document IEC 61400, 2013.

[18] P. D. Clausen and D. H. Wood, "Research and development issues for small wind turbines," *Renew. Energy*, vol. 16, nos. 1–4, pp. 922–927, Jan. 1999.

[19] Global Wind Energy Council. (2023). *Global Wind Report 2023*. Accessed: May 20, 2025. [Online]. Available: https://gwec.net/global-wind-report-2023/

[20] World Wind Energy Association. (2023). *Small Wind World Report 2023*. Accessed: May 20, 2025. [Online]. Available: https://wwindea.org/small-wind-world-report-2023/

[21] O. O. Ajayi, O. Ojo, and A. Vasel, "On the need for the development of low wind speed turbine generator system," *IOP Conf. Ser., Earth Environ. Sci.*, vol. 331, no. 1, Sep. 2019, Art. no. 012062, doi: 10.1088/1755-1315/331/1/012062.

[22] H. Jiang, J. Wang, J. Wu, and W. Geng, "Comparison of numerical methods and optimization algorithms for estimating parameters for wind energy potential assessment in low wind regions," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 1199–1217, Mar. 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032116310176

[23] K. A. Adeyeye, N. Ijumba, and J. S. Colton, "A techno-economic model for wind energy costs analysis for low wind speed areas," *Processes*, vol. 9, no. 8, p. 1463, Aug. 2021.

[24] R. Iliev and T. Tsalov, "Harnessing of the low energy wind potential," *IOP Conf. Ser., Earth Environ. Sci.*, vol. 1234, no. 1, Aug. 2023, Art. no. 012001.

[25] C. Sudhakar, D. Joshi, and N. R. Chitragar, "A review on design of low wind speed wind turbines," *Int. J. Innov. Res. Electr., Electron., Instrum. Control Eng.*, vol. 7, no. 12, pp. 23–28, 2019.

[26] A. Kusiak, *Engineering Design: Products, Processes, and Systems*. New York, NY, USA: Academic, 1999.

[27] J. R. R. A. Martins and A. B. Lambe, "Multidisciplinary design optimization: A survey of architectures," *AIAA J.*, vol. 51, no. 9, pp. 2049–2075, Sep. 2013, doi: 10.2514/1.j051895.

[28] J. Anderson, *Aircraft Performance & Design*. New York, NY, USA: McGraw-Hill, 1999. [Online]. Available: https://books.google.com.br/books?id=PwtO7aiwbBwC

[29] C. EPRI, P. Alto. (2024). *Climate Data User Guide: Climate Model Downscaling*. [Online]. Available: https://books.google.com.br/books?id=Yv1TAAAAMAAJ

[30] Global Wind Atlas. (2020). *Science Global Wind Atlas*. Accessed: Jul. 31, 2020. [Online]. Available: http://science.globalwindatlas.info/methods.html#header

[31] B. Timbal, E. Fernandez, and Z. Li, "Generalization of a statistical downscaling model to provide local climate change projections for Australia," *Environ. Model. Softw.*, vol. 24, no. 3, pp. 341–358, Mar. 2009. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364815208001333

[32] A. T. Silva dos Santos, C. M. Santos e Silva, D. Faro do Amaral Lemos, L. de Lima Oliveira, and L. André Cruz Bezerra, "Assessment of wind resources in two parts of northeast Brazil with the use of numerical models," *Meteorol. Appl.*, vol. 23, no. 4, pp. 563–573, Oct. 2016. [Online]. Available: https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/met.1595

[33] *InflowWind*, National Renewable Energy Laboratory (NREL), Golden, CO, USA, 2024. [Online]. Available: https://www.nrel.gov/wind/nwtc/inflowwind

[34] B. J. Jonkman, "TurbSim user's guide: Version 1.50," Nat. Renew. Energy Lab., Tech. Rep. NREL/TP-500-46198, Aug. 2009. [Online]. Available: https://www.osti.gov/biblio/965520

[35] M. Buhl. *IECWind*. Accessed: Jun. 2024. [Online]. Available: https://www.nrel.gov/wind/nwtc/iecwind.html

[36] A. Deperrois. (2024). *XFLR5: An Analysis Tool for Airfoils, Wings, and Planes Operating at Low Reynolds Numbers*. [Online]. Available: http://www.xflr5.tech

[37] Z. Du and M. S. Selig, "A 3-D stall-delay model for horizontal axis wind turbine performance prediction," in *Proc. AIAA*, 1998, pp. 1–12.

[38] L. A. Viterna and D. C. Janetzke, "Theoretical and experimental power from large horizontal-axis wind turbines," NASA Lewis Research Center, Cleveland, OH, USA, Tech. Rep. NASA TM-82923, Jun. 1982. [Online]. Available: https://ntrs.nasa.gov/citations/19820022844

[39] National Renewable Energy Laboratory (NREL). *OpenFAST*. Accessed: Jun. 2024. [Online]. Available: https://github.com/OpenFAST/openfast

[40] S. Guntur et al., "Fast v8 verification and validation for a mw-scale wind turbine with aeroelastically tailored blades," in *Proc. 34th Wind Energy Symp.*, 2016, doi: 10.2514/6.2016-1008.

[41] J. Rinker et al., "Comparison of loads from HAWC2 and OpenFAST for the IEA wind 15 MW reference wind turbine," *J. Phys., Conf. Ser.*, vol. 1618, no. 5, Sep. 2020, Art. no. 052052, doi: 10.1088/1742-6596/1618/5/052052.

[42] J. P. Blasques and M. Stolpe, "BECAS: A cross section analysis tool for anisotropic and inhomogeneous beam sections," Dept. Risø, Tech. Univ. Denmark (DTU), Roskilde, Denmark, Tech. Rep. Risø-R-1785, 2012. [Online]. Available: https://backend.orbit.dtu.dk/ws/portalfiles/portal/7711204/ris_r_1785.pdf

[43] M. Barone, J. Jonkman, and A. Robertson, "MLife user's guide," National Renewable Energy Laboratory, Golden, CO, USA, Tech. Rep. NREL/TP-5000-78647, Jan. 2021. [Online]. Available: https://www.nrel.gov/docs/libraries/wind-docs/mlife-user.pdf?sfvrsn=1bb1c40c1

[44] P. A. Vikhar, "Evolutionary algorithms: A critical review and its future prospects," in *Proc. Int. Conf. Global Trends Signal Process., Inf. Comput. Commun. (ICGTSPICC)*, Dec. 2016, pp. 261–265.

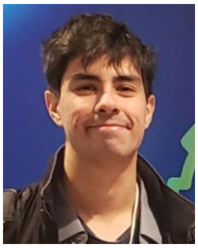
[45] P. Bortolotti et al., "A detailed wind turbine blade cost model," Nat. Renew. Energy Lab. (NREL), Golden, CO, USA, Tech. Rep. NREL/TP-5000-73585, 2019, pp. 1–69, doi: 10.2172/1529217.

[46] O. A. C. do Amarante, F. J. L. Silva, and P. E. P. Andrade, *Atlas Eólico: Minas Gerais*. Minas Gerais, Brazil: Companhia Energética de Minas Gerais (CEMIG), 2010.

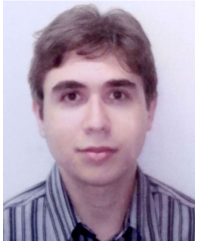
JAMES ROJAS WATERHOUSE received the B.Sc. degree in mechanical engineering, with an emphasis on aircraft, the M.S. degree in engineering, and the Ph.D. degree in aeronautical renewable fuels from the University of São Paulo (USP), Brazil, in 1995, 2000, and 2010, respectively. He is currently a Researcher and a tenured Professor with the Department of Aeronautical Engineering, São Carlos School of Engineering, USP.

CRISTHIAN R. MORANTE VILLARREAL received the B.Sc. degree in aeronautical engineering from the University of São Paulo, Brazil, in 2021. He is currently with the Wind Energy Sector, NewCo Blades Technology, as a Project Engineer. His research interests include structural layout, dynamic simulation, and wind energy.

GUILHERME BEPPU DE SOUZA received the B.Sc. degree in aeronautical engineering from the University of São Paulo, Brazil, in 2024. He is currently an Engineer in the aerodynamics and dynamics area at NewCo Blades Technology. His research interests include wind energy, dynamic simulations, and multidisciplinary optimization.

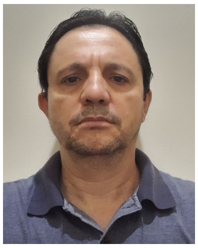


FERNANDO VILAS BOAS RIBEIRO received the B.Sc. degree in aeronautical engineering from the University of São Paulo (USP), Brazil, in 2023, where he is currently pursuing the M.S. degree in aeronautics with the Department of Aeronautical Engineering, São Carlos School of Engineering. He is also with NewCo Blades Technology, as a Composites Structural Engineer. His research interests include composite structures, O&M, and wind energy.



CARLOS HENRIQUE GASPARETTI received the B.Sc. degree in aeronautical engineering from the University of São Paulo, Brazil, in 2025. He is currently an Engineer in the aerodynamics and aeroacoustics area with NewCo Blades Technology. His research interests include renewable energy, design engineering, and fluid dynamics.

KAUAN PIRES QUEVEDO is currently pursuing the degree in mechanical engineering with the University of São Paulo, Brazil. His research interests include heat transfer, thermodynamics, and wind energy.



JOSIEL GONÇALVES DOS SANTOS received the M.Sc. degree in production and systems engineering from CEFET/RJ, in 2014, and the degree in control and automation engineering and mathematics. He is currently an Engineer with Eletrobras Furnas and a Faculty Member of electro-electronics with FAETEC-RJ. His experience includes project management in research and development for the electrical sector, industrial automation, and instrumentation, and teaching in engineering programs.

GEORGE CAMARGO DOS SANTOS received the Electrical Engineering degree from the Federal University of Rio de Janeiro (UFRJ), in 2002, the M.Sc. degree in electrical engineering from COPPE, UFRJ, in 2006, and the M.Sc. degree in energy engineering from the Federal University of Itajubá (UNIFEI), in 2016. He has over 21 years of experience in Brazilian Electricity Sector.

MARLOS JOSÉ RIBEIRO GUIMARÃES received the Civil Engineering degree from the Catholic University of Goiás, in 1993, and the M.Sc. degree in structures and the Ph.D. degree in structures and civil construction from the University of Brasília, in 2000 and 2005, respectively. He has worked in structural design for telecommunications towers and held teaching positions across various institutions. He is currently with Eletrobras Furnas, contributing to green hydrogen, energy prospecting, and innovation projects.

Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) - ROR identifier: 00x0ma614