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Design and Analysis of Darrieus Vertical Axis Wind Turbines as an Energy Source for Speedboat Navigation and Lighting System

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ABSTRACT

This research explores integrating a Darrieus Vertical Axis Wind Turbine (VAWT) system to enhance speedboat energy efficiency. With the rising need for sustainable marine energy solutions, harnessing wind power through VAWT technology can reduce fuel consumption and environmental impact. The study focuses on the aerodynamic design, turbine placement, and energy output estimation under varying maritime wind conditions. Vertical-axis turbines efficiently operate without needing wind alignment, making them suitable for marine use. A VAWT was mounted on a 12-meter, four-engine speedboat, powering essential systems like spotlights and navigation. Simulations and field tests assessed power generation, stability, and drag impact. At a speed of 14 knots (7.2 m/s), the turbine produced 11.39 watts, outperforming laboratory results due to uniform wind distribution across the blades. Laboratory experiments confirmed these findings, showing an electrical output of 8.2 watts, sufficient for battery charging. Increasing the wind sweep area could further boost power while maintaining stability. The Darrieus VAWT model demonstrated effective energy harnessing at lower speeds and fuel consumption reduction, highlighting its potential for sustainable maritime applications. Future work will focus on improving material durability and developing automated wind angle adjustments for optimal performance.

1. INTRODUCTION

In the archipelago area, where waterways are the main routes for transportation and connectivity, speedboats play a crucial role in daily life and economic activities. By integrating small Vertical Axis Wind Turbines (VAWT) as a renewable energy source, speed boats can harness wind power efficiently, even in varying wind conditions often experienced on open waters. This reduces reliance on fossil fuels and promotes sustainable maritime practices, aligning with global efforts to mitigate climate change and support energy conservation in island communities. These turbines, characterized by their unique orientation and adaptability, redefine how speedboats generate and utilize power. Integrating VAWTs on speedboats is a technological marvel and a significant step toward green energy in maritime travel.

Many studies discuss the use of renewable energy on fast ships. Even in the archipelago area like North Maluku, many ships are equipped with solar panels as an energy source. However, this solar panel has disadvantages when the sun sets or the weather is cloudy. Of course, the performance of this rooftop solar panel is not optimal. A vertical-axis wind Turbine (VAWT) is distinct from the traditional horizontal-axis wind turbine in terms of orientation. Instead of rotating horizontally like conventional wind turbines, VAWTs rotate around a vertical axis. This orientation allows them to harness wind energy from all directions, making them highly effective in the unpredictable and shifting wind conditions expected on the open sea. Integrating Darrieus Vertical Axis Wind Turbines (VAWTs) into speedboat designs represents a forward-thinking approach to clean energy. These turbines, known for their vertical blade configuration and aerodynamic efficiency, are increasingly being explored for marine applications.

Integrating a small-scale Darrieus vertical-axis wind turbine (VAWT) on this speedboat marks a significant advancement in the application of renewable energy for maritime use. This system is critical in ensuring a sustainable and reliable power supply, particularly for the boat’s navigation and lighting systems. By harnessing wind energy, the turbine reduces dependence on conventional fuel-based power sources, enhancing environmental sustainability and operational efficiency.

One key advantage of this innovation is its ability to generate electricity without compromising the boat’s stability. The VAWT’s design is particularly well-suited for maritime environments due to its omnidirectional wind capture capability, enabling consistent power generation regardless of wind direction. Unlike conventional horizontal-axis wind turbines, the Darrieus-type VAWT features a compact structure with a lower center of gravity, minimizing its impact on the boat's balance and maneuverability.

Moreover, this implementation represents a groundbreaking development, as it has never been previously applied to small-scale speedboats. Traditional renewable energy solutions in maritime settings primarily focus on larger vessels or land-based wind energy systems. Introducing this technology to small speed boats creates new opportunities for improving energy efficiency and sustainability in marine transportation, particularly for ships operating in remote or off-grid locations with limited access to conventional power sources.

This initiative also serves as a potential model for future innovations in renewable energy adoption within the maritime industry. With continuous advancements in turbine efficiency and integration techniques, deploying small-scale wind energy solutions across various types of marine vessels could contribute to reducing carbon emissions and accelerating the transition toward sustainable transportation.

The Darrieus Vertical Axis Wind Turbine (VAWT) presents several advantages for marine applications compared to other wind turbine models, such as the Horizontal Axis Wind Turbine (HAWT) and the Savonius VAWT. One of its primary benefits is its omnidirectional functionality, allowing it to capture wind from any direction without requiring a yaw mechanism. This feature is particularly advantageous in marine environments, where wind patterns fluctuate due to wave movements, storms, and changes in ship orientation. In contrast, HAWTs rely on complex yaw systems, increasing maintenance requirements, while Savonius VAWTs, despite being omnidirectional, are less efficient in energy production.

Another notable advantage of Darrieus VAWTs in marine settings is their ability to perform efficiently in turbulent and gusty winds. Offshore and ship-mounted installations frequently encounter fluctuating wind speeds, and the aerodynamic structure of a Darrieus VAWT allows it to operate effectively under these conditions. This makes it more reliable than HAWTs, which require steady, laminar wind flows for optimal performance, and Savonius VAWTs, which handle turbulence well but at the cost of lower efficiency.

The compact and space-efficient design of Darrieus VAWTs further enhances their suitability for marine use. Their vertical configuration allows for installation in restricted areas such as ship decks, offshore platforms, and coastal sites where space is limited. Unlike HAWTs, which demand significant clearance and extensive support structures, Darrieus VAWTs can be positioned closer together and in locations where conventional wind turbines would be impractical.

Stability is crucial in marine applications, and Darrieus VAWTs offer an advantage due to their lower center of gravity. With the generator and drivetrain located at the base, these turbines are structurally more stable than HAWTs, which have top-mounted generators, making them top-heavy and less suitable for floating platforms or ship installations. While Savonius VAWTs also feature a low center of gravity, they lag in energy efficiency compared to Darrieus designs.

Another key benefit of Darrieus VAWTs is their reduced noise and vibration levels. Their smooth, continuous blade rotation reduces aerodynamic noise and mechanical vibrations, making them well-suited for ships and marine ecosystems. In contrast, HAWTs generate considerable noise due to blade pass effects, while Savonius turbines, though quieter, are less efficient.

Ease of maintenance is another area where Darrieus VAWTs excel. With the generator and critical mechanical components positioned at the base, repairs and servicing are significantly more accessible, particularly in offshore conditions. HAWTs require cranes and complex maintenance procedures due to their elevated generators, making repairs more challenging in marine environments. While Savonius turbines also offer easy maintenance, they do not match the power output of a Darrieus turbine.

Finally, the Darrieus VAWT's scalability and modularity make it highly adaptable for marine applications. It can be utilized for small-scale onboard auxiliary power on ships or scaled up for large floating offshore wind farms. Unlike HAWTs, which require greater spacing between units due to wake turbulence, Darrieus turbines can be arranged more compactly, maximizing space utilization.

The Darrieus VAWT is a highly suitable wind turbine for marine applications. It offers superior performance in fluctuating wind conditions, ease of maintenance, structural stability, space efficiency, and reduced noise levels. Compared to HAWTs, it is more resilient to turbulent winds and simpler to maintain while delivering higher efficiency than Savonius VAWTs. These advantages make it a practical and efficient choice for ships, offshore wind farms, and coastal energy generation systems.

Wind energy has rapidly evolved into one of the most advanced and influential technologies in the global push for renewable energy, setting major trends in the clean energy sector. Innovations like more significant, more efficient turbines, offshore wind farms, and floating wind technology have transformed how countries harness wind power. The trend is driven by the urgent need to combat climate change and reduce carbon emissions. This leads to widespread investments and breakthroughs, such as artificial intelligence for turbine optimization and hybrid systems that integrate wind with solar and battery storage. As wind energy becomes more cost-effective and scalable, it continues to shape the future of energy infrastructure, powering entire cities and driving the shift toward a sustainable, low-carbon world [1, 2].

Renewable energy is increasingly being integrated into ships to reduce fuel consumption and lower carbon emissions, transforming the maritime industry. Technologies like solar panels, wind-assisted propulsion systems, and onboard energy storage are now commonly used on commercial and recreational vessels. Modern ships also experiment with hybrid setups, where wind energy from vertical or horizontal turbines and solar power work together to support navigation, auxiliary systems, and lighting. These innovations are improving the environmental footprint of shipping and paving the way for cleaner, more efficient maritime transport [3-15].

Previous researchers have carried out several studies related to hybrid energy for ships. Techno-economic feasibility assessment model for integrating hybrid renewable energy systems into power systems of existing ships: A case study of a patrol boat [16]. Solar-Assisted Electric Boat Power and Propulsion System Simulations [17]. Hydrogen, solar power, and wind turbines [18]. A zero-emission super-yacht is one way to reduce emissions from vehicles at sea [19]. Although fossil fuel engines still dominate, using wind for propulsion is possible [20]. In a speeding, fast boat, there is a potential for wind energy that has not been adequately utilized. Installing a wind turbine gives you electrical energy to power lighting, signal lights, and the ship's navigation system. This research aims to design and analyze the installation of vertical-axis wind turbines on fast boats to utilize renewable energy. The main thing to pay attention to is not to let the presence of wind turbines on this ship interfere with its stability. Therefore, the Savonius-Darius hybrid vertical-axis wind turbine was selected for this study.

The research used theoretical approaches, simulations, and laboratory experiments. We are creating FEM-based computer modeling using ANSYS FLUENT and conducting simulations related to turbine performance and ship stability. After that, a wind turbine of actual size is made and equipped with a dynamo and electrical systems such as voltage stabilizers, dry batteries, and inverters. Electrical energy is a fundamental need today. Many appliances depend on electricity. However, it cannot be denied that much of the electrical energy used today still comes from power plants that are not environmentally friendly, such as those that use coal and diesel oil as fuel. This research is based on the conditions of the island region, where fast boats, often known as speedboats, are a very reliable means of sea transportation. So far, the need for electricity for ship navigation, such as GPS and other equipment, including lighting systems, uses conventional methods. Some fast boats already use solar cells to meet their electricity needs. However, solar cells cannot work optimally when it is cloudy or in the evening. Even though fast boats always get wind due to the movements they make. Therefore, applying a Savonius-Darrieus vertical-axis wind turbine is possible.

Previous research related to the application of wind turbines on ships was not equipped with computer-aided engineering (CAE) analysis. Usually, this is done by conducting experiments on-site. This research uses a CAE approach by designing, testing with related software, and validating with experiments in a new laboratory, followed by fabrication for prototype testing at the actual location. Using CAE will make design and experimentation more effective with techniques that have been simulated intensively, including design revisions when they fail at the simulation stage. Apart from that, the efficiency level of wind turbines is not too high, making the use of CAE very significant. Hopefully, this research will provide novelty to the VAWT system applied to fast ships.

The problem in this research is determining design parameters and conducting a comprehensive analysis in manufacturing wind turbines installed on fast ships using CAE, which are validated with laboratory experiments and prototype tests in actual conditions. This research focuses on simulation to obtain the required parameters.

Research and application of wind turbines on ships are currently still limited. This is related to the maximum efficiency level of PLTB of 59% and is considered not too large compared to the technological engineering that must be carried out. The Darius model vertical-axis wind turbine has higher efficiency, but this type of turbine cannot rotate itself from rest even when exposed to strong winds. There must be a mechanism to provide initial rounds. This research uses a Savonius-Darius hybrid vertical axis wind turbine to enable self-starting. Several previous researchers have proposed the use of wind energy on ships. In research in West Java, a wind turbine was installed on the Rancabuaya fishing boat. Able to provide the energy needed for the Rancabuaya fishing vessel, 720 WH per day [21].

Furthermore, wind technology has been used to assist the propulsion system of merchant ships. Each technology has been studied regarding its physical principles, operation, adaptation, and installation on board and the energy benefits it brings [22]. And the horizontal-axis wind turbine [23]. Research on the performance of solar power plants on fishing boats as a cheap and sustainable energy source has been carried out with a 219.98-watt capacity installed in parallel. It produces maximum electrical power in sunny weather with optimal temperatures [24]. Vertical-axis wind turbines can work in areas with low wind speeds, and the design can be very small or micro [25]. So they can be installed on ships. The use of a Wind Turbine Ventilator as an Alternator drive produces electrical energy on fishing boats at a wind speed of 5 m/s producing an electric voltage of 36 Volts, an electric current of 1.8 Amperes, minimum electric power of 64.85 Watts an efficiency of 21.18%, then at a wind speed 18 m/s produces a voltage of 105.5 Volts, an electric current of 6.4 Amperes, electric power of 672 Watts with a maximum efficiency of this generating system of 40.08% [26].

This research uses the Darius wind turbine as an electricity generator because the other VAWT type, Savonius turbines, generally have low efficiency; however, several studies have been conducted, such as selecting the optimal V-type blade angle [27]. Determine the aspect ratio of wind turbines [28], do a combination of the Darius and Savonius turbines so that they are self-focused [29], and design a vertical axis wind turbine that can open and close according to the wind direction if the wind is from the desired direction, the turbine opens and vice versa [30]. Besides paying attention to aerodynamics, wind turbine design must consider structural strength. Research on aerodynamic effects and structural stability has been carried out with the help of CFD [31]. CFD is a simulation software that can handle complex wind turbine analysis [32, 33].

This research focuses on designing and analyzing a vertical-axis wind turbine, Darreius type, applied to fast boats for navigation and lighting systems. The Savonius-Darius hybrid turbine can overcome the self-starting problem in Darius wind turbines [34]. This research contributes to developing vertical-axis wind turbine applications in real-world settings. It provides novelty because it has never been designed before and is original in ideas and problem-solving, especially with computer-aided engineering (CAE) in its analysis.

2. METHODOLOGY

Designing and building a Vertical Axis Wind Turbine (VAWT) based on the Darrieus configuration for installation on a speedboat involves a multifaceted methodology that addresses the unique dynamics of marine environments and the technical demands of renewable energy generation. Figure 1 shows the sequence of the research flow diagram process.

The process begins with a comprehensive analysis of wind patterns and the boat's operational profile, understanding how the relative wind speed and direction will impact turbine performance while in motion. Since the speedboat is a moving platform, it's crucial to model the apparent wind conditions to optimize the VAWT's orientation and efficiency.

Next, material selection must be carefully considered, emphasizing lightweight and corrosion-resistant materials. Marine environments are harsh, and the structural components must withstand saltwater exposure, humidity, and continuous mechanical stresses. Materials like carbon fiber or marine-grade aluminum balance durability and efficiency for the turbine blades. The design must also account for the speedboat's vibrations and oscillations, requiring a robust yet flexible mounting system to reduce the risk of structural fatigue and ensure stability.

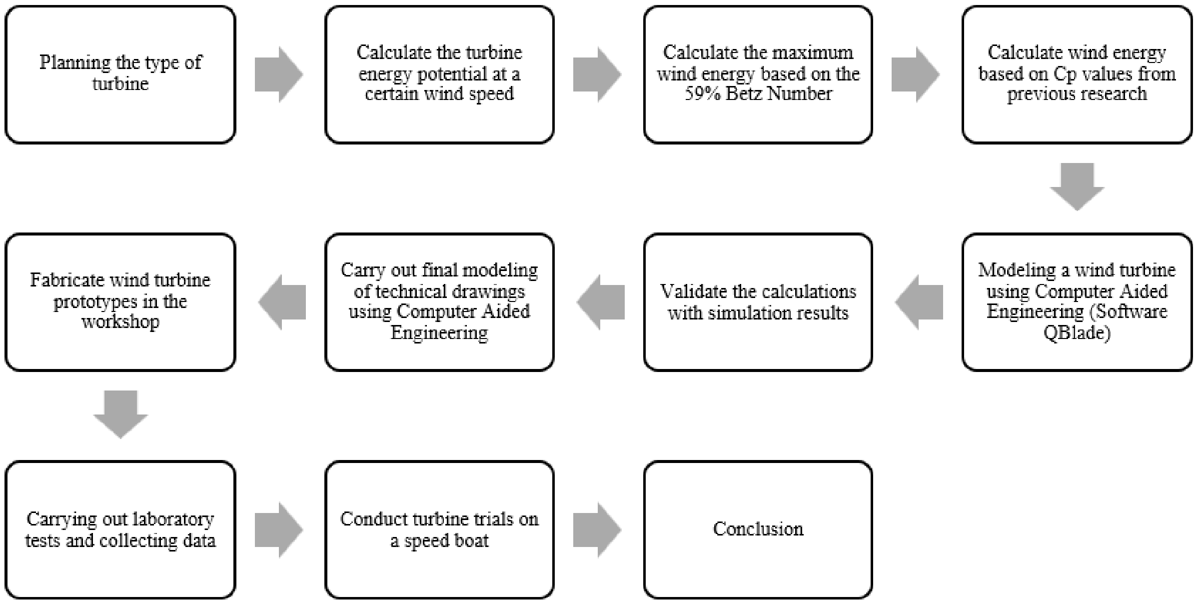

Figure 1. Flow chart of the research

Aerodynamic efficiency is another key focus, as the VAWT must operate effectively in varying wind speeds and directions. Computational Fluid Dynamics (CFD) simulations are essential to refine the blade shape and pitch to maximize energy capture. Additionally, drag forces created by the turbine when the boat is in motion should be minimized, necessitating a streamlined design that can adapt to changing angles of attack. The turbine's design can include passive or active yaw control mechanisms to ensure optimal alignment with the apparent wind.

The energy conversion system is integral to the turbine's function. The generator must be selected and calibrated for marine use, with a waterproof and vibration-resistant casing. An energy management system is required to efficiently store and distribute the generated power, potentially integrating with the boat's existing electrical infrastructure. Ensuring efficient power transfer involves optimizing the turbine's rotational speed and matching it to the generator's operating range, often necessitating a gearbox or a direct-drive configuration to minimize energy losses.

Structural integration with the speedboat demands meticulous engineering. The mounting system must distribute loads evenly across the boat's frame, avoiding stress concentrations that could compromise the hull's integrity. A modular design can enhance the ease of installation and maintenance, while retractable or collapsible features may improve maneuverability when the turbine is not in use or during docking. Safety mechanisms are also critical, including automatic braking systems to prevent overspeed scenarios and blade stalling features that protect against extreme conditions.

Developing a wind turbine for a speedboat begins with planning the type of turbine, which involves determining the most suitable design based on various factors such as efficiency and application. Next, the turbine's energy potential is calculated at a certain wind speed to estimate its performance. The maximum wind energy is determined using the 59% Betz Number, representing the theoretical efficiency limit. The calculation is further refined by incorporating Cp values from previous research to account for real-world conditions. The turbine design is then modeled using Computer Aided Engineering (CAE) software, specifically QBlade, to simulate and optimize performance. These calculations are validated through simulation results, ensuring the design meets expectations. Once the design is validated, technical drawings are finalized using CAE for fabrication. The wind turbine prototype is then fabricated in the workshop. Laboratory tests are conducted to collect data and assess performance, with any errors being addressed by improving the prototype. Finally, the turbine undergoes trials on a speedboat to test its real-world performance. The process concludes with drawing conclusions based on the results of the trials and tests. Finally, field testing and validation ensure the turbine's real-world performance meets expectations. This phase includes trials in various marine environments, adjusting the system as necessary based on empirical data. Continuous monitoring systems can gather performance metrics, providing insights for future optimization and ensuring the turbine operates efficiently and reliably under various conditions.

A hybrid system combining a Vertical Axis Wind Turbine (VAWT) and solar panels on a speedboat provides a reliable and efficient way to generate renewable energy in varying marine conditions. The VAWT captures wind energy from any direction, making it ideal for dynamic and unpredictable ocean environments, while the solar panels harness sunlight during the day. This complementary setup ensures a more consistent energy supply: when wind speeds are low, solar panels can continue producing electricity, and when the sun isn't shining, the VAWT can take over. Together, these renewable sources can power essential onboard systems, such as navigation, communication, and lighting, reducing the need for traditional fuel and enhancing the speedboat's sustainability and autonomy [35].

Wind Energy can be expressed by

$$P_w = \frac{1}{2}\rho . A . v^3 \tag{1}$$

P_w = power of the wind (Watt).
ρ = air density (Kg/m^3) = 1.164 kg/m^3.

A = area of wind captured by the windmill (m^2)
v = wind speed (m/s)

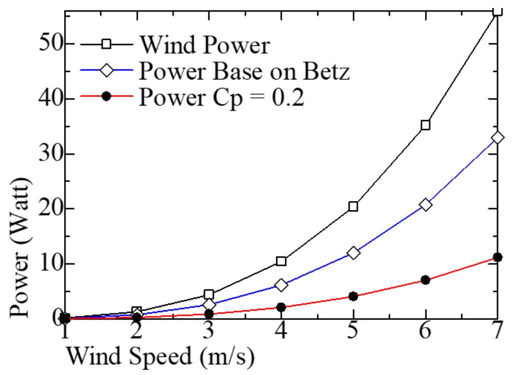

Figure 2. Wind power

Figure 2 shows the relationship between wind speed and power generated according to Eq. (1), according to the limit of the Betz number, and power assuming Cp = 0.2. The Betz Number is 59%, as has been determined based on previous research.

2.1 Modeling with QBlade

QBlade is a free software used to simulate wind turbines horizontally and vertically. Many previous researchers have used software to solve turbine problems. Such as the analysis of the Lifting Line Free-Vortex Wake (LLFVW) model, design and simulation of a vertical axis wind turbine with naca 0021 rotor blades with QBlade [2].

The QBlade modeling steps are as follows:

-Determine the type of airfoil that will be used, in this case NACA 0020 as seen in Figure 3.

Figure 3. NACA 0020

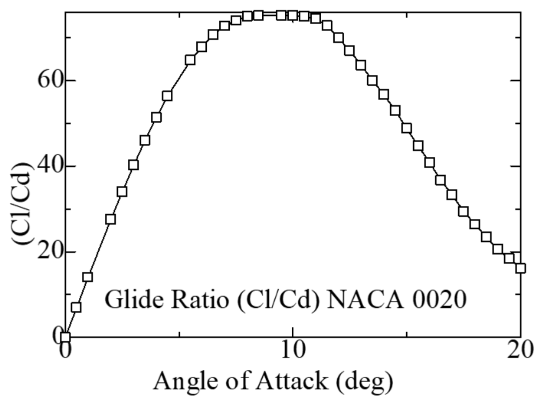

Figure 4. Glide ratio

-Determine the Glide Ratio (Cl/Cd) shown in Figure 4.

The Glide Ratio (Cl/Cd) of the NACA 0020 airfoil is a critical parameter influencing the aerodynamic efficiency of a vertical axis wind turbine (VAWT). The lift-to-drag ratio (Cl/Cd) quantifies the airfoil's ability to generate lift while minimizing drag, directly affecting the turbine's power output and overall efficiency.

As a symmetric airfoil, NACA 0020 offers distinct advantages in VAWT applications due to its adaptability to varying wind directions. Its moderate Cl/Cd ratio provides an optimal compromise between lift production and structural robustness, making it particularly suitable for VAWTs operating in fluctuating wind environments. Although its lift-to-drag performance is lower than that of thinner airfoils, such as NACA 0015, it compensates through enhanced structural rigidity, improving durability and resistance to deformation under elevated wind loads.

A higher Cl/Cd ratio contributes to an improved Tip Speed Ratio (TSR), which defines the relationship between blade tip velocity and wind speed. The use of NACA 0020 facilitates a relatively stable TSR, promoting efficient energy conversion while ensuring turbine operational stability. However, given its higher drag compared to thinner airfoils, optimizing its angle of attack is crucial for minimizing energy losses and maximizing aerodynamic efficiency.

For Darrieus-type VAWTs, reducing aerodynamic drag is essential to sustaining continuous rotation and enhancing performance. The NACA 0020 airfoil mitigates stall effects by maintaining smooth airflow over the blades, thereby ensuring a consistent power output even under turbulent wind conditions. Despite having a lower Cl/Cd ratio relative to thinner airfoils, its structural integrity makes it well-suited for larger turbines that experience substantial aerodynamic and mechanical loads.

NACA 0020 is a viable airfoil choice for VAWT applications, mainly where structural durability and stable performance under dynamic wind conditions are primary considerations. Although its moderate Cl/Cd ratio presents certain aerodynamic limitations, strategic design optimizations, such as blade pitch adjustments and TSR refinement, can enhance efficiency. By effectively balancing aerodynamic performance with mechanical resilience, NACA 0020 facilitates reliable energy conversion and extended turbine lifespan.

-Modeling the VAWT Rotor

In this research, simulations were carried out for three types of rotors: two-blade, three-blade, and four-blade. The most optimal one will be selected by considering constraint factors. Figure 5 is a Darius Rotor model of VAWT using software.

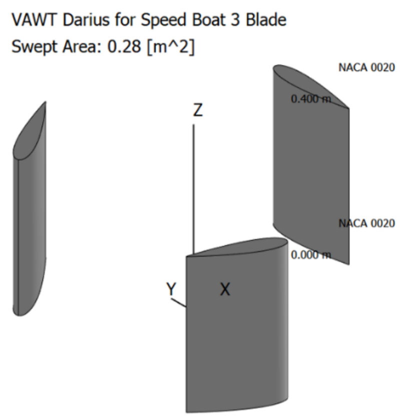

Figure 5. Darius rotor

According to the calculations, at a wind speed of 7 m/s, assuming Cp = 0.2, the power is 11.17906 watts. Based on the simulation results with CAE, the Cp value = 0.208942, and the maximum power is 11.86584 watts.

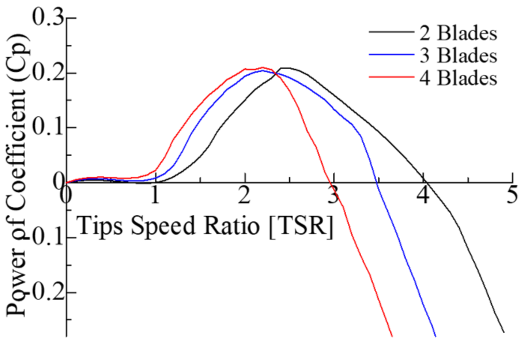

Figure 6. Cp vs TSR for every number of blades

The design of the number of blades is carried out by simulation. The results of the 2,3, and 4-blade simulations can be seen in Figure 6. The number of blades is selected as 3, considering efficiency in the production process.

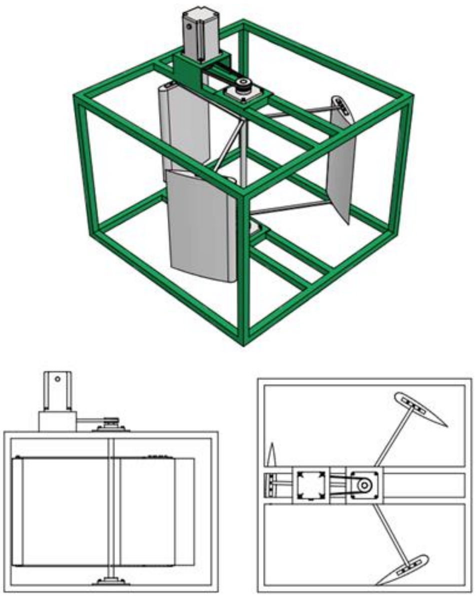

Figure 7. Engineering drawing of wind turbine prototype

Figure 7 is the final technical drawing of the VAWT to carry out the fabrication process.

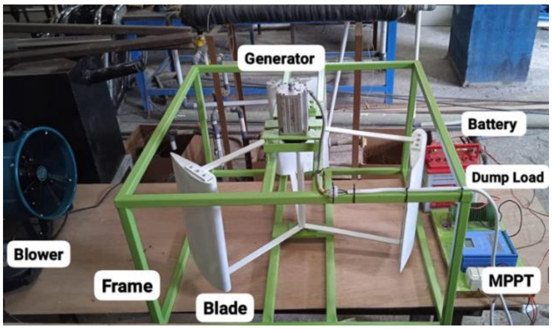

Figure 8. Prototype of a wind turbine

Figure 8 shows a wind turbine built and tested in a laboratory.

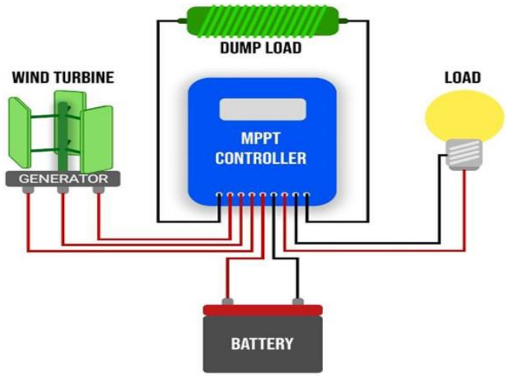

Figure 9. Electrical circuit

Figure 9 shows the electrical system of this wind turbine. The MPPT controller regulates the wind turbine's electrical power. Electricity from MPPT flows to the battery-charged Dump Load, which is installed to prevent electricity from being absorbed and converted into heat when the battery is full.

3. RESULT AND DISCUSSION

Turbine power is obtained from the generator's energy using the generator and mechanical efficiency. Test results are shown in Table 1.

Testing on a speedboat is shown in Figure 10.

Figure 10. Testing on a speedboat

Direct turbine testing was conducted in the coastal waters of Ternate using a 12-meter speedboat equipped with four engines. The wind turbine was mounted on the speedboat and then operated at varying speeds to evaluate performance. The highest speed achieved in this study was 7.2 m/s under relatively calm sea conditions. Given the minimal external wind influence on the boat, it was assumed that the wind speed experienced by the turbine matched the speed of the vessel. Testing a small Darrieus wind turbine installed on a speedboat in a real ocean environment presents a unique and practical approach to evaluating its performance under marine conditions. The Darrieus turbine, characterized by its vertical-axis design and aerodynamic, curved blades, is particularly well-suited for environments where wind direction frequently shifts, as it can capture wind from any angle. Mounted on a speedboat, the turbine can be maneuvered into different sea areas to experience a range of wind speeds and directions, providing a comprehensive understanding of its efficiency and resilience. However, testing in this setting presents significant challenges. The constant motion of the speedboat, influenced by waves and ocean currents, introduces vibrations and lateral forces that may affect the turbine's operation and the stability of its power output.

Table 1. Laboratory experiment result

V_{wind} (m/s)	V_{wind} (knot)	Rotation (RPM)	TSR	Generator Power (watts)	Generator Efficiency	Mechanical Efficiency	Turbin Power (watt)
1.1	2.1384	0	0	0	0.9	0.8	0
2.1	4.0824	0	0	0	0.9	0.8	0
3	5.8320	56	0.683822	0.43	0.9	0.8	0.597222
4.1	7.9704	96	0.857756	1.1	0.9	0.8	1.527778
5	9.7200	188	1.377413	2.5	0.9	0.8	3.472222
6	11.6640	345	2.106417	5.3	0.9	0.8	7.361111
7.1	13.8024	475	2.450822	6.2	0.9	0.8	8.611111

Despite these difficulties, conducting tests directly in the ocean allows engineers to evaluate how well the Darrieus turbine's materials and design withstand harsh marine conditions, such as saltwater corrosion, intense gusts, and turbulent waves. This real-world data is invaluable for enhancing the reliability and efficiency of Darrieus turbines for future offshore energy applications. Table 2 summarizes the field testing results of the Darrieus VAWT mounted on the speedboat, including performance metrics measured during open-sea trials.

Table 2. On the speed boat data result

V_{wind} (m/s)	V_{wind} (knot)	Rotation (RPM)	TSR	Generator Power (watts)	Generator Efficiency	Mechanical Efficiency	Turbine Power (watt)
1.2	2.3328	0	0	0	0.9	0.8	0
2.2	4.2768	0	0	0	0.9	0.8	0
3.1	6.0264	75	0.88629	0.7	0.9	0.8	0.972222
4.2	8.1648	125	1.090278	2	0.9	0.8	2.777778
5.1	9.9144	220	1.580261	3	0.9	0.8	4.166667
6	11.664	450	2.7475	5.3	0.9	0.8	7.361111
7.2	13.9968	610	3.103657	8.2	0.9	0.8	11.38889

It can be seen in the following figure.

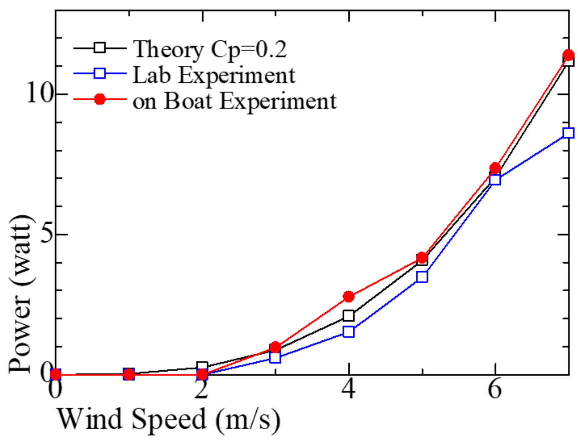

Figure 11. Power of the turbine

Figure 11 illustrates the wind turbine's power output (in watts) at various wind speeds, comparing results obtained through theoretical calculations, laboratory experiments, and real-world ocean testing. The figure highlights how turbine performance changes under different testing conditions, providing valuable insights into the turbine's efficiency and reliability.

The theoretical curve in Figure 11 is based on mathematical models that predict the power a wind turbine should generate at any given wind speed. These models use the turbine's aerodynamic properties, blade design, and the Betz limit—the maximum theoretical efficiency of a wind turbine (59.3%)—to estimate power output. The theoretical values often represent the idealized performance of the turbine under perfectly controlled conditions without accounting for environmental disturbances like turbulence or mechanical losses.

The laboratory data in Figure 11 typically show a slight deviation from the theoretical values. Wind speed is kept steady in controlled laboratory settings, and environmental variables, such as temperature and humidity, are regulated to minimize interference. However, actual turbines experience some unavoidable losses, such as mechanical friction and inefficiencies in the generator. These losses explain why the power output recorded in the lab is usually lower than the theoretical predictions. Nevertheless, laboratory experiments provide a reliable benchmark for turbine performance in a controlled but realistic setting.

The power output observed during real-world ocean testing significantly differs from theoretical and laboratory results. In the ocean environment, unpredictable factors such as fluctuating wind speeds, wave motion, and turbulence contribute to less consistent performance. For example, when the speedboat encounters waves, the turbine may experience vibrations and rapid airflow changes, reducing efficiency. Salt spray and humidity may also affect the turbine's components, adding further discrepancies. As shown in Figure 11, the power output on the ocean tends to fluctuate more. It may be higher overall than the laboratory data, especially at higher wind speeds with more pronounced turbulence and dynamic forces.

Figure 12 shows the maximum power from theory, the Lab experiment, the actual on-boat experiment, and CAE. The differences between theoretical, laboratory, and ocean testing results emphasize the importance of real-world testing to understand the practical limitations of wind turbine performance. While theoretical models provide an optimistic estimate of power output and laboratory experiments refine these predictions under controlled conditions, only ocean testing can reveal how environmental challenges impact the turbine's effectiveness. This comparison in Figure 10 underscores the need to design robust enough turbines to handle real-world conditions, ensuring they remain efficient and reliable when deployed in offshore applications.

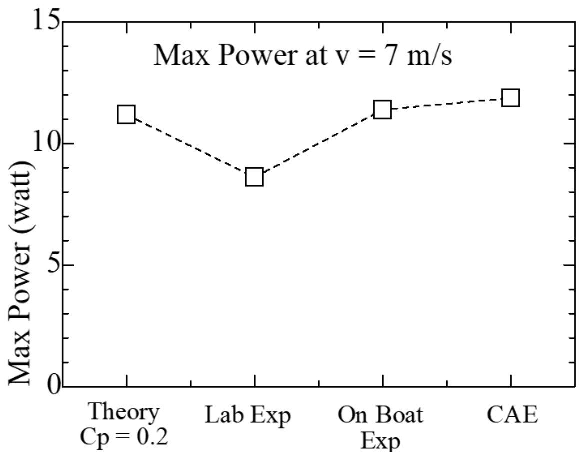

Figure 12. Turbine power at v = 7 m/s

A small Darrieus wind turbine producing 12 watts of electricity can effectively charge a 7 Ah (amp-hour) battery and provide sufficient power for essential systems on a speedboat, such as the navigation system and onboard lighting. Here's how this works: A 7 Ah battery, at 12 volts, has a total energy capacity of 84 watt-hours (7 Ah x 12 V = 84 Wh). If the turbine generates 12 watts continuously, it can recharge or top up the battery efficiently over time. For instance, charging the battery from empty to full would take about seven hours (since 84 Wh ÷ 12 W = 7 hours) in ideal conditions.

This energy is then used to power the speedboat's navigation system, which typically requires low energy, ensuring reliable operation during sea voyages. Additionally, highly energy-efficient LED lighting can operate on minimal power, maximizing the battery's utility. The continuous power generation from the wind turbine allows for ongoing battery replenishment, meaning that even as energy is drawn for lighting and navigation, the turbine helps keep the battery charged, ensuring that essential systems remain operational as long as wind conditions are favorable. This setup allows the speedboat to operate safely and efficiently in remote areas without relying on external charging sources.

The primary challenge in integrating a small-scale Vertical Axis Wind Turbine (VAWT) Darrieus onto a speedboat lies in addressing stability, vibrations, and aerodynamic and hydrodynamic drag. The addition of the turbine increases the vessel's weight, raising its center of gravity and potentially compromising balance, particularly in turbulent waters. Moreover, the turbine's rotational motion generates vibrations that can propagate through the boat's structure, accelerating wear and diminishing crew comfort.

Additionally, wind resistance on the turbine blades creates aerodynamic drag, which may reduce the boat's speed, lower fuel efficiency, and impact overall performance. To mitigate these issues, the proposed design incorporates lightweight aluminum as the primary material, supported by a wooden frame, to preserve structural integrity while minimizing additional weight. A vibration-damping system featuring complex rubber layers is implemented to absorb vibrations, thereby reducing their transmission to the boat's hull.

Furthermore, the aerodynamic optimization of the turbine blades is crucial for minimizing air resistance. This involves refining the blade shape and adjusting the blade angle to maximize energy generation while reducing interference with the boat's movement. Additionally, strategic turbine placement plays a vital role in maintaining stability; mounting it at an optimal height helps preserve balance, while a flexible mounting system allows for adaptation to varying sea conditions, ensuring enhanced performance and operational efficiency.

In this research, the velocity of the speedboat in the absence of external wind is solely governed by the propulsion generated by its engine. When no wind is present, the observed speed accurately represents the boat's actual velocity, uninfluenced by external forces.

However, when an external wind is introduced, the overall wind speed experienced by the boat is determined by the vector sum of the external wind speed and the boat's initial velocity. If the external wind moves in the opposite direction to the boat's motion, the total wind speed increases, creating greater resistance against the ship. On the other hand, if the external wind flows in the same direction as the boat's movement, the total wind speed decreases, leading to reduced wind resistance to the ship.

This study was conducted in relatively stable sea conditions, where wave activity and ocean currents exhibited minimal variation. Such conditions were chosen to ensure that the collected data accurately represented the impact of wind on the speedboat without interference from wave-induced disturbances. Excessive wave movement could destabilize the vessel, subsequently affecting turbine rotation and diminishing the overall efficiency of the turbine system. Therefore, maintaining a calm sea environment was essential for obtaining precise and reliable results in this study.

Suppose a Darrieus Vertical Axis Wind Turbine (VAWT) designed for small-scale research applications would be expanded for use on large marine vessels. In that case, several critical aspects must be thoroughly evaluated. One of the primary concerns is structural integrity, as scaling up the turbine would significantly increase centrifugal forces exerted on the blades. To address this issue, using high-strength yet lightweight materials, such as carbon fiber composites or corrosion-resistant alloys, is essential to minimize the overall load imposed on the vessel. Furthermore, the mechanical stresses affecting the support structure and bearings must be meticulously analyzed to ensure long-term durability, particularly in the demanding marine environment.

Another fundamental factor is the aerodynamic performance of a large-scale Darrieus VAWT. As the turbine grows, aerodynamic inefficiencies, including turbulence and drag, become more pronounced, potentially diminishing the turbine's overall energy conversion efficiency. Additionally, VAWTs generally require a minimum wind speed to initiate rotation, which could present operational challenges in low-wind maritime conditions. Advanced blade designs, such as optimized airfoil profiles or variable pitch mechanisms, may be necessary to enhance performance across various wind scenarios.

Ship stability is another key consideration, as the rotational motion of a large VAWT could introduce dynamic loads that impact the vessel's equilibrium, particularly in rough sea conditions. Therefore, careful positioning of the turbine is crucial to reduce its influence on the ship's center of gravity and hydrodynamic efficiency. Excessive aerodynamic drag could also hinder propulsion performance, emphasizing the need for comprehensive computational fluid dynamics (CFD) simulations and wind tunnel testing before full-scale implementation.

From an operational perspective, control and maintenance systems must be adapted to suit large-scale applications. A sophisticated control system capable of dynamically adjusting the turbine’s speed, blade pitch, or braking mechanisms in response to wind variations is necessary to optimize efficiency and mitigate mechanical failures. Additionally, a structured maintenance plan must be established to address potential concerns such as bearing wear, blade fatigue, and corrosion due to prolonged exposure to saltwater.

Integrating the VAWT into the ship’s energy system is essential to maximizing the utility of the generated power. The electricity produced could be stored in battery banks or hybrid energy storage systems, complementing other renewable energy sources like solar panels. A well-structured energy management system would facilitate efficient power distribution, reducing reliance on conventional fuels and lowering greenhouse gas emissions.

The scalability of Darrieus VAWTs for large marine vessels presents promising opportunities for sustainable maritime energy solutions and introduces significant engineering challenges. Ensuring structural resilience, optimizing aerodynamic efficiency, maintaining vessel stability, developing robust operational controls, and achieving seamless energy integration are all critical considerations. Addressing these aspects through innovative design and technological advancements will be imperative to ensure such a system's feasibility and long-term success in practical applications.

Incorporating Small Vertical Axis Wind Turbines (VAWTs) on speedboats signifies a groundbreaking advancement in integrating wind energy within the maritime sector. Characterized by their compact structure and capacity to efficiently harness wind from multiple directions, Small VAWTs enable speedboats to utilize renewable energy, thereby diminishing reliance on fossil fuels. This innovation reduces carbon emissions, enhances the vessel’s operational range by optimizing energy efficiency, and lowers operating expenses by minimizing fuel consumption. Moreover, the successful implementation of Small VAWTs on speedboats could pave the way for broader applications across the maritime industry, including their deployment on fishing vessels and yachts, thereby promoting sustainability in marine transportation. The naval industry moves toward realizing an eco-friendly and sustainable marine transport network by integrating wind turbine technology into hybrid energy systems.

4. CONCLUSION

The Darius Type vertical-axis wind turbine has been successfully manufactured and installed on a fast boat. It is an excellent and effective option for speedboat installations, particularly when wind speeds average around 7.2 m/s. Its aerodynamic efficiency and compact vertical-axis design make it well-suited to the variable wind patterns encountered on a moving vessel. Even in a speedboat's ever-changing and potentially unstable conditions, the Darrieus VAWT exhibits impressive stability and durability, thanks to its ability to harness wind energy from all directions without complicated yaw systems.

This speedy boat is 12 m long and has four engines. We conducted the research by varying the ship's speed up to 7.2 m/s, equivalent to 14 knots, which is a high speed in daily operations. The power produced at this speed is 11.39 watts, exceeding laboratory experiments. This is because, in the experiment on board, the wind blows evenly over the entire wind turbine area to perfect the rotation. Theoretical studies and computer-aided engineering validate data generated from experiments on board.

Producing 12 watts of power at the given wind speed highlights the turbine's potential to provide a consistent renewable energy source, which can help power the boat’s low-energy requirements, such as LED lights, sensors, or small electronic gadgets. Its efficient energy capture, use of corrosion-resistant materials, and thoughtfully engineered mounting system allow the turbine to endure marine environments while reducing drag and structural vibrations. The Darrieus VAWT stands out as a practical, robust, and energy-efficient solution for speedboats, offering a compelling option for environmentally conscious marine users seeking sustainable energy solutions.

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NOMENCLATURE

TSR	Tips Speed Ratio
C_P	Coefficient of Power
P_w	Power of the wind (watt)
A	Area of wind captured by the windmill (m^2)
v	Wind speed (m/s)