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A Prototype Design of a Vertical Axis Wind Turbine as One of the Renewable Energy Sources in Brunei

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Abstract— **Background**: According to the Asia Wind Energy Association, Brunei can harness the power of wind energy to meet its future demands for a reliable energy source that is both renewable and non-polluting. **Objective**: A preliminary study to design and manufacture wind turbines needs to be initiated earlier especially in the Brunei with has potential wind energy. **Methods**: This preliminary study compares several Vertical Axis Wind Turbine (VAWT) types and examines the optimal design in terms of mechanical parts for wind speed characteristics in Brunei. The project focuses on the engineering design stages to obtain a selected design that differs from other available designs. Results: The preliminary study successfully generated a small amount of electricity from the mechanical rotation of the VAWT. **Conclusion**: Although the preliminary study can generate a small amount of electricity, several design parameters need to be improved in further study. Proper manufacturing technologies are also needed to fabricate a better VAWT.

Keywords—Engineering Design; VAWT Prototype; Wind Energy

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I. INTRODUCTION

For thousands of years, humanity has harvested the benefits of using wind energy to improve their ways of life. Nowadays, wind turbine technology has become one of the leading technologies to provide an alternative solution regarding climate change issues, due to the nature of wind being renewable[1], [2]. The working principle of a wind turbine is the extraction of wind energy as wind passes the turbine's blade, this creates a rotational movement to the shaft that is connected to the blade producing kinetic energy, which then is transferred to the generator to be converted into electrical energy.

Based on the orientation of the axis, there are two primary types of wind turbines: horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) [3], [4]. A HAWT must always face the wind flow directly to harvest the energy from it. Aerodynamic lift causes the blades, which collect wind energy horizontally, to move. On the other hand, VAWTs have blades that revolve around the vertical axis perpendicular to the ground, and these wind turbines often come in smaller sizes. HAWT is superior to VAWT in the energy output category because it can produce more energy per unit of wind. However, VAWT has its advantages over HAWT, including the fact that it doesn't need to be perfectly oriented to the wind direction, doesn't require a constant and stable wind pattern, and can be used even at low wind speeds, which eliminates the need to put it on higher ground or construct a tall tower and makes it simpler to maintain[5]. However, the main advantage of this type of VAWT is that it requires an external startup mechanism due to the low torque it produces [6]. An example application for VAWT for wind farms is presented in [7]. A study of VAWT design and modelling in a Lab scale experiment is presented in [8], [9], [10].

A study on the design and performance of VAWT which focused on the development prospects, design parameters, and energy efficiency is presented in[10]. The study discussed the impact of various design components and parameters including the optimal number of blades, blade angles, and the ratio of turbine height to diameter on the turbine's output. The study was targeted for the large-scale VAWT which will need a lot of cost and is not suitable for initial study in university. VAWT was combined with a solar panel to efficiently convert wind and solar energy into electrical energy as hybrid power generation is presented in[9]. The study was limited by the scale of the prototype and testing conditions. Another limitation of the study is the data collected during the experiment was not measured under varied real-world conditions.

A VAWT proof of concept design study in Malaysia with relatively low wind speed is presented in[11]. The paper discussed the application of the Magnus effect to improve the VAWT design. The result of the experiment shows that the prototype can generate electricity between 45 to 70 mV which is still relatively low. The experiment uses a standing fan which does not represent reality.

Darrieus type VAWT, designed by George Darrieus, in the 1920s, is a type of wind turbine that operates using lift force, and it is believed that this type of turbine can produce energy higher than any other type of wind turbine [6], [12], [13]. The turbines are designed to have curved and long blades, where each end blade is connected to the top and bottom of the rotor shaft. As wind moves closer to these blades, they start to flow around them, creating a vacuum on the other side of the blade, forcing the blade to start moving towards the vacuum and creating rotational movement in the rotor. Once it starts, the rotation will gain speed exponentially[7], [10]. Some subtypes or variants use the same principles as the Darrieus VAWT like the H-blade, Variable-Pitch (Giromill), Delta rotor, Diamond rotor, V/Y rotor, and Gorlov Helical Turbine[12].

Savonius VAWT rotors are driven by drag forces created by the wind captured by its blades. Unlike most wind turbines, Savonius VAWT usually has a much larger blade surface facing to efficiently receive wind. Blades are usually formed into an almost semicircular or half-cylinder gradient[14], [15]. It will be placed and connected to the shaft rotor as illustrated in Figure below. The side facing the rotor is the inner side and the other is the outer side. As wind moves into the inner side, it will provide a push force for the rotor. On top of that, due to the circular surface of the blade, the wind will redirect into the other blade, thus increasing the amount of push force each blade receives. For this reason, the Savonius VAWT does not usually need a starter mechanism, due to having enough torque to make it rotate. A study of small-scale Savonious wind turbines is presented in [16], [17].

This study outlines the initial stages of the VAWT design that will be employed by the climate and wind patterns of Brunei Darussalam. Many countries are already thinking about reducing oil use and developing renewable energy including Brunei. As one of the countries in Southeast Asia where sunlight and wind are the most potential sources of renewable energy, Brunei through Universiti Brunei Darussalam has started to take a part in this renewable energy development. With this preliminary study, the wind potential energy will be discussed and the manufacturing technologies to support the preliminary study will also be investigated.

Studies on wind energy in Brunei are currently few and statistics are not yet comprehensive, much less about wind turbines. A study by[18], [19] concluded that by increasing the L/D ratio of a turbine blade, it is possible to make a small-scale HAWT work. However, further simulations and testing needed to be conducted to verify these data. Another study was done on renewable energy usage in Brunei, but the article mainly focuses on the potential of its geometric positions, climate, and wind patterns. Throughout the study, 5 and 6 years of wind speed data both offshore and onshore were collected respectively. It was determined that the onshore average wind speed is unlikely feasible for wind turbine power generation, however, it differs from the offshore wind data where it shows adequacy. These data [20], [21] suggested that harvesting around 372 MW per annum of electrical energy by offshore wind turbines is possible. However, this study lacks the proper studies that could support this theory.

In this study the proposed method consists of three parts: (1) the analytical calculation and parametric design of the wind turbine general equations; (2) the computer-aided design (CAD) and Computational Fluid Dynamic (CFD) analysis in SolidWorks; and (3) the manufacturing and assembly part. The contribution is the study provides a preliminary study on VAWT as one of the renewable energy alternatives in Brunei. The aim is to design a VAWT prototype that can generate electricity. The gap between the previous prototype design studies[5], [7], [10] is the presentation of the CAD and CFD analyses. It is important that the VAWT performance can be simulated before the manufacturing process to improve the design.

II. RESEARCH METHOD

A summary of the research method is presented in Figure 1. It starts with the literature study on the potential development of VAWT in Brunei. The main methods consist of wind data acquisition, design components, and engineering design. In the design component, a decomposition diagram and design parameters are presented. SolidWorks design and CFD analysis are presented in engineering design. The VAWT design is manufactured and the experiment is conducted to measure the generated electrical power.

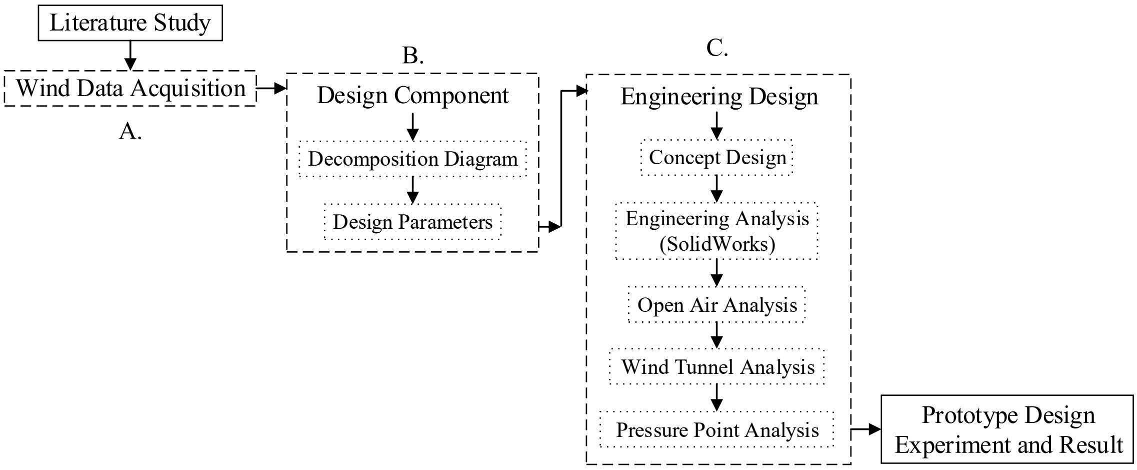

Fig. 1. Research Method Flowchart.

A. Wind Data Acquisition

Brunei Darussalam is a tropical country with an equatorial climate and wind patterns are random and turbulent most of the time and months. A study on the wind characteristics in Brunei is presented in[22]. The study was conducted in two locations A (near Berakas area) and B (Kuala

Belait beach) from 2012 to 2014. In location A, it was observed that the highest wind speeds were between 14:00 and 16:00. The wind speeds from January to March are higher compared to other months. In location B, it is recorded that the highest wind speeds were between 15:00 and 17:00. The highest peak value of 4.5 m/s was observed in January 2014. This pattern is part of why HAWT has become very inefficient for use in Brunei. The VAWT, however, theoretically has a superior potential for use in Brunei's wind pattern due to its design and performance. There are two types of VAWT, determined by the main operations: the Derrius type, which mainly operates through lift force, like how a helicopter works, and the Savonius type, which uses drag force.

Wind speed and pattern are some of the more important parameters must be determined before designing a VAWT system. By determining the average wind speed of an area, it is easier to determine the appropriate size and shape of the VAWT blade will be efficient. Not only that, appropriate materials for the VAWT structures can also be properly analyzed when the wind speed data is known.

Data collection was done manually using a handheld anemometer from Benetech. The function of the anemometer includes air velocity (m/s, km/h, ft/min, Knots, mph) and temperature measurement, max/average/current air velocity measurement, and temperature (C/F), Data was collected over several days, where three sets of three data were taken each day. Data collection was done for at least 7 days straight. Wind patterns, weather conditions, temperature, and any abnormalities were noted throughout the data collection. A suitable area was chosen for data collection which was on the rooftop of the Integrated Sciences Building (ISB) Block D.

B. Design Component

This section will outline the structural build of a VAWT, its functions, applications parts breakdown, and the functional parameters that help determine the build of the final product. This study will further highlight the importance of each smaller unit or component of the product and how they interact and integrate with other system parts. These details can help further determine the design problems, subassemblies, decompositions, and a better analysis of the expected performance, risk, and Failure Mode Effect and Analysis (FMEA).

Decomposition Diagram

In this study, the VAWT prototype was design as a modular system where a decomposition diagram of the VAWT prototype is presented in Figure 2. It shows the components and parts of the VAWT which consists of (1) external structure, (2) rotating parts, (3) energy converter and generator, and (4) safety mechanism as the main components. Guide wire, hub, blades, and base were included in external structure. Rotating parts consists of rotor, shaft, and gear. Generator is the only part in energy converter and generato component. The prototype is also equipped with brakes as a safety mechanism component.

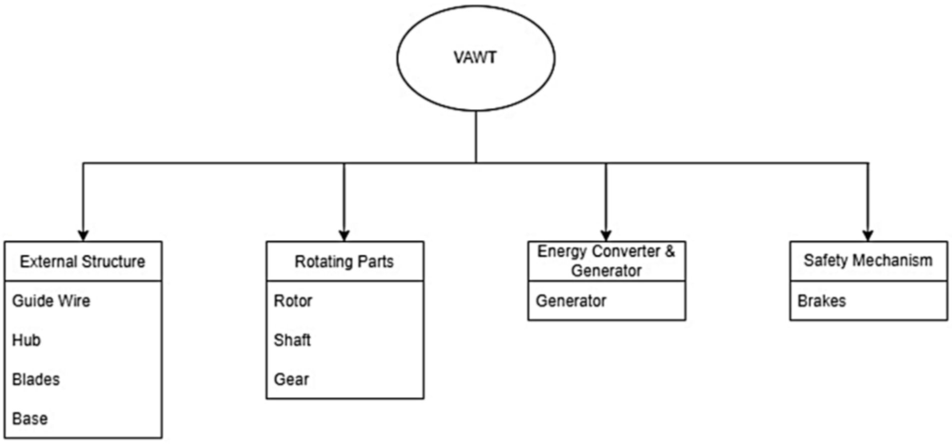

Fig. 2. Decomposition Diagram of VAWT Prototype.

Design Parameters

Design parameters are one of the most important phases of product design engineering. In this phase, all aspects of the component will be determined. Design parameters phases can simulate the cost, structure, look, design, materials, risk, and the performance of the final product. The parameters above are the general parameters used in the design of a VAWT. However, these parameters are subjected to some changes depending on the types and the fundamental design of the VAWT itself. This is due to some parameters being nonexistent or negligible in some VAWT types.

Throughout the design phase of this project, several important calculations and formulas were used to determine the critical parameters for the design of a VAWT system[23].

1. Turbine swept area.

In designing a wind turbine, the swept area is the crucial information for capturing wind energy. It refers to the circular region (or effective area) formed by its rotating blades as they sweep and catch the air (wind).

$$A = D \times H \qquad (1)$$

where A refers to the turbine sweep area, D is the diameter of a wind turbine, and H refers to the height of the turbine blade.

2. Available wind power.

This refers to the coefficient of wind power utilized by the turbine when the wind passes it. In another definition, the available wind power represents the energy available in the air (wind) that the turbine can obtain.

$$P_{wind} = ½ \, x \, \rho \, x \, v^3 \, x \, A \qquad (2)$$

where $Pwind$ is the available wind power, ρ refers to the air density, and v is the wind speed.

3. Efficiency loss

Turbine loses some of its operating efficiency due to several factors including:
The wake loss due to surrounding, is usually taken from 3% - 10%. Mechanical loss from gearbox and blades, 0% - 0.3%. Electrical loss, 1% - 1.5%. Electrical loss to the grid, 3% - 10%. Time out of order. 2%-3%. Typical turbine efficiency by the Betz limit (59.3%), between 30% - 40%.

4. Output power

The power output from the turbine generator can be calculated using Eq. (3).

$$P_{output} = \mu \times P_{wind} \qquad (3)$$

5. Revolutions Per Minute (RPM)

The rotation of the VAWT can be defined in the Eq. (4).

$$RPM = 60 \, x \, v \, x \, (Tip\ Speed\ Ratio \, / \, \pi D) \qquad (4)$$

Tip Speed Ratio (TSR) refers to the speed of the blade tip to the wind speed. This typically depends on the number of blade configurations. In detail, TSR is the wind turbine ratio between the tangential speed of the tip of a blade and the actual speed of the air (wind). This parameter is the a crucial factor in efficiency and blade design. A typical tipp speed ration according to [24], [25], [26] is presented in Table 1.

Table 1. Typical Tip Speed Ratio

No. of Blades	***Tip Speed Ratio***
2	6 - 7
3	5 - 6
5 or more	2 - 3

6. Torque

The torque of the VAWT can be calculated using Eq. (5).

$$\tau = (P_{output} \, / \, RPM) \, x \, (30 \, / \, \pi) \qquad (5)$$

where RPM is the revolutions per minute and τ is torque.

Eqs. (1)-(5) will be used further to calculate the result presented in Table 2.

One of the most crucial phases of any design effort is the design parameter stage. The term "design parameter" will be used in this project to refer to the engineering requirements used in constructing a VAWT. The components that will be used for electrical generation and even the manufacturing process of the design will be determined by these criteria. The parameter will also be used to compare which designs produce the best desirable results for the needed specification and to assess feasibility. Table 2 shows the results obtained through the use of available parameter formulations as described in the Eqs. (1)-(5). Design 1 (hook-blade Savonius), Design 2 (drum Savonius), design 2 (curved-blade Savonius), and design 3 (drum Savonius).

Table 2. Comparison of VAET Design Parameters

Input Parameters and Looses Calculation			
	Hook-blade	***Curve-blade***	***Drum***
Basic Parameter			
Blade diameter (m)	1.18	0.54	0.512
Blade height (m)	0.3	0.3	0.8
Wind speed (m/s)	2.5	2.5	2.5
Sweep area (m^2)	0.354	0.162	0.4096
Available wind power (kW)	0.00339	0.00155	0.00392
Turbine efficiency (%)	30	30	30
Looses			
Wake loss (%)	5	5	5
Mechanical loss (%)	0.2	0.2	0.2
Electrical loss on turbine (%)	1.5	1.5	1.5
Electrical loss due to transmission (%)	5	5	5
Time out of order (%)	3	3	3
	Expected Output		
Torque			
Tip Speed Ratio (TSR)	1	1	1
Revolution per Minute (RPM)	40	88	93
Torque (N.m)	0.2399	0.0502	0.1204

C. Engineering Design

Concept Designs

Concept designs relate to a stage of product design engineering when various designs are presented and contrasted to determine which concepts best meet the majority of the specified requirements. The client and engineering specifications, the relationship between form and function, the system boundaries, the possibility of improvements, and the entire design process are among the factors that are given weight. Three ideas that were looked into for this study project are listed in this section. While Drum Savonius is one of the most frequently studied Savonius VAWT, Hook Blade Savonius and Curved BladeBlade Savonius were built based on Savonius WAVT concepts. Figure 3(a) shows the design of the hook blade Savonius VAWT type. Figure 3(b) shows the design of the curved blade Savonius VAWT type. Figure 3(c) shows drum savonius VAWT type.

The VAWT's total system tip speed ratio is based on the number of blades. When developing a wind turbine, this is crucial. When utilized under conditions of continuous wind, fewer blades are more efficient; but, when the wind is turbulent, more blades are more effective. The effectiveness of the rotor is decreased because additional blades indicate that there is greater obstruction from blade overlap as the wind tries to reach each blade's surface. The predicted RPM of the turbine is calculated using the tips speed ratio, which also aids in identifying the generator that the turbine can run. The total number of blade components, bolts and nuts, and shaft dimensions impact the simplicity of production and assembly as well as the final cost of the turbine. Table 3 shows the difference between the three designs for the elements comparison.

Table 3. Elements Comparison for The Concept Design

Design	*No. of blade*	*Blade size* (mm)	*Joint*	*Support structure*
Hook-blade	3	800 x 500	Use slot mechanism	Need a shaft
Curved-blade	3	350 x 250	Bolts and nuts (14)	No need for a shaft
Drum	2	200 x 800	Bolt and nuts (8)	No need for a shaft

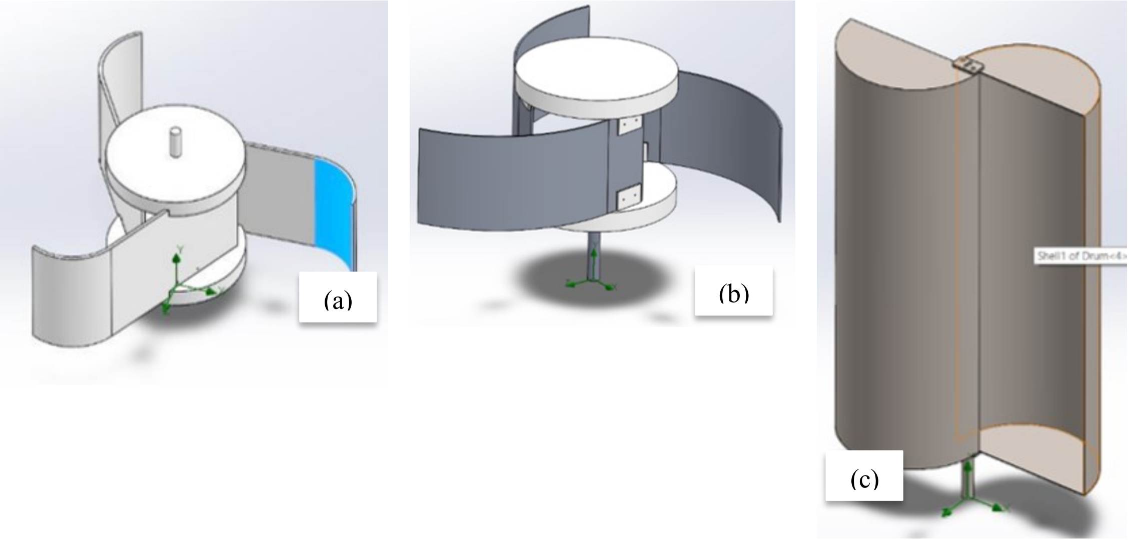

Fig. 3. VAWT SolidWorks Design: (a) Hook-blade Savonius; (b) Curve-blade Savonius; (c) Drum Savonious

Engineering Analysis (SolidWorks CFD)

Engineering analysis is a technique that involves an in-depth examination of a system, including its state under various conditions and its many interactions with its surroundings and supporting structure. This was carried out before the manufacturing stage to find potential design flaws and unanticipated outcomes. Before a design is finalized, the analysis will give more information about the theoretical system's overall performance, allowing for revisions and improvements. To generate a theoretical condition to impose on the system, engineering analysis often uses mathematical computation using variable data that is available or assumed. However, with the emergence of simulation technology, it is possible to get a graphical representation of the expected scenario. SolidWorks is used for all analyses for this particular project, and CFD, or computational fluid dynamics, is a built-in feature of SolidWorks. Each concept design underwent of several tests to simulate the wind flow pattern around each system and pressure point during wind activity. Additionally, designs were tested in a wind tunnel and open spaces with wind conditions.

Open Air Analysis

Figure 4 shows an open-air CFD analysis of the VAWT drum Savonius type. A color indicator indicates the velocity distribution code from the highest (dark red) to the lowest (dark blue). Figure 5 presents an air air open-air CFD analysis on the Hook blade Savonius type. Figure 6 shows an open-air CFD analysis on a curve blade Savonius type.

As can be seen from the aforementioned Figures 4(a), (b), and (c), the Savonius VAWT with the curved blade effectively captures and circulates wind throughout its system. By deflecting and transferring wind from one blade to another before it dissipates, wind circulation aids in increasing the rotational force that each blade is subjected to. When compared to the hook blade Savonius, the blade's low curvature angle allows for superior wind deflection. This is explained by the fact that sudden direction changes result in a higher rate of energy loss, as seen by the behavior of both drum and hook blade Savonius.

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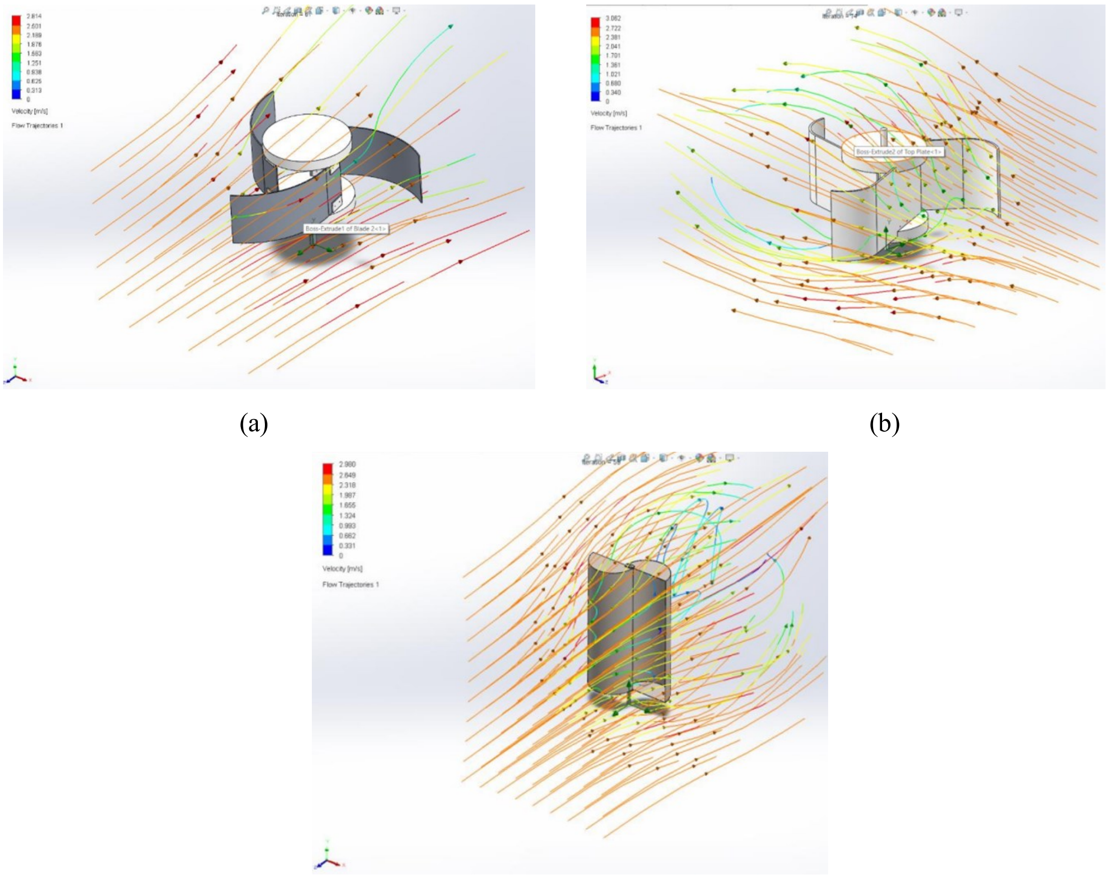

(a) (b)

(c)

Fig. 4. Open Air CFD Analysis in SolidWorks: (a) Hook-blade Savonius; (b) Curve-blade Savonius; (c) Drum Savonius

Wind Tunnel Analysis

The wind tunnel CFD analysis of drum, hook blade, and curved blade Savonius is presented in Figures 5(a), (b), and (c), respectively. The wind tunnel experiment also shows similar wind pattern results for all three designs, with a slight difference of a lower wind speed due to the condition being controlled i.e. wind tunnel.

This experiment aims to examine each turbine while maintaining a consistent air supply. The wind pattern remains the same for drum and curve-bladed Savonius, with the latter capturing more air volume due to the lower deflection angle. For the hook-blade Savonius, it creates a minimal residual air circulation in the appropriate rotational direction. The little air clearance given in the construction is thought to be the root of this potential loss of rotational efficiency.

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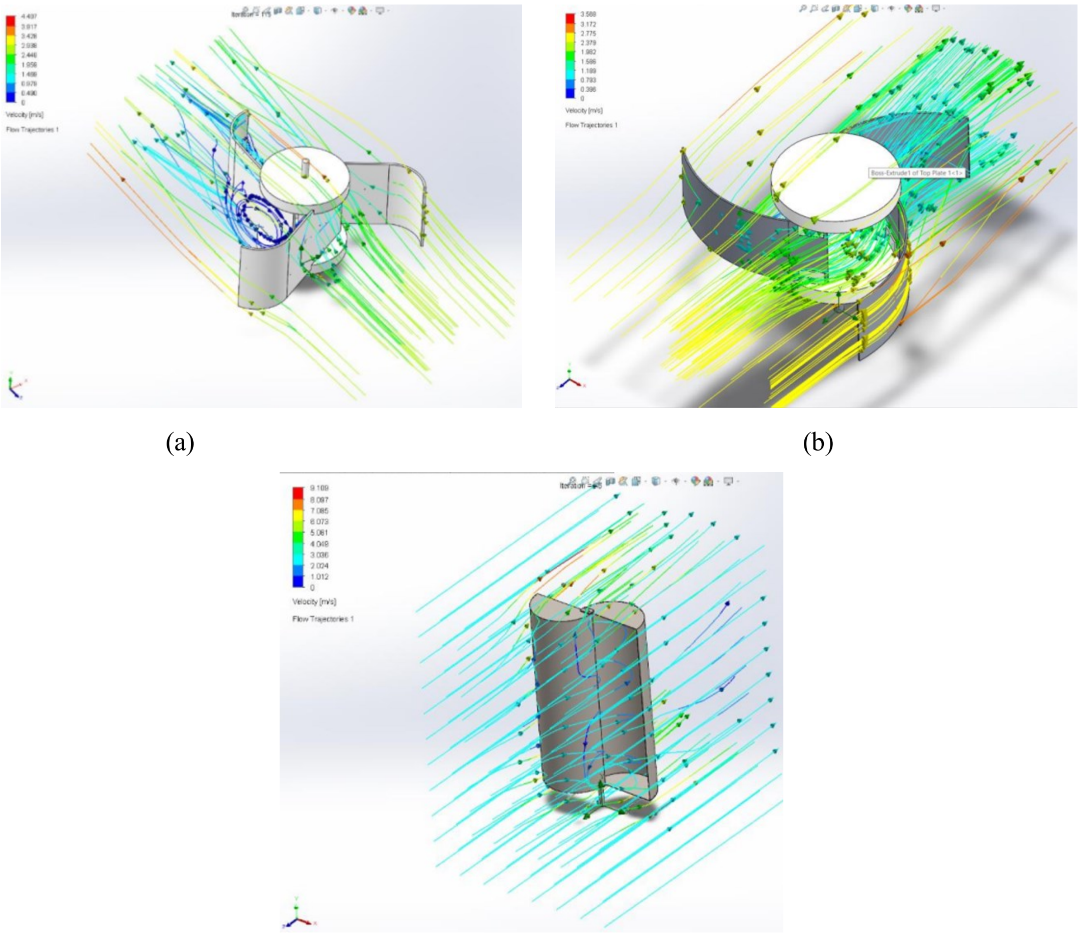

(a)

(b)

(c)

Fig. 5. Wind Tunnel CFD Analysis in SolidWorks: (a) Hook-blade Savonius; (b) Curved-blade Savonius; (c) Drum Savonius

Pressure Point

The results of the pressure analysis of drum Savonius, hook blade Savonius, and curved blade Savonius are presented in Figures 6(a), (b), and (c), respectively. The objective of the pressure point analysis is to assess whether the right pressure will cause the turbine to rotate in the desired direction by doing a pressure analysis on the blade surface. Similar pressure distributions are observed for both open-air and wind tunnel blade pressure results. Dark red denotes the greatest pressure and dark blue the lowest pressure in the pressure distribution shown in Figures 6(a)-(c).

The higher-pressure point for drum Savonius falls inside the blade diameter, which is advantageous in this situation. This indicates that the pressure would drive the turbine's blade in the right direction. The system may become structurally unbalanced as a result of the highest pressure point being at the blade's base, which would necessitate redesigning the design or adding the necessary structural support. Unfavorable pressure distribution can be seen in the hook blade Savonius, where the highest pressure point is located on the blade's outside diameter. This will

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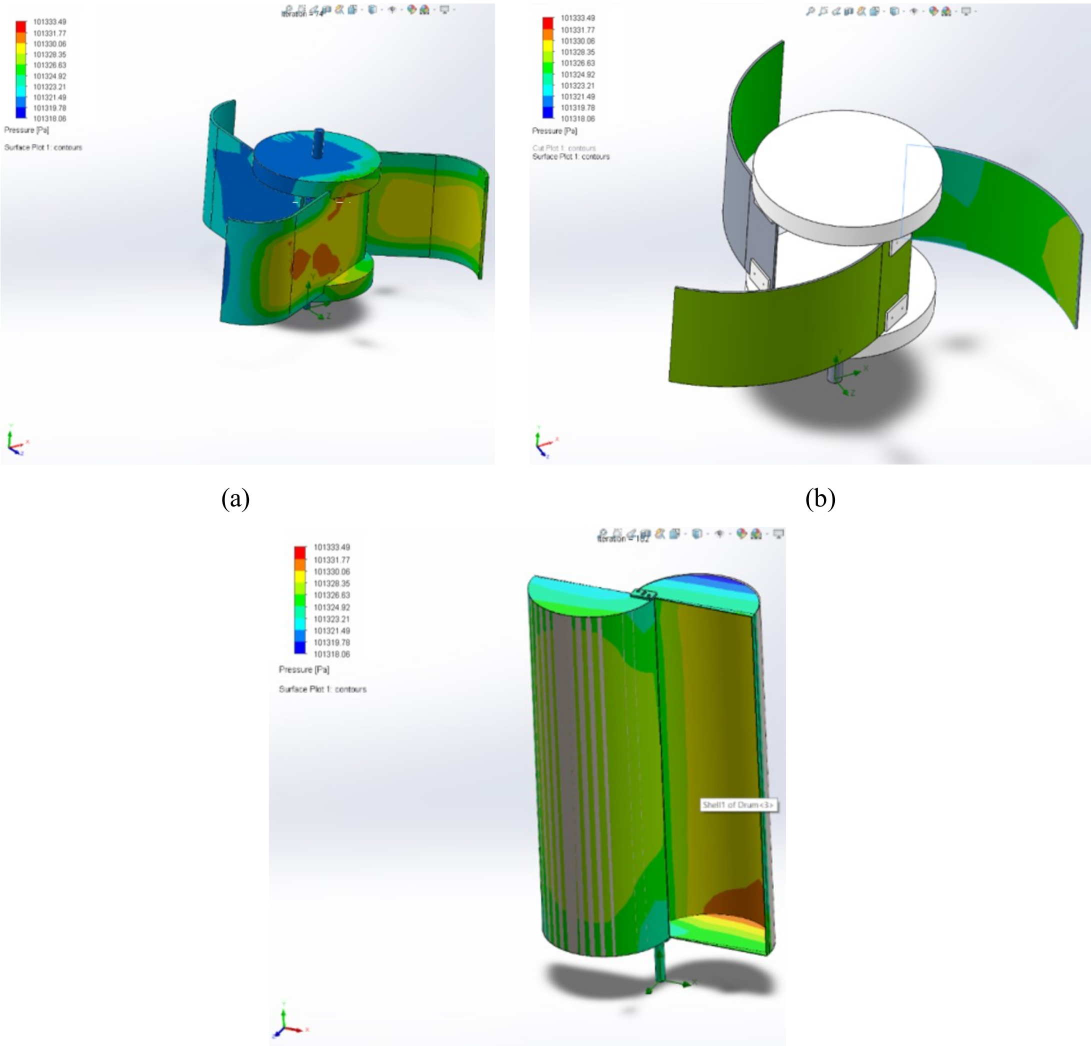
force the blade to rotate counterclockwise to the rotor's intended direction. Last but not least, the curved blade Savonius yields respectable outcomes with pressure distributed uniformly across the blade's inner diameter.

Curved blade and drum Savonius exhibit encouraging findings throughout the analysis. Curved blade Savonius outperformed drum Savonius in terms of wind capturing efficiency much better, which can be attributed to its lower curve angle, which allows for a smoother wind deflection and lower rate of energy loss. Due to its bigger blade surface area, the drum Savonius has a higher ideal pressure distribution point.



(a)

(b)

(c)

Fig. 6. Pressure Analysis in SolidWorks: (a) Hook-blade Savonius; (b) Curved-blade Savonius; (c) Drum Savonius

III. RESULTS AND DISCUSSION

Manufacturing and Fabrication

After some design revisions and finalization, and all the critical components and materials have been acquired, the fabrication stage will proceed. Manufacturing processes for each part have been predetermined prior to the design for the manufacturing process and by what material each component was made of. In this stage, the author has decided to employ a mixture of both advanced and traditional manufacturing methods. Advanced manufacturing process here refers to the utilization of advanced technologies that allow for the manipulation of nanoparticles or atoms in the manufacturing process either through ultraprecision processing or nanotechnology processing[27], [28]. This method is also known as “bottom-up” processing, due to its nature in building up rather than removing materials. Traditional or conventional manufacturing refers to the already long-established manufacturing process, including forming and subtractive processing, where materials are usually removed from the original workpiece to form a desired part or component [29], [30], [31].

Assembly

After all the fabrication was done, the assembly phase proceeded. The VAWT was designed for ease of assembly and disassembly. This is to make it easy to switch out or repair any parts that arerequire. Blades can also be varied to adapt to certain wind conditions to get better efficiency. As such, the assembly process takes only a minimal step and a shorter total time. A final fabrication and assembly of the VAWT prototype is presented in Figure 7.

For the final assembly, generator model XD-3420 was chosen and used as it has a lesser frictional force in the rotating mechanism when compared to the MY 1016. This will give a lower starting torque required for the turbine to start, hence lowering the starting wind speed. Another adjustment made was a hole was bored at the bottom of the shaft, to accommodate for direct integration of shaft to generator, without relying on the extension. Testing and data collection. The testing and collection phase aims to check for the capability and performance of the turbine by measuring its revolutions per minute against wind speed. Another important parameter observed was the voltage and current produced for each obtained RPM. To help in the data collection, several instruments were used including the aforementioned anemometer, tachometer, and a multimeter.

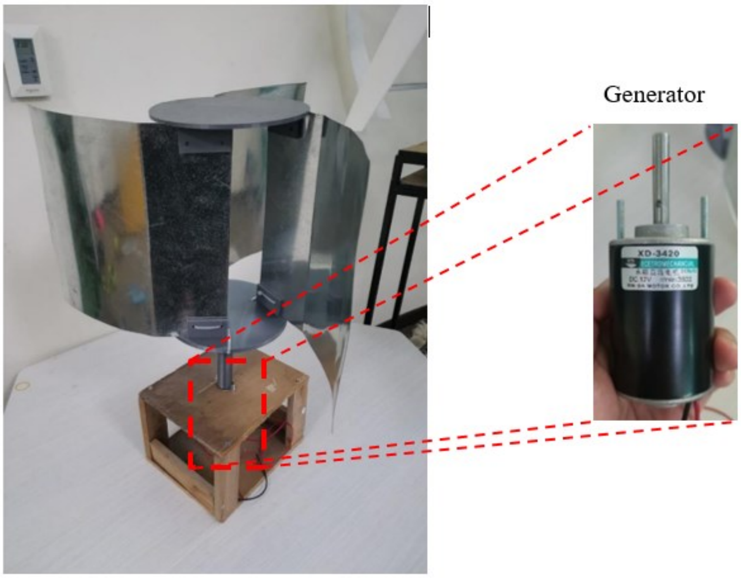


Fig. 7. Final Fabrication and Assembly of VAWT Prototype

Results

A result of the power generated by the selected VAWT design and prototype is presented in Table 4.

Table 4. Experimental Results of VAWT Prototype

VAWT Prototype Performance			
***Wind speed* (m/s)**	***Current* (A)**	***Voltage (V)***	***RPM***
1.0	1.392	0.080	23
1.2	1.670	0.096	28
1.4	1.949	0.112	33
1.6	2.227	0.128	37
1.8	2.506	0.144	42
2.0	2.784	0.160	47
2.2	3.062	0.176	51
2.4	3.341	0.192	56
2.6	3.619	0.208	61
2.8	3.898	0.224	65
3.0	4.176	0.240	70
3.2	4.454	0.256	75
3.4	4.733	0.272	79
3.6	5.011	0.288	84
3.8	5.290	0.304	89
4.0	5.568	0.320	93

The experiment varies the wind speed from 1 m/s to 4.0 m/s. This variation is selected according to the wind speed conditions in Brunei. This variation is selected according to the wind speed conditions in Brunei. It is shown that the VAWT prototype can generate 0.32 V with a wind speed of 4.0 m/s. This conditon is still below the expectation and further study will be conducted in the future. However, it is proof that the wind speed potential energy could generate electricity even thougheven though still a small amount of voltage.

Table 5 compares lab-scale VAWT design and experiment focused only on the voltage output generated by VAWT. The highest voltage achieved is performance in[32], [33] with 1.6 V, however, the wind speed of 9 m/s is not suitable in Brunei as the wind speed maximum in Brunei is 4.5 m/s on average. Another study [7], [10] generated lower voltage output i.e. 0.07 V compared to the present study even with higher wind speed i.e 5.9 m/s.

Table 5. Comparison Results with Previous Selected Studies

Reference	*Wind speed* (m/s)	*Voltage (V)*
Hussein et al. (2021) [7]	5.9	0.07
Memon et al. (2016) [18]	9	1.6
Present study	4	0.32

Discussion

Table 4 shows that the starting wind speed for the VAWT using the XD-3420 generator is 1 m/s, producing around 0.08 V and 23 RPM. As wind speed increases, the voltage and rpm rating almost proportionally increase. At 4 m/s, the rpm rated was 93, and 0.32 V was produced. From this observation and the results obtained, it can be concluded that the wind turbine and the low wind speed cannot produce enough rpm to push the efficiency of the generator beyond even 10%. To produce a maximum voltage, for this generator, the rpm required is around 3500, and to produce such rpm with the same turbine design, an upward speed of 150 m/s is required, which is fairly unrealistic, especially in Brunei. The maximum effective wind speed in Brunei can reach up to 8 m/s, and through mathematical methods it can be assumed that at this speed, only 187 rpm and 0.64 V can be produced. This disparity can be assumed to be attributed to the high rating of the generator used, which may not be suitable for low wind speed usage.

However, to further analyze and find a more suitable generator and improve the output efficiency, some scenarios of utilizing a lower rpm generator were mathematically simulated. The two generators were rated at 148 rpm, 24 V, and 150 rpm, 12 V. Take note that assumptions made in these calculations were that, the rpm produced is the same regardless of the different generators used. The comparison results are presented in Figure 8.

According to Figure 8, a major discrepancy can be observed between results from using a lower-rated rpm generator. This is because a lower rpm generator requires lesser rotational speed and thus requires a smaller wind speed to operate at top efficiency. The only problem with using a low rpm generator is that at a certain rpm and wind speed the voltage maxed out and does not go beyond its rated voltage. This means that the extra wind power has been wasted thus also impairing the actual efficiency in wind speed harnessing.

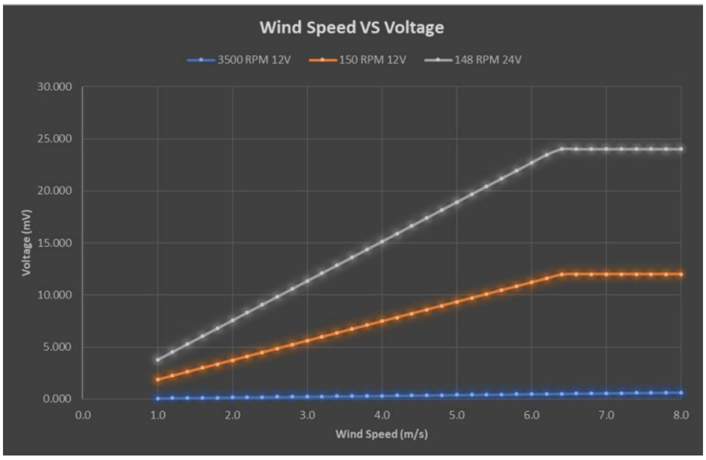


Fig. 8. Comparison of Voltage Output from Different Generators

Another observation that could be made was the incongruity between the theoretical or analytical rpm calculated from Eqs. (1) – (5) [23] and the actual rpm observed. Theoretically at 2.5 m/s, the turbine should operate around 88 rpm. However, the observed rpm rated 2.4 m/s was 56 rpm which is almost 40% lower than the theoretical value. This can be attributed to the weight and strong rotational friction in the generator used. Higher-rated rpm generator tends to have a higher torque requirement to properly and efficiently power them. These theoretical calculations assume the use of ideal generator specifications. Another justification can be made for the 59 build and assembly of the turbine parts and structure itself. The curvature of the blade is not smooth due to the manual bending process, and the shaft itself might not be properly centered with the generator shaft which might cause an imbalance rotational pattern, thus leading to a loss of momentum and energy, the turbine also has no proper lateral support which means vibration might be higher than a theoretical assumption, which may also contribute significantly to the energy loss.

IV. CONCLUSION

According to the literature study, the harnessing of wind energy in Brunei has not been fully explored, and this study has provided a bit of a surface scratch in the advancement of wind energy and harvesting. Through this study, it can be seen that the potential of wind energy in Brunei is not entirely unfeasible and unreliable. A lab-scale VAWT has been designed and simulated using SolidWorks CAD and CFD. The fabricated design was tested and able to generate a voltage output of 0.32 V at 4 m/s wind speed. Although the generated voltage output is still does not meet the expectation, this study can be improved in the future work. By creating a more efficient VAWT for low wind speed and turbulent wind application, an improved voltage can be generated . An improved design need to be process with the appropriate manufacturing methods. Further studies, research, and experimentation should be conducted on this subject matter, as it is one of the easily available and renewable forms of energy and this aligns with Brunei's vision of transitioning to a much greener environment while significantly reducing the use of traditional energy production.

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