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Research Article

# A Comprehensive Review and the Efficiency Analysis of Horizontal and Vertical Axis Wind Turbines

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**ABSTRACT**

The Wind has the potential as an alternative source of renewable energy. Natural wind from the earth's atmosphere is captured before converted into mechanical energy and then electrical energy. This paper presents a comparison of the efficiency of the horizontal axis wind turbine (HAWT) and vertical axis wind turbines (VAWT). The efficiency is determined using SOLIDWORKS Flow Simulation considering the wind scenario, a constant wind speed of 5 km/h with constant wind direction. It has been found that the drag coeffiecient of HAWT, VAWT–Savonius and VAWT– Darrieus are 0.5175, 0.2605 and 13.5622 respectively. This paper also proposes building a wind farm in Seamatan where the average wind speed is highest in Sarawak, Malaysia ranging from 4 km/h to 9 km/h.

**Keywords:** horizontal axis wind turbine, vertical axis wind turbine, efficiency comparison, renewable energy, green energy

## INTRODUCTION

Historically, as early as 5000 B.C., wind energy was used to propel boats (4C Offshore, 2013a). By 200 B.C., windmill in China was used for water pump purposes, while in Persia and the Middle East vertical-axis windmills used to grind grain (4C Offshore, 2013b). The windmills technology was further developed, the usage of the technology was widening into the agricultural industry, transportation, and food productions. European and American colonists used windmills to pump water for farms, grind corn and wheat, and cut wood. In the nineteenth and early twentieth centuries, the windmill was developed for generating electrical energy. Small scale wind plants are used to power farms and residences, while large-scale plants used to generate electricity for industry. During World War II, a 1.25-megawatt wind turbine was made in Denmark known as the Grandpa's Knob, purposely to fulfil the electricity demanded from the industry and homes (Aeolos Wind Energy Ltd., 2016; AWEC, 2015; Belarusian web portal on renewable energy, 2012; Charles, 2014; Clean Green Renewable Energy, 2016; David, 2010; GWEC, 2015). However, due to the availability of cheap oil in the market during the time, has suspended the usage of the wind turbine as the main source of energy. Following the OPEC Oil Embargo in 1973, as the oil prices change and continue to increase due to the demands, wind energy seems to gain its popularity again (IEC, 2016). Government policies and the increasing awareness of the effects of oil usage on health and the environment helped the growth trends of wind energy. In the late 1970s, the wind industry had gained solid markets, with almost 50 manufacturers of wind turbines (IEC, 2016). In the 1980s, the wind farm was introduced in the market to reduce the cost of independent wind plants and increase production efficiency (IEC, 2016; Karen, 2012; Merle et al., 2016; Paul, 2012). The cost of installing wind power plants continuously decreased, which promoted wider usage of wind energy.

According to Rao and Gantayat (2010), the global wind energy industry had the largest average growth in the renewable energy sector about 27% within the years of 2004 to 2009. Asia is the biggest wind energy harvester with about 41% of the world's total wind turbine number, as China controls the wind industry market (GWEC, 2015; Rigzone, 2016). The ranking is followed by Europe, with a production of about 34% of energy. Europe generates about 76152 MW in 2009, and the number is continuously growing. In the US alone, AWEC

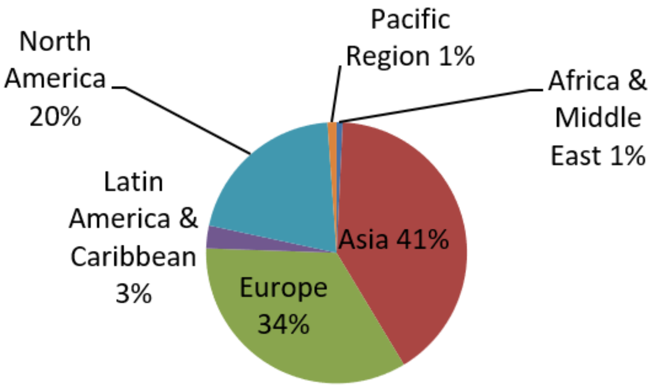


**Figure 1.** The percentage of the usage wind turbine by regional distributions

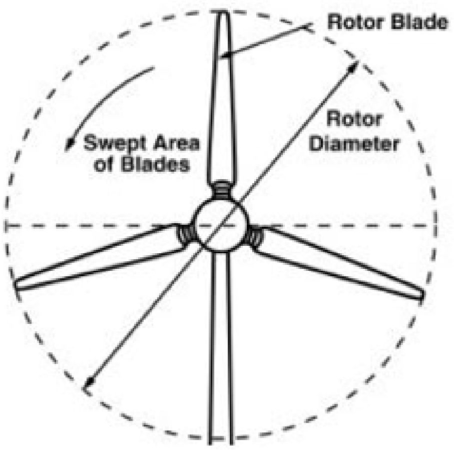


**Figure 2.** The swept area of the horizontal axis wind turbine (Clean Green Renewable Energy, 2016)

(2015) reported that wind turbine technology is capable of providing about 19 million houses with low-cost electricity usage. The usage of a wind turbine in the Pacific, Africa, Middle East, Latin America, and the Caribbean is started to grow. The high availability and affordable price boost the growth among these regions. **Figure 1** is derived from GWEC (2015), shows the percentage of the global wind turbine applications by region.

The wind turbine is categorized into two main types:

1) *Horizontal axis wind turbine (HAWT):* The wind turbine rotational axis is parallel to the wind stream and ground. The rotor, generator, and gearbox are installed at the back of the blades.
2) *Vertical axis wind turbine (VAWT):* The turbine rotational axis is perpendicular to the ground. The rotor, generator, and gearbox are located on the base.

## LITERATURE REVIEW

The swept area of a wind turbine is determined by the rotor blade where the swept area of the horizontal axis wind turbine is the front plane of the rotor blades, where it is given as:

$$A = \pi R^2 \quad (1)$$

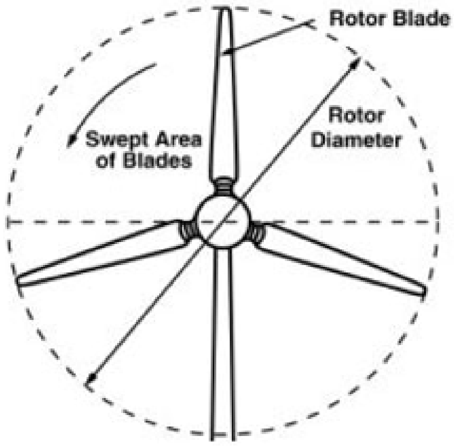


**Figure 3.** The swept area of the Savonius vertical axis wind turbine (Belarusian web portal on renewable energy, 2012)

The swept area of Darrieus vertical axis wind turbine is the plane parallel to the ground, where it is given as:

$$A = 0.65DH \quad (2)$$

The Savonius vertical axis wind turbine has the same operation as the Darrieus vertical axis wind turbine, and its swept area is given as:

$$A = DH \quad (3)$$

The swept area of a vertical axis wind turbine is typically twice the swept area of the horizontal axis wind turbine (Clean Green Renewable Energy, 2016; Paul, 2012).

Three-blade wind turbines are commonly used in the market. The number of blades directly relates to the efficiency of the wind turbine due to the wind turbine has a high frequency to extract wind power. The common numbers of blades are 2, 3, and 5. The greater number of blades improves the reliability and safety of the wind turbine (Clean Green Renewable Energy, 2016; turbinesinfo, 2011; Wang and Fan, 20115; WEF, 2016; Wind Energy – The Facts, 2009; Windpower Engineering, 2011).

The cost of a two-blade wind turbine is slightly lower than that of the three-blade wind turbine. A two-blade wind turbine spins fast, but in return, it produces a higher level of noise compared to the noise pollution of the three-blade wind turbine. The three-blade standard makes the wind turbine spinning more smoothly and reduces the damage to the bearing.

Lift and drag forces are produced by the differential pressure based on Bernoulli's principle. Drag force has the same direction as that of the flow against the front side of the blades. Either one or both of these forces is needed to rotate the blades of a wind turbine. The lift and drag forces on a blade also involve the coefficient lift, $C_L$, the coefficient of drag, $C_D$, the density of air, ρ, wind speed, v, the length of the blade, b, and the chord length, c.

The wind turbine has fixed conversion efficiency for converting wind energy into electrical energy. The conversion efficiency is called power efficiency, $C_P$ whereof the actual electrical output power over the input power or the available wind energy. These formulae can be expressed as:

$$C_P = \frac{P_{out}}{P_{in}} \quad (4)$$

$$P_{out} = 0.5 C_P \rho A v^3 \quad (5)$$

$C_P$ can be further differentiated into turbine efficiency, $\eta_t$, mechanical efficiency, $\eta_m$ and electrical efficiency, $\eta_e$.

Turbine efficiency is also called aerodynamic efficiency. The kinetic energy loss occurs during the conversion of kinetic energy into mechanical energy of the turbine shaft, which contributes to the efficiency reduction.

Mechanical efficiency involves energy losses in bearing and gear tooth friction. The shaft support bearings contribute a little friction to the shafts. The energy losses turn out to be heat and noise during energy transfer. Electrical efficiency involves power losses to windage, bearings, and electrical resistance (David, 2010).

Rotor blades are mostly made of carbon fiber to take advantage of its properties – lightweight, low density, and high stiffness, and the alternative materials that can be considered for small wind turbines are aluminum and fiberglass due to heavyweight and then leads to material fatigue (World Wind Energy Association, 2014). Karen (2012) stated carbon fiber has proven to be an enabling technology for the turbine. The wind turbine tower and other components are made of steel. The wire and cable used are copper-clad steel to be more reliable and cost-effective (Malaysian Department of Statistics, 2010; Windpower Engineering, 2011).

The angle of attack, also called pitch, is calculated using wind speed, rotating blade velocity, and pitch angle, $\beta$ as follows:

$$v_r = \sqrt{v_\infty^2 + (\omega R)^2} \quad (6)$$

$$\alpha = sin^{-1}(v_\infty / v_r) - \beta \quad (7)$$

The angle of attack results in the coefficients of lift and drag. The coefficients of lift and drag can then be calculated using:

$$C_L = C_N \cos\alpha + C_T \sin\alpha \quad (8)$$

$$C_D = C_N \sin\alpha - C_T \cos\alpha \quad (9)$$

The coefficients of thrust and torque can then be determined using:

$$C_{thrust} = C_L \cos(\alpha + \beta) + C_D \sin(\alpha + \beta) \quad (10)$$

$$C_{torque} = C_L \sin(\alpha + \beta) - C_D \cos(\alpha + \beta) \quad (11)$$

(Merle et al., 2016).

The chord length of a blade is defined as the distance between the leading edge and trailing edge. The chord length of a blade contributes torque and thrust, and the formulae are as follows:

$$F_{thrust} = 0.5 C_{thrust} \rho v^2 c \quad (12)$$

$$F_{torque} = 0.5 C_{torque} \rho v^2 c \quad (13)$$

$$T = F_{torque} R \quad (14)$$

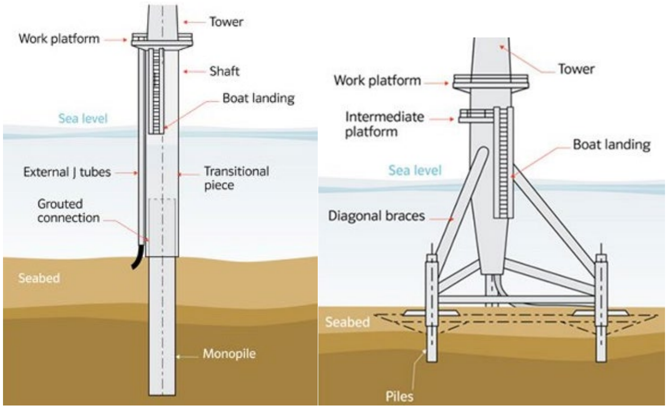


**Figure 4.** The monopile and tripod foundation (4C Offshore, 2013a)

(Merle et al., 2016).

Foundations used on offshore wind projects today are monopile, gravity foundation, tripod foundation, and tension leg platform. Monopile foundation is made of either concrete or steel which is driven approximately 10 meters to 20 meters into the seabed and depending on soil condition, and it is suitable for water depth up to 30 meters. Similarly, the tripod foundation consists of steel tripod and concrete piles, and it is suitable for a range of water depths from 25 meters to 40 meters. Energy generation from solar (Ahmed et al., 2017, 2019; Ashraf et al., 2021; Chowdhury and Kashem, 2018; Hong et al., 2018; Karuppasamy et al., 2020; Kashem et al., 2020a; Kho et al., 2017; Mubarak and Kashem, 2016; Sheikh et al., 2017; Tabassum et al., 2017; Touati et al., 2020), wind (Kashem et al., 2020b; Khandakar and Kashem, 2020; Safe et al., 2014), and biomass (Kashem et al., 2020c, 2020d, 2020e; Siddique et al., 2017, 2018) have advantages and disadvantages. Similarly, Hydropower has pros and cons (Azmi et al., 2017; Kashem et al., 2018a, 2020f). The proper way of energy distribution and considering economic and environmental impact may mitigate the drawbacks (Kashem et al., 2018b, 2021a; Tabassum et al., 2016, 2018). Moreover, people can use less energy through green buildings (Che Hamzah et al., 2020; Kashem et al., 2021b; Shabrin and Kashem, 2017; Shabrin et al., 2017). According to researchers, wind energy is still the best way to harness renewable energy.

A gravity foundation is a large base constructed on the seabed that is made of either concrete or steel to allow the wind turbine remains erect.

The tension leg platform consists of piles driven into the seabed, tension legs to secure the wind turbine, and buoyant hull supports. The mooring tension leg platform allows horizontal movement due to wave disturbances but does not allow vertical movement. Wang and Fan (2015) stated tension leg platform is cost-effective when the water depth reaches 50 meters.

Sematan is a fishing village where approximately 67.5 kilometres away from the state capital Kuching with a population of 7602 (Malaysian Department of Statistics, 2010). The energy usage over a year in Sematan is **Figure 7**. The availability of wind energy in Sematan is studied through weather information (Climate History for Kuching, 2016).

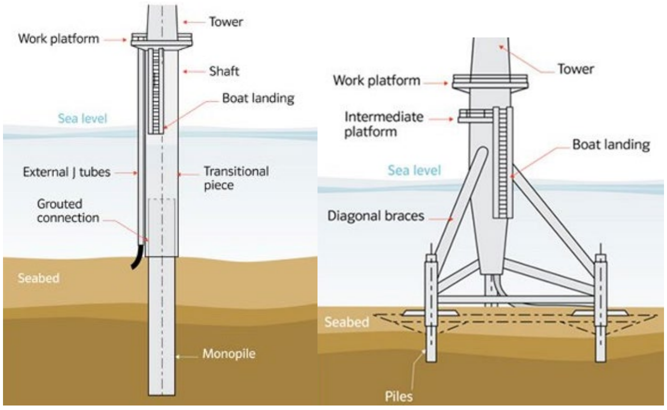


**Figure 5.** The gravity foundation (Wind Energy – The Facts, 2009)

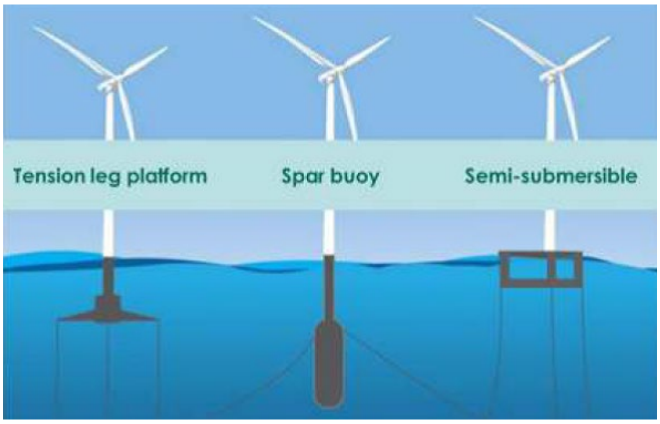


**Figure 6.** The types of tension leg platforms (Charles, 2014)

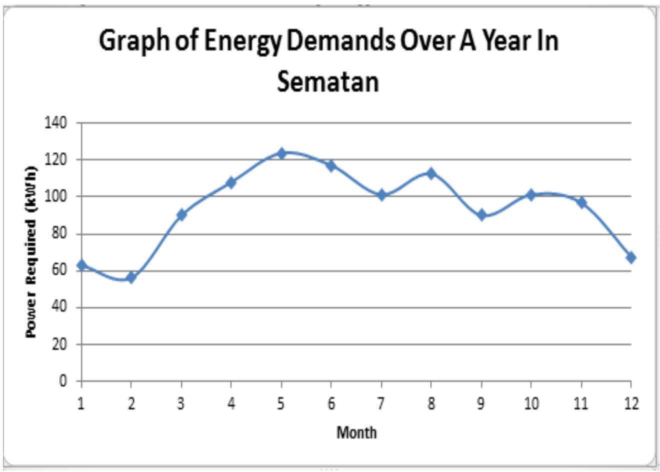


**Figure 7.** The graph of energy demands over a year in Sematan

## RESULTS OF PERFORMANCE ANALYSIS OF HAWT AND VAWT

Inflow simulation of the turbines, several parameters have been considered. The wind flow at the velocity of 1.389 m/s or 5 km/h from one direction and 1.225 kg/m$^3$ of air density have been used. The performance analysis for each turbine is evaluated based on its pressure and velocity generated.

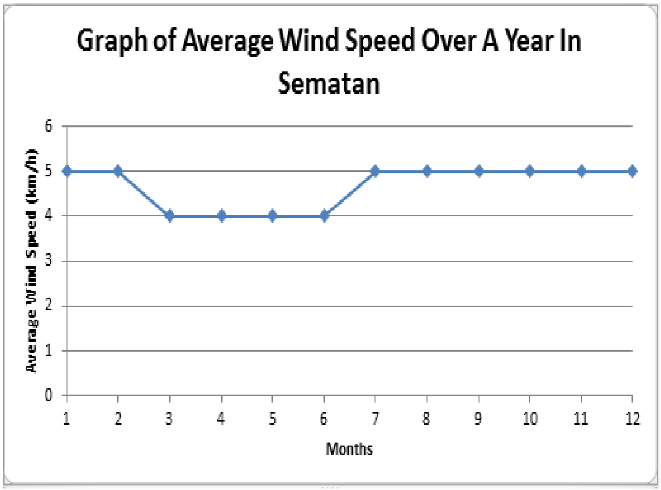


**Figure 8.** The graph of the average wind speed over a year in Sematan

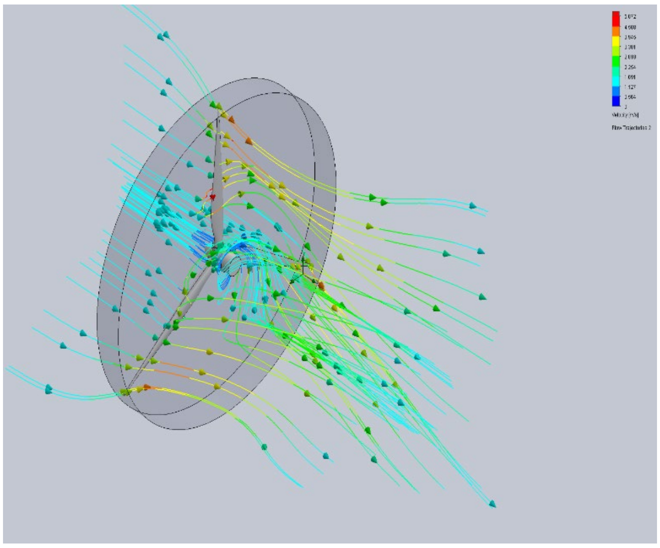

**Figure 9.** The velocity analysis of HAWT

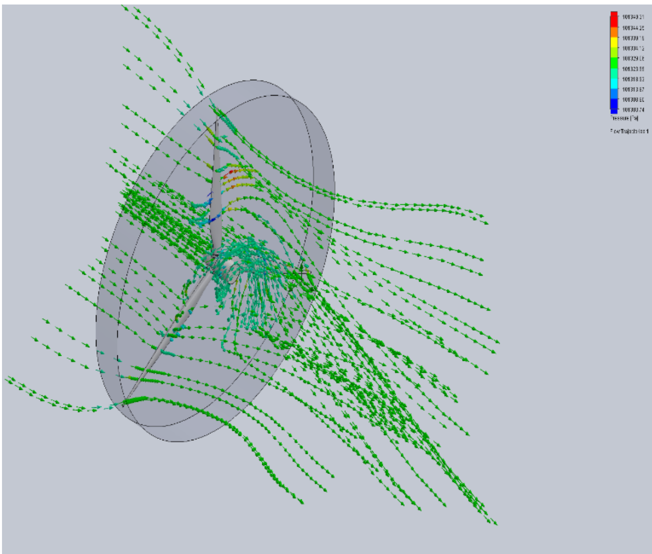

**Figure 10.** The pressure analysis of HAWT

**Figures 9** to **14** show the velocity and pressure analysis for HAWT and VAWT.

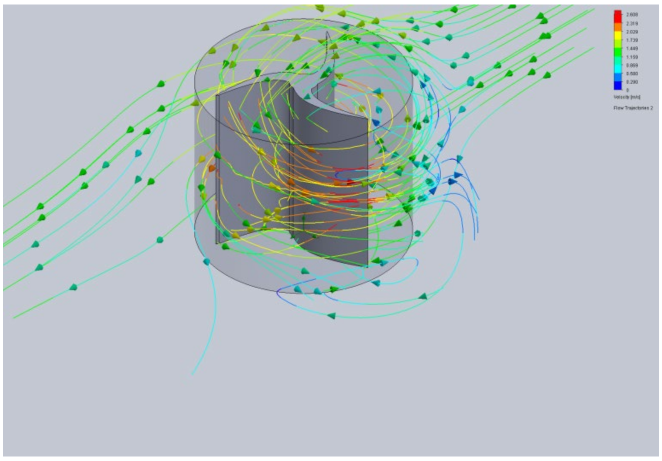

**Figure 11.** The velocity analysis of the Savonius wind turbine

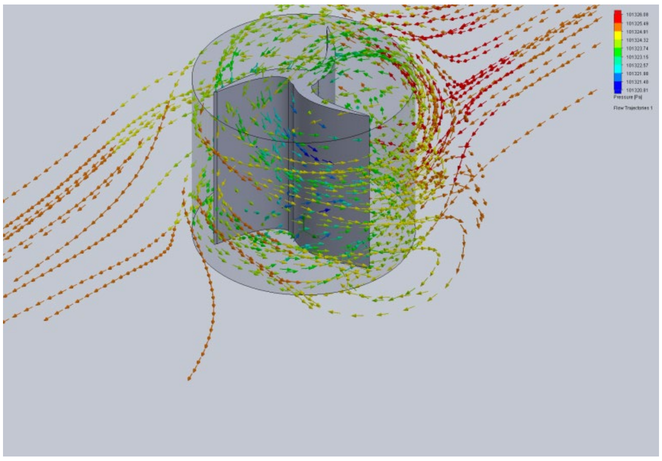

**Figure 12.** The pressure analysis of the Savonius wind turbine

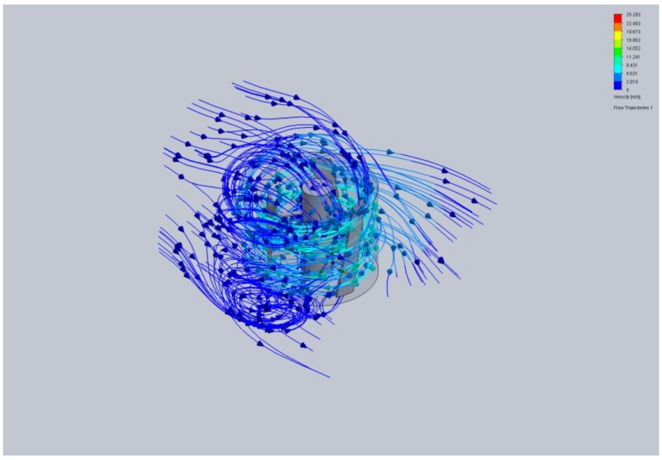

**Figure 13.** The velocity analysis of the Darrieus wind turbine

### Horizontal Axis Wind Turbine (HAWT)

The dimension of HAWT is 10m diameter by 1m depth. The swept area covered by HAWT is 78.53 $m^2$.

### Vertical Axis Wind Turbine (VAWT)

#### *Savonius wind turbine*

The dimensions of VAWT, Savonius wind turbine is 1m diameter by 1m height. The swept area covered is 1 $m^2$.

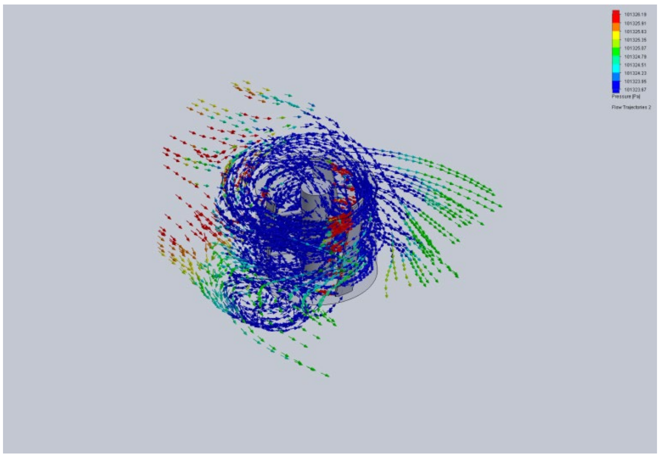

**Figure 14.** The pressure analysis of the Darrieus wind turbine

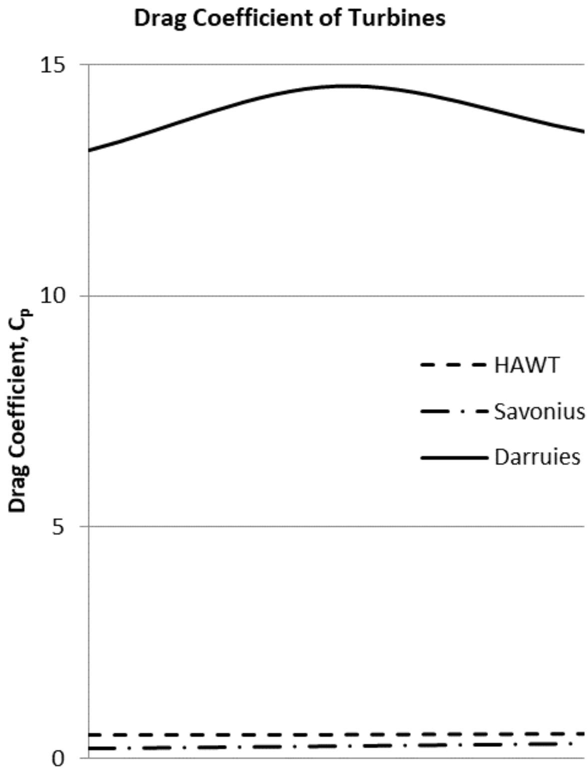


**Figure 15.** The comparison of the drag coefficient of each turbine

#### *Darrieus wind turbine*

The dimensions of VAWT, Savonius wind turbine is 1m diameter by 1m height. The swept area covered is 0.65 $m^2$.

## DISCUSSION OF PERFORMANCE ANALYSIS OF HAWT AND VAWT

From **Tables 1-3**, it has been found that the maximum and average velocity of VAWT– Darrieus shows a higher drag coefficient compared to HAWT and VAWT–Savonius. The maximum pressure of HAWT shows a higher drag coefficient compared to VAWT– Darrieus and VAWT–Savonius. However, average drag force of VAWT– Darrieus shows a higher drag

**Table 1.** Performance analysis of HAWT

| | Minimum | Maximum | Average |
|---|---|---|---|
| **Velocity (m/s)** | 0 | 5.072 | 2.536 |
| **Pressure (Pa)** | 101303.74 | 101 349.31 | 101326.52 |
| **Drag force (N)** | 0.5985 | 0.6407 | 0.6116 |

**Table 2.** Performance analysis of VAWT – Savonius Types

| | Minimum | Maximum | Average |
|---|---|---|---|
| **Velocity (m/s)** | 0 | 2.608 | 1.304 |
| **Pressure (Pa)** | 101 320.81 | 101 326.08 | 101323.445 |
| **Drag force (N)** | 0.247805 | 0.368880 | 0.30785 |

**Table 3.** Performance analysis of VAWT – Darrieus Types

| | Minimum | Maximum | Average |
|---|---|---|---|
| **Velocity (m/s)** | 0 | 5.621 | 2.8105 |
| **Pressure (Pa)** | 101 323.71 | 101 326.19 | 101324.95 |
| **Drag force (N)** | 15.54959 | 17.17494 | 16.026627 |

**Table 4.** Drag Coefficient Analysis of Turbines

| Drag Coefficient, ($C_p$) | Minimum | Maximum | Average |
|---|---|---|---|
| **HAWT** | 0.5064 | 0.5421 | 0.5175 |
| **VAWT–Savonius** | 0.2097 | 0.3121 | 0.2605 |
| **VAWT– Darrieus** | 13.1586 | 14.5330 | 13.5622 |

coefficient compared to HAWT and VAWT–Savonius. The drag coefficient of the turbine can be further calculated from the value of drag force using equation (5) which is depicted at **Table 4**. According to equation (5) the value of Cp could be increased corresponding the value of the velocity.

## CONCLUSION & FUTURE WORK

To conclude, it is well known that HAWT has better output power performance than VAWT in normal condition. However, Darrieus of VAWT shows a higher drag coefficient compared to HAWT and VAWT–Savonius. This paper includes the comparison of the turbines in terms of maximum and minimum Velocity (m/s), Pressure (Pa), Drag force (N) and Drag Coefficient, (Cp). The mesh independency, energy analysis, optimization and CFD analysis will be included in future work. Since Sematan is a fishing remote village in Sarawak, Malaysia and population is only 7602, a wind firm can support their electricity need efficiently. Therefore, this paper proposes building a wind farm in Seamatan to support the community. The average wind speed in Sematan is highest in Sarawak, Malaysia ranging from 4 km/h to 9 km/h. Hence, in the Sematan profile, the most suitable turbine is VAWT – Darrius as it provides better performance.

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**Declaration of interest:** The authors declare that they have no competing interests.

**Ethics approval and consent to participate:** Not applicable.

**Availability of data and materials:** All data generated or analyzed during this study are available for sharing when appropriate request is directed to corresponding author.

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